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FATIGUE OF ALUMINUM STRUCTURAL WELDMENTS

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FATIGUE OF ALUMINUM STRUCTURAL WELDMENTS

As the speed and displacement of high-speed aluminum craft continues to increase, so do the fatigue related cracking problems. At present, most owners treat this problem as a maintenance issue and simply repair the cracked structure. This report attempts to shift the emphasis of this problem from maintenance to design. It allows owners to address fatigue related cracking problems during the design of the vessel and avoid the costly repairs associated with continued re-welding of fatigue cracks in structures. This report addresses loads acting on high-speed craft and identifies the state-of-the-art as well as "holes" in the data required to develop a complete and consistent set of fatigue calculations for aluminum in the marine environment.

The report also addresses the damage tolerances of cracked aluminum structures and provides information that will help designers and engineers determine the urgency with which a specific crack may need repair. Information on the fatigue design practices and design codes of other aluminum industries are included to provide helpful insight while more data is developed for the marine industry and aluminum high-speed craft. The report concludes with recommendations for continued research and development based on the holes identified during the development of the current effort.

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16. Abstract

As the speed and displacement of high-speed aluminum craft continues to increase so to do the fatigue related cracking problems. At present, most owners treat this as a maintenance problem and simply repair the cracked structure. This report attempts to shift the emphasis of this problem from maintenance to design. It will allow owners to address fatigue related cracking problems during the design of the vessel and avoid the costly repairs associated with continued re-welding of fatigue cracked structure. The report addresses loads acting on high-speed craft and identifies the state of the art as well as "holes" in the data required to develop a complete and consistent set of fatigue calculations for aluminum in the marine environment.

The report also addresses the damage tolerance of cracked aluminum structure and provides information that will help designers and engineers determine the urgency with which a specific crack may need repair.

The report also identifies and provides information on the fatigue design practices of other aluminum industries and design codes. This provides helpful insight while more data is developed for the marine industry and aluminum high-speed craft.

The report concludes with recommendations for continued research and development based on the holes identified during the development of the current effort.

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CONVERSION FACTORS
(Approximate conversions to metric measures)

To convert from	to	Function	Value
LENGTH			
inches	meters	divide	39.3701
inches	millimeters	multiply by	25.4000
feet	meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
$inches^2$ feet	$centimeters^2$ meters	multiply by	1.9665
$inches^2$ feet	$centimeters^3$	multiply by	196.6448
$inches^3$	$centimeters^3$	multiply by	16.3871
MOMENT OF INERTIA			
$inches^2$ $feet^2$	$centimeters^2$ meters	divide by	1.6684
$inches^2$ $feet^2$	$centimeters^4$	multiply by	5993.73
$inches^4$	$centimeters^4$	multiply by	41.623
FORCE OR MASS			
long tons	tonne	multiply by	1.0160
long tons	kilograms	multiply by	1016.047
pounds	tonnes	divide by	2204.62
pounds	kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
$pounds/inch^2$	$Newtons/meter^2$ (Pascals)	multiply by	6894.757
kilo $pounds/inch^2$	mega $Newtons/meter^2$ (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tonnes	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo $pound/inch^2$ $in\sqrt{in}$)	mega Newton $MNm^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	$Joules/mm^2$	multiply by	0.1753
kilo pound/inch	kilo $Joules/m^2$	multiply by	175.3

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AA Aluminum Association

AAR Association of American Railroads

ABS American Bureau of Shipping

CEN Comit Europ en De Normalisation (European Committee For Standardization)

DNV Det Norske Veritas

HAZ Heat Affected Zone

Δ Displacement of vessel

$\Delta\sigma$ Stress range

η Fatigue usage factor for Palmgren-Miner summation

σ_a Stress amplitude

σ_m Mean stress or membrane stress

σ_{min} The minimum stress occurring in a stress range

σ_{max} The maximum stress occurring in a stress range

υ Zero crossing frequency or Poisson’s ratio

ω Wave frequency

ω_e Wave encounter frequency

θ Angle of attack between ship and wave

a crack length or one-half crack length depending on definition

da/dN Crack growth rate per cycle of loading

$f(\sigma_a)$ Long term response of the stress amplitude

f_* Probability density function for short term stress response

g acceleration due to gravity

k Number of stress blocks or ranges for use in the Palmgren-Miner summation

m Experimentally determined material constant for linear region of da/dN vice ΔK crack growth curve

m moment associated with a sea state spectrum

n_* Average number of responses per unit time for short term response

n_i number of stress cycles in block i for Palmgren-Miner summation

p_x weighting factors for various sea states

r_x weighting function for crossing rates

r_y Crack tip plastic zone size

A_x Stress function per unit load application for spectral analysis

B Specimen thickness

C Experimentally determined material constant for linear region of da/dN vice ΔK crack growth curve

CTOD Crack Tip Opening Dimension used in fracture mechanics

D Accumulated fatigue damage in Palmgren-Miner summation

F_b Allowable working stress

F_m Ultimate tensile strength of the material

F_y Yield strength of the material

$F_{\Delta\sigma}$ Short term and long term stress range distribution

H_s Significant wave height

H_x Transfer functions for spectral analysis

K Crack tip stress intensity

K_I Crack tip stress intensity for Mode I failure

ΔK Range of crack tip stress intensity experienced during fatigue cycling

K_x	Stress concentration or notch factors
L	Length of vessel
N	The number of cycles associated with a fatigue spectrum
N_i	Number of cycles to failure in stress block i for Palmgren-Miner summation
R	Stress ratio of $\sigma_{min}/\sigma_{max}$
S	The stress associated with a fatigue spectrum
S_η	Sea state
S_σ	Stress spectrum associated with a given sea state
T_z	Zero crossing period
V	Speed of vessel
Y	Geometric factor used to calculate the crack tip stress intensity factor, K

Executive Summary

This report provides an initial data gathering effort for the fatigue and damage tolerance analyses of aluminum weldments in high-speed craft. It has confirmed that there are gaps in the data required to perform these analyses and recommends actions to help alleviate these gaps, including further research and testing.

To help designers of high-speed craft, this report also presents a number of fatigue design standards. This includes a proposed standard to be released later this year by DNV as well as three standards from other industries. Although not consistent with the maritime industry, these other standards provide good insight to the problem of fatigue and how to account for its action during the initial design stages.

For the damage tolerance analysis, this report recommends material testing to generate the necessary fatigue crack growth rate and other data. Testing is also recommended to determine the most suitable fracture-toughness criteria for the marine grade aluminum alloys. In addition, this report provides a preliminary comparison of available fatigue/fracture software packages and proposes a program to evaluate the packages and identify those most suitable for the subject application.

1. Introduction

1.1 Fatigue and Damage Tolerance Analysis Background

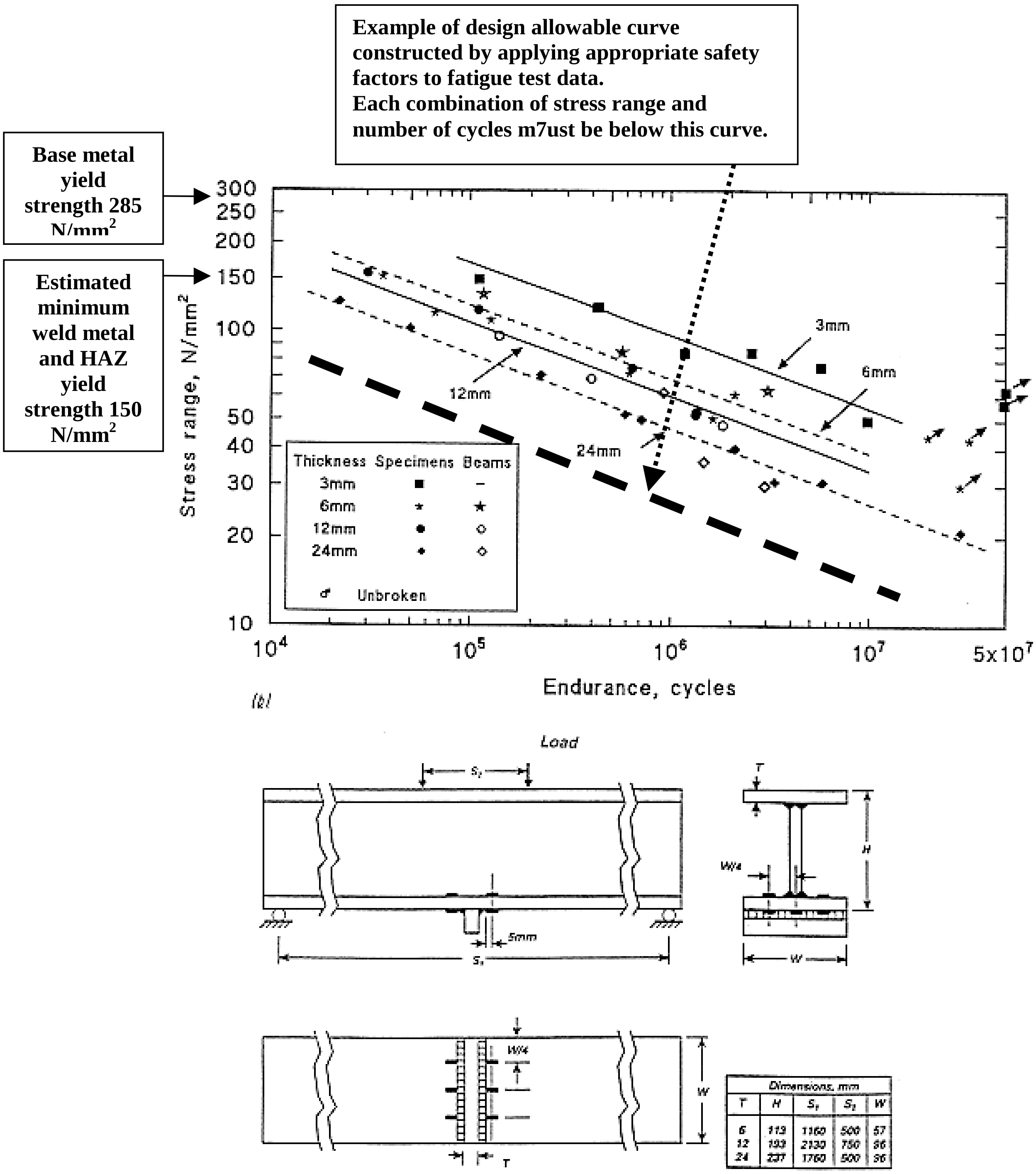
This report addresses fatigue and damage tolerance analysis requirements for weldments in high-speed aluminum vessels. Specifically, it discusses the availability of design information and material property data required for these analyses. These issues have been addressed at length for the steels used in traditional monohulls and for high-strength aerospace aluminum alloys, but not to the same degree for the marine grade aluminum alloys being used in high-speed vessels. Some of the typical alloys used by the subject industry are listed in Table 1–1, [1-1].

The term "fatigue design" in this report refers to the evaluations conducted during ship design to prevent fatigue crack initiation in structural members. Such cracks typically initiate under normal cyclic loads at stress concentrations such as changes in geometry (e.g., notches, corners, weld toes, brackets, cutouts, etc.) or weld discontinuities (e.g., porosity, slag inclusions, microcracks). Determination of allowable fatigue stresses is accomplished through use of design fatigue curves (S/N curves) an example of which is shown in Figure 1-1, [1-2]. This figure illustrates the point that the S/N region of primary concern covers moderate to high number of cycles. The nominal stresses associated with these cycles are governed by the allowable design stresses, i.e., the long-term damaging fatigue cycles occur under the action of nominal stresses that satisfy the allowable stress design algorithms associated with most design codes. Although the nominal stresses are elastic, fatigue damage results from cyclic plastic deformation at the roots of stress concentrations or crack tips. This plasticity is not specifically considered in S-N or nominal stress fatigue analysis, but must be addressed in certain cases for damage tolerance analysis as discussed below. The S-N curves should be based on axial or bending fatigue tests of welded details rather than rotating beam tests of smooth or notched specimens. The axial or bending tests better simulate actual loading, and testing of a welded detail includes the base metal, weld metal, weld defects, and base metal heat-affected-zone (HAZ) as well as geometrical stress concentration and residual stress effects. Primary test variables are the R ratio (ratio of minimum to maximum fatigue stress), test frequency (Hz), and environment (air, seawater spray, seawater immersion or temperature).

If the design shows that fatigue cracks may initiate at certain details and it is not practicable to modify the detail, damage tolerance analysis, using fracture mechanics techniques, is used to determine the time for first inspection of the detail. This will allow corrective action (removal from service or weld repair) to be taken before the crack reaches a critical size. Growth of the crack to critical size could cause brittle fracture, ductile tearing, large-scale yielding/overload failure, or buckling. Discussion is presented regarding the determination of critical crack size and failure criterion and its dependence on the specific detail and application being evaluated. If structural cracks are found during service, these same techniques can be used to assess the suitability of the cracked structure for continued service and the interval for the next inspection. It should be noted that field weld repair of cracks may not necessarily extend service life because new fatigue cracks may initiate from weld defects, and crack growth rates may increase from the presence of weld residual stresses [1-3]. Thus, damage tolerance analysis will be beneficial if it shows a cracked detail is suitable for continued service in which case repairs can be delayed until they can be made under more controlled conditions.

Table 1–1 Commonly used Marine Grade Alloys

Form	Grade and Temper	Typical Yield Strength (ksi)	Typical Tensile Strength (ksi)
Plate	5083-H116	33.4	45.7
	5086-H116	29.7	42.1
	5454-H34	34.8	44.2
	5456-H116	37.0	50.8
	6061-T6, T651 (also shapes and tube)	39.9	45.0
Extruded shapes	5086-H111 or H112 (also tube)	18.9 (H112)	39.2 (H112)
	5454-H111 - H112	26.1 18.1	37.7 36.3
	5456-H111 or H112	23.9 (H112)	45.0 (H112)
Tubing	5086-H34	37.0	



Dimensions, mm				
T	H	S_1	S_2	W
6	113	1160	500	57
12	193	2130	750	86
24	237	1760	500	96

Figure 1-1 S/N curve for welded 6061-T6 Aluminum beam in bending

1.2 Objectives

In accordance with the Statement of Work for this task, the objectives of this report are threefold:

1. Assist the designers and fabricators of high-speed vessels by providing information on the fatigue of commercial aluminum structural details.
2. Develop database fatigue design criteria for both the design and damage tolerance analysis of welded aluminum ship structures.
3. Enhance the durability, reliability, efficiency and safety of aluminum structures. Assist in the growth of the high-speed ship industry in North America, helping to produce ships that will be structurally reliable but have low hull weight.

The authors of this report also felt that it is a good platform for the dissemination of some fundamental information regarding the concepts of fatigue, fracture mechanics and damage tolerance. Fatigue cracks have typically been viewed as a maintenance problem and the issue of fatigue was not addressed during the design cycle. It is only during recent history that the concepts of fatigue and fatigue avoidance have entered the design phase of surface ships. This has been promulgated by the increasing number of structural fatigue cracks in large displacement monohull vessels classed for open-ocean, unrestricted service. As a result the designers of these vessels have begun to develop fluency with the concepts of fatigue, fatigue avoidance, damage tolerance and related issues. As these problems continue to escalate in the high-speed community the authors thought it would be important to introduce the concepts behind fatigue as well as the desire to address this problem during the design phase of these vessels.

A literature survey was conducted to help determine the state-of-the-art of information regarding both fatigue and damage tolerance analysis of aluminum. As a result of this survey and other information gathered during the task, it became apparent that there are gaps in the information required to perform these analyses. Identifying these gaps and a program to gather or develop the necessary data is also included in this report. The gaps in the data required to perform the fatigue and damage tolerance analyses preclude the development of a meaningful database for use in these analyses. Therefore, discussion and samples are provided of similar data and procedures used by other industries. It is suggested that a true database for aluminum high-speed craft can be developed after the appropriate data has been developed for this specific application.

In addition to the information provided for the designers to assist in the fatigue and damage tolerance analysis this report also presents a variety of ideas for use by fabricators to help extend or improve the fatigue life of a detail thereby enhancing the service life of the vessel. These suggestions include the investigation of new aluminum alloys specifically developed for the marine environment.

As discussed in the third objective, it was the intention of this project to assist in the growth of the high-speed craft industry. Much of the research focused on high-speed ferries due to their emergence in the market place and the fatigue related problems that these craft have been experiencing. Regardless, the information presented herein is of a general nature and should be adaptable to a wide range of applications. This information should provide designers insight into the fatigue problem and allow them a variety of alternatives for fatigue and damage tolerance analysis associated with aluminum high-speed craft.

It is also worth recognizing that the focus of this document is towards the designer and fabricator, i.e., the primary objective is for implementation of fatigue and damage tolerance into the design and build processes. This helped to streamline the report in a direction that would satisfy this goal without extraneous technical derivation which, it was felt, often hinders the use of such a document intended for use during the design process.

1.3 Why Aluminum?

In terms of tonnage, steel is used for a far greater percentage of the maritime vessels than aluminum. Steel is cheaper than aluminum, more forgiving to production, fabrication and welding induced flaws and more tolerant to damage. In addition, steel is stronger than aluminum and does not lose any of its strength in the Heat Affected Zone of the weldment, as does aluminum. The interest in aluminum is directly related to the marketplace addressed by this report, i.e., the high-speed craft market.

To satisfy the “need for speed” in this market owners seek every advantage to minimize a vessel’s weight which is precisely the advantage that aluminum brings to the high-speed craft industry, reduced weight. Aluminum has approximately one-third the density of steel and 70% of its tensile strength. This allows for the production of aluminum high-speed craft with a lower structural weight than a similar vessel constructed from steel. For a given displacement, the reduction of hull structural weight allows for increased payload, typically fare-paying passengers in the high-speed ferry industry.

Aluminum has been used in the shipbuilding and marine industries for over 40 years and in recent history its use for high-speed ferries has been on the rise. As the speed and displacement of these vessels continues to grow, so too do the fatigue problems related to the aluminum details.

In accordance with Figure 1-2 [1-4] it can also be seen that the cost of aluminum has come down significantly from the late 1980's and early 1990's when there was a sharp spike in its cost to approximately $1.10 per pound. In 1998, the latest year for available data, the price of aluminum was approximately $0.63 per pound. This reduction in price for aluminum makes a more attractive hull girder material when combined with the market forces for "higher speeds, larger vessels and decreased hull structural weight."

1.4 Welding of Aluminum

Wrought aluminum alloys, as shown in Table 1–2 [1-5], are either non-heat-treatable or heat-treatable. The non-heat-treatable alloys are solution-strengthened, primarily, by magnesium. These alloys are work-hardenable but can be annealed. The weld heat-affected zone (HAZ) will have the strength of the annealed alloy.

The heat-treatable alloys are strengthened through solution heat-treating, i.e.; precipitation hardening followed by either natural or artificial aging. The solution-strengthening agent may be magnesium, copper, zinc, or silicon. Welding will overage the heat-treated material in the HAZ and the HAZ will be softened significantly.

Table 1–2 Composition of Aluminum Alloys and Their Heat Treatment

Wrought Aluminum Alloy Group	Series	
	Non-heat-treatable	Heat-treatable
Aluminum	1xxx	
Aluminum + Copper		2xxx
Aluminum + Manganese	3xxx	
Aluminum + Silicon (Si)		4xxx
Aluminum + Magnesium (Mg)	5xxx	
Aluminum + Mg + Si		6xxx
Aluminum + Zinc		7xxx

The acceptable fusion welding processes for wrought aluminum alloys include gas metal arc, gas tungsten arc, and resistance (spot and seam). Shielded metal arc and gas welding are used only when quality is not essential. Submerged arc welding is never used. High welding speeds are preferred to restrict heat input and reduce the width of the HAZ. Effect of heat increases with thickness. Oxidation of aluminum is one of the major problems in obtaining a sound weld. Aluminum-oxide films must be removed before welding.

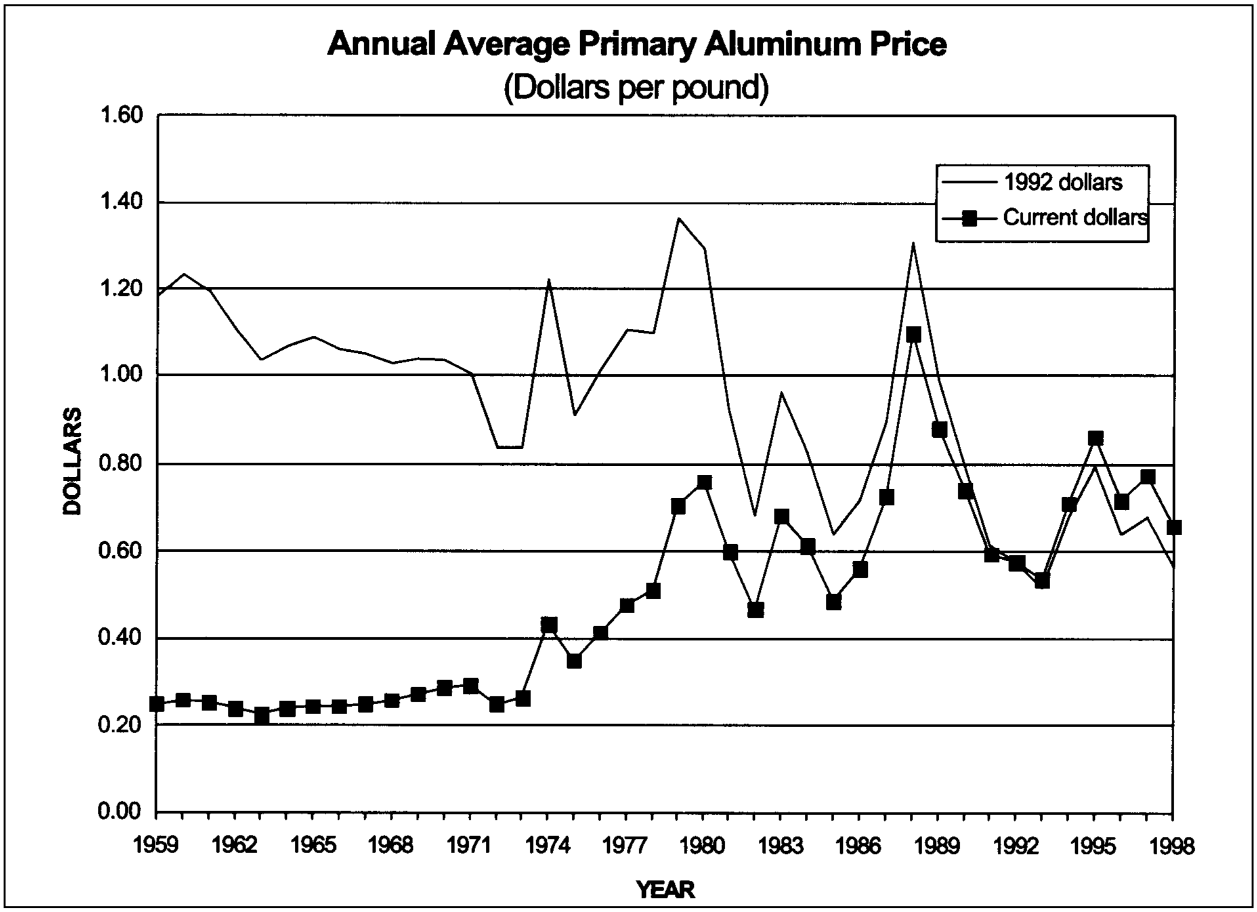


Figure 1-2 Annual Cost of Aluminum

1.5 Summary of Report

This report is organized to follow the same progression as typically envisioned for the fatigue and damage tolerance phenomenon, i.e., discussion on loading, which is a central issue for both, precedes fatigue which is followed by damage tolerance.

Section 2 presents discussion on the loads acting upon a high-speed craft. The loads experienced by a vessel are central to the entire discussion of fatigue and damage tolerance and led to the decision to present this information up front. Global loads resulting from the environment as well as secondary loads resulting from the environment and mission or payload of the vessel are both discussed. Section 2 also presents discussion regarding the relative influence of the primary and secondary loads on high-speed craft and the manner in which they differ from the typical applications associated with large monohulls classed for unrestricted, open ocean service. Section 2 also recognizes that most of the existing fatigue failures are a result of local excitation from machinery or other mechanical systems but suggests the increasing role of primary structural response as vessel lengths continue to increase.

Section 3 presents discussion on fatigue beginning with a brief review of this subject and some of the concepts central to a basic understanding of the causes of fatigue induced cracking. Discussion is presented on the effects of mean stress, stress ratio and stress range on the fatigue behavior of aluminum along with the effects of alloy composition on fatigue behavior. An introduction to the mechanics associated with crack initiation, propagation and failure is also presented. Discussion on Safe-Life and Fail-Safe design philosophies is presented along with a summary of current experience gained with a variety of new aluminum alloys developed specifically for the marine environment and shipbuilding. Finally, Section 3 introduces the work being developed for the friction stir welding of aluminum alloys for use in the marine industry.

Section 4 continues with methodologies used to develop the necessary input for a fatigue analysis. This includes cycle counting methods and the use of probability distribution functions for load or stress histogram development, stress calculation techniques and the importance of nominal stress and hot-spot stress calculations.

Section 5 introduces design standards used by a variety of industries for the fatigue design of aluminum. These include the DNV Fatigue Analysis of High-Speed Craft scheduled for release later this year as well as three other design codes from outside of the marine industry. At this time, DNV is the only maritime classification society with a set of rules developed to specifically address the concerns of aluminum fatigue in high-speed vessels.

Section 6 of this report discusses damage tolerance analysis and the techniques available to determine the time to failure for a crack in a given detail. It also discusses some of the differences between steel and aluminum and the reason for different damage tolerance assessment techniques for the two materials. Of the design codes reviewed for this task only one, EuroCode 9, contains any information concerning crack growth rate and actual calculation procedures for this aspect of the problem. Discussion is presented regarding EuroCode 9 along with information in Appendix C. Section 6 also provides preliminary discussion on a variety of software packages developed to analyze fatigue and fracture mechanics.

Section 7 concludes this report with recommendations for continued research and future development tasks. It introduces the concept of Service-Life, an extension of the Safe-Life and Fail-Safe design philosophies already used for damage tolerance analysis.

1.6 Conclusions

As with any introductory task it is impossible to conduct a complete screening of all possible sources and resources of relevant information. Additional information may still be gained through research of the auto and aerospace industries. However, with environments so divergent from the marine industry it is not likely that any data would be completely consistent with the maritime requirements. Similar to the information uncovered from other outside industries it would require interpretation for application to the current concern. Additional investigation of research and development being undertaken around the world is also suggested as this did prove to be a valuable source of information and current studies. Regardless, this report presents good, representative data for the state of affairs regarding the fatigue design of aluminum weldments in high-speed craft. It also presents good information for the designers of such craft to help avoid the problems associated with fatigue during the early design stages.

In order to help the designer with the development of fatigue analyses for aluminum weldments, this report presents basic discussion concerning the issue along with guidelines from other design standards. Included in these standards are:

- DNV Fatigue Analysis of High-Speed Craft.
- Aluminum Design Manual from the Aluminum Association. See Appendix B.
- EuroCode 9: Design of Aluminum Structures – Part 2: Structures Susceptible to Fatigue from the European Committee for Standardization. See Appendix C.
- Manual of Standards and Recommended Practices, Section C – Part II from the Association of American Railroads. See Appendix D.

The DNV document is scheduled for release later in 2000 and is not available for general usage at the time this report was written. None of these design codes presents complete information required for the fatigue design of aluminum weldments in the marine environment. Each of them presents good and useful information that may be of assistance for a specific design. The user needs to recognize the application of the respective standards compared to the chosen use in the marine environment and select factors of safety accordingly.

Another consideration for designers is the use of new aluminum alloys developed specifically for the marine environment. This report discusses three such alloys:

- AA5383 [1-6]
- RA7108 [1-7]
- AluStar5059 [1-8]

All three have been developed in recent years and have been certified for use by DNV and various other classification societies such as Bureau Veritas, Lloyd's Register, Germanischer Lloyd's and the Korean Register. ABS is also investigating some of these new materials for certification in accordance with their rules.

Research undertaken for this report has discovered that not all the information required to perform fatigue and damage tolerance analyses exists for aluminum weldments in the high-speed craft industry. These "gaps" in the data have been identified and recommendations suggested to alleviate these shortcomings.

1.7 References

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2. Prediction of Loads on High Speed Craft

2.1 Introduction

Before proceeding to the fatigue or damage tolerance analysis addressed by this report, discussion is presented regarding the loads and load spectra acting on high-speed craft.

Definition of the loading environment is required for both fatigue and damage tolerance analysis. In general, the loading data required to perform the fatigue and damage tolerance analyses for high-speed craft was found to be lacking. Research conducted for this report revealed very little long-term loading information collected on high-speed craft. General methodologies do exist for the determination of global loads acting on a vessel but most of this has been developed for larger, displacement monohulls. Very little information was discovered to quantify the various secondary loads, their phasing with primary loads and the number of cycles associated with each. For shorter craft with relatively smaller primary loads and stresses it will be necessary to gather more information regarding secondary loads as they can form the major component of the stresses acting throughout the vessel. Some loading information reflecting short-term data was discovered for a number of high-speed craft operating in the waters off the Scandinavian countries however, there was not enough data collected in this sample to be of any use for this task.

In order to fully develop all the loading information required for high-speed vessels, it is necessary to instrument various craft operating in different regions. This can be augmented with laboratory testing to measure loads associated with vessel accelerations, payloads, i.e., wheeled vehicles on ferries, sloshing loads, etc.

2.2 Definition of High Speed for High-Speed Craft

In order for a vessel to be considered high-speed it must satisfy a given condition as defined by the various classification societies. In accordance with DNV [2-1], a vessel is considered high speed when it satisfies the following equation:

$$V = 7.16\Delta^{0.1667} \tag{2.1}$$

where V is the speed of the vessel in knots and Δ is the displacement of the vessel, in metric tonnes corresponding to the design waterline.

In accordance with ABS criteria [2-2], a vessel is defined as high speed when it satisfies the equation:

$$V = 2.36\sqrt{L} \tag{2.2}$$

Again, V is defined as the design speed of the vessel in knots and is generally the maximum speed in calm water. L is the length of the vessel in meters and is defined in section 3/1.1 of reference [2-2]. For L defined in feet the coefficient on the right hand side of equation 2.2 is 1.30, i.e., $V = 1.30\sqrt{L}$.

The rules associated with other societies need to be checked for the relevant definition of a high-speed vessel.

2.3 Definition of Primary and Secondary Loads

The definitions of primary and secondary loads used throughout this report are the same as those generally accepted for the design of monohulls and other surface ships. Primary loads are the bending moments and shear forces acting on the hull girder of the vessel as a result of its operation in a seaway. They are a result of the buoyancy forces and gravity forces acting along the length of the ship. The primary loads result in three components of bending moment and their associated shearing forces. These moments are vertical, transverse and torsional. Typically, only one component of these moments will govern the design of a vessel. In a displacement type monohull, the vertical bending moment tends to govern the response of the vessel whereas transverse moments tend to govern the design of SWATH and catamaran hullforms. Torsional moments rarely govern the design of any vessel but certainly need to be considered in SWATH and catamaran hullforms. The effects of torsional moments must also be considered in the design of monohulls with large cutouts through their strength decks.

As opposed to the globally acting primary loads, secondary loads act locally. They result from numerous sources but include tank sloshing and overflow loads, inertial loads due to ship motion, wind, snow, ice and other weather effects, loads resulting from the operation of wheeled vehicles onboard the ship, aircraft handling decks, hydrostatic and wave slamming loads acting on the side shell, cargo stowage, mission system and machinery operation loads, etc. The secondary loads often govern the required scantlings in a given area. Depending on the phasing of certain secondary loads it is necessary to combine their effects with the primary loads to develop a complete stress prediction for the ship and its required scantlings.

Both primary and secondary loads play a significant role in the development of the scantlings for a displacement vessel. Similarly, both loading components can have a significant effect on the fatigue of various details depending upon their location in the ship. Discussion is presented below regarding the importance of these two loading components relative to the high-speed craft and the influence they will have on the fatigue and damage tolerance analyses.

2.4 Loads Acting on High-Speed vice Displacement Vessels

For the consideration of fatigue design the loads acting on displacement vessels are fairly well understood. They consist of primary and secondary load components and procedures exist for the analysis of such vessels for consideration of fatigue. The same definition of the loads acting on high-speed vessels and the manner in which they define the fatigue loading environment is not as well understood.

Displacement vessels are typically designed for open-ocean, unrestricted service. The implication for design resulting from this classification requires these vessels to be designed for extreme sea-state conditions. The primary hull girder bending moments are generated to reflect no less than sea-state 7, often sea-state 8 conditions. For the North Atlantic these are defined as:

Sea-State	Significant Wave Height (Meters)	Wind Speed (Knots)
7	6 – 9	48 - 55
8	9 – 14	56 – 63

Not only will the high-speed craft never operate in such extreme environments but they are also significantly shorter in length and would develop smaller primary bending moments even if subjected to these same conditions. Both ABS and DNV recognize the reduced exposure of high-speed vessels compared to the displacement monohulls and allow for classifications considering service area restrictions to account for less severe environments. Table 2.1 in this report is taken from the DNV Rules for High Speed and Light Craft [2-1]. It shows the manner in which service areas other than open-ocean, unrestricted are defined for high-speed craft. Other sections of these rules also allow for the application of reduced primary and secondary loads consistent with these service area definitions.

Therefore, it can be concluded that the magnitude and influence of the primary loads acting on a high-speed vessel should not be as great as those acting on a displacement vessel. The two principal factors accounting for this are the reduced length of the high-speed craft and the less severe operating environments.

The nature and magnitude of the secondary loads acting on high-speed craft also differs from those acting on displacement vessels. Due to their very size, the tank overflow and sloshing loads are quite large on most displacement ships and often govern the design of tank boundaries. Inertial loads on a high-speed craft result more from the high speed of the vessel than from the sea states in which they operate. Similarly, the secondary hydrostatic loads that act on a displacement vessel are associated with the extreme sea states and wave heights encountered throughout the life of the vessel. Local slamming loads are also a function of the adverse sea state conditions in which the ship must operate. For high-speed craft, the secondary hydrostatic loads are associated with the high-speed operation of the craft and reflect the slamming loads due to the increased forward speed. As the operating environment of the high-speed craft worsens, their forward speed is reduced with an associated change in the slamming pressures experienced by the craft's structure. Research needs to be developed to help define the relationship between the inertial and slamming load spectra associated with the high-speed craft as a function of its forward speed. In general, the phasing of primary and secondary loads acting on high-speed craft needs to be addressed to determine the appropriate load cycles and histories.

Not many high-speed craft accommodate flight operations but many ferries experience wheel loads similar to those on displacement vessels. Altogether, it is seen that the nature of the secondary loads acting on high-speed craft differs from those on displacement vessels. In particular, accounting for the different secondary loads acting on the side and bottom shell will help define a critical area for potential fatigue problems.

It is also suggested that the relative magnitudes of the primary and secondary loads acting on high-speed craft differ from displacement vessels. With much lower primary load and stress magnitudes in the high-speed craft, the secondary loads can have a much more significant influence on the selection of scantlings and the overall stress and fatigue environment existing in the craft. Work needs to be done to help define the magnitudes and interaction of the primary and secondary loads acting on the various types of high-speed craft, i.e., the interaction and magnitudes for SWATH or catamaran vessels could be significantly different from those acting on a monohull.

The discussion presented below is based on current technology and design practices regarding displacement vessels. It is augmented to highlight the potential differences that will exist for use with high-speed craft. This discussion is presented herein to provide the designer with a basic understanding of the procedures currently available to displacement designers and the direction required for high-speed research for implementation in the design process.

2.4.1 Increasing Length of High-Speed Craft

Presentations made at the recently conducted 4th International Forum on Aluminum Ships, (New Orleans, May 2000), suggest that most of the fatigue failures currently experienced on aluminum high-speed craft are the result of local vibration problems. This confirms that primary bending does not play a significant role in the fatigue response of aluminum HSC. The fatigue induced cracks are treated as a maintenance issue with cracks continually being repaired as part of the vessel upkeep. There is no effort to address any fatigue issues during the initial design of the vessel. It is the intent of this report to help address these problems during the design stage and reduce the maintenance costs and issues resulting from these problems.

Also addressed at this forum were the continuing trend for increased length and the relatively young age of the aluminum HSC fleet. The average age of an aluminum high-speed vessel is in the range of six years with few vessels exceeding 10 years in service. This too demonstrates the potential for an increasing rate of fatigue induced cracks as the vessels continue to age. The young age of the fleet suggests that while the primary response of the hull girder should be a less significant contributor to the fatigue environment than for monhulls, more time is required to confirm this as typical vessels age into maturity and the expected time for the observance of long-term fatigue related cracking.

The trend toward increasing length of vessels is reflected by DNV which currently classes high speed monohulls and catamarans from 25 meters up to 120 meters in length [2-3]. This includes the Superseacat ferries which are 88 meters long and have a maximum continuous speed of 40 knots [2-4].

In addition to the demand for the increased length of high-speed ferries it is also expected that there will be future investigation of aluminum cargo vessels. The length and displacement of these cargo vessels will exceed the current expectations for ferries and continue to highlight the significance and increased attention on primary loads and their interaction with secondary loads.

2.5 Loading for Fatigue and Damage Tolerance

Fatigue is a metallurgical-level damage response mechanism resulting from cyclic straining. Damage tolerance is the ability of a structure to sustain anticipated loads in the presence of fatigue, corrosion or other damage.

As related to this report, fatigue and damage tolerance are part of the same loading history for the vessel. They both represent the response of the vessel's structure subjected to the cyclic loading environments inherent throughout a ship or high-speed craft. The loads of principal interest to this report are the primary and secondary environmental loads and the secondary loads resulting from the vessel's payload and operation. These loads are variable in magnitude and generally random in nature. Except for the loads induced by the presence of any cracks, all the global and secondary loading spectra experienced by a vessel are independent of the structural integrity of any details. This implies that the same global loading spectra will continue to develop as the detail shifts from one that is crack free to one that contains a crack. The presence of the crack will introduce local secondary loads and stresses not originally acting on the intact detail and these are generally not considered for the fatigue analysis.

This report is not concerned with the cyclic loads typically generated in way of rotating or oscillating machinery or mission systems. Such loads are more deterministic in nature with slight or predictable variation over time. Analysis of structure subjected to these rotational loading spectra can be analyzed as being subjected to a constant amplitude loading with greater confidence then regarding the variable loads associated with the environment. Although not specifically addressed by this report, techniques are presented that will allow the designer to analyze these scenarios using the straight-forward techniques as presented by the Aluminum Association [2-5]. See Section 5 and Appendix B for this information.

2.6 Loads and Stresses

Without considering the secondary load effects that may be generated in a detail where a crack has been initiated, the loading environment acting on a detail is independent of the structural integrity of the detail. In other words, the hull girder, hydrostatic and other secondary loads acting on a vessel are independent of the cracks in a detail. However, extensive cracking or structural damage could lead to significant load re-distribution or changes in the load path provided that there is adequate structural redundancy. This in turn could trigger a chain reaction of failures or progressive collapse.

The stresses resulting in a detail which is experiencing localized crack growth are a strong function of its structural integrity and the presence of any cracks. On a local level, stresses will be introduced into a detail resulting from a crack that would not be present if the detail were intact. More discussion regarding this aspect of a detail's behavior is presented below.

2.7 Load Development Procedures in DNV High-Speed Craft Rules

DNV is scheduled to release a document later this year for the Fatigue Analysis of High-Speed Craft [2-6]. Similar to other documents that deal with fatigue and damage tolerance analysis [2-6] suggests that the fatigue information be developed with respect to the most likely loading scenarios. In addition, damage tolerance analysis needs to account for the extreme loads because of the large effect they can have on the behavior of the damaged detail.

The DNV document recognizes two procedures for load calculation. The first is a direct load calculation procedure and the second is a simplified approach. The simplified approach addresses preliminary or earlier stages of design whereas the former addresses the more detailed load development associated with the final design stages.

Neither of these approaches contains enough detail on the specific means for developing such calculations to account for all the possible loading sources defined below. The document provides the steps that need to be followed for the load development but no details on how to perform those steps or determine the number of cycles associated with each of the secondary loads. The DNV report does provide some preliminary guidance on the combination of primary and secondary loads. It recognizes that further work needs to be done in this area which may be used as an indicator of the loading information available for high-speed craft.

In a portion of the document dealing with the simplified loading approach, DNV does recognize that, "In some cases, the combination of global and local stresses must be used." Earlier in the document the types of loads to be considered are enumerated as:

- Wave loads.

- Pressure variations due to waves.
- Pressure variations in tanks due to acceleration of the craft.
- Acceleration forces due to the movement of the craft.
- Vibration loads from machinery.
- Pressure pulses from propulsion.
- Repeated local loads from moving vehicles.

Indeed, these all represent secondary loads except for primary hull girder loads that would result from wave loads. With regard to high-speed craft and the plentitude of hull forms associated therewith, the primary hull girder loads could be longitudinal bending, transverse bending, torsional bending or a combination of all three. DNV [2-6] does present information relating to these global loads that would enable the designer the information required to develop the wave loading information for a fatigue analysis. The document contains exposure time and scatter diagram information for vessel types and service restrictions. This information can be used to develop the primary hull girder loads and resulting stresses acting in the vessel or through a detail of concern in the fatigue analysis.

The types of loads shown above are also consistent with the loads identified in an earlier DNV document that addresses the Fatigue Assessment of Ship Structures, Classification Notes, No. 30.7, [2-7]. In that document, DNV presents a more detailed development of the global loads and transfer functions required to represent the primary, wave induced loads acting on the hull girder. This procedure is also similar to that presented in SSC 402 [2-8] and it is included herein for completeness. It will be up to the user to develop the appropriate primary and secondary loading information for each design. The DNV criteria in [2-7] can be used as a guideline for the global loads.

2.8 General Comment on Loads

Before proceeding with the general loading algorithms required for the detailed, primary hull girder load predictions, it is worth making note of the following with regards to loads, fatigue design and the costs associated with a vessel. Also, the methodology presented below was developed more specifically for displacement monohulls subjected to unrestricted service. It reflects the development of loads consistent with the spectral fatigue analysis. It is included in this report to perhaps form the basis of similar techniques that could be developed for high-speed craft.

The fabrication cost associated with any given structural design will be dominated by the plate and stiffening weights and number of pieces required for the design. Fatigue cracking problems tend to be located at the intersection of structural members or perhaps at termination points. In many instances, good ship building practice will require details wherein stress concentrations and crack initiation sites can be developed during fabrication. These details will probably be included in the design and the only variables may be the geometry, thickness or size associated with the detail's components. It is recommended that the designer investigate the influence of various combinations of these variables when developing details in fatigue prone areas to determine the overall weight and cost impacts to the design. If these impacts are not significant it might be prudent to assess the loads and their associated cycles in a conservative manner. With the lack of precise histories for both primary and secondary loads regarding high-speed craft, it may be a little optimistic and analytically expensive trying to refine this portion of the calculation to a very fine level. As discussed throughout this report the designer is encouraged to use conservative factors of safety for the fatigue design.

2.9 Global Load & Stress Prediction Methodology

Figure 2-1 gives a schematic "flow-chart" of the procedures to be used and the steps in predicting loads on high-speed craft. As seen in this figure, there are two separate methods that can be used to develop the loads. The Spectral Method is analytic in nature whereas the Alternative Method requires the collection of significant test and model data.

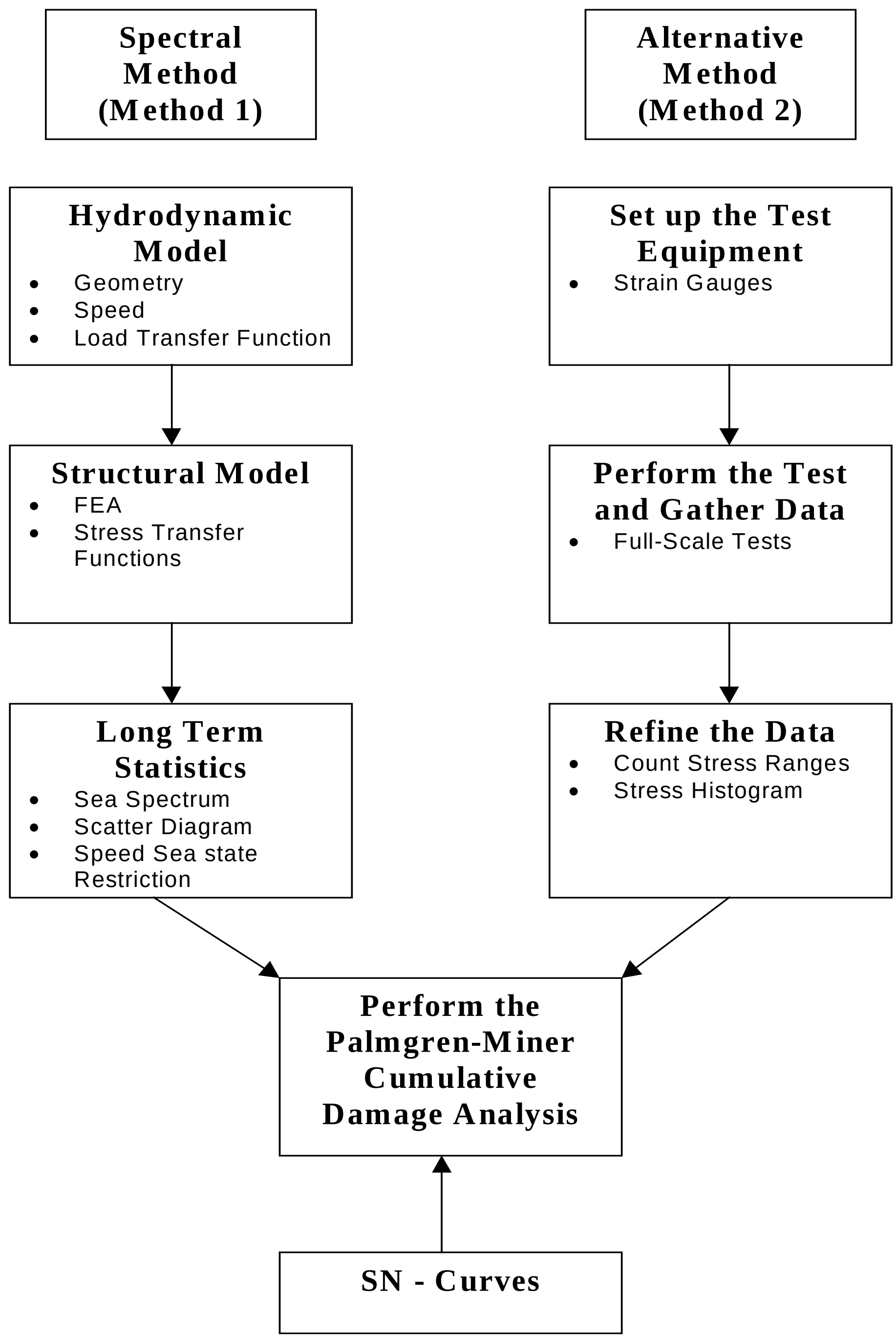

Figure 2-1 Flow Chart For Load Prediction

The global load predictions for fatigue and damage tolerance originate with the same theoretical background. This is consistent with the idea that the global loading spectra are not influenced by the structural integrity of a detail. Although stemming from the same origins, there are slightly different perspectives and goals to determine the relevant loading information for the fatigue and damage tolerance aspects of the spectra. For damage tolerance analysis it is necessary to identify and include the extreme loads that will be acting on a detail after a crack has been initiated. It is important to capture the extreme loads because of the stress concentration factors also at work after crack initiation and the effect they have on the subsequent behavior of the detail. Together, the extreme loads and the stress concentrations cause extreme stresses within the cracked detail. These extreme load cycles and their associated stresses have a significant effect on the time to failure of a detail. For fatigue however, it is generally agreed that the most detrimental loads effecting fatigue life are the high cycle/moderate load magnitudes. The extreme loads are generally too few in number to add significantly to the total damage experienced by a detail undergoing fatigue damage, i.e., the extreme loads do not generally contribute significantly to the crack initiation of a fatigued detail. Tveiten and Moan (1997) showed that low and moderate stresses could be more detrimental to the fatigue life then extreme stresses [2-9]. Another difference is the time range for the analysis. While both are considered long-term, the time associated with damage tolerance is typically in the range of 2-5 years. To develop an adequate long-term fatigue spectrum the typical range is more on the order of 20 years. Although unwritten, this is approximately the useful design life associated with many commercial maritime design codes such as the American Bureau of Shipping, ABS.

Until recently, most commercial design codes addressed the effects of fatigue implicitly within their rules. The general approach was to keep all primary and secondary stresses below certain allowable limits based on empirical equations and an “allowable stress” approach to design. The implication inherent within these approaches suggested that if all design operational stresses are kept below the recommended allowable stresses then fatigue considerations will also be satisfied. The rules are designed to accommodate a great variety of high-speed craft and must therefore include a certain degree of conservatism. Using the direct calculation procedures provided in this report will give a more precise prediction of the loads and stresses in the structure. This will allow a certain amount of design optimization in way of the details used for the vessel.

As outlined below the procedure to develop the loads and their resulting stresses can be quite extensive and requires a lot of time and accurate input data. Depending on the refinement of the output data desired, it can also demand significant time in finite element model development and analysis. All this leads to increased analytical costs that need to be justified by the life cycle maintenance and operational savings that will be realized through a more accurate fatigue analysis. Again it is worth remembering that a lot of the input data required for the analysis is also in the formative stages. This can aggravate the search for reliable or applicable data once a design has been undertaken. It can also add to the uncertainty, or risk, associated with any conclusions developed by the design.

Simplified procedures can be used for quick, preliminary or early stage designs or for designs that do not demand the sophistication of a detailed analysis. DNV [2-6] and [2-7] provide guidelines for conducting a simplified prediction of the long-term loads on a ship.

Simple hand calculations can be used to find the nominal stresses acting throughout a vessel using basic prismatic beam theory. Some special consideration regarding large openings, unique hull forms and in-plane deformation may need to be addressed for use on high-speed craft. Unique hull forms, such as SWATHs and catamarans, may experience simultaneous primary bending due to transverse, longitudinal and torsional response of the hull girder. While the phasing of these loads will not likely sum the maximum component of each, it is important to realize that these types of vessels do not behave as typical monhulls where consideration for longitudinal bending can often satisfy the primary portion of the hull girder structural analysis. To sum the stresses resulting from the interaction of these three loading components it is acceptable to use the principle of superposition as all stresses should be below the elastic limit of the material.

Large window openings or rows of window's, deck openings or cutouts through the major transverse bulkheads can also reduce the ability of a vessel to resist certain global loads and the effects of these large openings need to be considered for the nominal stress calculations.

Similar to monohulls, the global loads acting on high-speed craft increase with ship length. Fredriksen (1997) [2-10] found that local loads had a significant effect on fatigue and that global loads are not as critical for short craft. This work needs to be further investigated and expanded to develop the primary and secondary load relations discussed earlier. This is consistent with small vessel rules similar to ABS Rules for Building and Classing Steel Vessels Under 61 Meters (200 Feet) in Length [2-11]. These rules contain only simplified consideration for the global stresses acting on a small vessel. Many of the high-speed craft and high-speed ferries experiencing fatigue problems are small vessels of short length. It will be important to evaluate the magnitude of the primary hull girder loads and stresses associated with these craft since they would not typically be a significant concern for design other than fatigue considerations.

Figure 2-2 [2-2] shows some of the critical areas for cyclic stress variations that need special consideration for a catamaran.

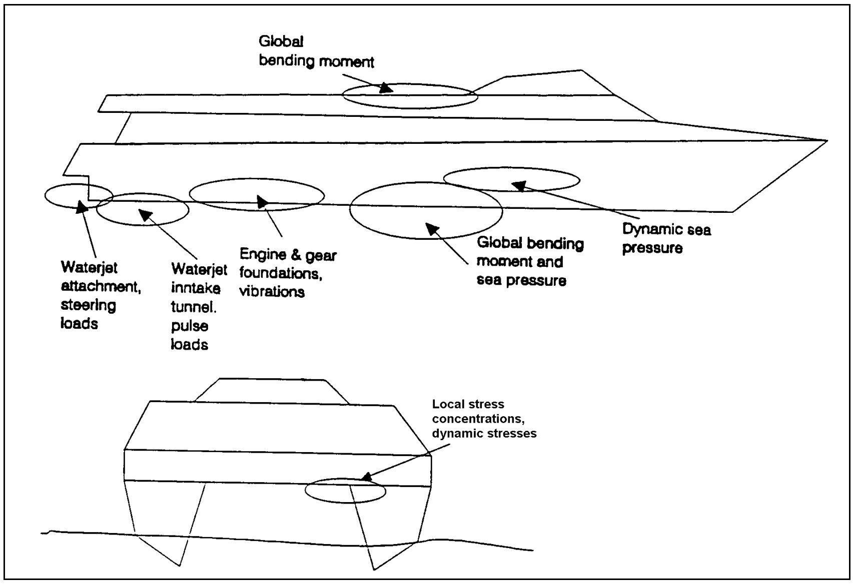

Figure 2-2 Critical areas for fatigue consideration of high-speed catamarans.

2.10 Derivation of the Load and Stress Transfer Functions

This Section provides a brief outline for developing the load and stress transfer functions for the global loads used for the detailed fatigue analysis. Research has been performed at DNV and NTNU in Trondheim in developing the global loads acting on high-speed craft. The procedure presented in this report is based partly on that research, [2-12], [2-13], [2-14].

Classic hydrodynamic load prediction for monohulls is based on strip theory. (Salvesen, Tuck and Faltinsen, 1970), [2-15]. This theory subdivides the hull into infinitesimal transverse strips and integrates over the length of the ship to determine the overall loads. As applied to monohulls this theory assumes that there is no interaction of the loads acting upon adjacent transverse strips. Using strip theory to predict the loads acting on high-speed craft requires modification of the non-interaction assumption used for monohulls. As the speed of the vessel increases the correlation between the strips needs be accounted for. Faltinsen and Zhao (1991) [2-16] extended the theory to account for high forward speed and the equations affected by this are in the load transfer functions.

2.10.1 Spectral Method Load and Stress Transfer Functions

The Spectral Method requires both hydrodynamic and structural response input data in order to establish the loading and stress transfer functions. Some of the typical data required to develop the spectral analysis are:

- Geometry of the vessel.
- Mass distribution over the vessel length.
- Speed and operational profile of the vessel.
- Oceanographic data.
- Operational restrictions.
- Structural model of the vessel.

Operational restrictions are very specific for high-speed craft and are identified as a separate line item from operational profile for a specific reason. Most people familiar with the idea of the operational profile of a ship would expect any restrictions to be included herein. Indeed, most monohulls are designed for open-ocean, unrestricted service and do not have significant service restrictions. In their Rules for Classification of High-Speed and Light Craft [2-1], DNV defines a variety of service restrictions that can be taken to apply to any high-speed craft depending upon the intended service of the vessel. The service restrictions account for the type of environment to be encountered by a vessel and range from unrestricted, open-ocean service to sheltered areas. Table B1 from [2-1] is shown below in Table 2–1. This table defines a series of maximum distances, in nautical miles, from safe harbor or anchorage that apply to each class of service restriction and account for the type of environment, location and season of the year. Included elsewhere in [2-1] are definitions that reduce the loads acting on a vessel as a function of the service area restrictions. This allows owners to take advantage of the fact that the loads are smaller in restricted service than they are out in the open-ocean. A typical speed/wave height restriction curve is shown in **Error! Reference source not found.**. ABS has a similar philosophy regarding service restrictions presented in their Guide for Building and Classing High-Speed Craft [2-2]. The ABS Guide also allows designers/owners the flexibility to design for the environmental loading scenarios appropriate to the intended service of the vessel.

Table 2–1 DNV Service Restrictions for High-speed Craft

Condition	*Notation*	*Winter*	*Summer*	*Tropical*
Ocean	None	1)	1)	1)
Ocean	**R0**	300	1)	1)
Ocean	**R1**	100	300	300
Offshore	**R2**	50	100	250
Coastal	**R3**	20	50	100
Inshore	**R4**	5	10	20
Inland	**R5**	1	2	5
Sheltered	**R6**	0.2	0.3	0.5

1) Unrestricted service notation is not applicable to craft falling within the scope of the HSC Code, i.e., service and type notations **Passenger, Car ferry** or **Cargo.**

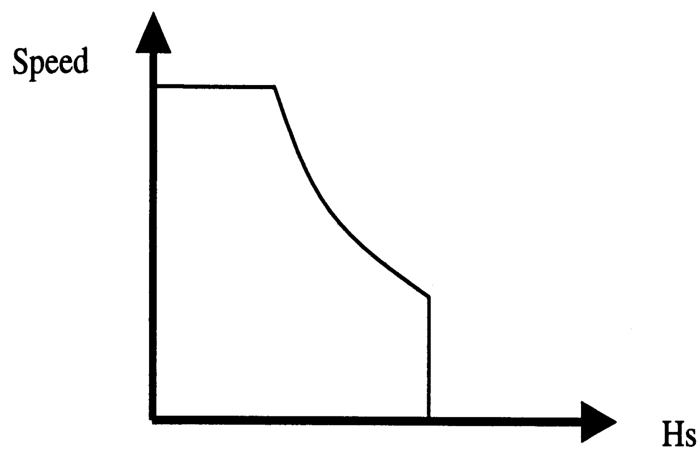

Figure 2-3 Speed/Wave Height Restriction Curve for High-Speed Craft

2.10.2 Hydrodynamic Model to Develop Load Transfer Functions

The hydrodynamic response of the high-speed craft will be provided through a transfer function, *H*, as a function of heading, θ, and wave frequency, ω, $H(\omega,\theta)$. The transfer functions are complex functions containing both real and imaginary components.

To determine the primary loading response functions or transfer functions the following data will be required:

- Lines plans and/or offset table – to define the hull form of ship.
- Weights – to define mass distribution of ship.

- Operational profiles with service restrictions.
- Vessel loadout information.
- Intended speed profile of the vessel.
- Heading of the vessel relative to the seas.
- Exposure-time during a given year and intended service life of the vessel in years.

The transfer functions define the loading experienced by the vessel in response to waves of a unit amplitude. Typical transfer functions for global wave-induced loads and secondary loads are usually defined as:

$H_v(\omega,\theta)$ = Transfer function for vertical bending moment.

$H_h(\omega,\theta)$ = Transfer function for horizontal bending moment.

$H_t(\omega,\theta)$ = Transfer function for torsional bending moment.

$H_p(\omega,\theta)$ = Transfer function for external pressure.

$H_c(\omega,\theta)$ = Transfer function for liquid cargo pressure.

Additional transfer functions may be needed to define the transverse and torsional bending moments associated with SWATH, catamaran or other unique hull-forms. The function $H_v(\omega,\theta)$, developed for vertical bending moment is traditionally referred to the longitudinal bending moment acting on a monohull. The additional transfer functions may be defined as:

$H_{trn}(\omega,\theta)$ = Transfer function for transverse bending moment associated with SWATH or catamaran vessels.

$H_{tor}(\omega,\theta)$ = Transfer function for torsional bending moment associated with SWATH or catamaran vessels.

Transfer functions will also be needed for the loading functions for all the appropriate secondary loads acting on a given detail. In a similar manner, transfer functions can be defined for any loading component of interest for a given detail.

2.10.3 Structural Model to Develop Stress Coefficients

The structural model will take the loading information developed above and be used to develop the stress coefficients corresponding to the loading transfer functions. For the detailed analyses typically associated with a spectral analysis the structural modeling will require at least one, and possibly more levels of finite element modeling. The models are usually developed with increasing definition, i.e., decreasing mesh size, to more closely investigate the local stress fields associated with a detail. This is typically accomplished starting with a global finite element model of the entire ship, which is then subjected to the primary and secondary loading functions of interest. This model will develop global stresses and displacements as part of its output. The displacements from this analysis will then be used for input to the more localized and refined models down to the detail level. This process can be developed with as many interim models as desired, or practicable, to achieve the desired results. The FEA can also be run to analyze all appropriate loads and load combinations to determine the critical stress coefficients for various details located in different areas of the craft.

The stress transfer functions, defined below as A_x, express the values of a certain stress component resulting from a unit load, i.e., A_h is the stress coefficient at the location of interest and for the stress component of interest resulting from the application of a unit horizontal bending moment. The actual stress can then be determined by increasing A_h in the same ratio as the actual load to the unit load. For calculations associated with a spectral analysis it is not recommended that the stress coefficients can be determined by hand. The effects of geometric stress concentrations can best be determined using FEA and this is more consistent with the overall philosophy of a spectral analysis.

Although hand calculations are not recommended for the final determination of the stress coefficients, it is possible to get an approximation for the correct stress levels by performing simple hand calculations. These could be augmented using textbook stress concentration factors, if appropriate. This can be done for any type of loading.

The stress coefficients are defined in association with the loading transfer functions defined above and are given as:

A_v = Stress per unit vertical bending moment.

A_h = Stress per unit horizontal bending moment.

A_t = Stress per unit torsional bending moment.

A_p = Stress per unit external pressure.

A_c = Stress per unit liquid cargo pressure.

In a manner similar to the additional load transfer functions defined above for SWATH and catamaran hull forms, corresponding additional stress coefficients can also be defined.

For each loading, and the corresponding structural response, i.e. vertical bending moment, there will be at least one transfer function relating the loads to the stresses developed in the structure. The load and stress transfer functions depend on the conditions acting on the details to be analyzed. If the entire stress history of a given detail is dominated by a single load component the stress transfer function will only have to relate information from this one condition. If, as is usually the case, the stress history of a detail is a function of numerous load components, then it will be necessary to develop more detailed transfer functions. For this type of condition the transfer functions are linearly summed to develop a combined stress transfer function defined as $H_\sigma(\omega,\theta)$ and computed as.

$$H_\sigma(\omega,\theta) = A_v H_v(\omega,\theta) + A_h H_h(\omega,\theta) + A_t H_t(\omega,\theta) + A_p H_p(\omega,\theta) + A_c H_c(\omega,\theta) \qquad (2.3)$$

with additional terms included in the summation depending on the loads acting upon the hull or the detail. Equation 2.3 develops the transfer function for a single component of stress acting through the area of interest, i.e., bending stress. Additional transfer functions would be required for each component of stress required at the same location, i.e., a second relation would have to be developed for the axial stress acting through the same area. Equation 2.3 represents a simplified linear summation of the various load components. It does not consider the interaction between the load components and would result in an approximation of the stress coefficients. Therefore, the stress coefficients are typically determined through a simplified analytical approach or finite element analysis. The individual stress coefficients and linear summation are used in conjunction with the simplified analysis. FEA is usually developed at increasing levels of detail and mesh refinement to more accurately define the stress coefficients. The stresses and displacements output from global FEA are used as the input for local FEA at the detail level. In this manner, H_σ is calculated directly for a specific location and loading conditions.

2.10.4 Calculation of Short Term Response

Equation 2.3 represents the load and stress transfer functions required to develop the response of the vessel subjected to unit amplitude loads. It is now necessary to develop the information to account for the actual load magnitudes, i.e., other than the unit loads currently assumed. It is also necessary to include spectral information of the waves to account for the load and stress variations over time. It is assumed that wave scatter diagrams and sea spectra are available and have been chosen appropriate to the service route of the vessel to be designed.

The input data required for the calculations are:

- Operational Conditions.
- Stress Transfer Functions.
- Sea/Wave Spectra.
- Scatter Diagrams.
- Service Speed & Headings.

2.10.4.1 Sea/Wave Spectrum

A sea spectrum provides a representation of the waves at a specific, stationary location over time. Figure 2-4 shows a typical sea spectrum and helps to visualize the means by which it is developed. It is the summation of several, regular sinusoidal waves each having a different frequency, ω. One of the more commonly used sea-spectra is the Pierson-Moskowitz and this will be used for the demonstration presented below. Some of the critical assumptions for the Pierson-Moskowitz sea-spectra relate to the fetch and duration of blowing wind required to fully develop any given sea-state. The higher, more extreme sea-states require significant fetch and time to become fully developed and will not be representative of the environments for smaller craft to be operated in protected or inland areas. For offshore constructions that are stationary, such as drilling platforms, the predicted loads will be more accurate. There has been a significant amount of research developed over the years to determine good models for sea-state spectra. The Bretschneider and JONSWAP models are two alternative definitions of sea-spectra. The following formula represents the Pierson-Moskowitz sea-state spectra:

$$S_\eta(\omega \mid H_s, T_z) = \frac{H_s^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-5} \exp\left(-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right) \tag{2.4}$$

Where:

S_η = Sea-state to be defined.

ω = Wave frequency.

H_s = Significant Wave height.

T_z = Zero crossing period.

Equation 2.4 can be used to develop the Pierson-Moskowitz sea-state information for all levels of seas. In the case of high-speed craft, it is worth remembering that service limitations, such as those seen in Figure 2-3 or Table 2–1 will put upper limits on the bounds of the analysis.

It will be up to the user to determine what the appropriate design levels should be for any given application.

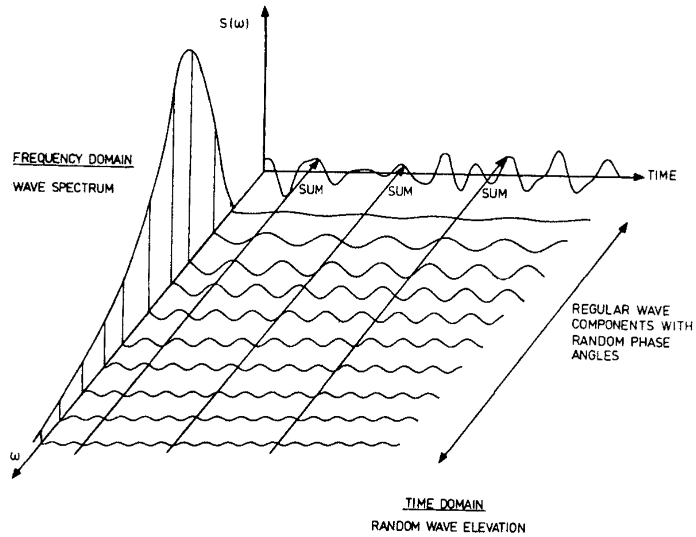

Figure 2-4. A schematic description of a sea spectrum.

2.10.4.2 Scatter Diagrams

Once the sea spectra have been defined for a given service area it is necessary to use the scatter diagram associated with the same area to determine the probabilities associated with the occurrence of a given sea-state. These probabilities are defined as, p_{ij}. Table 2–2, [2-1] presents a typical scatter diagram. The variables plotted in this diagram are T_z, the zero-crossing period and H_s the significant wave height. The sum of all the cellular values in the scatter diagram represents the total number of events reflected by the diagram. An event represents a unit of time, i.e., a day, a week or an hour. The value in each cell represents the number of events that occurred during the total time of observation of all events. In other words referring to Table 2–2, it is noted that the sum of all the cellular values is 997. (Round-off error probably shifted this number from 1000.) The scatter diagram suggests that during 997 hours of observation, 29 hours will be experienced with a zero crossing period of 7 seconds and a significant wave height of 0.5 meters.

Table 2–2 Typical Scatter Diagram From DNV HSLC Rules

	Tz (seconds)															
Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0,5	0	0	9	41	61	50	29	14	6	2	1	0	0	0	0	0
1	0	0	1	12	37	47	36	20	9	4	1	1	0	0	0	0
1,5	0	0	0	4	21	40	39	25	12	5	2	1	0	0	0	0
2	0	0	0	1	10	28	35	26	14	6	2	1	0	0	0	0
2,5	0	0	0	0	4	18	28	24	14	6	2	1	0	0	0	0
3	0	0	0	0	2	10	20	20	13	6	2	1	0	0	0	0
3,5	0	0	0	0	1	5	13	16	11	6	2	1	0	0	0	0
4	0	0	0	0	0	3	8	11	9	5	2	1	0	0	0	0
4,5	0	0	0	0	0	1	5	8	7	4	2	1	0	0	0	0
5	0	0	0	0	0	1	3	5	5	3	1	1	0	0	0	0
5,5	0	0	0	0	0	0	2	3	3	2	1	1	0	0	0	0
6	0	0	0	0	0	0	1	2	2	2	1	0	0	0	0	0
6,5	0	0	0	0	0	0	1	1	2	1	1	0	0	0	0	0
7	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
7,5	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The probability is then derived as the ratio between the amount of a typical wave combination of H_s and T_z compared with the total amount of waves in the diagram.

Different scatter diagrams will be found for different applications and services. It is typical practice to develop a composite scatter diagram for the design of vessels whose operation will cover an area greater than that represented by any single scatter diagram.

2.10.4.3 Transform from Stationary to Moving Reference

The wave spectra defined above refer to a stationary point in the ocean. To account for the fact that a vessel moves forward over time it is necessary to modify the spectrum. As a ship moves forward, it experiences a wave encounter frequency, ω_e, which differs from the frequency associated with the waves, ω at the stationary point. This is taken into account by the following equation:

$$\omega_e = \omega\left(1 - \frac{\omega V}{g}\cos\theta\right) \tag{2.5}$$

In a similar manner, it is also necessary to account for the relative motion experienced by the vessel compared to the stationary point which undergoes no translations. To transform the reference axes from the fixed point to a set that is translating with the ship the wave spectrum is modified in accordance with the following equation:

$$S_\eta(\omega_e) = S_\eta(\omega)\frac{1}{1-\left(\frac{2\omega V}{g}\right)\cos\theta} \tag{2.6}$$

It is also common practice to account for the "short crestedness" of the seas when developing the complete response spectrum for a spectral analysis. Where measured data is not available, this is typically done through the application of a cosine squared spreading function:

$$S_\eta(\omega_e,\theta) = S_\eta(\omega_e)\cdot\frac{2}{\pi}\cos^2(\theta) \tag{2.7}$$

The response spectrum is then given by:

$$S_\sigma(\omega \mid H_s, T_z, \theta) = \mid H_\sigma(\omega \mid \theta)\mid^2 \cdot S_\eta(\omega_e, \theta \mid H_s, T_z) \quad (2.8$$

where $S_\sigma(\omega \mid H_s, T_z, \theta)$ is the spectrum of the stress for a given combination of H_s, T_z, and θ.

The moments for the stress spectrum for the ith sea-state and jth heading are given as:

$$m_{kij} = \int_{\infty} \omega^k S_\sigma(\omega \mid H_s, T_z, \theta)\, d\omega \tag{2.9}$$

where m_{kij} is the k^{th} moment.

2.10.4.4 Calculation of Short-term Stress Range Distribution

Equation 2.10, given below, presents the formulation for the short term stress range distribution for the ith sea-state and jth heading and is given by:

$$F_{\Delta\sigma ij}(\sigma) = 1 - \exp\left[-\frac{\sigma^2}{8m_{0ij}}\right] \tag{2.10}$$

with the corresponding zero crossing frequency given by:

$$\nu_{ij} = \frac{1}{2\pi}\sqrt{\frac{m_{2ij}}{m_{0ij}}} \tag{2.11}$$

Equation 2.10 is a cumulative probability distribution function that assumes that the variation of stresses in a short-term sea-state is a narrow banded, random process. This has been shown to be valid for the displacement vessels for which this procedure has been developed. If this is not true for high-speed craft, i.e., if the short-term stress range is broad banded, then different methodologies will have to be developed to determine the short-term stress range distribution.

2.10.4.5 Long Term Response

It is recognized that the equations presented above were developed for open-ocean service and that many high-speed craft will not obey this assumption. Regardless, the philosophy behind these procedures can also be applied to any of the sea-states or conditions that would be appropriate for any high-speed vessel.

All the data developed through equation 2.11 represents the short-term loading and response of a vessel to the global sea-states in which it will operate. As stated previously, both fatigue and damage tolerance represent long-term events. This makes it necessary to extrapolate the data to reflect long-term behavior and response. The short-term data developed through equation 2.11 is considered to be representative of realistic conditions. Therefore, it is only necessary to extrapolate this behavior to the desired number of load cycles to reflect the long-term exposure of any given design. For a typical monohull the typical number of long-term cycles may be as high as N=100 million. The number of cycles required for any given vessel needs to be determined for the design of that vessel.

The long-term extreme response, presented in equation 2.12 below, is developed from the Ochi methodology wherein he assumed that the long-term response is merely a summation of the short-term responses over the duration of interest. This results in a probability density function for long-term response that is expressed as:

$$f(\sigma_a) = \frac{\sum_i \sum_j n_* p_i p_j f_*(\sigma_a)}{\sum_i \sum_j n_* p_i p_j} \qquad (2.12)$$

Where:

σ_a = Stress amplitude.

f_* = Probability density function for short-term response.

n_* = Average number of responses per unit time during the short-term response.

$= \frac{1}{2\pi}\sqrt{\frac{m_{2ij}}{m_{0ij}}}$ where m_{0ij} and m_{2ij} are as defined above.

p_i = Weighting factor for the i^{th} sea-state.

p_j = Weighting factor for the j^{th} heading.

This leads to the development of the total stress range equation given below for the long-term stress range distribution:

$$F_{\Delta\sigma} = \sum_{i=1,\,j=1}^{\substack{allseastates \\ headings}} r_{ij} F_{\Delta\sigma ij}(\sigma) pij \qquad (2.13)$$

Where:

p_{ij} = The probability of occurrence of a given sea-state and heading.

$r_{ij} = \frac{v_{ij}}{v_0}$ The weighted function that consist of the crossing rate in a given sea-state and the average crossing rate.

$v_0 = \sum p_{ij} v_{ij}$ The average crossing rate.

2.10.5 Extreme Loads, Long-term Response and Damage Tolerance

The procedures presented above will account for the entire spectrum of loads to be included in both the fatigue and damage tolerance analyses. With the presence of the extreme loads that will occur over the long-term exposure of the vessel a complete damage tolerance analysis can be developed. The phenomenon of extreme loads, or overloads, and damage tolerance is discussed further in Section 6 of this report. In summary, it is interesting to note that the time to failure of a detail that experience’s overloads can exceed the time to failure of the same detail subjected to constant or moderately variable loads. This counter-intuitive behavior has to do with crack retardation that occurs at the crack-tip as a result of the overload.

2.11 The Alternative Method – Fatigue Assessment Using Measured Loads

Also shown in Figure 2-1 is the Alternative Method for the development of load and stress information acting on a vessel. This method is not analytic. It relies on the development of physical models of the ship and measuring or monitoring the response to determine the loads. The models are subjected to tank testing or other procedures that allow for the instrumentation and measurement of loading and response information. It is intended that the model will be operated in a series of environments that reflect the operating environment of the vessel being deigned. It is necessary to be able to control the environment and the operating parameters of the vessel such as speed and heading relative to the sea-state. The model will be equipped with strain gauges and other relevant equipment to measure and record all loads and responses to the loads. This information can be used to develop stress ranges and stress histograms for use in a Palmgren-Miner assessment.

The model associated with the vessel will be relatively coarse compared to the detail required for the local investigation concerning the behavior or response of any given detail on the ship. Therefore, it may be necessary to take the loading information developed during the tests and use this as input to a finite element analysis. This will allow for a complete development of the stress transfer functions required for the analysis.

A second option available for gathering measured data is to use existing vessels. These too can be outfit with the required strain gauges and data gathered over their typical operating routes. While this has the benefit of using existing craft on routes that may be similar to design routes for future vessels, it also has the drawback in the control of the environments for which data can be gathered. Tank tests using models can control the environment to develop a full spectrum of responses whereas using existing craft may limit the environments due to other operational constraints experienced by the craft in the more extreme sea-states.

2.12 References

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[2-9] Tveiten B. W., and Moan T., Fatigue Analysis of High Speed Aluminum Catamarans, 3rd International Forum on Aluminum Ships, May 1998.

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[2-16] Faltinsen, O. M. and Zhao, R. (1991). Numerical Prediction of Ship Motions at High Forward Speed. Phil. Trans., Royal Soc., Vol. A334, London.

3. Fatigue

3.1 Development of the Fatigue Database

To help support the fatigue and damage tolerance analyses conducted in this report, a database of references has been gathered and is presented in Appendix A. This database represents a variety of references and industry standards used for the fatigue analysis of aluminum structures. Some of these references discuss fatigue and damage tolerance analysis in generic terms, not related to any specific material but provide the user with good information and understanding. Appendix A also includes reference to the design codes from the maritime and other industries that address fatigue along with a series of papers presented at the recently completed 4th International Forum on Aluminum Ships.

Performing the initial research to start the development of the database it was necessary to inquire about existing work that had already been done regarding the fatigue of aluminum. Discussion with personnel at NAVSEA (Naval Sea Systems Command) and NSWC-CD (Naval Surface Warfare Center – Carderock Division) revealed experience that had dealt primarily with the damage suffered by the FFG 7 class of vessels in the areas of their aluminum superstructures. It was not felt that this information was relevant to the current effort regarding high-speed vessels for a number of reasons. This included the different functions and loading environment being served by the aluminum applications and unknown design, fabrication and repair problems involved with the FFG 7 problems. Among the information gained from the discussions with the NAVSEA and NSWCCD personnel was contact with additional personnel in other areas associated with aluminum craft.

One of the more important contacts resulted from discussion with Jeff Beach (NSWCCD) [3-1], who provided introduction to Professor Wallace Sanders of the University of Iowa [3-2]. Discussion with Professor Sanders revealed significant work developed on his part in compiling perhaps the first, large scale aluminum database. During the 1970’s and early 1980’s Professor Sanders was involved in the development of an aluminum database. In the early 1970’s the Welding Research Council (WRC) tasked Professor Sanders to prepare a WRC Bulletin on the state of the art knowledge on fatigue of aluminum weldments. As part of that effort Professor Sanders studied published works from the United States and around the world. In addition, with the help of the research laboratories of the U.S. and Canadian aluminum industry, unpublished data from these laboratories was made available. Although the private industry data was restricted to an internal study by the University, WRC Bulletin 171 was published in 1972, which covered studies of all of the data. The data available were the basis for the development of the aluminum fatigue database. Over the next 15 years, Iowa State conducted studies on fatigue behavior of aluminum weldments for the Welding Research Council, The Aluminum Association and the U.S. Navy. The efforts continued on the expansion of the database. This database was considered an industry standard and contained significant information on all aspects of aluminum behavior including fatigue. Unfortunately, all the information in the database was based on small specimen testing similar to those shown in Figure 3-1, [3-3]. The problem with these small specimens is the deviation from actual weldments. Actual details in a ship's structure are more complicated containing geometry effects, size and scale effects along with the base metal, weld metal, the residual stresses in the HAZ, potential imperfections in the weld area and other factors.

Although the Sanders work represented a powerful database at its time it has since been updated and expanded. In the early 1980's, Professor Sanders joined in the data bank efforts with Professor Dimitris Kosteas of the Technical University of Munich (TUM). Since most of the research was being conducted in Europe, the focus of the work on the data bank transferred to Munich being conducted jointly by Professors Sanders and Kosteas. Much of the effort centered around the work of the Task Committee on Aluminum Structures of the European Convention on Constructional Steelworks. The continuation of the efforts on the data bank transferred completely to TUM in the mid 1990's and the effort shifted to support the European Community codes. Professor Kosteas inherited the work of Professor Sanders and expanded upon it to include large specimen testing and the effects of adverse environments. The work developed under Professor Kosteas forms the basis for the fatigue and damage tolerance information and design processes contained in EuroCode9, a preliminary release for a new European design standard for aluminum.

Discussion with other respected individuals in the field of aluminum continually cited Professor Sanders and Professor Kosteas as the appropriate points of contact for information regarding aluminum database information.

A List of Contacts, Appendix F, was compiled to help document the sources interviewed for the database development for this report. The list compiled in Appendix F was not intended to represent each time a given individual was contacted, only the fact that they were contacted for the report.

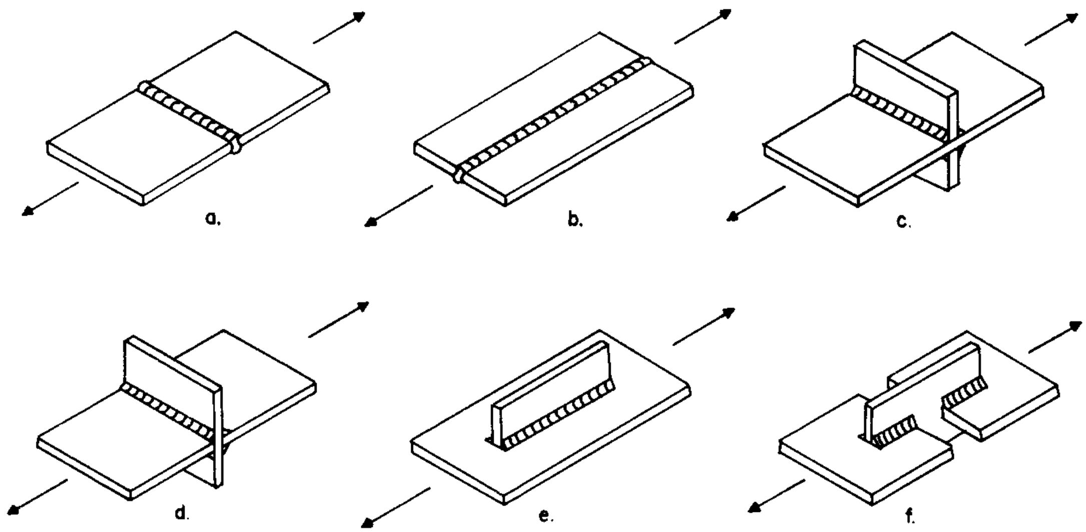

Figure 3-1 Typical Small Specimen Geometry

3.2 Brief History of Fatigue

Fatigue induced cracking and failures are commonly recognized occurrences not unknown to the layperson. It has been responsible for many structural and mechanical failures causing various accidents throughout history resulting in the loss of human life, property and unnecessary monetary expenditures. Around the 1840's the fatigue phenomena was first identified. During the 1850's and 1860's extensive research was conducted by August Wohler who conducted a number of tests on a variety of specimens that were exposed to cyclic loadings. He then introduced the S/N Diagram (Wohler curve) which plotted the life of a specimen as a function of its stress level. These diagrams demonstrated the decreasing life of a specimen for increased stress levels and conversely, showed that the number of cycles sustainable by a specimen increased as its stress level decreased. The S/N Diagrams have continued to be a very useful tool in the fatigue design process ever since.

During the 1920's Palmgren suggested a criterion for fatigue damage on structural details and Miner formulated a damage summation method called cumulative fatigue damage criterion. It was based on the Palmgren suggestion and is today referred to as the Palmgren-Miner cumulative damage analysis.

The combination of these two procedures and the development of the Palmgren-Miner cumulative damage assessment technique has made it possible for the safe and simplified fatigue design of numerous structural and mechanical details in a wide variety of applications. Similarly, the use of the Palmgren-Miner technique will form the foundation of the fatigue analyses presented for use in the maritime industry for high-speed craft.

3.3 The Fatigue Environment

There is a wide range of factors that contribute to the fatigue environment and they include:

- Constant or Variable amplitude loading.
- The stress ratio and stress range resulting from the loading.
- The effects of mean stress.
- The size and geometry of the detail.
- The stress concentrations acting through the detail.
- The corrosive or aggressive nature of the environment in which the detail functions.

As stated above, fatigue is the damage resulting from the cyclic loading and unloading of a structural member with a resultant variation in the stresses. Damage from fatigue only occurs in the region of a detail that deforms plastically or experiences plastic stresses during the loading cycle. Since ship structures are typically designed within the elastic range of the material it can be assumed that stress raisers must be increasing the local stresses to levels above the yield of the material. After undergoing enough cycles of yielding cracks will develop. In the case of obvious geometric changes or welding imperfections, the sources for these stress raisers is obvious and on the macroscopic scale. For smooth specimens with no apparent stress raisers visible to the naked eye, the stress raisers occur at the microscopic level such as slip bands, grain boundaries and inclusions or voids.

The stress ratio mentioned above, is the ratio between the minimum and maximum stresses acting at a point. It is defined as:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{3.1}$$

Figure 3-2, [3-11], gives a graphic example of the potential fluctuations in R:

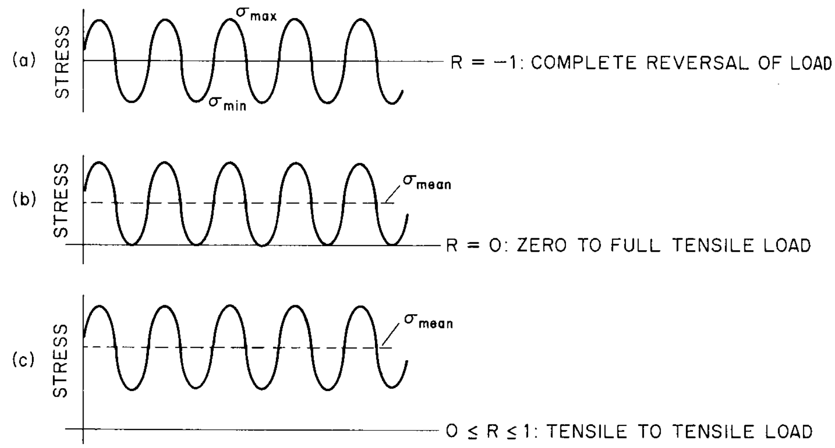

Figure 3-2 Range of Variations in the Stress Ratio, R.

A typical S/N diagram for steel is shown in Figure 3-3, [3-11]. This figure shows that a material, or detail, can withstand a virtually infinite number of load cycles if the maximum stress never exceeds a certain value, i.e., the so-called fatigue or endurance limit. If the fatigue limit of a material is exceeded crack initiation will occur. Aluminum, on the other hand, does not display a well-defined fatigue limit when subjected to random or variable load spectra. For specimens subjected to variable loading cycles the maximum allowable stress range continues to decrease as shown in Figure 3-4, [3-11]. This suggests that aluminum details subjected to variable loads will develop fatigue cracks regardless of their quality although the time to failure can be significantly greater than the service life to experience the number of cycles required at such low stress levels. For constant amplitude loading, design codes such as the Aluminum Association do provide for a bi-linear S/N diagram. Reference [3-4] agrees that the presence of an endurance limit can be defined for aluminum specimens subjected to constant amplitude loading. The Aluminum Association suggests a change of slope at $N = 5 \times 10^6$ cycles for the constant amplitude load scenario but has a constant, single slope S/N diagram for the variable load spectra. This would suggest that designers of high-speed craft should follow the same guidelines. For structural details subjected to constant amplitude loading spectra it would be acceptable to define a fatigue limit for the material. For variable amplitude loads, the principal subject of this report, no such change in slope should be allowed or expected in the behavior of the material.

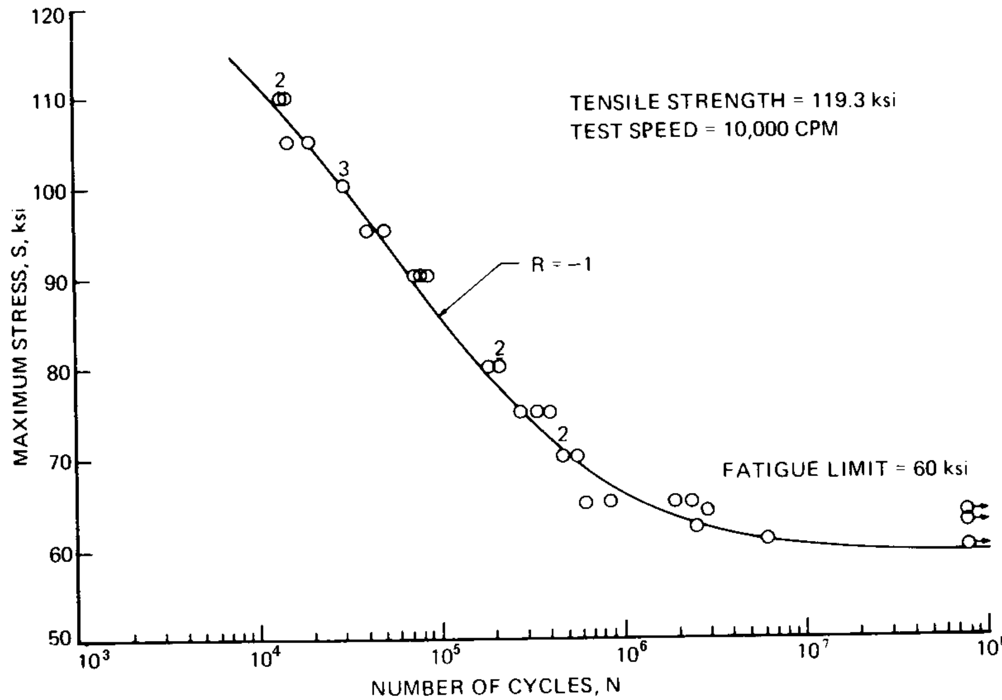

Figure 3-3 Typical S/N Diagram For Steel

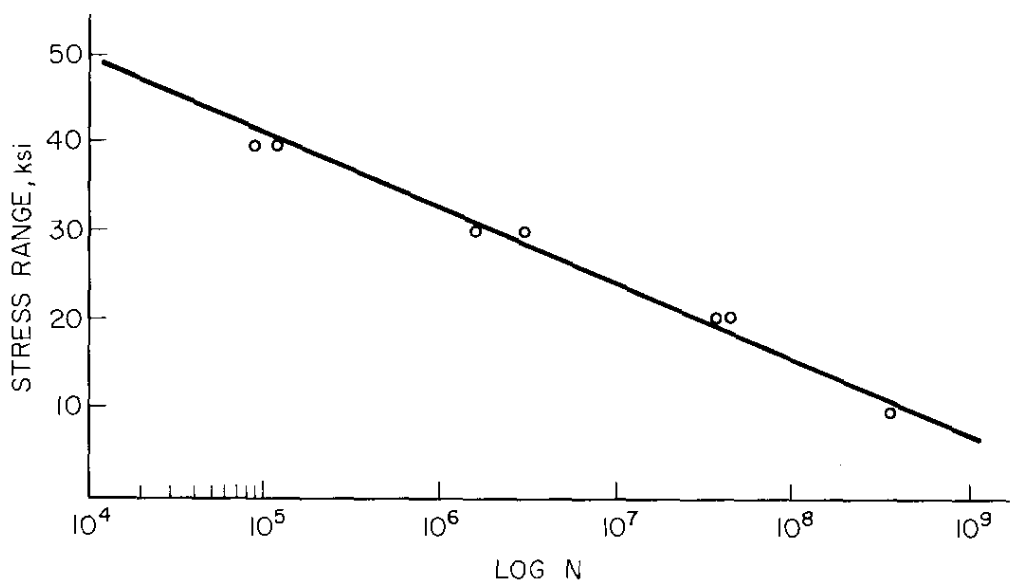

Figure 3-4 Long Life Fatigue for Aluminum

3.3.1 Effects of Seawater on Fatigue of Aluminum

As shown in Figure 3-5, [3-4] fatigue tests were performed on a number of 6061-T4 specimens with R = 0.1. The specimens ranged from smooth to containing stress concentration factors up to K_t = 12. Two smooth specimens were tested, one in air and the other in seawater. The figure demonstrates the rapid loss of strength for the seawater specimen as the number of cycles increases. For cycles greater then N = 10^7 the strength of the smooth specimen in seawater is rapidly approaching the strength of the specimens tested in air with a stress concentration notch factor of K_t = 12. This presents a very graphic demonstration of the degrading effects of seawater on the long-term fatigue life of aluminum. The smooth specimen data would rarely be appropriate for actual high-speed craft details and it must be assumed that stress concentration factors on the order of K_t = 3 would not be unusual as a minimum. Combining this with the accelerated deterioration experienced with the smooth specimen suggests the reduced fatigue life available to aluminum details in the marine or seawater environment.

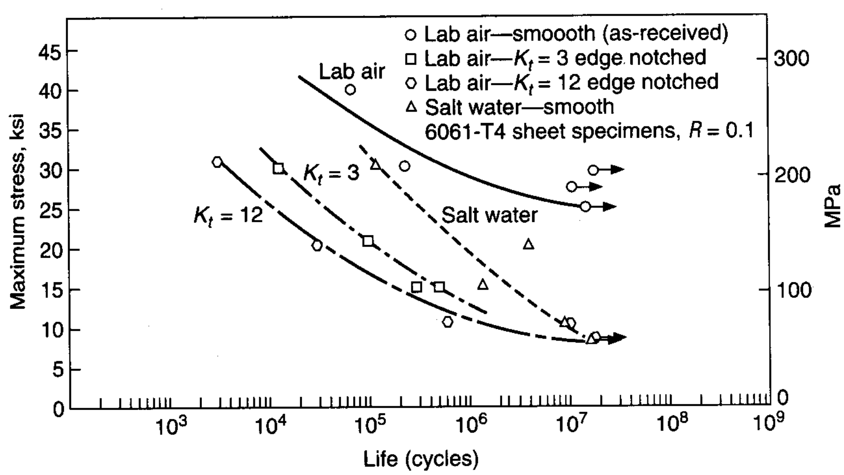

Figure 3-5 Effect of Seawater on Aluminum Fatigue Tests

There was no available data on the behavior of notched specimens subjected to the seawater environment. While it might seem that the individually deleterious effects of notches and seawater would further accelerate the loss of fatigue strength when operating together, it is recommended that this would be another area requiring further research to establish fatigue behavior of aluminum under these combined effects.

The data provided in Appendix E also demonstrates the deleterious effects of the marine environment on the fatigue lives of simple aluminum specimens compared to their behavior in air. The effects of the aggressive marine environment certainly needs to be included in any design procedures developed in the future or used as a result of this report. Additional research is required to quantify the magnitude of the corrections that should be included for the design of such details.

Among the results from the specimens tested in seawater was the beneficial effect of a paint or coating system applied to the aluminum. Further testing would be required to determine the increased fatigue life which could be used for design but recommended practice would suggest the use of painting systems in the areas of a high-speed craft susceptible to fatigue.

3.4 Fatigue Aspects of Aluminum

This section discusses three particular aspects of welded aluminum and compares them with steel as appropriate. Limited data on aluminum was found for the first two subjects, which suggests that additional research may be required. The third area is well documented and will not require any additional research. These three aspects are:

1. The mean stress effect and stress ratio.
2. The effect of alloying elements on the fatigue behavior of aluminum.
3. The strength of welded and unwelded aluminum specimens.

3.4.1 Mean Stress Effect and Stress Ratio in Steel and Aluminum

The stress ratio, R, has been previously defined in equation (3.1) as the ratio between σ_{min} and σ_{max}. Figure 3-2 provides a graphic display for the stress ratio with three separate plots, all of which are depicted to have the same waveheight or amplitude, i.e., all three plots have the same stress range where:

$$StressRange = \Delta\sigma = \sigma_{\max} - \sigma_{\min} \tag{3.2}$$

The mean stress is calculated as:

$$MeanStress = \sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{3.3}$$

The critical difference between stress range and mean stress is demonstrated in Figure 3-2(b) and (c). Both of these plots demonstrate the same stress range but the loading depicted by 3.2(c) has a greater mean stress than that displayed in 3.2(b).

It is generally accepted that the fatigue life of steel weldments is relatively insensitive to the stress ratio, R, and the mean stress, σ_m. This is a result of the tensile residual stresses near the toe of a steel weldment which approach the yield strength of the material. As a result, any cyclic loading applied to the detail will stress it from yield to some lesser value. Therefore, the stress range, $\Delta\sigma$, is usually adequate to determine the fatigue life of a steel detail.

Discussion presented in [3-4] suggests the same behavior for aluminum weldments as that described above for steel. Tensile residual stresses approach the yield strength of the base material in the toe of the weldment and the cyclic stress ranges from the yield strength of the material to some lesser value. Under these circumstances, the stress range acting upon the detail is critical for design while neither the stress ratio nor the mean stress has a significant influence on the design.

Meanwhile, data presented in the appendices of [3-4] suggests a potential discrepancy with the discussion presented above. As shown in Figure 3-6, the effect of stress ratio appears to have a pronounced effect on fatigue life. This figure was assembled from the data in Appendix A of reference [3-4], Figures A.2 and A.3.5, and was developed from axially loaded, transverse butt-welded 3/8 inch aluminum plate test specimens. It suggests a rather strong dependence of the fatigue life on the stress ratio of the loading environment. The pulsating tension loads, R = 0, 0.5 and 0.75 depict the expected trend for smooth or unwelded specimens with a decrease in fatigue life resulting from an increase in the positive value of R. Additional investigation of the experiments conducted for the data in Appendix A of [3-4] needs to be undertaken for a better understanding of the results before any conclusions can be drawn.

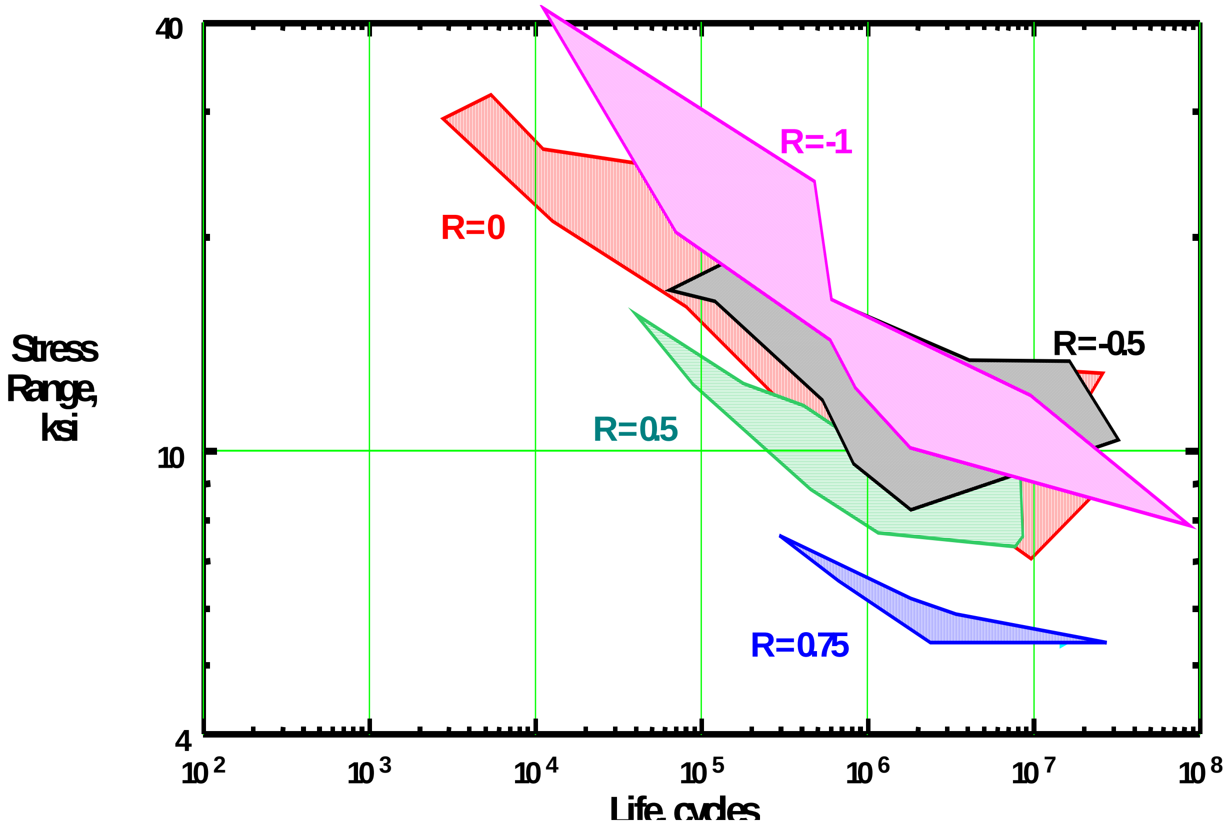

Figure 3-6 Effect of Stress Ratio on Fatigue Life of Aluminum

In addition to the information in Figure 3-6, Figure 3-7 also suggests a dependency of the fatigue life on the stress ratio of the applied loading. Taken from "Welding Alcoa Aluminum", 1972, [3-5] the fatigue tests performed on this simple specimen show a pronounced effect of the stress ratio on the fatigue life as early as 2000 cycles into the loading history.

As a result of the conflicting information gathered during the research for this report, it must be concluded that the effects of stress ratio cannot yet be determined for aluminum alloys. This suggests that additional research is required to determine the effects of stress ratio and the manner to account for this effect during the design process.

For unwelded aluminum alloy specimens or structures, the fatigue strength is influenced by the mean stress and the stress ratio. This needs to be accounted for in design although no information was found to suggest the manner in which the fatigue resistance should be reduced for this situation in the design process. For the unwelded specimen tensile stresses will cause crack initiation and propagation while portions of the loading cycle that cause compressive stresses will prolong the time to crack initiation and impede propagation. For a given stress range, the fatigue life decreases as the mean stress is increased.

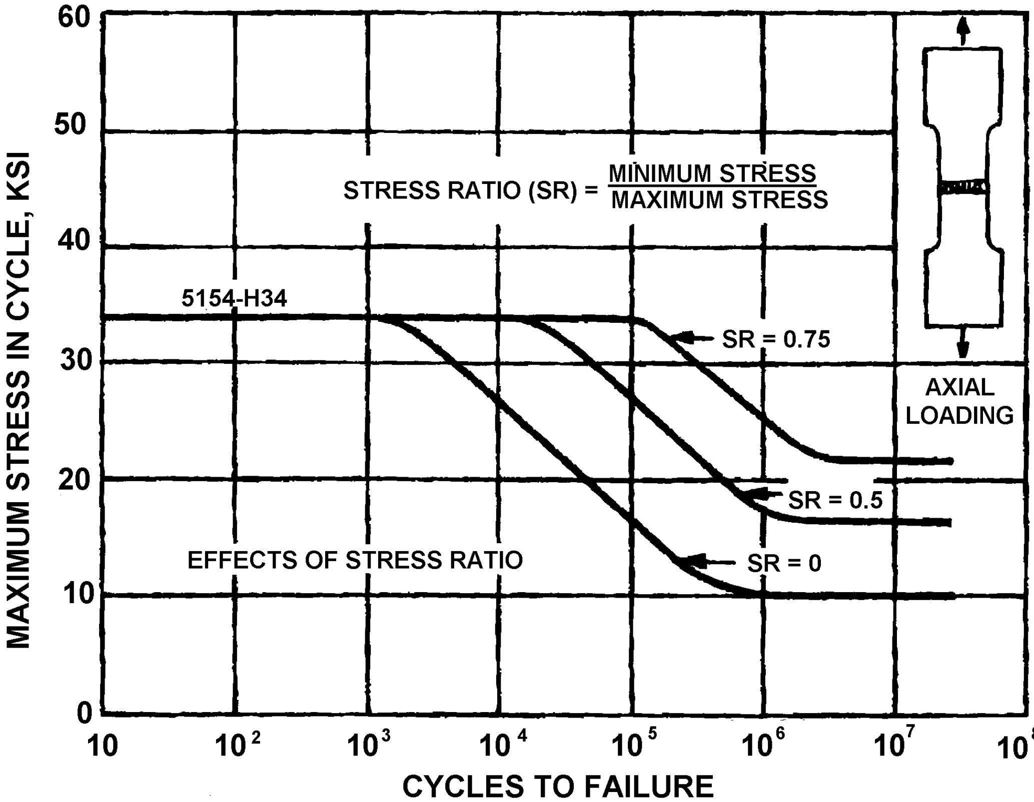

Figure 3-7 Effects of Stress Ratio on 5154-H34 Aluminum

3.4.2 The Effect of Alloy on Aluminum Fatigue Behavior

Sharp, Nordmark and Menzemer, [3-4] report that the fatigue behavior of aluminum is effected by the alloying elements at low fatigue lives. The differences between the weldments of different alloys tends to be minimized at longer fatigue lives due to the welding residual stresses and typical stress concentrations inherent in the fabrication. The same is true of smooth specimens, i.e., the fatigue life reflects the tensile strength of the alloy at shorter lives but this difference is minimized for longer lives. This is consistent with the behavior for steel alloys with different yield strengths, i.e., for long lives the fatigue strengths of steel tend to approach a common design value.

Data taken from [3-4] was manipulated to develop the information in Figure 3-8 and Figure 3-9. The information in these figures demonstrates the trend in this behavior for the longer fatigue lives of interest to this report.

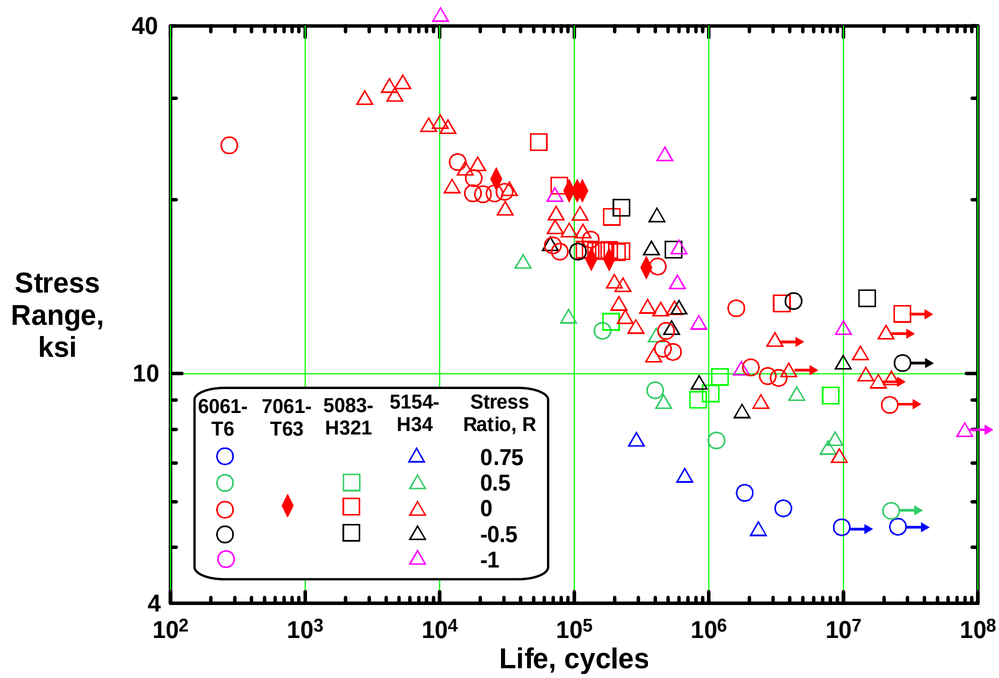

Figure 3-8 Axially Loaded, Transverse Butt-Welded 3/8 inch Aluminum Plate

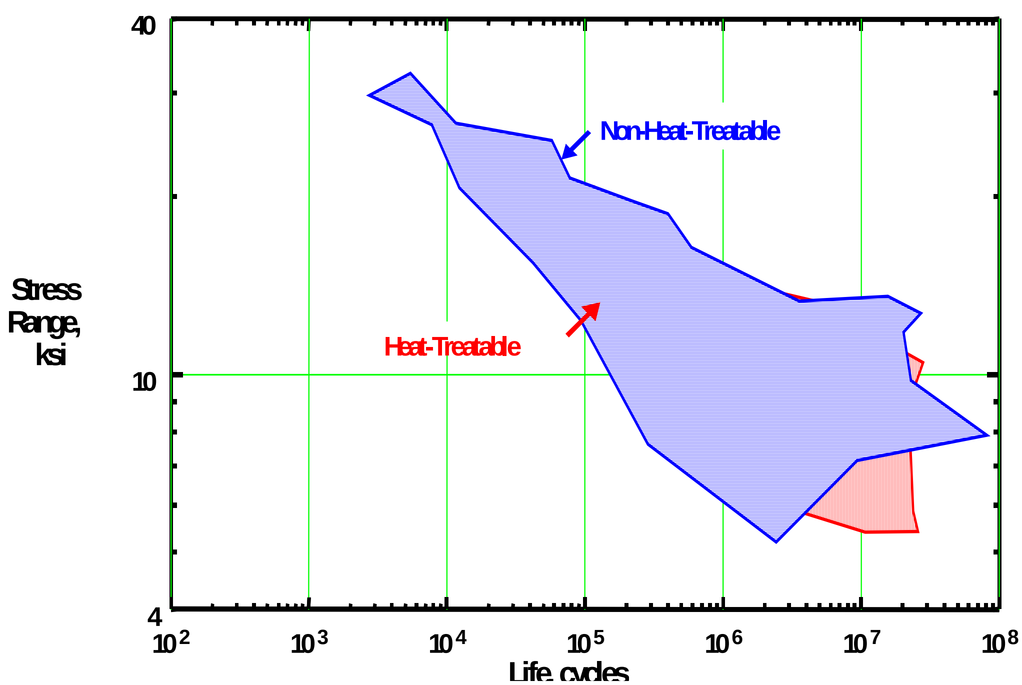

Figure 3-9 Axially Loaded, Transverse Butt-Welded 3/8 inch Aluminum Plate

Further confirmation for the influence of this effect is also demonstrated in Figure 3-10. This figure was taken from [3-5] and agrees with the conclusions presented by [3-4] that the effect of alloy is significant early in the fatigue life of a specimen but this dependence tends to disappear at longer fatigue lives. For consideration in the design of fatigue resistant details in high-speed aluminum craft, the details would all be considered long life relative to the information shown in these figures. This would suggest that the effects of alloy should not be a concern during the design stage of the details.

The conclusion presented above contradicts the findings reported in Sections 3.9.1 and 3.9.3 of this report regarding the comparison between 5083 and the new alloys, 5383 and 5059. The results presented in [3-6] and [3-7] respectively, and reflected in this report, suggest that the high-cycle fatigue life of 5383 and 5059 is greater than that of 5083 at 10^7 cycles, see Figure 3-21 and Figure 3-24. Discussion presented in [3-6] suggests the premature nature of their findings and the need for additional fatigue testing. The authors of this report agree that in order to refute the primary findings, which suggest the effect of alloy on long lives is not critical, additional fatigue testing of both 5383 and 5059 would be required. This testing would have to be conducted by sources other than the developers of the alloys to confirm the long-term fatigue behavior of all three alloys.

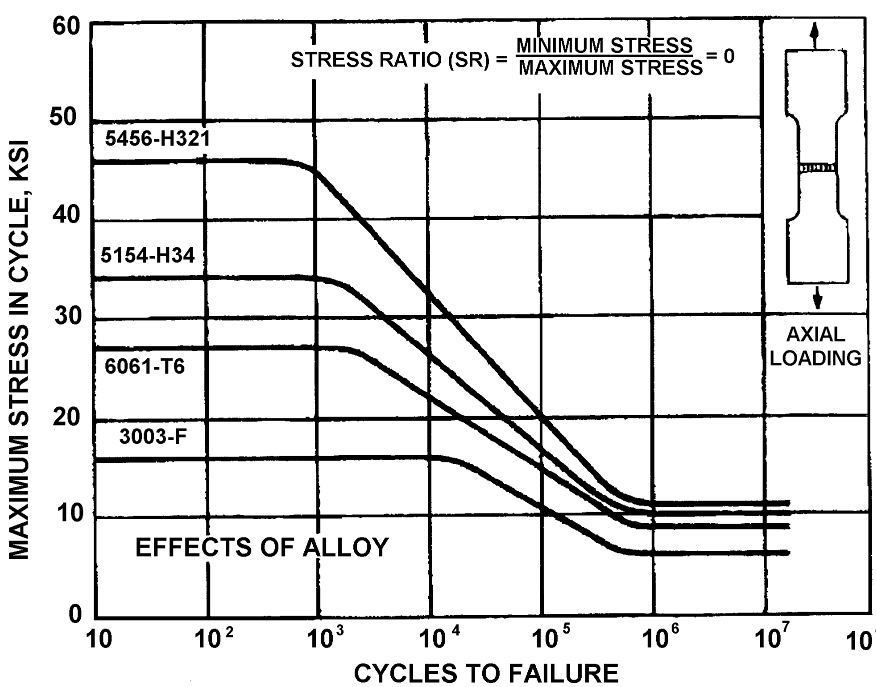

Figure 3-10 The Effect of Alloy on the Fatigue Life of Aluminum

3.4.3 The Strength of Welded and Unwelded Aluminum Specimens

It is well known that the process of welding aluminum reduces the strength of the parent metal through the heat-affected zone so that it is not possible to take advantage of the full, unwelded strength of the material.

This same effect does not occur in steel weldments and the yield strength of the parent metal is used as the baseline for all design calculations. (Although there is some evidence that the HAZ of TMCP steels may be softened.) Also, in quenched and tempered (Q&T) structural steel, a portion of the HAZ may be softened, i.e., of lower strength than the base metal, but the change may not be as significant as the change in heat-treated aluminum. All factors of safety are developed relative to the properties of the parent steel in the weldment with no reduction in strength as a result of material changes through the HAZ. The U.S. Navy has developed an empirical relationship to define the allowable working stresses of the various steel alloys typically used for combatant construction. This is shown below as equation 3.4: [3-8]

$$F_b = 0.5\left[\left(F_m / 2.15\right) + \left(F_y / 1.26\right)\right] \qquad (3.4)$$

Where: F_b = the allowable working stress.

F_m = the ultimate tensile strength of the material and,

F_y = the yield strength of the material.

This empirical relationship tends to develop allowable working stresses for the lower grades of steel that are a higher percentage of the material yield strength. This occurs because of the greater spread between the yield and ultimate tensile strengths for the lower grades of steel alloys.

Table 3–1 [3-8] shows the acceptable values for the yield strength of welded and unwelded parent material used for the design of aluminum weldments in accordance with US Navy practice. As noted by the values in this table, the reductions in the yield strength of the aluminum weldment are significant compared to the yield strength of the unwelded material. The allowable working stresses shown in Table 3–1 are developed in accordance with NAVSHIPSINST 9110.46

Table 3–1 Strength of Aluminum Alloys from US Navy Structural Design Manual

ALLOY	F_m (ksi) Ultimate Tensile Strength	F_y (ksi) Yield Strength		F_b (ksi) Allowable Working Stress	
		Prime Material	Welded	Shear	Tension & Compression
Plate					
5052-H34	34	26	20	10	16
5086-H32	40	28	22	11	18
5086-H116	40	28	22	11	18
5086-H117	40	28	22	11	18
5454-H34	39	29	16	8	14
5456-H321	46	33	26	13	21
5456-H116	46	33	26	13	21
5456-H117	46	33	26	13	21
Shapes					
5086-H111	36	21	16	8	14
5454-H111	33	19	16	8	14
5456-H111	42	26	21	10	17
Tubing					
5086-H32	40	28	22	11	18
5086-0	35	14	14	8	13

3.5 Defining the Fatigue Related Problem for High-Speed Craft

The specific fatigue problem of interest to this report relates to the increasing number of fatigue cracks and failures in aluminum high-speed craft in recent years. Recent history of steel ships would reveal a similar observation. The culprit is often thought to be an over zealous effort to reduce the structural weight of a vessel and increase its payload capacity for a given displacement. This will push owners and designers to reduce scantlings to minimum levels to meet the rule-required nominal stress levels. These “optimized” structural designs have been facilitated by the availability of software packages that allow the designer easy access to a tool capable of performing numerous design revisions in a short period of time. Unfortunately, there is still uncertainty regarding the loads and this “optimization” reduces the margins of safety while increasing the nominal stresses acting throughout a vessel. The increased nominal stress levels are acted upon by stress concentration factors that can produce local yielding of the material in the way of structural details. Stress concentrations will arise through areas of geometric or stiffness changes in the structure as well as in the area of the welds. Stress concentrations in the way of welds can compound the stress concentrations resulting from geometric increases. As a result of welding, stress concentrations can arise for numerous reasons, including voids or inclusions contained within the weld, lack of fusion, cracking or weld undercut. Further discussion concerning stress concentrations is presented later in this report.

Due to the predominance of steel vessels in the navy and commercial maritime industries, there is a fairly significant database of fatigue related information for steel ships and techniques available to reduce the fatigue related problems. Although many of the techniques used to reduce or control the fatigue of aluminum details would be the same as those used for steel ships, a similar database of information relative to the fatigue of aluminum weldments in the marine environment does not currently exist.

3.6 The Fatigue Crack

Brief discussion regarding the fatigue crack is presented in this section. Further detail is developed in Section 6 of this report.

Cyclic loading is not a problem unless cracks are initiated as a result of its action. It is generally recognized that all weldments contain microscopic fissures at the crystalline level in both the parent metal and the weld metal deposited during fabrication.

Basically, there are three phases in the life of a fatigue-induced crack:

1. Crack initiation.
2. Crack propagation.
3. Failure (growth of the crack to its critical crack size.)

Problems only exist when the time until crack initiation is less then the service life of the vessel. For all such scenarios it is necessary to have inspection schedules that monitor the condition of a detail and insure that crack propagation is proceeding as predicted by the damage tolerance analysis. Repair and maintenance are critical to areas determined to be prone to fatigue cracking. For critical or inaccessible details it is recommended that the design be developed to insure crack-free service lives greater than the service life of the vessel or application, i.e., a Safe-Life design philosophy. Appropriate factors of safety need to be included in these analyses depending on the critical nature of the detail and the consequences of its failure.

Figure 3-11, [3-9], provides a schematic representation of two crack initiation sites. These locations, at a deep bracket in a transverse web frame, indicate the effects of poor detailing combined with the stress concentrations resulting from the geometry of the bracket.

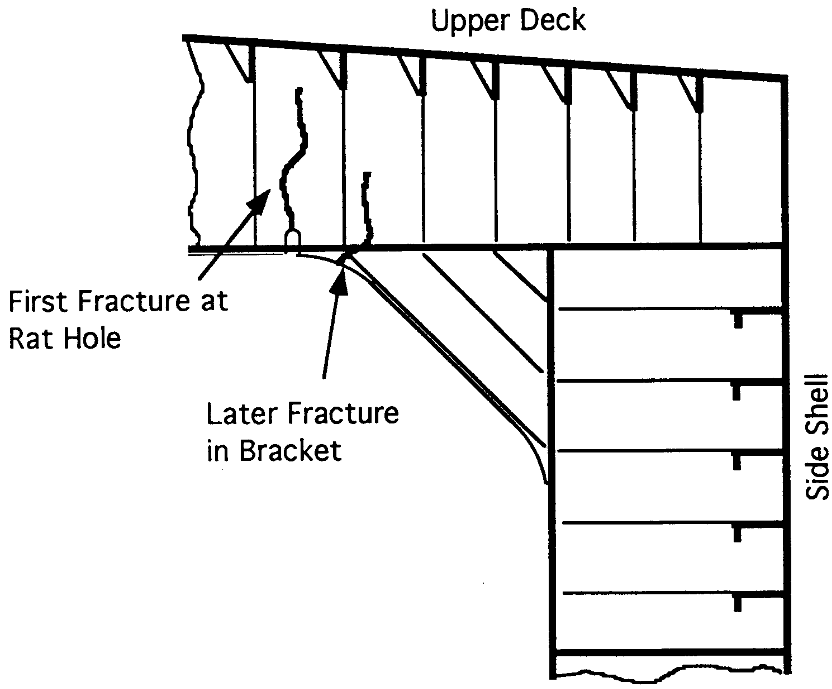

Figure 3-11 Typical Crack Initiation Sites

Figure 3-12, [3-10], presents a photograph of a fatigue-induced crack not typically thought of as a problem in ship structural design. The stress concentration effects at the cover plate detail, along with any stress raisers that may have been introduced when welding the cover plate, can also cause fatigue problems. Figure 4-6 demonstrates some of the stress concentration effects associated with various details.

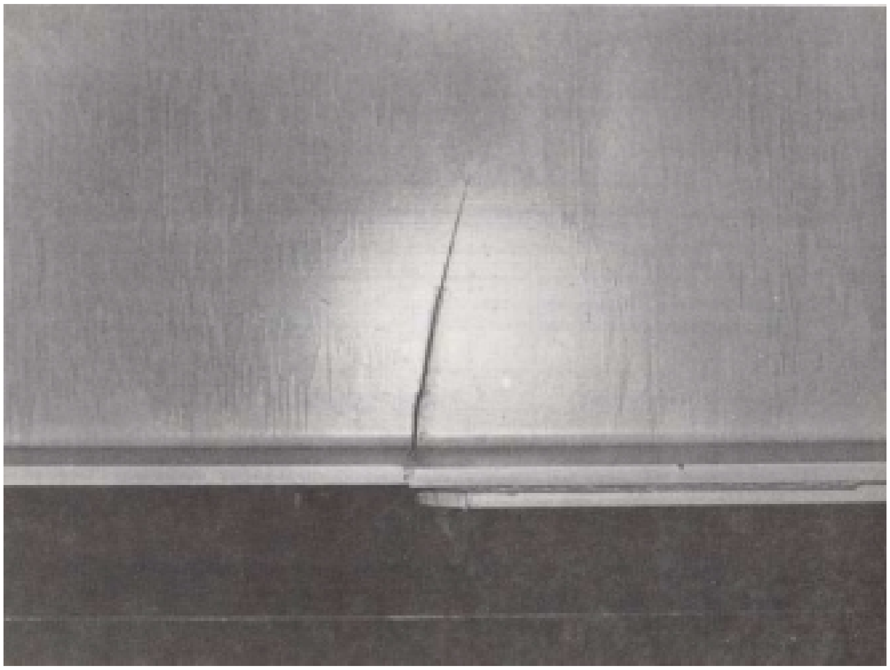

Figure 3-12 Fatigue Crack at Cover Plate Detail

3.6.1 Crack Initiation

Crack initiation occurs under the cyclic action of plastic deformation at either the macro- or microscopic level. The critical number of cycles for crack initiation to occur will vary depending upon the stress levels and stress concentrations experienced through the detail. As the load magnitude increases the number of cycles required for crack initiation will decrease. It is important for the designer to recognize the methods for controlling the onset of crack initiation. In general, it is important to minimize the stress concentrations to the greatest extent practicable. Most detailing and practices used for improved fatigue behavior in steel also apply to aluminum. It is important that notch effects are minimized and that welding is performed in accordance with acceptable and appropriate procedures for the application. Extending the crack-free portion of a detail's life is easiest to influence during initial design. Prediction of crack propagation rates and time to failure is much riskier and requires more inspection during the life of the vessel. Research conducted for this report also reveals a lack of crack propagation rate information for aluminum in the marine environment, further complicating this phase of the design.

For use in the marine industry, crack initiation is often defined as the time when a visible crack length can be seen during routine investigation. It is often assumed that the crack will have a length between 6 mm (¼") and 12 mm (½") at the definition of crack initiation. This represents an arbitrary definition and needs to be more completely defined, perhaps relative to the function, location or size of the detail in question. Similar to steel ships, it can be difficult to find cracks of lengths exceeding 150mm (6") during the routine survey of an aluminum craft. If future survey experience demonstrates the difficulty in detecting cracks below a certain limit this can be factored into the design of damage tolerant details. The analysis for such details will have to insure that the structure is acceptable until this minimum crack size can be assumed to be readily detectable through a routine survey with a given level of confidence.

3.6.2 Crack Propagation

After the crack has been initiated it will continue to grow as long as the cyclic loading continues. The stress concentrations in the area of the crack tip also increase as the crack propagates. Therefore, nominal stresses that caused minimal or no damage prior to crack initiation can now become damaging load cycles. Figure 3-13, [3-11], demonstrates the plastic zone at the crack tip of a test specimen and actual structural element. It indicates that plasticity will always be present regardless of the load magnitude once the crack has been initiated.

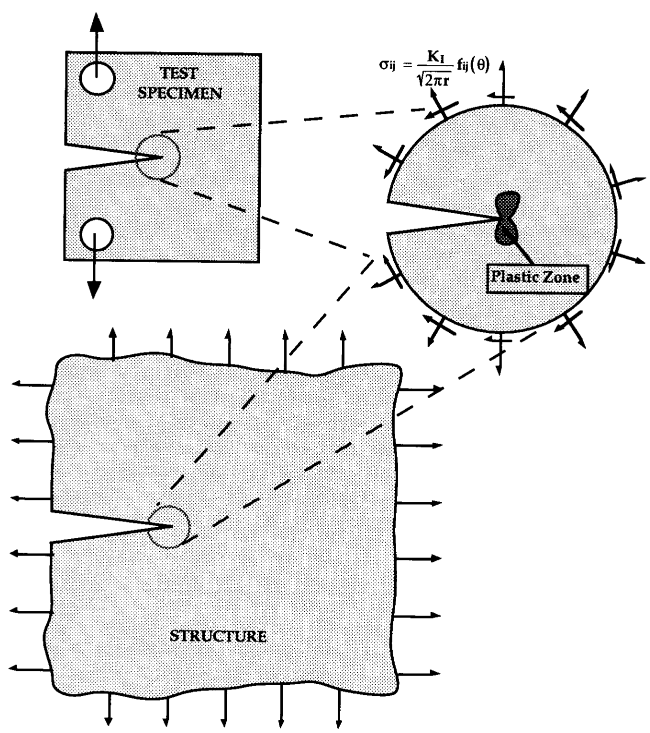

Figure 3-13 Schematic of crack-tip plasticity in test specimen and structure.

Damage tolerance analysis addresses crack propagation using fatigue-crack-growth-rate (FCGR) curves, an example of which is shown in Figure 3-14, [3-11]. These curves plot the crack extension per cycle (da/dN) vs the difference between maximum and minimum K values for each cycle (ΔK) where K is the crack tip stress-intensity which is a function of applied stress, crack dimensions, the extent of plasticity at the crack tip, and geometry. For crack propagation in a linear-elastic material the general formula for K is:

$$K = Y\sigma\sqrt{\pi(a)} \qquad (3.5)$$

Where: K = Crack tip stress intensity factor. See Section 6.4 of this report for discussion on the failure modes.

Y = geometric factor.

σ = applied global stress.

a = crack length.

Figure 3-15, [3-12], shows a plot of some actual FCGR curves for various aluminum alloys in a benign environment. These crack growth rates correspond to regions II and III, the sections of constant and accelerating crack growth rate, as shown in Figure 3-14.

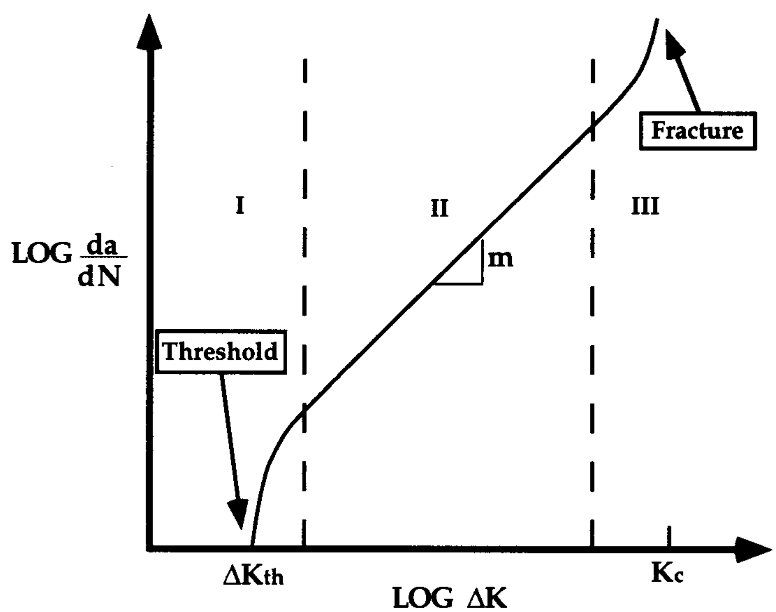

Figure 3-14 Typical Fatigue Crack Growth Rate, FCGR Curve

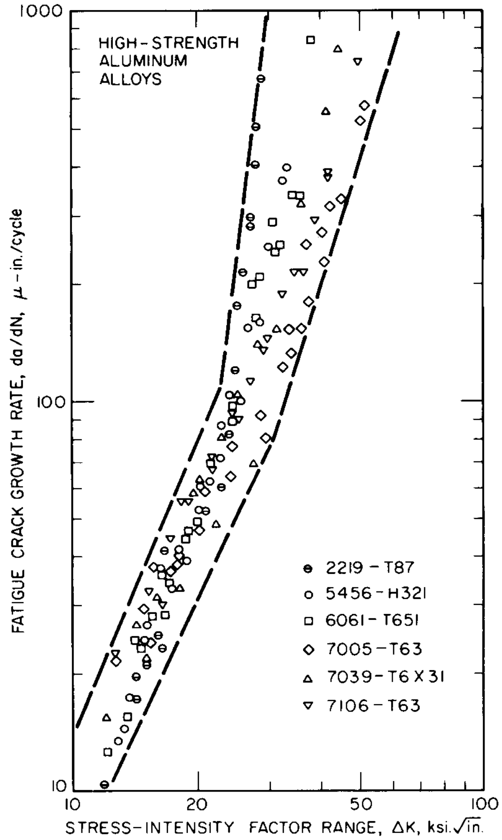

Figure 3-15 Actual FCGR data for various aluminum alloys in a benign environment.

3.6.3 Critical Crack Length or Failure

A crack will continue to propagate in accordance with Figure 3-14 as it progresses through region II and into region III. Eventually the crack growth rate will accelerate and the structure, or detail, will exceed the residual strength of the member which will then fail from any number or combination of damage mechanisms. These include the possibility of fracture, buckling, tearing or plastic collapse. The length of the crack at fracture is defined as the critical length and although the fracture toughness is constant for a given material, the critical crack length varies with the application and operating environment of the detail utilizing a given material. The critical length will be a function of a number of variables. These include:

- The toughness of the material used for the detail.
- The size and geometry of the detail containing the crack.
- The stress range and stress concentration effects acting through the detail.

After a fracture mechanics analysis has determined the critical length for any given detail, it will be necessary for the designer to determine an allowable crack length. This would be some reduced percentage of the critical length, i.e., the allowable crack length may be taken as 50% of its critical length. Various factors for each detail may influence the decision for determining the allowable crack length. These would include:

- The structural redundancy in way of a particular detail.
- The consequences of failure of the detail.
- The accessibility of the detail for inspection, maintenance and repair.

There may be some detail functions or locations that are not allowed to sustain any crack damage during their entire service life. These would require details typically termed as "Safe-Life". Other details will sustain some crack damage prior to the end of their service lives and these are termed "Fail-Safe".

The critical crack length would only be defined for details that are part of the Fail-Safe category. Typically, this would be a crack length above which there is too great a risk for complete loss of structural integrity, load carrying capacity or some other catastrophic type of failure. This could include loss of cargo or payload such as a leak through a tank resulting in discharge to the environment.

The critical crack length can be determined analytically or empirically depending on the function of the detail. The concepts of Safe-Life and Fail-Safe design are discussed below.

3.7 Safe-Life and Fail-Safe Definitions and Design Philosophies

The Safe-Life and Fail-Safe design philosophies were developed by the aircraft industry [3-13]. Along with damage tolerance they are defined as:

- Safe-Life - Safe-Life components are those whose failure would result in the catastrophic loss of a structure. Safe-Life components must remain crack-free during their entire service life.
- Fail-Safe – Structure will support load with any single member failed or partial damage to an extensive portion of the structure. Remaining stiffness is adequate to prevent excessive vibration or deflection, etc.
- Damage Tolerance – Ability of a structure to sustain anticipated loads in the presence of fatigue, corrosion or accidental damage until such damage is detected through inspection or malfunction and repaired.

For a Safe-Life design the aircraft industry required a significant margin of safety for the predicted time to crack initiation compared to its intended service life. This relationship was established as:

$$\text{service life} = \frac{\text{life from fatigue analysis or tests}}{\text{life reduction factor}}$$

where the life reduction factor could range from 2.36 (based on 4 test specimens) to 3 (based on 1 test specimen) for FAA applications to 4 for the USAF.

The technology associated with fatigue and damage tolerance allows the designer flexibility when developing the initial design. The flexibility allows development of details with a service life greater than the service life of its application using fatigue design technology only. Alternately, the designer can also develop details with fatigue lives less than the service life of their application. The latter requires the use of fatigue and damage tolerance technology where the damage tolerance analysis can predict the time to failure using crack growth rate and loading data to predict the total life of the detail before the critical crack length is developed.

The two design philosophies described above reflect the Safe-Life and Fail-Safe designs. The preferred method is the Safe-Life design. It is characterized by having a life to fatigue crack initiation greater than its intended service life. The Fail-Safe design is characterized by details with fatigue lives that are less than their intended service life.

3.7.1 The Safe-Life Design

A Safe-Life design is one with a life to crack initiation greater than the service life of the vessel, i.e., there will be no crack initiation in the detail until after the service life of the vessel has been exceeded. A Safe-Life design will be developed for critical details where the result of failure, defined as crack initiation, is catastrophic or where there is no load path redundancy after the detail fails. Similarly, it will be recommended to develop Safe-Life details for applications that do not permit ready access for inspection, maintenance or repair.

An Owner may also decide to employ the Safe-Life design philosophy if analysis shows a nominal increase in initial cost compared to the life cycle costs required to inspect, maintain and repair a detail that is less fatigue resistant developed in accordance with the Fail-Safe approach. This trade off should be developed for all Fail-Safe details.

3.7.2 Fail-Safe Design and Damage Tolerance Analysis

A Fail-Safe design has a life to crack initiation less than the service life of the vessel, i.e., it is predicted through calculation that crack initiation will take place in the detail prior to the end of the service life of the vessel. As part of the Fail-Safe design for use in the high-speed craft industry, it will also be necessary for the designer to establish an inspection schedule for each of the Fail-Safe details used in the design. This schedule should include inspections prior to the expiration of the predicted crack-free life of the detail to insure behavior in accordance with the calculations predicting the crack free portion of its design life.

A Fail-Safe design may be developed when the consequences of failure are not catastrophic and when access for inspection, maintenance and repair can be readily achieved. The designer proposing this approach should perform analysis or otherwise verify that redundant load paths exist that can carry the loads shed by the detail, should total failure occur, without becoming overstressed or resulting in other forms of unacceptable behavior, i.e., excessive displacement. It is understood that the initiation of a crack does not typically define failure for a Fail-Safe category detail. The critical extent of damage which defines failure, i.e., crack length and depth, needs to be developed for all Fail-Safe details.

When assessing the adequacy of a structural system for a Fail-Safe design, the designer needs to consider the effects of aging on that system. Swift and Goranson discuss this effect relative to aircraft structures in a number of papers. For ship systems, the effects of aging can be accounted for by assuming certain material wastage toward the end of a vessels life to determine the stresses that will be acting in the vessel at this time.

3.7.2.1 Brief Example of Safe-Life & Fail-Safe Designs

The following examples help to explain the relationships between the different design philosophies for fatigue resistant design. The first example is included to demonstrate an *unacceptable* Safe-Life design and emphasizes the factors of safety required for such as evaluation.

Assume a proposed detail has an analytically predicted fatigue life, i.e., time to crack initiation life, of 23.2 years while the vessel is designed for a 20-year service life. This may seem like a Safe-Life detail because its fatigue life is predicted to be greater than the service life of the vessel. However, upon closer inspection it is determined that this design only has a margin of safety equal to 23.2/20 = 1.16. This would not be considered acceptable for a Safe-

Life design that typically will have a margin of safety on the order of 3 to 4 times the anticipated service life. These higher margins include the use of conservative load estimates coupled with conservative S/N curves. If the analysis cited above resulted in a crack free service life for the detail equal to 77.2 years with a resulting margin of 77.2/20 = 3.86 a Safe-Life design could be assumed. For the latter situation, it is not necessary to perform a damage tolerance analysis on this detail because its crack free service life satisfies the Safe-Life design criteria.

The Fail-Safe analysis becomes required for details that are predicted to have crack-free lives less than the service life of the vessel. For instance, a proposed detail is predicted to have a fatigue life of 17.2 years for the same 20-year service life assumed above. This means that after 17.2 years of service, a crack will be initiated in the detail and this detail would be categorized as Fail-Safe. Now it is necessary to perform a damage tolerance analysis if the structure is allowed to sustain this crack as it grows.

For purposes of this discussion, it is assumed that crack initiation means a crack that is visible to the naked eye and is taken to be 6mm (¼") long. A fracture mechanics analysis is then performed and determines that the critical crack length is 305mm (12"). The number of loading cycles to reach this crack size will be developed as part of the fracture mechanics analysis. As seen above, the crack-free life of the detail extends to within 2.8 years of the service life of the vessel. Therefore, if the time to compile the critical number of load cycles determined by the fracture mechanics analysis is more than 2.8 years the detail could be considered acceptable. If the time to failure is less than 2.8 years it will be necessary to perform maintenance on this detail prior to the end of the service life of the vessel or replace the detail with something predicting a greater service life. These are all depicted in Figure 3-16.

Regardless of the results of the fracture mechanics analysis and the decisions regarding the use of the detail, it will be necessary to inspect the detail prior to the predicted end of the crack-free life. Similarly, inspection will be required during the "crack propagation" phase of the detail's service life to insure that the crack is progressing at the rates predicted by the analyses. Should the crack growth exceed this rate at any time prior to or after the predicted crack-free life it will be necessary to revise the fracture mechanics predictions and the associated inspection schedule.

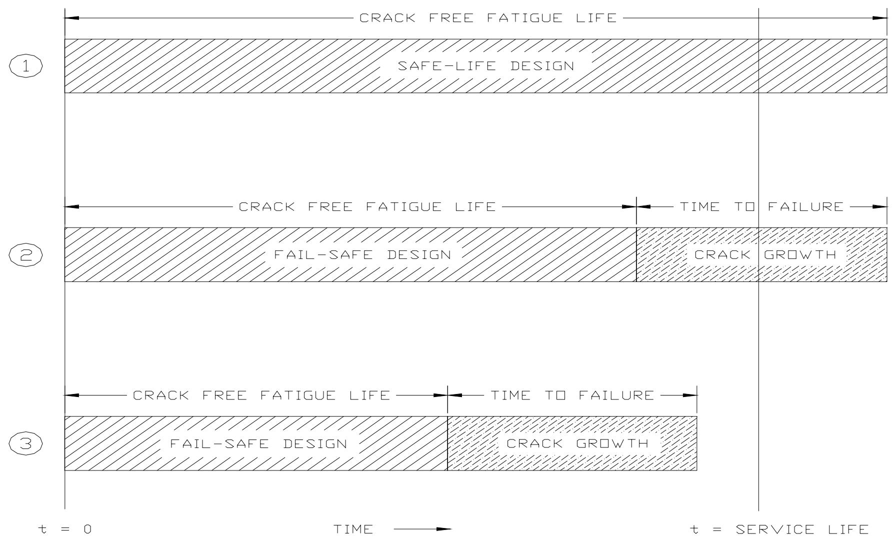

Figure 3-16 Schematic Representation of Fatigue Life to Service Life

3.8 Welding and the Introduction of Crack Initiation Sites

The discussion presented in this section represents well-known technology and phenomena. The discussion presented on this topic along with Figure 3-17, Figure 3-18 and Figure 3-19 is taken from Barsom and Rolfe [3-12].

The development of welding technology has allowed for the design and construction of new systems that were not possible using riveted construction. Increased fabrication rates, automated welding procedures and computer controlled welding have all revolutionized various aspects of different industries. Similar to any other technology or process improvement, welding too has introduced certain concerns that need to be addressed to insure optimal utilization of the process.

When a structure is welded there are three different characteristics that can be introduced to the weldment. All three are important in the present discussion and can lead to fatigue and fatigue cracking problems. The welding procedure can introduce residual stresses, stress concentrations and imperfections to the weldment, all of which can effect the fatigue behavior of the detail. These are reviewed below to remind the designer of these phenomena and the ability to control certain aspects during the design and fabrication process.

3.8.1 Residual Stresses

The welding process introduces residual stresses into the welded joint. A three dimensional state of residual stress is set-up in the weldment with the maximum tensile stresses approaching the yield stress of the deposited weld metal. The tensile residual stresses tend to extend from the toe of the weld to the root or other toe and can compound environmentally induced tensile stresses helping to aggravate any fatigue problems through this area.

When a weld is produced the molten filler metal sits in a cavity alongside the pieces to be joined. As the filler metal cools, it contracts along the length of the weld (longitudinally) and at right angles to the weld (transverse) (as well as through the thickness). This contraction is resisted by the surrounding base metal which has remained at or near ambient temperature. This contraction results in residual tensile (+) and compressive (-) stresses as indicated in Figure 3-17.

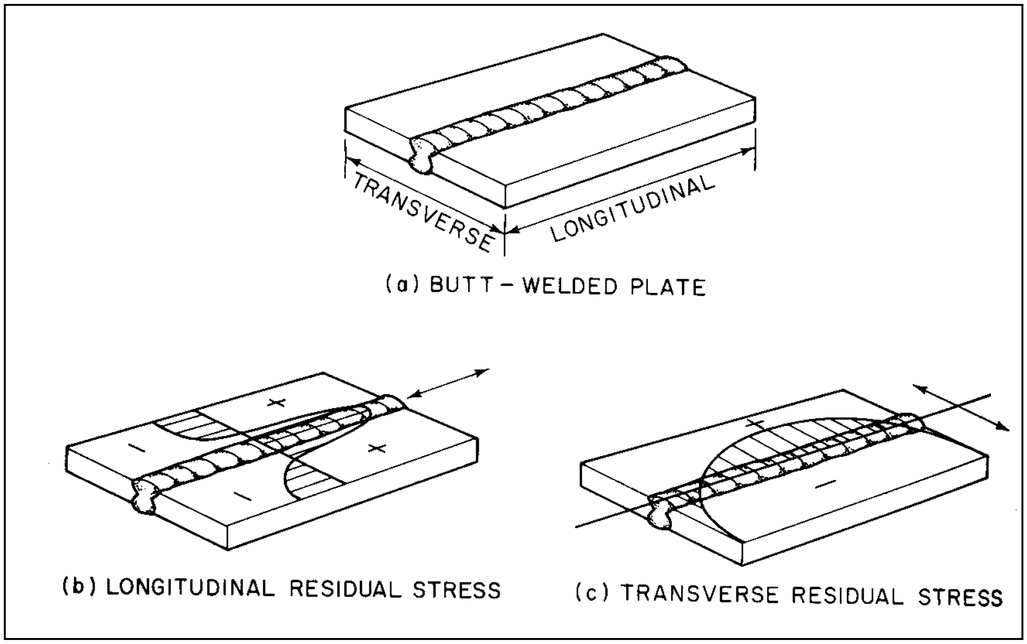

Figure 3-17 Residual Stresses For Butt-Welded Plate

The heat introduced by the welding process not only introduces residual stresses but also weakens the aluminum alloys in the 5XXX and 6XXX series. The heat from welding will anneal the 5000 series alloys and upset the specific heat treatments which were applied during the precipitation hardening phase of the 6000 series. These two phenomena, the introduction of residual stresses and the reduction of material strength in the HAZ have a measurable impact on the strength of the material after welding. This is reflected in design codes with lower allowable stresses for welded aluminum then for the base material. This is reflected in Table 3–1 taken from the US Navy Structural Design Manual for Surface Ships, [3-8]. Note that the yield strength and ultimate strength are consistently lower than the values shown in Table 1–1 for the same alloys. This represents conservative design practice typical of a generic design code. Similar strength reductions are not required for steel weldments.

Compressive residual stresses have been shown to offset the operational tensile stresses and thereby relieve the fatigue environment. This is not an important consideration for the current discussion because most of the compressive stresses are outside of the weld where tensile stresses and fatigue dominate the scenario of concern.

3.8.2 Welding Imperfections

Cracks, inclusions, porosity, lack of fusion and weld undercut represent a few of the welding imperfections that may be introduced by the welding process. These all represent locations of potential crack initiation due to the resulting stress concentrations. Figure 3-18 presents a schematic view of a variety of the welding imperfections typically seen in ship, and other, welded constructions.

3.8.3 Stress Concentrations

Utilizing the welding process for construction will invariably result in stress concentrations from weld imperfections or geometric discontinuities. A variety of stress concentration cites are shown in Figure 3-19.

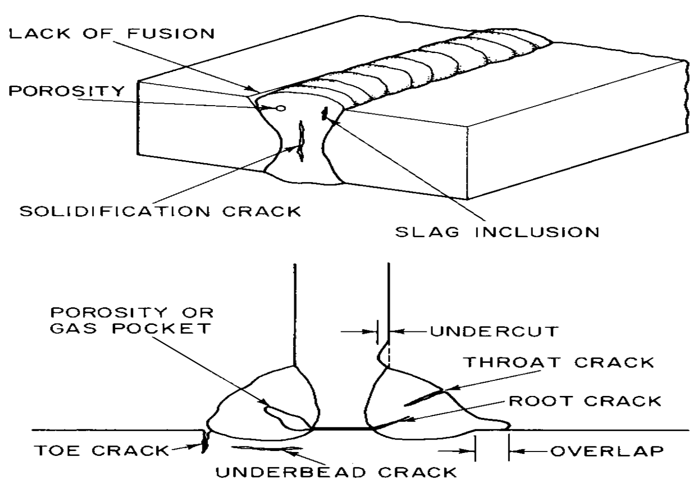

Figure 3-18 Potential WeldFlaws as a Result of Improper Welding

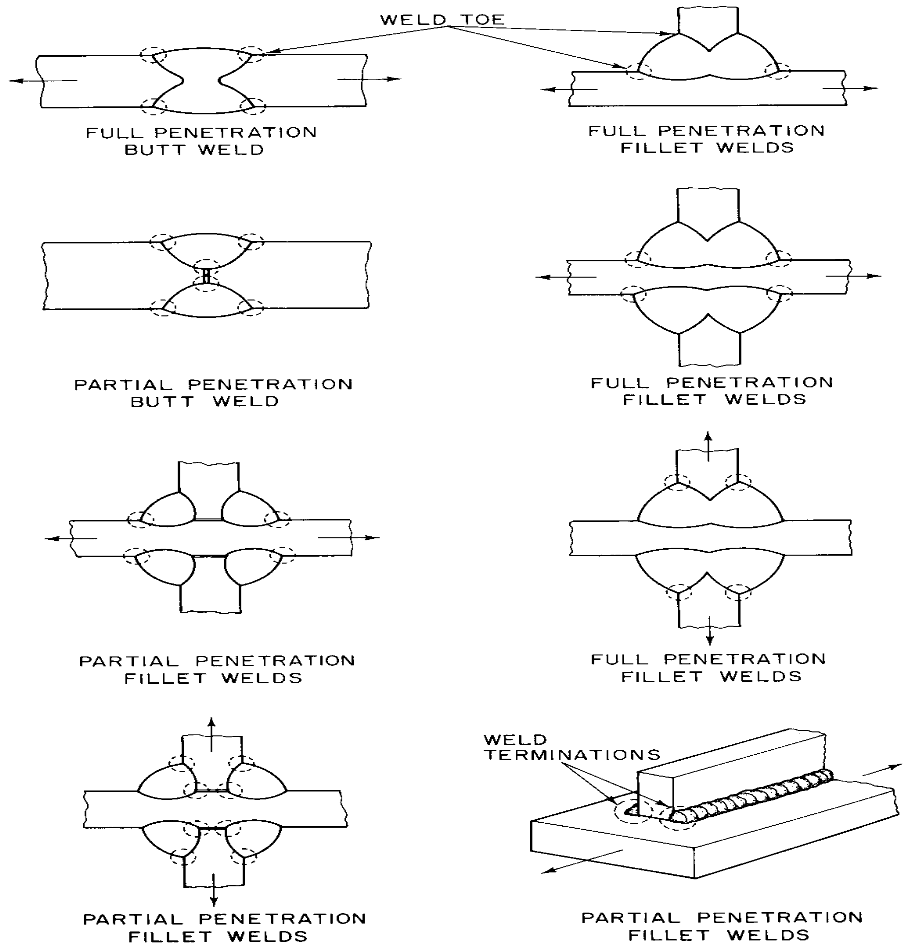

Figure 3-19 Stress Concentration Locations In Typical Welded Joints

3.8.4 Crack Initiation Sites in Steel and Aluminum

The three sources of crack initiation sites discussed above are a product of the welding process and will occur in welded steel joints and welded aluminum joints with similar frequencies. Steel is a more tolerant material than aluminum regarding its resistance to crack initiation as a result of these fabrication-induced problems. Recognition of these problems help to emphasize the importance of developing welding procedures for aluminum that are correct for the application and insure the quality control throughout the construction of the vessel. Employment of qualified aluminum welders is also critical for the fabrication of vessels that will minimize fabrication induced crack initiation sites.

3.8.5 Repair Welds in Aluminum Details

It is well known that when a crack appears in a steel structure or detail the quickest and simplest fix is often employed, especially for a ship at sea. This “quick fix” solution for steel typically back gouges the material in way of the cracked detail followed by re-welding of the detail. This “returns” the detail to a “sound” condition and, assuming the continuation of the same load history, will result in a detail with a somewhat reduced life compared to the original detail. This same technique is also employed in way of cracked aluminum details. Unfortunately, the results are not nearly as effective. The heat input from the repair weld can initiate new fatigue cracks at weld defects and the crack growth rates may increase as a result of the additional weld residual stresses. (The same flaws may result in steel weldment repairs.)

3.9 New Aluminum Alloys and Welding Techniques for High-Speed Craft

In recent years there has been a continuing increase in the demand for aluminum in high-speed craft. At the same time, fatigue-cracking problems continue to increase repair and maintenance costs because of the poor understanding surrounding this problem. One of the solutions investigated at various facilities is the development of new aluminum alloys designed for the rigors and demands of the marine environment. In particular this report presents a brief review of three of these new alloys developed at the companies cited below.

- Pechiney Rhenalu alloy 5383, which is a variant of 5083 [3-6].
- Hydro Aluminum Maritime alloy RA7108, which is a variant of 7108 [3-14].
- AluStar 5059 which is also a derivative of alloy 5083 [3-7].

All three of these new alloys have been developed for the marine industry and shipbuilding applications. There was no cost information available for any of these new alloys although the articles citing them also reported that they have each been selected for use on new ship design programs.

3.9.1 New Marine Grade Aluminum Alloy, Grade 5383

One of the aluminum alloys most widely used for the production of high-speed craft is 5083 for plate components [3-6]. The Aluminum Association defined the chemical composition for alloy 5083 in 1954 and it yields a material with a good combination of strength, formability, corrosion resistance and weldability. This alloy is also available in a large number of tempers that allow for broad application to many uses. Although 5083 performs well in its marine applications it is important to realize that it was not developed specifically for this environment and 5383 was developed to help optimize aluminum behavior in the marine environment.

With the development of new processing techniques it is now commonplace to control the chemical composition, cleanliness and other parameters of aluminum and other alloys with far greater precision than previously. Recognition of these controls and the possibility to develop an alloy that retains the long-term reliability of 5083 led Pechiney Rhenalu to the development of 5383. This alloy was specifically developed for marine applications and the considerations of shipyard fabrication, weldability and ease of forming were all evaluated while developing the new alloy.

In side-by-side corrosion tests, 5383 proved superior to 5083 in regards to both exfoliation and pitting corrosion. Until recently, 5083 was the only alloy allowed in direct contact with seawater because of its proven superior resistance to corrosion. It is now possible to use 5383 for this application.

Table 3–2 presents a comparison of the mechanical properties of the unwelded 5083 and 5383 aluminum alloys. Table 3–3 provides a comparison of the mechanical properties for the same two alloys after welding. In both instances, it is seen that 5383 has greater strength than 5083. As shown in Table 3–3, 5183 weld wire was used for all 5083 and 5383 test specimens.

Table 3–2 Mechanical Properties of 5083 and 5383 Alloys

5083 H116/H321 sheets and plates

Thickness range (mm)		Sample	Average U.T.S.	Average Y.S.	Average elon-gation
From	Up to and included	direction	(MPa)	(MPa)	(%)
3.2	6	LT	350	252	18.3
6	10	LT	351	257	18.7
10	20	LT	345	235	20.8
20	40	LT	347	238	17.9
5383 H116/H321 sheets and plates					
3.2	6	LT	373	255	21.9
6	10	LT	377	257	22.2
10	20	LT	375	247	21.1
20	40	LT	363	238	18.6

			Across the weld DNV procedure			In the weld			Along the weld in the HAZ		
Alloy	Thick. (mm)	Temper	Y.S. (MPa)	T.S. (MPa)	El (%)	Y.S. (MPa)	T.S. (MPa)	El (%)	Y.S. (MPa)	T.S. (MPa)	El (%)
5083/5183	6	H116	137	287	11.4	125	266	21.5	135	296	23.8
			134	286	12.7	135	272	28.5	144	304	20.5
			139	286	12.5	129	271	20.1	139	302	26.2
			129	288	13.7	129	274	13.2	146	304	30.3
			133	288	13.5	121	272	26.5	-	-	-
		Average	**134**	**287**	**12.8**	**128**	**271**	**22.0**	**141**	**301**	**25.2**
5383/5183	6	H116	153	299	9.3	139	277	15	170	336	21.7
			152	302	10.5	145	282	22.8	175	345	22.5
			148	300	10.4	146	280	25.2	165	330	18.9
			144	298	10.5	135	278	25.7	170	332	22.2
			149	299	10.3	143	276	20.2	-	-	-
		Average	**149**	**299**	**10.2**	**141**	**279**	**21.8**	**170**	**336**	**21.3**

Table 3–3 Welded Properties for Alloys 5083 and 5383

3.9.1.1 Fatigue Strength of 5383

Figure 3-20 shows a sketch of the simple specimen that was used for fatigue tests comparing 5383 to 5083. All the tests were performed with R = 0.1 on as rolled H116 plates. Figure 3-21 shows the Wohler curves for the fatigue tests carried out on samples produced and tested in a laboratory. Neither of the two curves shown in Figure 3-21 are explained in [3-6] which provided this figure. It is not obvious that either curve correlates to either of the data samples provided by the figure and seems to imply an optimistic behavior of 5383 by correlating this alloy with the solid line and 5083 with the dashed line. However, there is no specific discussion regarding these curves in [3-6] and both seem shifted to the right relative to the shapes and alloys with which they seem intended to correlate.

Figure 3-22 shows the results for fatigue tests conducted on specimens that were fabricated at a shipyard. The results of both samples suggest the same trend of increased fatigue strength for the newer alloy, 5383. Additional fatigue testing is required and it is recommended that future tests include large specimen details representative of shipbuilding. Regardless, the preliminary results for both mechanical properties and fatigue behavior are encouraging for this new alloy.

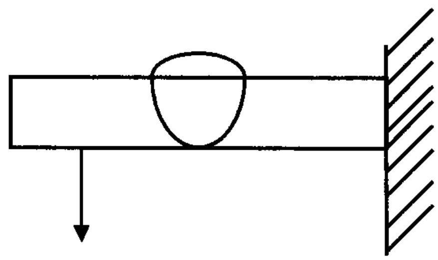

Figure 3-20 Small Specimen for 5383 Fatigue Tests

At the time [3-6] was written the new aluminum alloy, 5383, had been certified for use by DNV, Bureau Veritas, Lloyd's Register, Germanischer Lloyd's and the Korean Register. It was under review for certification at ABS and Nippon Kaiji Kyokai.

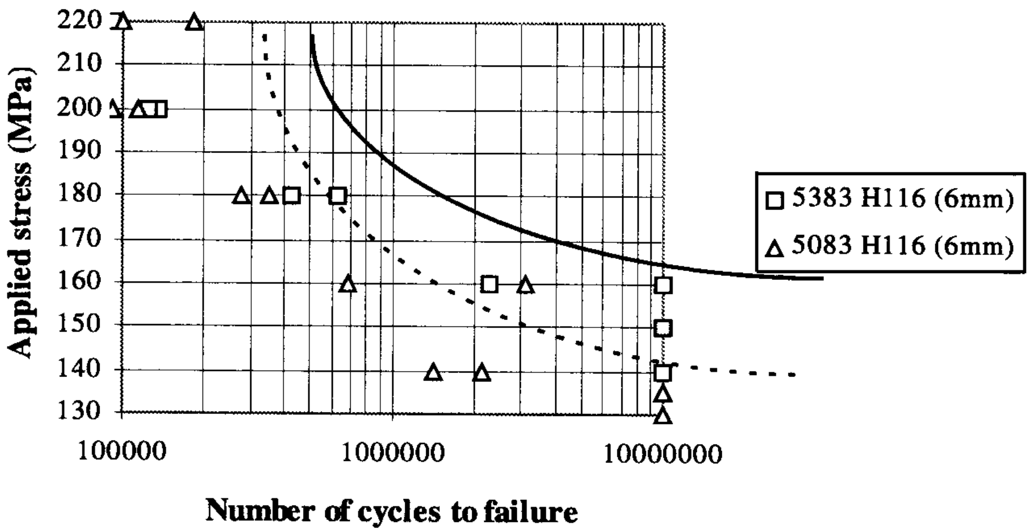

Figure 3-21 Fatigue Tests on 5083 and 5383 conducted at laboratory

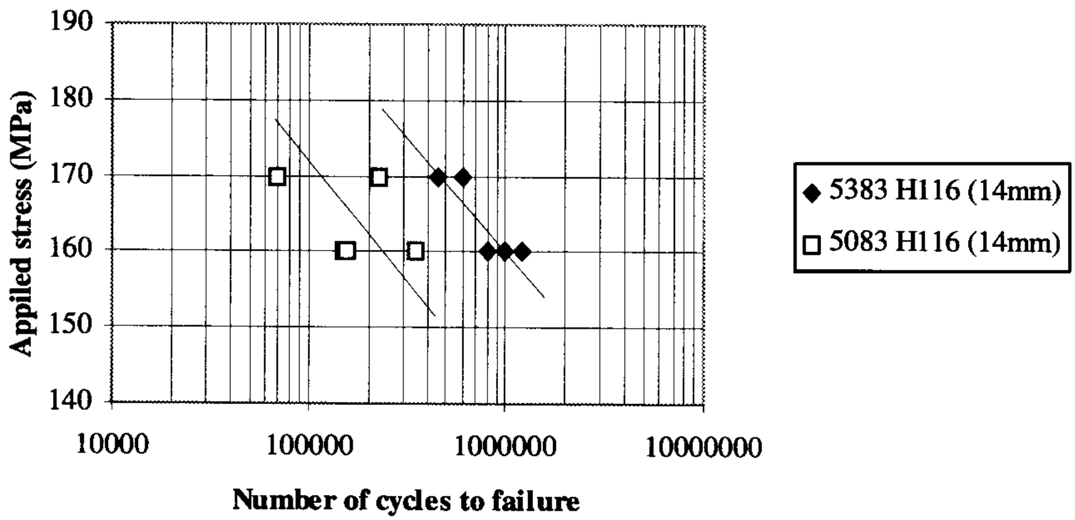

Figure 3-22 Fatigue Tests on 5083 and 5383 details built at shipyard

3.9.2 New Marine Grade Aluminum Alloy, Grade RA7108

Similar to 5383, Grade RA7108 was developed by Hydro Aluminum Maritime for specific use in the maritime environment [3-14]. It is an AlZnMgZr based variant of the commonly used alloy, AA7108. The alloy has proven superior weldability compared to conventional aluminum alloys used in shipbuilding. The new alloy has proven superior corrosion properties compared to AA6082 which is currently a common alloy for profiles. It has also proven to be comparable, or sometimes better than, AA6082 for extrudability. The alloy has potential for numerous structural applications and DNV has approved its use in two catamaran ferry projects.

Table 3–4 demonstrates the yield and tensile strength properties of the few alloys allowed by DNV, for use in high-speed, light craft. 7108-T79 refers to the older alloy that was used for the baseline of RA7108.

Alloy	Yield strength, [MPa]	Tensile Strength, [MPa]	Elongation, A_5, %
5083-H321	215	305	10
5383-H116	220	305	10
6082-T6	260	310	10
7108-T79	290	330	10

Table 3–4 Design Properties for DNV Aluminum Alloys

The allowable stresses for the same alloys, in accordance with DNV rules for high-speed, light craft are shown in Table 3–5. Table 3–6 compares the tensile strengths of alloy 6082 and RA7108.50-T79 using two different welding procedures. Gas-metal arc, GMA, welding is a traditional welding procedure used throughout the shipbuilding industry. Friction stir welding, FSW, produces noticeably improved strength through the weld area. Friction stir welding also results in improved ductility through the weld area as well as enhanced fatigue properties.

Alloy	Allowable stress, [MPa]
5083-H321	125
5383-H321	140
6082-T6	115
7108-T79	140

Table 3–5 Allowable Stresses for DNV Alloys

Alloy	Tensile Strength	
	GMA	FSW
6082-T6	215	239
7108.50-T79	270	340

Table 3–6 Weld Strengths of Aluminum Alloys

The new alloy, RA7108.50-T79 shows promise for use in extrusions and profiles. It has demonstrated extrudability superior to AA6082 and along with higher strength and increased resistance to corrosion has displayed significant reason for consideration in the marine environment. Specific fatigue data was not available for this alloy. Reference [3-14] makes a number of comments inferring improved fatigue behavior relative to 6082 but presents no test data. Regardless, this would be considered a new alloy and would require an increased test base for fatigue samples regardless of those demonstrated by small specimen testing to date.

3.9.3 New Marine Grade Aluminum Alloy 5059

The last of the new aluminum alloys reviewed by this report and developed for the marine environment is Alustar 5059. Also a derivative of 5083, many of the mechanical, fatigue, formability, corrosion and weldability properties are reported in [3-7]. Similar to 5083 and 5383, Alustar 5059 is an aluminum/magnesium alloy that is not heat treatable. Figure 3-23 demonstrates the strength and elongation properties of Alustar 5059 compared to 5083 and 5383. This figure suggests that the Alustar alloy exceeds the other two alloys in its mechanical behavior.

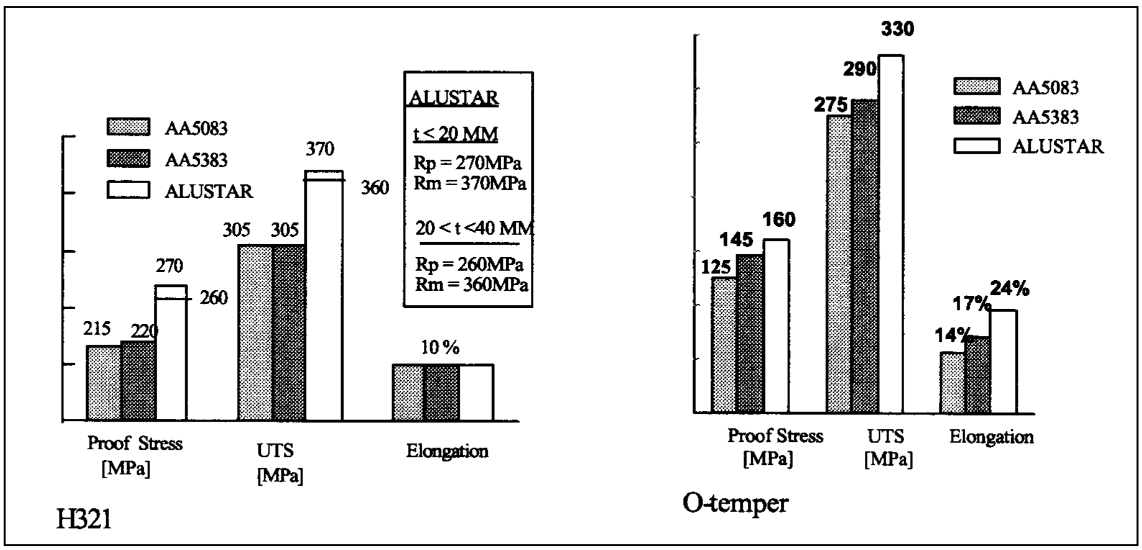

Figure 3-23 Comparison of Material Strength for 5083, 5383 and 5059

Figure 3-24 also demonstrates that the fatigue strength of the Alustar alloy exceeds that of 5083. Unfortunately, the information in this figure has significant variation from the data shown for 5083 by Pechiney Rhenalu in their comparison of 5383 to 5083. One possible explanation could lie in the type of detail used for the fatigue tests, the information for which is not provided by Alustar in [3-7]. Other variables reflected by the two tests would have to be reviewed to establish a complete comparison. Regardless, comparison of these two figures suggests that it is required that at least one independent test agency would have to test all three alloys under consistent conditions before complete and meaningful comparisons could be developed.

This result would also need further testing, along with 5383, to refute contradictory evidence that suggests the effect of alloy does not have a pronounced effect on the long-term fatigue life aluminum alloys, i.e., the long-term fatigue strength tends to converge to a similar value independent of the yield strength of the material. Further discussion on this phenomena is presented in Section 3.4.2 of this report.

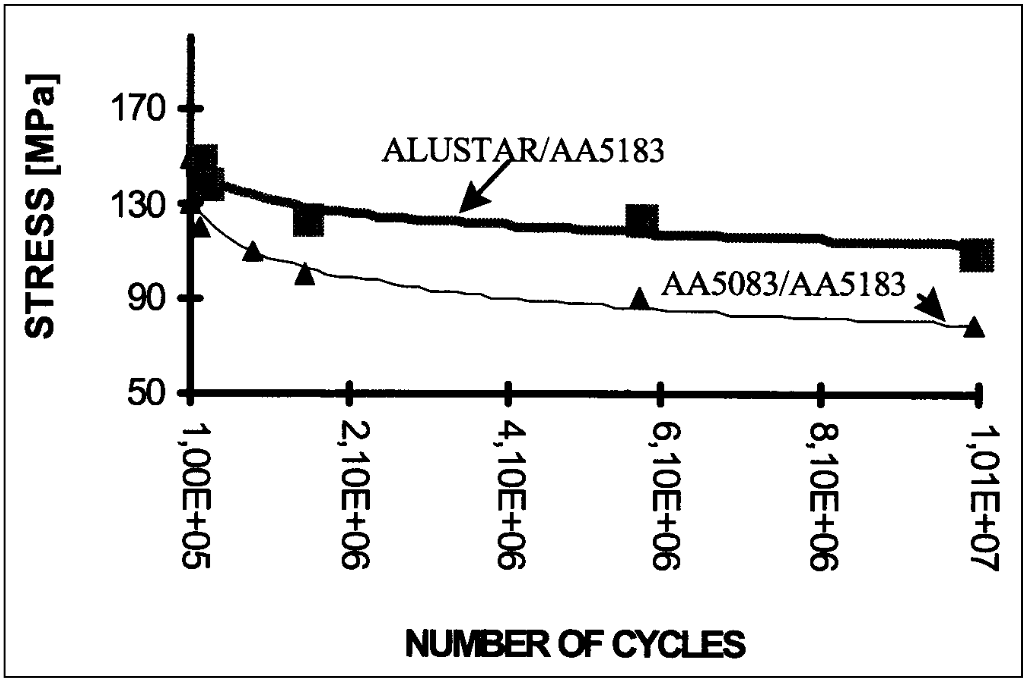

Figure 3-24 Comparison of 5083 and 5059 S/N Curves

3.9.4 Friction Stir Welding

Friction stir welding is a relatively new technique to the marine industry although the technology itself is not new. It can be used to join various materials including aluminum, zinc, titanium and steel. There is an increasing interest for this welding procedure in the aluminum marine industry in Europe where significant investment has been made to incorporate this new procedure.

Friction stir welding does not require any consumables and creates the welded joint at a temperature below the melting point of the material. This results in lower residual stresses in the HAZ with better retention of strength through the weld. Figure 3-25 presents a schematic overview of the setup required to effect the friction stir welded joint. As seen in this figure, a wear resistant, rotating tool is placed between the two pieces of aluminum to be welded. The probe at the base of the tool guides it along the weld joint. Vertical pressure is applied through the tool as it rotates. This produces the friction necessary to generate the required heat, i.e., the fusion temperature of the material, [3-15]. The vertical pressure also forces the two components into the backing structure which is required to support the two pieces as they are welded. The requirement for the backing structure is one of the drawbacks of the procedure and can require extra setup that may become prohibitive for limited production. Elaborate machinery has been developed in Europe for the production of flat panels used in aluminum maritime construction and they are currently being used for an ever increasing range of applications.

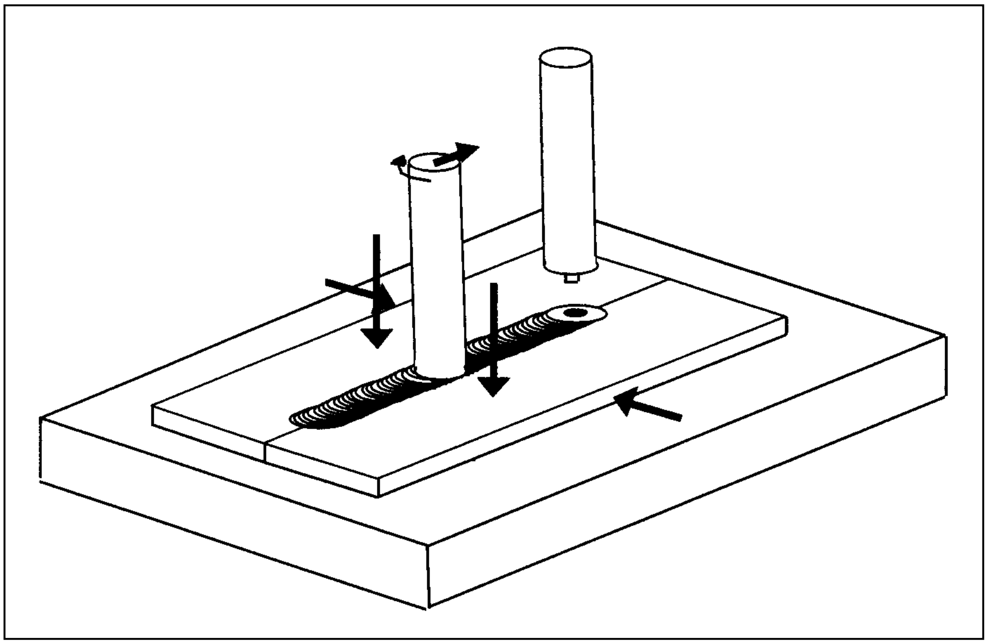

Figure 3-25 Schematic of Friction Stir Welding Operation

Friction stir welding has been successfully used on aluminum plate thicknesses ranging from 3 mm (1/8 inch) to 51 mm (2.0 inches). It has also been used to join plates of different thicknesses, the fillets between plates and stiffeners and honeycomb construction.

Three papers were recently presented on friction stir welding at the Fourth International Forum on Aluminum Ships and they were:

1. Application of Friction Stir Welding for the Manufacture of Aluminum Ferries, Mr. Stephan Kallee of The Welding Institute.
2. Application of pre-fabricated friction stir welded panels in catamaran building, Mr. Ole Terje Midling of Hydro Aluminum Maritime.
3. Possibilities with Friction Stir Welded Aluminum Extrusions, Mr. Jan Backlund of SAPA AB.

For a complete listing of all the papers presented at this forum, please see Appendix A.

3.10 References

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4. Fatigue Design of High Speed Aluminum Craft

This chapter provides information on the generic fatigue design for application to aluminum weldments in high-speed craft. It presents a variety of options for stress calculations including nominal, hot-spot and notch stress calculations. It discusses a variety of techniques to determine the load distribution for long term exposure for development of the required load/stress histograms for the fatigue assessment. Most of the techniques are described briefly. Information regarding the fatigue behavior of various details and alloys is also presented in Appendix E. The S/N curves provided in this appendix might be applicable to the details under investigation for certain designs and can be used to help provide the information required for the complete fatigue analysis.

Section 5 presents the fatigue design procedures used by various other industries. The information regarding the procedures used by other industries is provided to demonstrate the manner in which they handle the lack of explicit definition for all loads that may be acting upon a given detail. The procedures used in other industries are also presented to allow the designer the freedom of choosing a procedure that might better fit the design of a given detail. It must be emphasized however, that the designer must incorporate appropriate factors of safety when using the procedures developed for other industries.

It is worth restating that, regardless of the procedure selected for fatigue design and analysis, there are many assumptions regarding loading and material behavior. In particular, with regard to fatigue of high-speed craft, quantifying the primary and secondary loads acting on the vessel is a new science in the early stages of development. It is suggested that the designer select an analysis technique consistent with the stage of design, i.e., preliminary or final detail design, and magnitude of the overall program. It is intended that this report assist the designer during the design process and not impose burdensome procedures that result in frustration and analysis that is inconsistent with the rest of the design. The gaps identified in the loading and material behavior need to be filled with further research. In the meantime, it is still possible to reduce the fatigue-related problems associated with the operation of aluminum high-speed craft. This can be done using the knowledge and information that does currently exist and applying either first principal solutions or the design codes utilized by other industries augmented with appropriate factors of safety.

4.1 Palmgren-Miner Cumulative Damage Fatigue Assessment

The method used for the fatigue analysis is the Palmgren-Miner cumulative damage fatigue assessment. The Palmgren-Miner assessment is a linear method that provides a reasonably accurate, cost-effective result that is consistent with the level of available information in the high-speed craft industry. The methodology assumes that every cycle of loading produces some finite level of fatigue damage if the stresses generated by that cycle of loading are above the endurance limit of the material. The Palmgren-Miner methodology sums the damage from all cycles above the endurance limit to determine whether the cumulative damage has exceeded the allowable limit. For aluminum alloys subjected to a variable amplitude loading history, it is generally agreed that there is no endurance limit and all cycles would be considered to produce damage. The Palmgren-Miner methodology is widely used and also forms the basis for analysis in the design codes of the other industries presented in Section 5.

The formulation of the Palmgren-Miner linear cumulative damage assessment is given as:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \leq \eta \tag{4.1}$$

Where:

D = Accumulated fatigue damage.

k = Number of stress blocks or stress ranges.

n_i = Number of stress cycles in block i.

N_i = Number of cycles to failure in stress block i.

η = Fatigue usage factor usually taken as 1.0.

When assuming linear cumulative damage it is assumed that:

1. Damage is independent of the stress levels acting in the detail, i.e., $D = \Sigma n/N$ is true regardless of the stress levels.
2. The accumulation of damage is independent of the order of load history, i.e., $D = \Sigma n/N$ is true regardless of the order of load application to the detail.

It is known that neither of these assumptions is strictly true. Regardless, the Palmgren-Miner model for damage assessment provides accurate analysis that is not improved upon with the more rigorous methods that have also been developed.

The number of stress blocks, k, relates to the stress histogram constructed for the analysis. A typical stress histogram is shown in Figure 4-1, taken from SSC 318 [4-1]. The stress histogram in Figure 4-1 has k = 40 stress blocks although some of them contain zero occurrences. Again, referring to Figure 4-1, it is seen that the maximum number of occurrences for a single stress range is 7446 between 1 ksi and 2 ksi. An occurrence is defined as 1920 cycles in Figure 4-1 which means that the total number of load cycles with a stress range between 1 ksi and 2 ksi is 1920 x 7446 = 14,296,320 or approximately $n_i = 14.3 \times 10^6$ cycles. The number of cycles to failure, N_i, would be found from the appropriate S/N diagram using the maximum stress in the stress range, i.e., 2 ksi. This summation would be performed for all 40 stress ranges, assuming it applied to a specific detail, to determine whether it satisfied equation 4.1. If the equation is satisfied, i.e., the summation were less than or equal to 1.0, then the detail would be assumed satisfactory. If the summation is greater than 1.0 and equation 4.1 is not satisfied then the detail would have to be modified to reduce the local stresses acting in the detail. This may be accomplished with heavier scantlings on the same detail or a more fatigue resistant detail that can sustain an increased number of load cycles.

The fatigue usage factor, η, provides a damage criterion for the detail to be analyzed. Typically, the value for η is taken equal to 1.0. If a designer wishes to increase the factor of safety for a given analysis this factor can be taken as less than 1.0, i.e., the value of η could be taken as 0.85 or any other value less than 1.0. This is one way in which designers using the design codes from other industries may wish to incorporate increased factors of safety to account for any analysis data not intended for use in the marine environment.

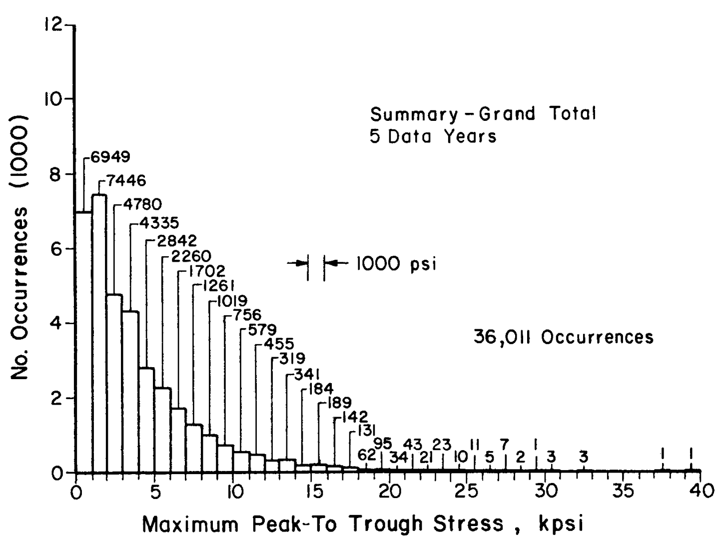


Figure 4-1 Stress histogram reproduced from Figure 6.7 of SSC 318

(Each occurrence is approximately 1920 cycles)

4.2 Determine the Details to be Analyzed

In accordance with equation 4.1 it is necessary to develop the stress history acting on a detail for input to the equation through the variable n_i. In order to develop the stress history it is necessary to determine the location or detail at which the stresses are to be calculated and the load history acting upon that detail. Therefore, before the load and stress histories can be developed it is necessary for the designer to select the detail, or details, for which these histories will be developed.

There are numerous locations that are subjected to repeated, cyclic loading and could be an initiation site for a crack and crack propagation. Similar to Figure 2-2 for catamarans, Figure 4-2 illustrates some of the areas on a SWATH that will be subjected to critical stresses and cyclic loading. All of these represent areas that need to be examined for fatigue. Similar areas can be identified for other hull forms including monohulls. Experience will help determine typical problem areas associated with the various hull forms.

As stated earlier, this report will not directly address the fatigue analysis of structural details in way of machinery-induced loads. These represent fatigue scenarios where it should be easier to quantify the load magnitudes and number of cycles. The analysis should be dominated by the response to the machinery and should be essentially a constant amplitude type problem. Procedures are presented in Section 5 and Appendix B that will help the designer analyze these types of situations.

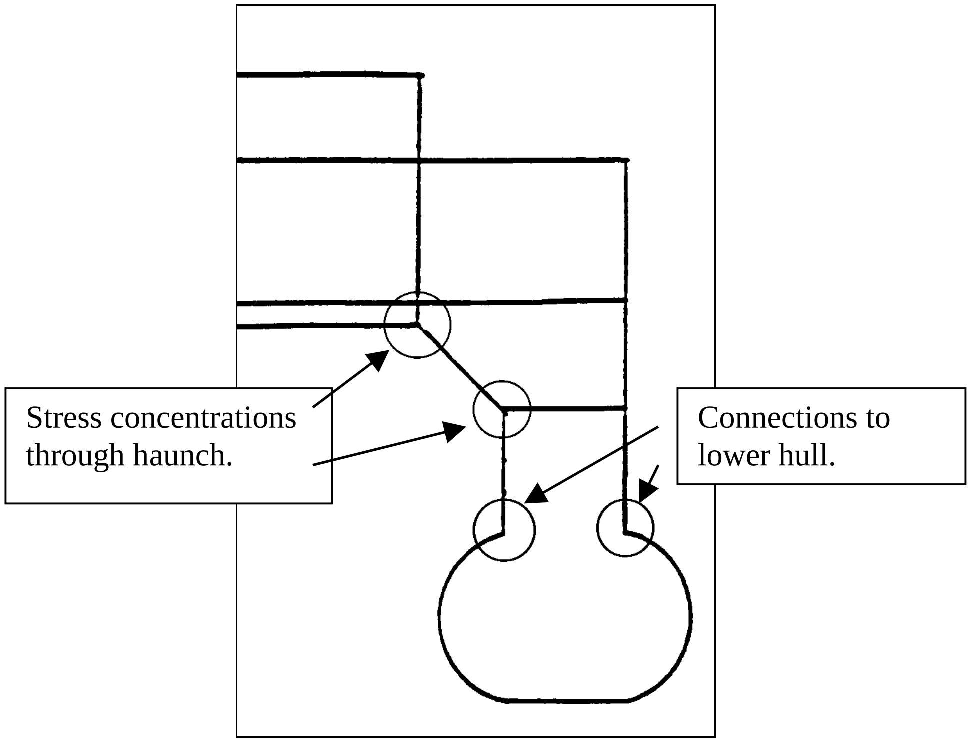


Figure 4-2 Typical Problem Areas On A SWATH

On any high-speed craft, just as with most monohulls, there are a number of fatigue and crack-prone areas. The weld toes and the weld terminations on the structural details in these areas are locations where stress concentrations increase the probability of fatigue cracking. To help reduce the potential problems in these areas the following practices should be avoided:

- Improper design that restricts accessibility and prevents the use of the correct electrode angle. Improper access can also create maintenance problems that increase the likelihood of fatigue cracking problems that can be amplified by the effects of corrosion.
- Incorrect selection of a welding process or welding parameters for the material or detail geometry, such as improper energy input or travel speed.
- Incorrect fabrication procedures, such as incorrect electrode or incorrect positioning of the detail, i.e., misalignment.
- Improper care of the electrode or flux, entrapping dirt or other impurities within the weld metal.

If it is known that a design will include some these areas because of poor access it may be wise to investigate their fatigue environments. Should such an analysis reveal the potential for problems it is recommended that the design or structural detailing be modified to help alleviate or offset these problems.

The following practices should be followed to improve the fatigue resistance of details:

- Minimize geometric stress concentration factors. This is one of the more critical components to the total stress acting through a detail and should be fairly easy to control during the design and construction phases.
- Insure proper welding and QA procedures throughout the fabrication process.
- Allow conservative factors of safety for the loading spectra and S/N data used for the fatigue life calculations.

4.3 Development of the Loading History

Once the specific details and their locations onboard the vessel have been selected, development of the load and stress histories can begin. To perform the fatigue analysis of the proposed details it is necessary to have a loading history representative of the long-term exposure experienced by the detail. The loading history is then translated into a stress history for the detail.

In order to develop the loading history it is necessary to determine the number of cycles associated with each load range. The rainflow cycle and reservoir methods for cycle counting are two popular methods for use with testing scenarios. For the development of the long-term exposure to environmental and operational loads acting on large displacement monohulls the loading histories are developed using probability density functions. The use of probability distribution functions needs to be investigated for application to the loading history and spectra of high-speed craft.

Before proceeding to these techniques a brief review will be held for the constant amplitude loading scenario. This is only mentioned for completeness. It does not pertain to many situations on-board ship's addressed by this report.

It has long been recognized that the constant amplitude fatigue environment is easier to analyze than that associated with the variable amplitude loads. With constant amplitude loads and corresponding stresses, the analysis of structural details in this environment is straightforward. The Palmgren-Miner assessment can still be used but it will only contain one ratio in the summation. Therefore, the assessment can be re-stated as an allowable stress problem. Once the number of cycles have been calculated it is only necessary to determine the allowable stress level from the appropriate S/N diagram. Using the information contained in this diagram, the designer determines the allowable stress associated with the number of cycles associated with the life of the detail. Either the allowable stress is satisfied or it isn't. If not, the detail must be redesigned. If the actual stress is less than the allowable stress the detail is satisfactory and the analysis is complete. Figure 4-3 shows the relations that can be completely defined through the following parameters, which make the situation easy to analyze. (A number of these definitions are repeated here from earlier in the report for ease of reference.)

Mean Stress $\sigma_m = \dfrac{\sigma_{\max} + \sigma_{\min}}{2}$

Stress Ratio $R = \dfrac{\sigma_{\min}}{\sigma_{\max}}$

Stress Amplitude, $\sigma_a = \dfrac{\sigma_{\max} - \sigma_{\min}}{2}$

Stress Range, $\Delta\sigma = 2 \cdot \sigma_a = \sigma_{\max} - \sigma_{\min}$

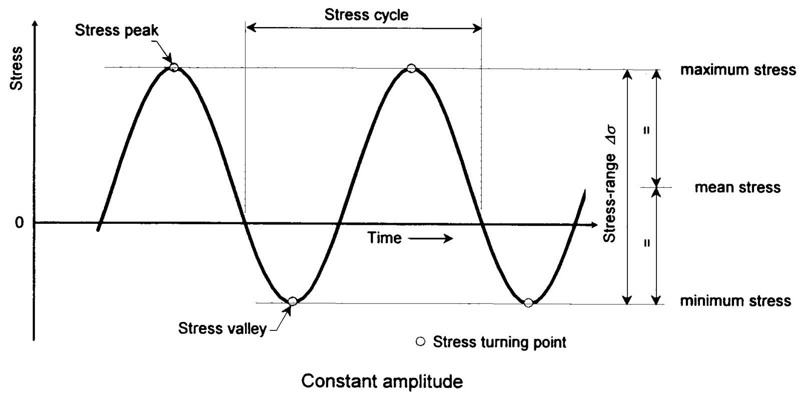


Figure 4-3 Constant Amplitude Curve

For use with the allowable stress approach it is only necessary to compare the stress range, $\Delta\sigma$, to the allowable stress range corresponding to the number of cycles determined for the service life of the detail.

4.3.1 Effect of Vessel Length and Speed on Loading History of High-Speed Craft

The majority of the work done to date studying the loading histories acting on vessels has been done for displacement vessels. As used in this report, the term displacement vessel implies a ship that is long enough such that primary bending is known to be a crucial condition for the structural design of the vessel. The term also implies a vessel with a relatively low forward speed, i.e., they do not satisfy the definitions for high-speed craft put forward by DNV or ABS as discussed earlier in Section 2.2 of this report. These ships are typified by tankers, bulk cargo carriers, container ships, RO/RO vessels and many surface combatants and other large displacement commercial and naval vessels. A significant amount of work has been developed regarding the loading histories experienced by these types of vessels. Not nearly the same effort has been devoted to the loading histories experienced by high-speed craft.

Among the important differences between these two types of vessels are the sea-states in which they operate and their forward speeds. High-speed craft are significantly shorter than most displacement vessels, operate in relatively protected waters and operate at higher forward speeds. The effect of these differences needs to be addressed when establishing the loading history for high-speed craft.

There are two factors that will help to reduce the relative magnitudes of the primary hull girder bending moments and stresses acting throughout a high-speed vessel relative to a displacement hull, i.e., length and sea-state. The structural design of many shorter vessels, such as high-speed craft, are governed by the secondary loads, i.e., it is not necessary to increase scantlings based on secondary loads to account for the primary loads and stresses. This trend is further emphasized for high-speed craft that operate in protected waters and will not experience the same extreme wave heights and sea-states that generate the higher bending moments in shorter vessels classed for unrestricted service.

The high forward speed also results in loading conditions and histories not typically encountered in displacement vessels. The high forward speed results in increased bow and side slamming loads. These slam loads, which only occur lower in the craft, will contribute to the secondary load profile and confirm the differences between the loading profiles of high-speed and displacement craft.

An additional source of fatigue loading is the excitation introduced by the machinery. Although considered constant amplitude in nature this source of loading may contribute to the overall loading profile acting in certain areas that are not governed by response to the machinery, i.e., the variable load profile of certain details may include the constant amplitude component of the machinery. Due to the shorter lengths of many HSC most of the fatigue failures currently experienced by these vessels result from the excitation provided by the machinery. As a result, knowledge about the manner in which to deal with this type of failure could be critical to the design of similar boats in the future. It is suggested that designers review the constant amplitude loading procedures presented by the Aluminum Association and reprinted in Appendix B of this report. Displacement vessels tend to be driven by low rpm diesel engines that introduce low frequency excitation sources into the ship's structure. High-speed craft are powered by high-speed, high rpm propulsion systems that can introduce a much wider band of excitation frequencies into the ship's structure.

This discussion helps to understand the different composition of the loading spectra acting on high-speed and displacement vessels. It reinforces the need to investigate these issues and determine a manner in which the relative amplitudes of the primary and secondary loads can be assessed for the different types and lengths of high-speed craft.

4.3.2 Probability Distributions used for Vessel Loading History

As discussed above, this is an area that needs more work relative to high-speed craft. Not only does the future work need to investigate the applicability of probability distributions to high-speed craft loading profiles, but it will also need to help quantify the relative magnitudes and importance of the primary and secondary loads on different classes of high-speed craft.

The work discussed below regarding the use of probability distributions for displacement vessels is concerned only with the primary hull girder loading histories experienced by a vessel. There is brief discussion in SSC 318 regarding the applicability of probability functions to the distribution of secondary loads and their conclusion suggest that this too can be successfully developed.

This information is presented to introduce the concepts of probability functions used to define loading histories. Further discussion is presented in SSC 318 and SSC 351 [4-2]. SSC 318 discusses six different probability distributions and their applicability to the long-term loading encountered by monohulls in a random sea. The six different distributions are:

1. Beta distribution.
2. Lognormal distribution.
3. Weibull distribution.
4. Exponential distribution.
5. Rayleigh distribution and,
6. Shifted Exponential distribution.

There has been good agreement established between actual loading data and the Weibull distribution for long term exposure to random seas. DNV Fatigue Assessment of Ship Structures [4-3] uses the Weibull distribution in conjunction with its spectral analysis. This experience suggests that the spectral analysis for high-speed craft could benefit from using standard probability distributions to define their long term loading histories.

4.3.3 Rainflow and Reservoir Cycle Counting Methods

A constant amplitude approach will rarely give the appropriate results for the environments of concern to this report. The random loading associated with a high-speed vessel will not behave in a constant manner. More accurate results will have to be obtained using the variable amplitude approach, which is the more representative of the actual behavior in high-speed craft. This is consistent with the approaches assumed for both Method 1 and Method 2 as shown in Figure 2-1.

It has already been proposed that the use of probability distributions needs to be investigated for the definition of the loading histories that act upon a high-speed vessel. Another source of loading histories would be the actual loading applied to a test specimen. To replicate the environment of a high-speed craft it would be necessary to subject such a specimen to random loading for the generation of its S/N curve. Throughout the duration of the test it is necessary to record the load magnitudes acting upon the specimen. This loading history would be turned into a loading histogram after the testing and could easily be converted to a stress histogram for the specimen in question. There are two procedures that are commonly used for the recording of the loading histories. These two procedures are the rainflow and reservoir cycle counting methods. A brief review for each of these procedures is presented below.

Similar and consistent with the linear Palmgren-Miner analysis is the loss of stress history using either the rainflow or reservoir cycle counting methods. These approaches do not account for the order in which the stress history was applied to the detail.

In general, the reservoir method is recommended for shorter stress histories with simpler loading scenarios. The rainflow method is recommended for more complex stress histories such as those developed for the instrumentation of actual details. Both methods can be adapted to the computer for automation of the cycle counting process, which augments nicely with the automated fatigue testing of specimens.

4.3.4 Rainflow Cycle Counting Method

The rainflow cycle counting method is illustrated in Figure 4-4, [4-4]. To understand this method it is best to visualize the time axis being vertical with Figure 4-4 rotated 90^0 in the clockwise direction. The rotated figure is now considered a section through a roof with rain flowing down from each peak and each valley. The beginning of a half cycle of load is defined at the start of the peak or valley. The end of the same half cycle of loading is defined where the rainflow stops. The rainflow is defined to stop when:

- The peak opposite the starting peak is equal to or more positive than the starting peak. Similarly, the rainflow will stop if the valley opposite the starting valley is equal to or more negative than the starting valley.
- It runs into rainflow from the roof above.
- The rainflow reaches the end of the stress spectrum.

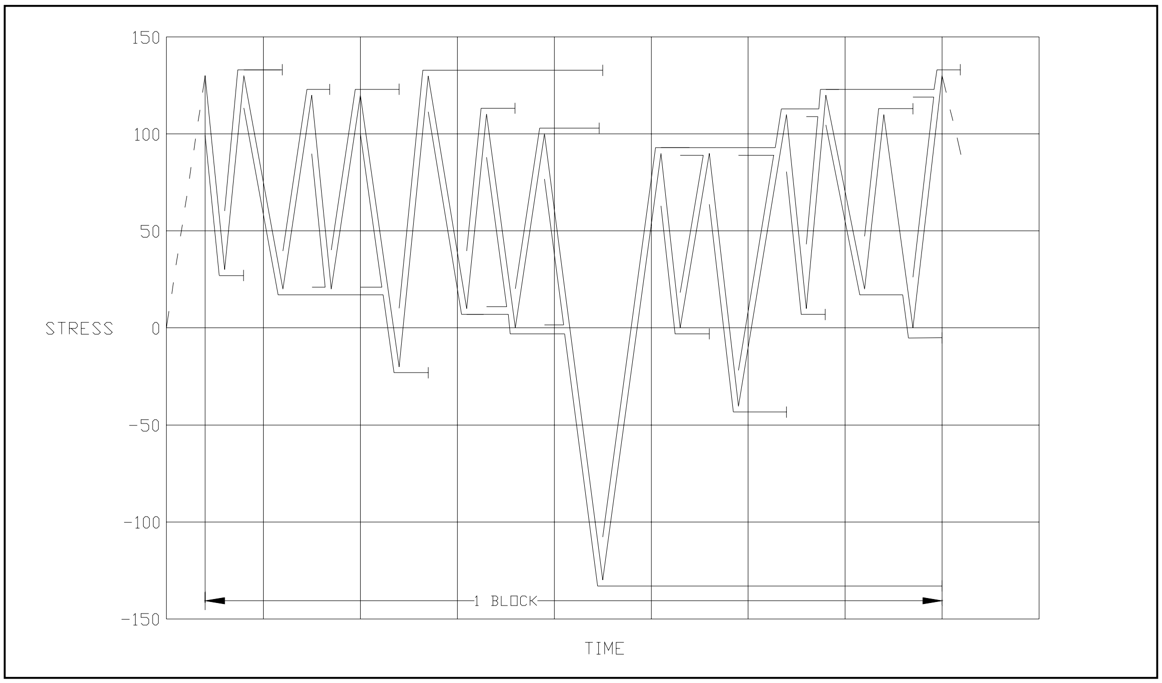


Figure 4-4 Rainflow Cycle Counting

The rainflow method counts reversals of loading with the number of load cycles equal to one-half the reversals.

4.3.5 Reservoir Cycle Counting Method

The reservoir cycle counting method is shown in Figure 4-5, [4-5]. It represents a quick and easy procedure to convert a load history into a stress histogram for use with the Palmgren-

Miner cumulative damage assessment. The procedure for using the reservoir method is explained in Figure 4-5. For a larger number of cycles it would be convenient to define stress ranges into which each load or stress cycle would be included. This will help produce a stress histogram similar to that shown in Figure 4-1 (SSC 318 fig 6-7).

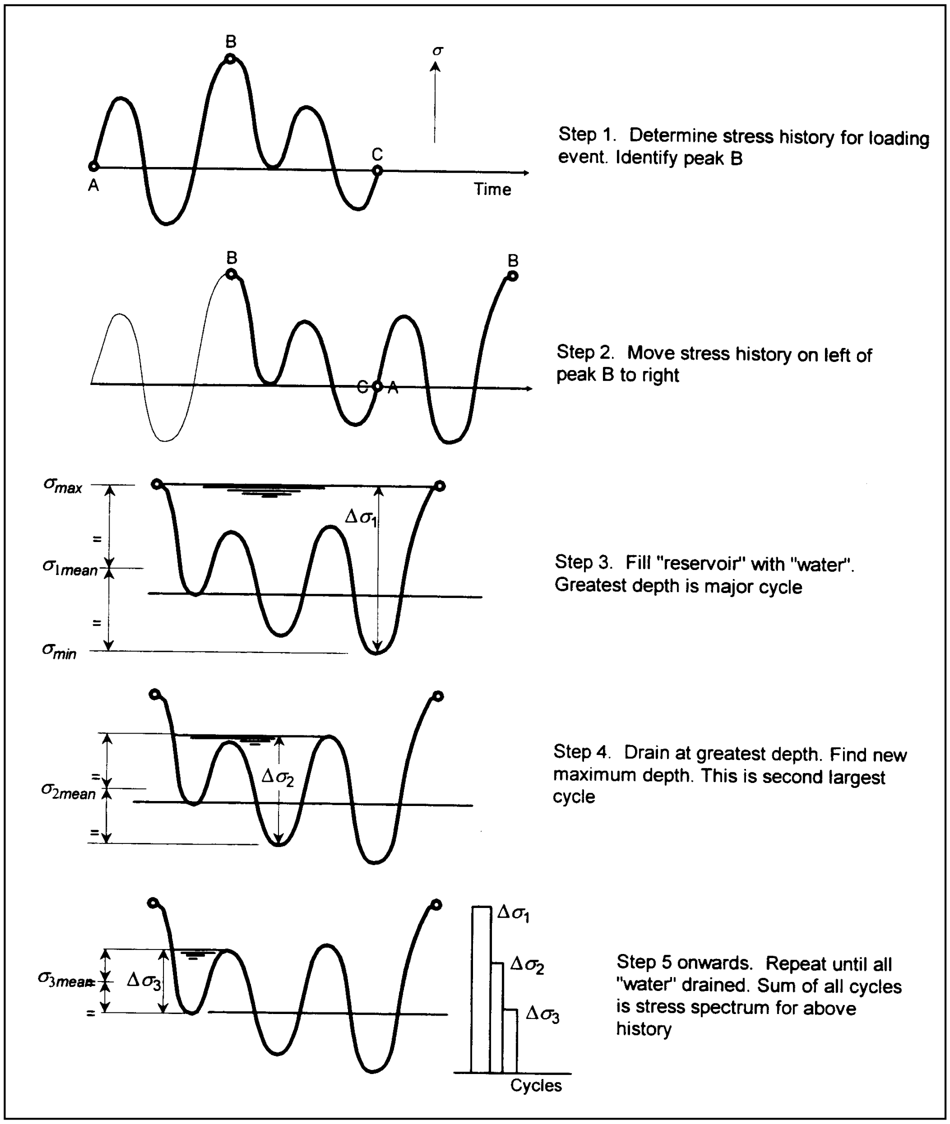


Figure 4-5 Procedure for Conducting The Reservoir Cycle Counting Method

4.4 Development of the Stress Histogram

In accordance with equation 4.1 it is necessary to evaluate n_i, the number of stress cycles in each block of the histogram. Now that the loading histories have been developed using one of the procedures from the previous section it is only necessary to determine the stresses that result from the load histogram. As shown in Figure 2-1, this report presents two methods to establish the load and stress histograms:

1. Method 1: The Spectral Method.
2. Method 2: Alternative Method.

Significant discussion was presented in Chapter 2 on the spectral analysis method and the development of load and stress transfer functions. That information, along with the probability distribution for loading, is used as the baseline for the development of the stress histogram associated with a spectral analysis.

The Alternative Method, presented as method 2 in Figure 2-1, was also discussed in Chapter 2. It requires significant time and expense. It is necessary to develop the physical models and perform the required testing. The model tests are then followed up by finite element analysis to develop detailed information on the stress transfer functions. It is also possible to gather this data on vessels in service.

Neither of these methods may be appropriate to all designs, particularly smaller craft with minimal hull girder loads. The choice of analysis tool and stress histogram construction is ultimately up to the designer. The various procedures are presented herein to allow a broader range in the tools available to he marine industry.

4.4.1 Stress Histogram Development using the Spectral Analysis Method

The development of the stress histogram requires that the stress transfer functions have already been developed as indicated by Figure 2-1. Using the procedures defined above it is assumed that the designer will be able to develop the loading history for the detail or vessel in question. It may be some time before the probability distributions have been defined to the point where they can be readily applied to the design of high-speed craft in a manner consistent with that for displacement vessels. Regardless, it is assumed that the designer can develop a loading history consistent with the detail under investigation. Then, using the stress transfer functions this load history is converted into a stress history and the stress history is broken into k stress blocks, in accordance with equation 4.1, for use in the S/N diagram appropriate to the detail. Additionally, FEA will be used to develop much of the stress information required for the analysis.

The following summary represents the necessary steps to generate a stress histogram consistent with the spectral analysis. It summarizes the approach which has been outlined in Section 4 of the report to this point.

- Determine the details to be analyzed, i.e., find the area where the stresses are likely to be too high resulting in possible crack initiation or fatigue failure. Figure 2-2 may be a relevant guide as well as past experience.
- Determine the load history acting on the detail. The load cycles are either constant or variable amplitude loads. The latter is the dominating behavior in a realistic environment and the only one considered for a spectral analysis.
- Using the stress transfer functions or FEA results, convert the loads into stresses and stress histories. Determine the total stress range experienced by the detail.
- Determine an appropriate number of stress ranges or stress blocks based on the total stress range experienced by the detail. This corresponds to the value of "k" in equation 4.1.
- Determine the total number of cycles associated with each stress range using one of the cycle-counting methods presented in the report or an appropriate probability distribution function.
- Combine all the stress range blocks to form a stress histogram similar to the one presented in Figure 4-1.

After the stress histogram has been developed it will be necessary to select an appropriate S/N curve that represents the detail being analyzed. This needs to include the material used for the detail and the environment in which the detail will exist, i.e. will the detail be in clean-air, seawater, etc. Appendix E presents S/N curves for a variety of structural details some of which replicate shipboard construction and may be used for limited fatigue assessment.

All the information for the development of the Palmgren-Miner assessment has now been developed and the final calculation can be performed.

There are many good examples that can be used as guidance to help understand this procedure which will remain the same regardless of the material used for the construction of the detail. References in Appendix A provide a source for a number of these examples.

4.5 Stress Calculations & Stress Concentrations

One of the critical variables in determining the acceptability of a structural detail is the stress acting in the detail. The entire fatigue design and assessment process is grounded in being able to have an accurate assessment of the appropriate stress level and the calculated fatigue life can vary dramatically with a small change in the stresses taken to be acting in the detail. A significant difference between the various design codes is the manner in which the magnitude of the stresses for use in the fatigue assessment is determined.

Before proceeding to the generic discussion, a brief summary will be made of the approaches used in the other industry design codes.

4.5.1 Design Stress in the Industry Codes

In their Aluminum Design Manual, [4-6], the Aluminum Association uses the nominal stress for input to the fatigue analysis. Discussion provided in their code, See Appendix B, suggests that the designer needs to select details similar to those shown in their design manual to avoid the effects of stress concentrations and other factors that can result in crack initiation. Both the EuroCode 9, [4-5] and the Association of American Railroads, [4-7] allow for the use of nominal stresses when certain conditions are satisfied but require the amplification of this stress to account for stress concentrations when they are not. For further discussion on the EuroCode 9 and AAR design codes appropriate information is provided in Appendices C and D, respectively.

The guide proposed by DNV in their Fatigue Analysis of High Speed Craft, [4.8], effectively requires the use of nominal stresses modified by a notch stress factor, K, for use in their S/N diagrams which were all developed from smooth test specimens. There are five K_x factors defined by DNV that all require evaluation to determine the final value of K and they are defined as follows:

K_g = Stress concentration factor due to the gross geometry of the detail considered.

K_w = Stress concentration factor due to weld geometry.

K_{te} = stress concentration factor due to eccentricity tolerance.

$K_{t\alpha}$ = stress concentration factor due to angular mismatch.

K_t = stress concentration factor for plate thickness exceeding 25mm.

The final notch stress range, $\Delta\sigma_{notch}$, to be used in the S/N curves for the DNV approach is then determined as:

$$\Delta\sigma_{notch} = K \times \Delta\sigma_{nominal} \quad (4.2)$$

Where:

K = The notch factor = $K_g \times K_w \times K_{te} \times K_{t\alpha} K_t$.

$\Delta\sigma_{nominal}$ = The nominal stress range determined through typical elastic stress calculation procedures.

The DNV document does provide some guidance for the determination of the K_x values shown above. Regardless, it is interesting to note that the DNV guide for the Fatigue Analysis of High Speed Craft has less definition than any of the other three industry codes regarding S/N curves yet they require the most rigorous load development and stress analysis.

4.5.2 Further Discussion on Stresses

This section presents discussion on various different stresses that are defined for fatigue analysis and used within the field for the consideration of different effects. Their use for input to the S/N diagrams required for a Palmgren-Miner analysis is also presented. In general, the type of stress calculation developed for a given design should be consistent with the type of S/N data available to the designer. If this is not possible it will be necessary to modify the stress calculations to approximate the type of stress data presented in the S/N diagram. Review of the DNV [4-8] and industry approaches to this problem in Appendices B, C and D is highly recommended before the designer proceeds on their own.

The discussion in this section focuses on the stresses that result from the loading and geometry of a detail. They do not include the effects of fabrication, i.e., there is no consideration of the effects of residual stresses due welding.

There are four stress categories presented in this discussion:

1. Nominal stresses.
2. Structural stresses.
3. Hot-spot stresses and,
4. Notch stresses.

It should be remembered that there are no absolute definitions for the stresses associated with the categories listed above. The terminology presented herein introduces the concepts associated with the different types of stresses and suggests that different terminology may be used for the same concepts in different applications.

In general, the type of stress used for the Palmgren-Miner analysis will depend on the manner in which the data was collected for the S/N diagrams relevant to the detail under consideration. The data used to develop the S/N diagram should be consistent with the application of the detail.

Most of the S/N curves presented in Appendix E were developed on simple welded specimens with inherent stress raisers. The exact value for the K_x factors is unknown but could be determined. This means they were developed to reflect structural stresses, as defined below, and macro-structural behavior of the specimen.

Discussion is presented below on nominal stresses as well as the various sources of stress amplifiers due to geometric and fabrications factors. It is suggested that the designer review all the different codes presented in this report along with the discussion below to help suggest the appropriate approach for a given set of calculations. Generally, if the details selected for use are similar to details for which S/N diagrams have been generated then it should be possible to use a nominal stress approach. This is justified because any stress concentrations acting in the selected detail would have been acting in the tested detail and accounted for as a result of the test. This would also require the use of S/N diagrams that have been generated for the detail and its intended application, i.e., the seawater or marine environment needs to be considered in the fatigue testing.

4.5.2.1 Nominal Stresses Acting in a Structure

Nominal stresses are the most fundamental stresses calculated for every design. These are the global field stresses found in a structure using classical elastic stress analysis techniques without the impact of any stress concentrations, discontinuities or other geometric amplification effects. They can be determined through simple hand calculations such as axial stress equals P/A or bending stress equals My/I (See equation 4.3, below). For more complex structures they can be calculated with finite element models or other procedures that account for load distribution such as the Hardy-Cross moment distribution technique. All design codes such as ABS, DNV, Lloyds, American Institute of Steel Construction, AISC, etc. are based upon allowable stress design approaches that use nominal stresses for their calculations.

Determining the nominal stresses is often fairly simple and straightforward, which makes it a cost-effective procedure for simplified designs. The following formula can be found in any textbook to find the nominal stress when subjected to the combined effects of axial and bending loads:

$$\sigma_N = f_a + f_b = \frac{F}{A} + \frac{M}{I} \cdot y \qquad (4.3)$$

Where:

σ_N = Total nominal stress resulting from combined axial and bending stress components.

f_a = Axial Stress.

f_b = Bending Stress.

F = Axial force.

A = Original area of the cross-section.

M = Bending moment.

I = Moment of inertia of the cross-section.

y = Distance from neutral axis to the point of interest.

Equation 4.3 is used for typical hand calculations for simple structural systems. It will be necessary to use FEA to develop the nominal stresses associated with a structural detail of even moderate complexity. When nominal stress S/N curves are used for the evaluation of complex details it is necessary to account for the geometric stress concentration effects not inherently included in the S/N curves. The local nominal stress in way of the detail must be increased by the stress concentration factors for the local geometry and these amplified stresses used in the S/N curves.

4.5.2.2 Structural Stresses

The structural stresses acting in the area of a detail reflect the nominal stresses amplified as a result of the geometry, i.e., discontinuities, of that detail. Stress concentration factors are developed through discontinuities such as brackets, holes, cover plates, etc. Typical details illustrating different discontinuities are shown in Figure 4-6, [4-12]. The stress concentration factors, or the increase to the nominal stress, will be a function of various aspects for each different type of geometric configuration. For instance, the stress concentration factors acting in way of a bracket will be a function of:

- The thickness of the bracket.
- The presence of a flange on the bracket.
- The angle between the toe of the bracket and the supported member.

- Alignment of the bracket with the supported member, i.e., is the bracket co-planar with the web of the supported member or is it lapped onto the supported member?
- Is the free edge of the bracket linear or curved?

While this is not an exhaustive list it demonstrates that there are a significant number of sources for stress raisers in way of a typical detail. A similar list could be prepared for holes and the factors effecting the stress raisers in these areas:

- The diameter of the hole, if it is circular.
- The aspect ratio of any non-circular hole and its orientation to the principal stress in the member.
- The presence of a coaming or flat-bar reinforcement around the free edge of the hole.
- The quality of the cut edge if there is no reinforcement around the opening.
- The proximity of the hole to the neutral axis of a bending member or the proximity to the end of the design-span of a beam.

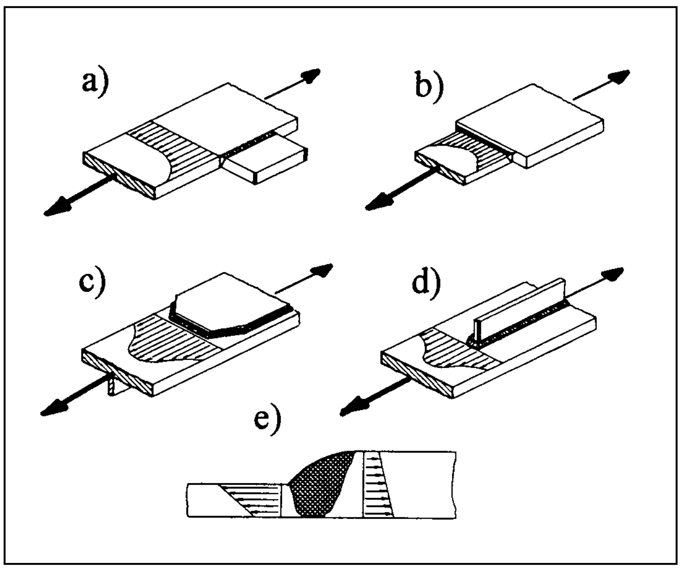


Figure 4-6 Geometric Stress Concentration Profiles

Similar to the bracket, there are a significant number of stress raisers associated with any hole cut through a structural member. Certain textbooks provide information regarding various aspects of these stress raisers [4-9]. To fully evaluate their impact and determine the structural stresses in a specific application, it would be necessary to develop a fine mesh, finite element model and study the actual behavior. If the stresses are assumed to remain elastic it may be possible to subject the finite element model to a unit load and develop the stress concentration factors based on the resultant nominal and peak stresses. These same factors could then be applied to the nominal stresses acting through the detail when subjected to the actual loads.

4.5.2.3 Hot-Spot Stresses

Hot spot stresses are the structural stresses located at a hot spot, i.e., the structural stresses at a likely crack initiation site. The hot spot stresses at a particular location can generally be determined through the techniques discussed above and the fatigue strength of a detail is often developed in terms of the range of hot spot stresses. The S/N data for a given detail will be considered appropriate for a proposed detail if they contain the geometric configurations that would result in the same hot spot load amplification of the nominal stresses. Test specimens for such details will report results in terms of stress range (not range in hot spot stress) but the effects of the hot spot will be included by the geometry of the specimen. For proposed details that vary slightly from test specimens it may be possible for the designer to modify the hot spot stress with minor adjustment to account for the differences. This will allow the use of existing S/N data for details with slight variation from proposed details.

4.5.2.4 Notch Stresses

Although the hot spots identified above generally lie in a local notch of the structure or detail, i.e., the toe of a weld, they do not include the nonlinear stress peak resulting from that notch. This is accounted for by the local notch stress that quantifies the total stress acting at the root of a notch. Figure 4-7, [4-12] demonstrates the various stress components that comprise the total stress acting in the local notch stress.

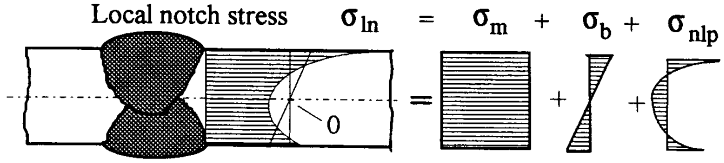


Figure 4-7 Local Stress Concentrations Due to Service and Residual Stresses

These stress components are defined as:

- σ_m = Membrane stress. This accounts for the nominal stress acting through the area of the detail.

- σ_b = Bending stress. This accounts for the discontinuities resulting from the local geometry of the detail.
- σ_{nlp} = Nonlinear stress peak. This accounts for the maximum stress caused by the local notch created by the detail.

As shown in Figure 4-7 and Figure 4-8, [4-12], the nonlinear stress peak is maximum at the surface of the structure. This helps explain the increased risk associated with a surface defect at the root of a notch compared to an embedded flaw which will usually be located at an area of less than maximum stress.

Determining the value for the notch stress requires detailed analysis using finite element modeling techniques. Because of the highly localized stress effects generated by the notch it is necessary to create a finite element model with a very refined mesh to capture the maximum value of the notch stress and the gradient throughout the area.

Luckily, neither the nominal stress nor the hot spot stress approach to fatigue strength assessment requires the effects of the notch stress to be included. Along the length of a weld, for instance, the notch stress varies continuously and this effect is inherently included in the testing of welded specimens and therefore must not be included on top of the nominal or hotspot stresses when either of these two are used for fatigue strength assessment.

As discussed above the new design code proposed by DNV [4-8] presents fatigue calculations using notch stresses that are developed by amplifying the nominal stress using a series of factors to account for the local geometry of the detail including the weld geometry. This same type of approach can be used for other S/N curves where the nominal stress are amplified by appropriate factors before entering the S/N curves to assess fatigue life.

4.5.2.5 The Effects of Welding on Stress

All of the geometric effects cited above are independent of the stresses introduced as a result of the welding process. As previously discussed in Section 3.8 of this report, even properly executed welds will introduce local effects to the state of stress around any weldment.

Residual stresses, welding imperfections and stress concentrations, Figure 3-17 through Figure 3-19, introduced by the welding process will all have an effect on the total stress acting in the area of a structural detail. Of course, not all welds contain imperfections and it is the intent that properly executed welds will minimize the effects on the overall stress acting in a weldment.

As seen in Figure 3-17, the residual stresses due to welding will be both tensile and compressive. Recognizing that fatigue and crack propagation only occur under the action of a tensile stress, it has been confirmed that the residual compressive stresses are beneficial to a detail by reducing the overall tensile stress developed locally. Similarly, the residual tensile stresses are detrimental to the fatigue life, as they will add to the nominal tensile stresses acting through the detail.

The information shown in Figure 3-17 and Figure 4-8 agrees with the diminution of the applied and welding residual stresses as a function of distance from the weld. The highly stressed areas in way of the weld can reduce the fatigue life of a detail and need to be controlled as much as possible through the use of proper welding procedures including cleanliness, electrode selection and heat input.

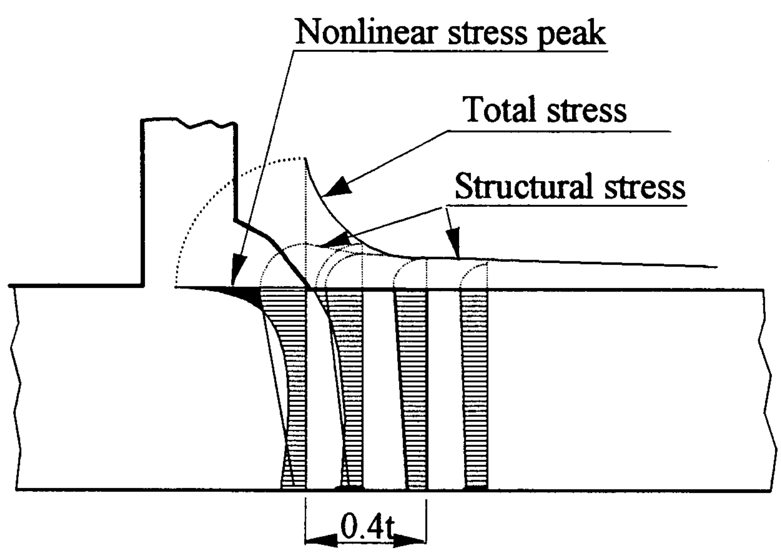


Figure 4-8 Local Stress Concentrations in Fillet Weld

4.5.2.6 Fabrication Flaws and Their Impact to Nominal Stresses

Certain types of fabrication flaws can result from the welding process. These were discussed earlier in Section 3.8 and shown in Figure 3-18. Briefly, they include lack of fusion, porosity or voids, weld undercut, inclusions and various cracks induced by the welding process. There are other types of flaws that can result during the fabrication process, but not specifically associated with welding. These include misalignment of non-continuous components or rotation of a component resulting in angular misalignment not intended for the design. Examples of these flaws are shown in Figure 4-9. Similar to the discussions presented above, these flaws will also generate stress concentrations that amplify the nominal stress acting through the area of the detail and DNV does present factors to account for this misalignment.

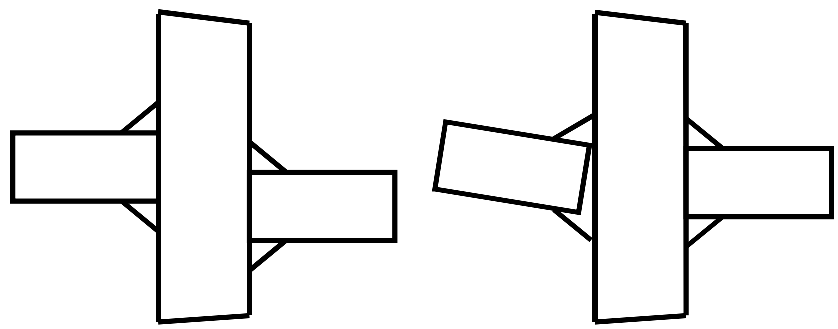


Figure 4-9 Typical Misalignment Problems During Fabrication

4.6 Determine the Appropriate S/N Curve

After all the load and stress calculations have been developed for a given detail, it is necessary to select the appropriate S/N curve to continue with the detail's evaluation. As stated above, the designer should review the available S/N data prior to developing the stress calculations and make every effort to coordinate the stress calculations with the available S/N data to simplify the use of the S/N curves. Obviously, it is not possible to have S/N curves for every type of structural detail for all loadings, environments, materials, etc. Therefore, it is up to the designer to select an S/N curve that most closely approximates the detail under consideration. The design codes tend to classify details into categories that help designers select an appropriate category and the corresponding S/N curve. Appendix E in this report presents the S/N curves for a number of small and large specimen details. These curves represent raw data as measured during the tests. They do not represent design curves similar to those established by the design codes reviewed in this report. No large specimen S/N curves were found for this task that reflected the marine or seawater environments.

Figure 3-5 displays the tremendous effect that the seawater environment can have on the fatigue life of smooth aluminum specimens compared to those with more realistic service conditions. The designer needs to consider this during the design phase if it becomes necessary to use in-air data for the fatigue analysis. It would be necessary to include appropriate factors of safety depending on the desired fatigue life and application of the detail when using such information. The small specimen S/N data in Appendix E is presented for both air and seawater environments. Similar to Figure 3-5, the S/N curves in Appendix E confirm the measurable impact of the seawater environment on the fatigue life of an aluminum weldment.

The data reflected in Table 4–1 and Appendix E demonstrate some of the current work being undertaken in the research of fatigue on aluminum weldments. Details 20 through 24 are taken from [4-10] and details 25 through 28 from [4-11]. The latter four details were studied as part of the research for the doctoral work summarized in [4-11]. Only the small specimens, details 20 through 24 were subjected to maritime and laboratory air conditions for their tests. The large specimen details, 26 through 28, were all tested in-air with no accounting for corrosive or aggressive environments.

This is a good indication of the work currently underway. It is consistent with the small specimen tests discussed for the new alloys presented in Section 3.9 of this report. All of this work was performed in Europe, which currently seems to be leading the research and development efforts for fatigue of aluminum weldments. This has been confirmed by discussion with numerous sources for this task including Menzemer, Sanders and Kaufman, the latter being a consultant recommended by the Aluminum Association. All sources agree that the state of the art resides with Professor Kosteas and the aluminum database he has helped develop over the past ten to fifteen years. This database forms the basis of the fatigue and damage tolerance analysis information in the EuroCode 9. It is imperative that, before any further work is recommended as a result of the gaps identified by this task, collaboration and review of this database be undertaken.

This report also presents information from the design codes of three other industries in Appendices B, C and D. This should allow the designer a modest beginning for the selection of S/N curves for the fatigue design of aluminum weldments with appropriate modification incorporated to account for the marine environment.

4.6.1 Procedure

The desired procedure is illustrated through the use of Table 4–1, Figure 4-10 and the associated S/N curves in Appendix E. Assuming the data were available to provide S/N curves for all the details in Figure 4-10, it would only be necessary for the designer to select the detail that mostly closely resembles the detail being designed. An S/N curve is referenced from Table

4–1 which is available as part of the design data. The S/N curve could be developed in a number of ways however, it should not include any factors of safety, which would be selected by the designer as a function of the application. The S/N curves could either reflect the raw data measured during the tests or design curves could be fitted to represent the results. Further discussion on this subject would be required to define the most appropriate tool for the industry. It is noted that DNV and the other three industry codes all use simplified design curves developed from the raw data. This helps to simplify the interpretation for the designer and allows for consistency in the industry. The S/N curve could then be used to assemble the appropriate data to complete the Palmgren-Miner analysis.

As it currently stands, there are numerous blank spaces in Table 4–1 for reference to the appropriate S/N curve. This was done intentionally to illustrate the lack of data for use in the current application. It also suggests the details that may need attention when future testing is developed. The first nineteen details listed in Table 4–1 and shown in Figure 4-10 are taken from the Aluminum Design Manual. They are very similar to the details listed in the AISC manual and demonstrate the more common details used in these two codes.

It would be necessary to re-address this table to the appropriate details used for high-speed craft construction. It is recommended that future research would survey the exact details used for high-speed craft and rank their priority of future S/N testing. Included in this ranking would be a rough assessment of the quality of the detail in its service. Commonly used details requiring significant or frequent repairs may not be considered a high priority detail for future S/N testing. Instead, recommendations suggesting the use of more durable details could be issued.

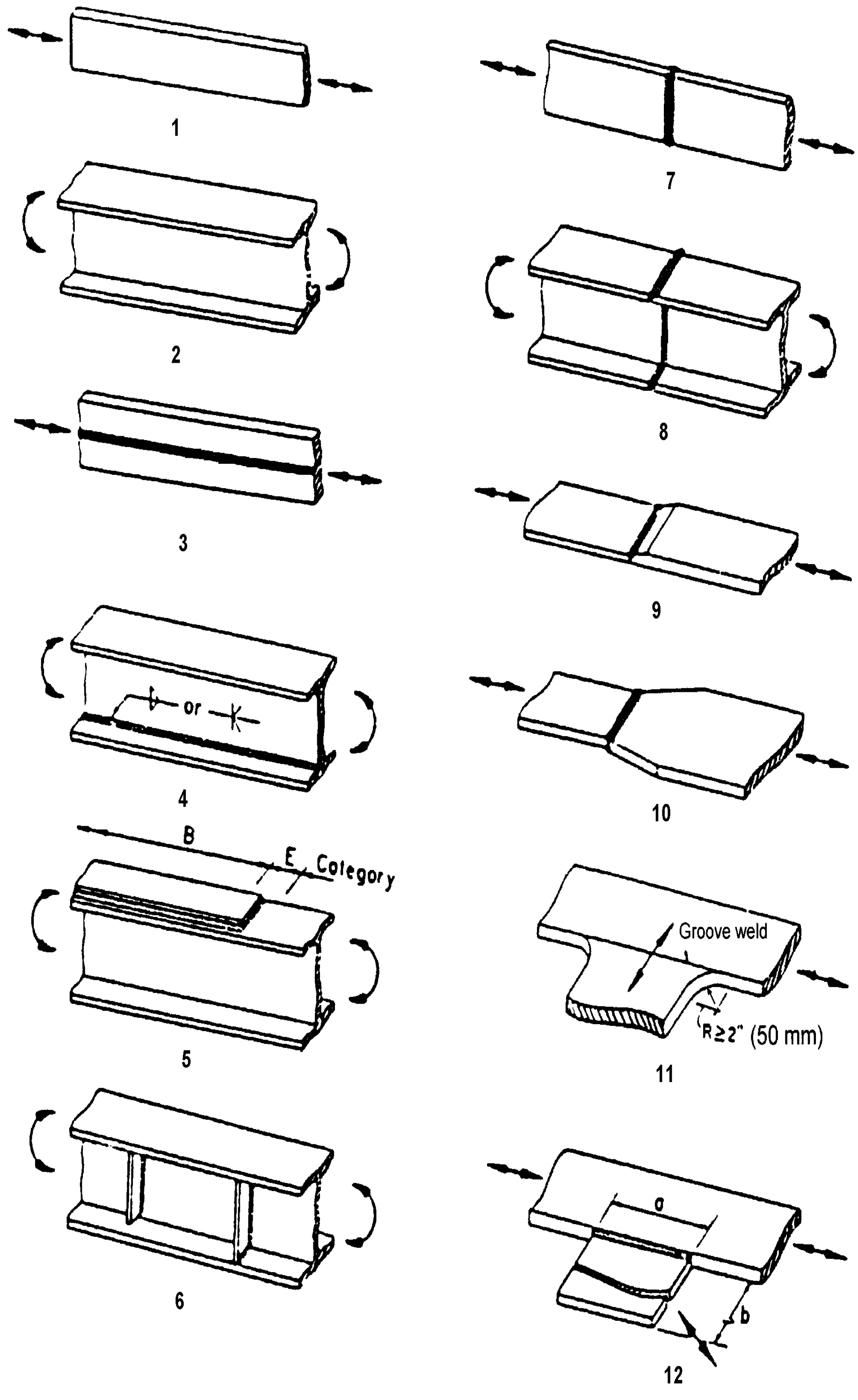


Figure 4-10 Typical Construction Details

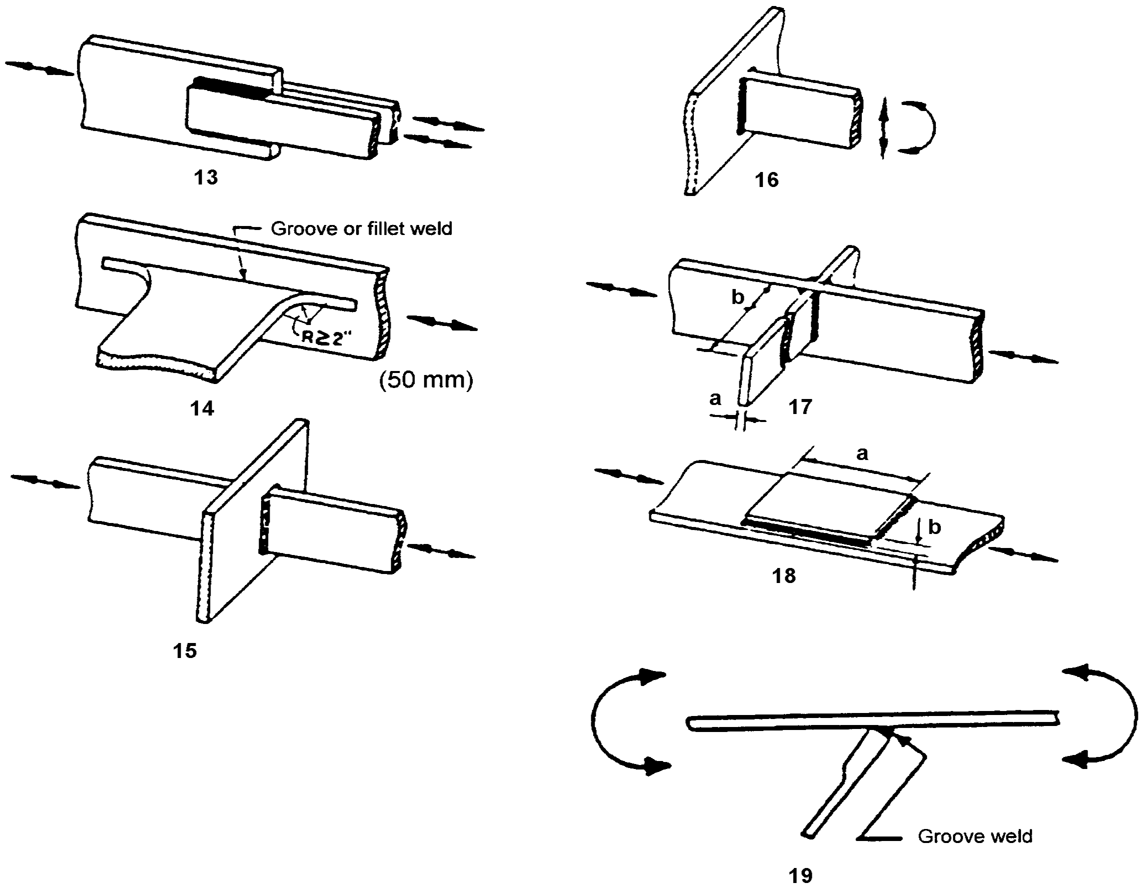
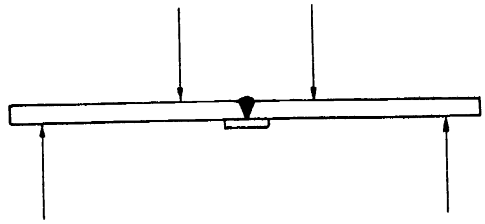
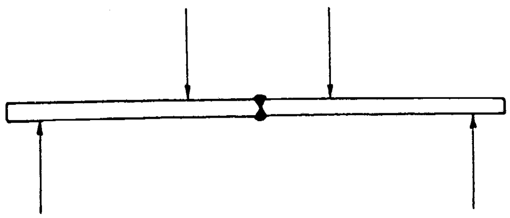


Figure 4–10 Typical Construction Details (Cont'd)

Details 20 through 25 are taken from references Sintef, Ref. ID A, B, C.

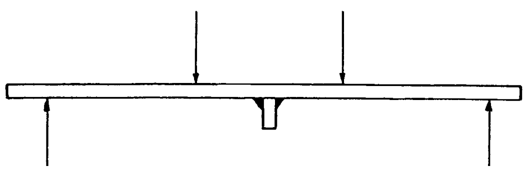


Detail 20 – Single V groove weld with backing bar.

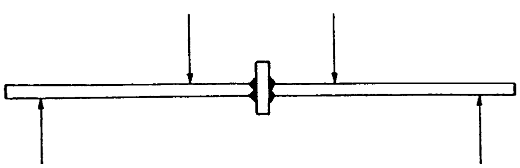


Detail 21 - Double V groove weld.

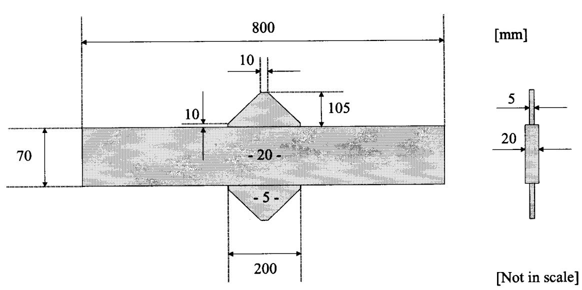
Detail 22 – T- intersection fillet welded.



Detail 23 T – intersection fillet welded.



Detail 24 – Cruciform weld.



Detail 25 Flatbar/Bracket connect, axial tension

Figure 4-11 Typical Small Specimen Fatigue Samples

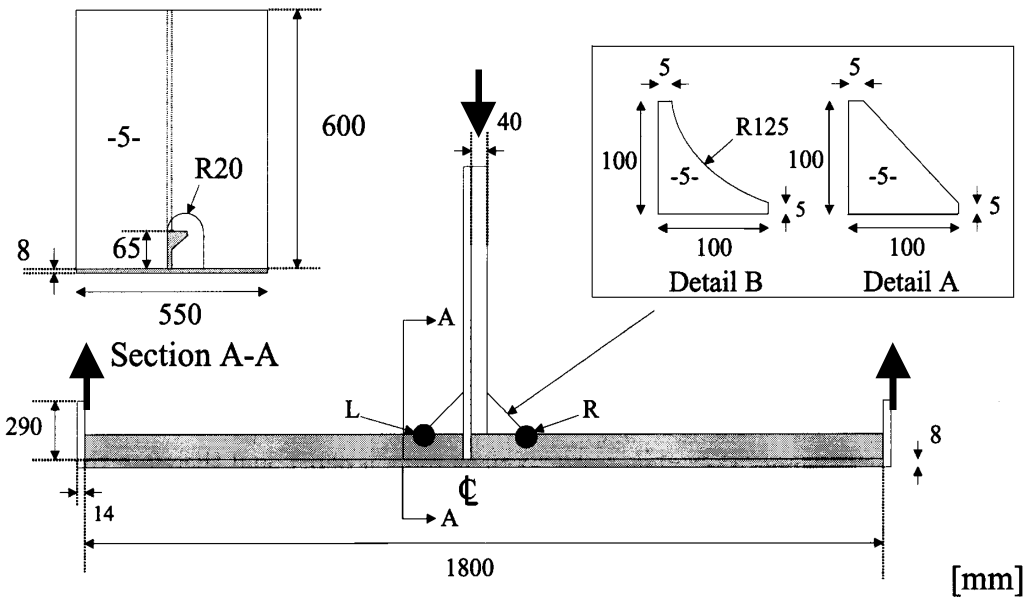


Figure 4-12 Detail 26 – Bulb Stiffener/Deep Frame Connection – Bending In Air.

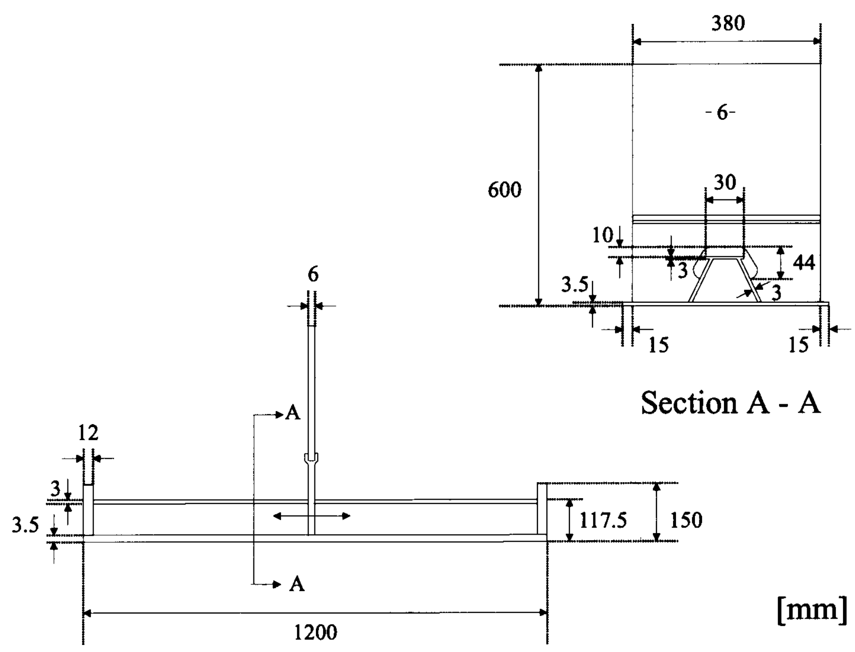


Figure 4-13 Detail 27 – Box Stiffener/Deep Frame Connection – Bending In Air.

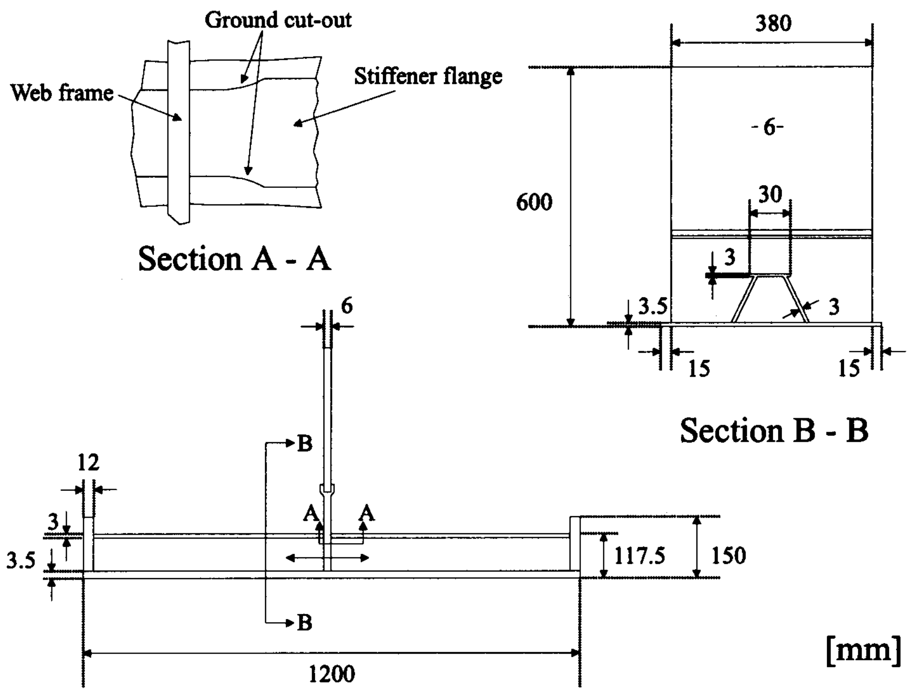


Figure 4-14 Detail 28 Box Stiffener/Deep Frame Connection – Bending In Air.

Table 4–1 Information for use in the fatigue analysis. S/N diagrams are in Appendix E.

Joint No.	Design Detail	S/N Diagram	Alloy	Environment	R-ratio	Ref. ID
1	Extruded Bar-Axial tension					
2	Extruded I-Beam-bending					
3	Longitudinally Welded Bar-axial tension					
4	Longitudinally Welded I-Beam-bending					
5	Extruded I-Beam with Cover Plate-bending					
6	I-Beam with ILS-bending					
7	Transversely Welded Bar-axial tension					
8	Transversely welded I-Beam-bending					
9	Plate change in thickness; Axial tension					
10	Plate change in width; Axial tension					
11	T-Joint; Bi-axial tension					
12	T-Joint; Bi-axial tension					
13	Lapped detail-axial tension					
14	T-joint; Longitudinal Weld; Axial tension					
15	Cruciform Joint					
16	Bar-on-plate-bending					
17	Cruciform-axial tension					
18	Cover plate-Axial tension					
19	Asymmetric detail – bending					
20	Transversely Butt Welded Plate- w/ backing bar –Single V groove -Bending	E-1 thru E-4, E-7, E-12	Various	Various	Various	X
21	Transversely welded Plate – double V groove –Bending	E-9, E-10	Various	Various	0.1	X
22	T-Joint; Axial	E-14, E-15, E-16	Various	Various	0.5	X
23	T- joint Bending	E-5, E-6,E-8, E-11,E14, E-15, E-16	Various	Various	Various	X
24	Cruciform Join t-Bending	E-13	AlMg4.5Mn	Various	0.1	X

Joint No.	Design Detail	S/N Diagram	Alloy	Environment	R-ratio	Ref. ID
25	Flatbar/bracket - Axial	E-17, E-18	5083	Air		X
26	Bulb stiffener/web frame – bending	E-17, E-18	5083, 6082	Air		X
27	Box stiffener/web frame – bending	E-19	7108-T79	Air		X
28	Box stiffener/web frame – bending	E-19	7108-T79	Air		X

4.7 The Alternative Stress Histogram Method

Method 2 depicted in Figure 2-1 is based upon monitoring the actual behavior of real vessels in representative operating scenarios. It can also be taken to apply to individual test specimens set up for fatigue testing. The vessels to be studied are outfitted with strain gauge measuring and recording equipment throughout the critical areas of the vessel. Of course, it is necessary to determine the critical areas and these will vary depending on the hull form under consideration. Strain gauging of SWATH and catamaran vessels to monitor response to transverse bending will be critical. Figure 2-2 and Figure 4-2 demonstrate the critical locations for vessels with these hullforms. For other vessels similar determination of the critical areas to be mapped is required when developing the test plan.

The test plan also needs to include time to insure that exposure to the environment is long enough to allow for the development of statistically valid data. This may require the outfitting of different vessels in the same operating area and/or extensive periods of testing.

The test plan to be developed also depends upon the application. Different test plans will be required if the data is only to be used for a single class of vessels in a predetermined set of operating scenarios. If broader application is desired, i.e., design of various classes operating in different environments, then it will be necessary to have data that can be extrapolated to design for the worst case scenarios.

Regardless, after the strain gauge data has been collected it will be necessary to develop histogram information similar to that displayed in Figure 4-1 although these histograms can be developed to record either load or stress histograms. To accommodate future design work the data should be collected into loading histories that can be applied to new vessels of similar design. The load histories will then be applied to the new designs to develop the stress range histories required for the fatigue analysis.

After the stress or loading and stress histories have been generated the fatigue analysis can proceed in a similar manner to Method I in Figure 2-1. The Palmgren-Miner cumulative damage analysis will be developed to assess the quality of the selected detail.

The following steps summarize Method 2:

- Develop a test plan with applicability to suit the intended function including exposure time to allow for statistically significant data.
- Set up the test equipment, perform the test and collect the data.
- Convert the data and turn it into a stress histogram as shown in Figure 4-1.
- Perform the Palmgren-Miner cumulative damage assessment for the required details.

Strain gauges are located on the weld and on the surrounding structure of the detail where it is assumed that a crack may initiate. As discussed above the stresses, and therefore the strains, acting through the critical areas of the weld will be in excess of the elastic limit of the material and represent typical locations for crack initiation.

Method 2 was used to outfit the SL-7's with strain gauges to develop information similar to that outlined above. These tests and the information obtained are the subject of, or were included in, many SSC reports. Figure 4-1 is a stress histogram resulting from these studies.

4.8 References

[4-1] Munse, W.H., Wilbur, T. W., Tellalian, M. L., Nicoll, K and Wilson, K. Fatigue Characterization of Fabricated Ship Details for Design, SSC 318, Ship Structure Committee, Washington, D.C., August 1982.

[4-2] Mansour, A., An Introduction to Structural Reliability Theory, SSC 351, Ship Structure Committee, Washington, D.C., January 1989.

[4-3] DNV Fatigue Assessment of Ship Structures, Classification Notes No. 30.7, September 1998.

[4-4] Reemsnyder, H., Life Assessment Under Variable Amplitude Loading, Short Course on Fatigue and Fracture, August 1998.

[4-5] EuroCode 9: Design of Aluminum Structures- Part 2: Structures Susceptible to Fatigue, Brussels, 1998.

[4-6] The Aluminum Design Manual, The Aluminum Association, Washington, D.C., 1994.

[4-7] Manual of Standards and Recommended Practices Section C – Part II, Association of American Railroads, Washington, D.C., 1997

[4-8] DNV Fatigue Analysis of High Speed Craft, Report No. 99-0551, 1999

[4-9] Peterson, R. E., Stress Concentration Factors, Wiley Interscience, 1974

[4-10] Paauw, A. J., Fredheim, S., and Engh, B., Konstruksjonsdata for dynamisk belastede aluminum sveiseforbindelser (Construction data for dynamic testing of aluminum weldments), SINTEF Report No. STF34 A83042, 1983

[4-11] Tveiten, B. W., Fatigue Assessment of Welded Aluminum Ship Details, Doctoral Thesis, Department of Marine Structures, Norwegian University of Science and Technology, Trondheim, 1999.

[4-12] Niemi, E., Stress Determination for Fatigue Analysis of Welded Components. The International Institute of Welding, Abington Publishing, 1993.

5. DNV and Other Industry Fatigue Analysis Standards

This report is among the first of efforts to present fatigue design procedures for aluminum weldments in high-speed craft. This effort has identified a number of gaps in the available data that prevent the development of fatigue design procedures using data specifically developed for the marine application. This is particularly true with regards to crack propagation and the data required for the damage tolerance analysis. Det Norske Veritas, DNV, is scheduled to release a new set of rules for the fatigue analysis of High-Speed Craft later this year, [5-1]. It will be their Classification Notes 30.9 and will utilize some of the same analysis procedures as contained in their Classification Notes 30.7, Fatigue Assessment of Ship Structures, [5-2].

Along with the generic design approach for the development of fatigue design for structural details, this report also presents the information in the DNV High-Speed Craft criteria and other industry standards. This will allow the marine designer future access to information not readily available for previous designs. The information utilized by the other industry codes can be used for the marine industry until such time that all the information is available to support a consistent set of data for use in the marine environment.

In addition to DNV, the three industry and design standards presented in this report are:

- The Aluminum Design Manual from The Aluminum Association, [5-3].
- EuroCode 9: Design of Aluminum Structures – Part 2 Structures Susceptible to Fatigue from the European Committee for Standardization, [5-4].
- The Manual of Standards and Recommended Practices Section C – Part II form The Association of American Railroads, [5-5].

It is intended that the information contained in the other codes can be used by the maritime industry after consideration of appropriate factors of safety and applicability. Even using factors of safety that may be relatively high should not have a large impact on the overall design developed for a given vessel. It is worth remembering that the fatigue problem tends to be very localized with crack initiation often occurring through areas of stress concentration including fabrication defects. The fatigue analyses developed herein will result in slightly greater scantlings for details or improved fabrication procedures. It is not expected that this will have a large impact on the overall weight or cost impacts to the initial design and will hopefully reduce the lifecycle costs and maintenance with the improved initial design.

The three industry standards outside of DNV were selected for the similarity of the basis of their codes relative to aluminum. It was not possible to perform a complete survey of all industry codes for this report and the three chosen do not represent an exhaustive collection. The Aluminum Association was selected because of its obvious involvement with the aluminum industry. It was also felt that the relationship between the Aluminum Association and the aluminum high-speed industry will continue to develop into one similar to the relationship between the American Institute of Steel Construction, AISC, and the steel maritime industry where many of the design standards have a basis in AISC codes. EuroCode 9, developed by the European Committee for Standardization, was selected because of its relationship with the European community and the sizable volume of recent large-specimen fatigue tests performed under this body for the development of the pre-standard. In addition, it is the only standard that contains any data on crack growth rates for damage tolerance analysis. While this data was not developed for the marine environment, the EuroCode 9 does present a well developed and logical approach to the damage tolerance analysis. The Association of American Railroads was first selected because of recommendations made during the development of this report. Review of the AAR standards revealed a slightly different technique for the fatigue analysis which may accommodate certain designers. The code also presents useful information on the fatigue of various details similar to those used in ship construction.

Reference [5-6] presents a series of papers regarding aluminum applications in the fast ferry market. It also recognizes the need for the domestic American market to join with the rest of the world and pursue the use of aluminum to satisfy the demands of the marketplace. These papers were assembled as part of a symposium which The Aluminum Association held in 1997 for the high-speed ferry marketplace.

5.1 DNV Fatigue Analysis of High-Speed Craft, Classification Notes 30.9

Still in its preliminary form, these rules are scheduled for release later this year, perhaps in the July 2000 time frame. A preliminary version of the DNV standard was available to the authors for the preparation of this report. It was noted by an associate of DNV, Fredricksen [5-7], in a 1997 FAST paper, that the fatigue of high-speed aluminum craft was an increasing problem. Reading [5-7] made it obvious that DNV has been investigating this problem area for a number of years.

The DNV guide presents a concise set of rules with specific information for aluminum. Both primary and secondary loads are considered for the fatigue assessment. Calculation of the primary loads and the associated cycles is similar to the spectral method described above and in DNV Fatigue Assessment of Ship Structures [5-2]. The primary load calculation considers the service restrictions for which the vessel will be classed. Different scatter diagrams are provided by DNV for primary load development with the different service restriction classifications. There is no specific definition on the load cycles associated with the various secondary load components however, the guide does provide a variety of coefficients for the combination of primary and secondary stresses. DNV seems to recognize the lack of specific data regarding secondary loads by the use of these coefficients but does provide a positive "first-step" allowing the designer to combine such effects. In addition, the guide does allow for "simplified" primary load calculations for early stage design or for designs not requiring the same level of detail. As noted by commentary at the recent 4th International Forum on Aluminum Ships, many of the fatigue failures in aluminum craft are the result of secondary loads caused by machinery vibration. This is particularly true for the shorter high-speed craft and helps justify the development of simplified primary loading profiles for these vessels.

The stress calculations associated with the DNV guide have been discussed previously in Section 4.5.1 of this report. Briefly, DNV requires the calculation of the local notch stress range in way of a structural detail for use with their S/N curves. The notch factor, K, and the associated notch stress range, $\Delta\sigma_{notch}$, are determined as:

$$K = K_g \times K_w \times K_{te} \times K_{t\alpha} K_t. \qquad (5.1)$$

Where:

K_g = Stress concentration factor due to the gross geometry of the detail considered.

K_w = Stress concentration factor due to weld geometry.

K_{te} = stress concentration factor due to eccentricity tolerance.

$K_{t\alpha}$ = stress concentration factor due to angular mismatch.

K_t = stress concentration factor for plate thickness exceeding 25mm.

And:

$$\Delta\sigma_{notch} = K \times \Delta\sigma_{nominal} \qquad (5.2)$$

Where:

$\Delta\sigma_{notch}$ = The notch stress range for use in the S/N curves.

$\Delta\sigma_{nominal}$ = The nominal stress range determined through typical elastic stress calculation procedures.

Appendix B of the DNV document provides some guidance on the K_x factors for some typical structural details used for construction. Due to its preliminary nature [5-1] appears to have a little confusion between the use of stresses and stress ranges in their S/N curves. It is the belief of the authors of this report that it is the intent of [5-1] to utilize stress range values in the fatigue calculation.

To continue the fatigue analysis, DNV presents four S/N curves. They are developed on log-log paper in accordance with the following formula:

$$\log N = \log a - m \cdot \log S \tag{5.3}$$

Where

N = Predicted number of cycles to failure for stress range S.

S = Stress range ($\Delta\sigma$).

m = The negative inverse slope of the S/N curve.

log a = The intercept of the log N-axis by the S/N curve.

The S/N curves, [5-1], are developed for smooth specimens with K = 1.0. As discussed above for other specimens the stress range, S, needs to be amplified to account for the notch stress factors.

Three of the four S/N curves presented in [5-1] account for structural details in air. The fourth curve is used for details in a corrosive environment, i.e., submerged in seawater without any corrosion protection. The final assessment of the detail is then performed with a Palmgren-Miner cumulative damage summation.

5.2 Other Industry Standards to Assist the Maritime Designer

As stated above, the other codes to be presented in this report are:

- The Aluminum Design Manual from The Aluminum Association, See Appendix B.
- EuroCode 9: Design of Aluminum Structures – Part 2 Structures Susceptible to Fatigue from the European Committee for Standardization., See Appendix C
- The Manual of Standards and Recommended Practices Section C – Part II form The Association of American Railroads, See Appendix D.

Each of these codes provides good information. All three of these standards represent land-based applications. Only the EuroCode 9 makes any accounting of the degrading effects of corrosive environments, including seawater and marine, on the fatigue behavior of aluminum. Neither of the other codes considers the adverse effects of corrosive environments and it is left to the designer to account for this effect.

The presentation of the industry standards is not made in any particular order or with any particular preference. It is recommended that the designer review all the standards presented herein before selecting the most appropriate procedures and data for a given application. Each standard contains different data that may be applicable to specific situations for the development of details in high-speed aluminum craft. The standards are straight-forward and easy to understand and the designer should be familiar with each if it is decided to utilize the information and approaches suggested by any specific design code.

5.2.1 Release From Liability

Appendices B, C and D contain information from the design codes of The Aluminum Association, EuroCode 9 and the Association of American Railroads, respectively. Copyright release was obtained from each of these organizations to reproduce their material in the various sections and appendices of this report. Included in the copyright release obtained from each organization was an agreement to release them from any liability that may result from the improper application of their codes. The authors of this report were in complete agreement with the three organizations concerning their release from liability. It is the intent of this report to disseminate the information currently available to the maritime industry regarding the fatigue design of aluminum weldments. It is expected that the use of any information reproduced from these documents would be handled in a manner acceptable to the designers and users of this information.

5.3 The Aluminum Association

In addition to the discussion presented in the body of this report, the Aluminum Design Manual present's additional discussion and explanation for the rules contained in their specifications. Please see Appendix B for the complete presentation of the fatigue design information and design philosophy presented by The Aluminum Association.

The Aluminum Design Manual presented by the Aluminum Association is similar in jurisdiction to the aluminum industry as the American Institute of Steel Construction Specifications is to the steel industry. The Aluminum Design Manual is a comprehensive specification for the design and fabrication of aluminum structures with typical civil engineering applications.

Section 4.8 of the Aluminum Design Manual presents the fatigue design approach for consideration of aluminum structures. There are two separate approaches presented in the Aluminum Design Manual, one for constant amplitude loading and the second for variable amplitude loading. Although most ship structures are typically thought to be subjected to variable amplitude loads, the constant amplitude loading scenario may also be applicable. The response of foundations or other structural components subjected to the cyclic effects of rotating or oscillatory machinery or equipment may very well be governed by the effects of loading spectrum that are effectively constant in magnitude. For such situations, it will be advantageous to utilize the constant amplitude analysis provided for this scenario.

Regardless of the type of loading, the designer must categorize a prospective detail in one of six categories ranging from A through F to start the analysis presented by the Aluminum Design Manual. This is done using the information in Table 4.8-1 and Figure 4.8-1 of the design manual. After selecting the detail category, the designer constructs the S/N curve corresponding to that category using the information in Table 4.8.1-1 and Figure 4.8.1-1, presented below in Table 5–1 and Figure 5-1, respectively.

There is no accounting for the marine environment in the fatigue portion of the Aluminum Design Manual. Therefore, it will be incumbent upon the designer to select the factors of safety relevant for a given detail in a specific application. To investigate the sensitivity of the final result to the factor of safety, it is recommended that the designer perform the analyses with a variety of different factors. This may reveal relatively small impacts to the overall cost of a project for increased factor of safety. Also, the designer may want to review the procedures included in the EuroCode 9 for corrosive environments. Although not exhaustive, this reference presents a technique whereby the fatigue lives of details are shortened to account for environments other then air.

5.3.1 Constant Amplitude Loading in the Aluminum Design Manual

For constant amplitude loading, the designer performs the following calculation in accordance with the Aluminum Design Manual:

$$S_{ra} \leq S_{rd} \qquad (5.4)$$

where:

S_{ra} = the applied stress range, the algebraic difference between the minimum and maximum calculated stress in the member or detail.

S_{rd} = the allowable stress range.

S_{rd} = $A\,N^{-1/m}$

A, m = constants from Table 4.8.1-1 and shown in Figure 4.8.1-1

N = the number of cycles to failure.

If the applied stress range is less than the constant amplitude fatigue limit as given in Table 5–1, then no further fatigue calculation shall be needed. If the applied stress range is greater than the fatigue limit then consideration must be given to the number of cycles experienced by the detail and satisfactory behavior must be demonstrated through the above equation.

5.3.2 Variable Amplitude Loading in Aluminum Design Manual

For variable amplitude loading, if the maximum stress range in the spectrum of stresses is less than the fatigue limit defined in Table 5–1 for the appropriate detail category, then no further fatigue consideration is needed for the detail.

For all other stress ranges it is necessary to perform the following calculation in accordance with the Aluminum Design Manual:

$$S_{re} \leq S_{rd} \qquad (5.5)$$

where:

S_{re} = equivalent stress range

S_{re} = $\left(\sum_{i=1}^{N_s} \alpha_i S_{ri}^{m} \right)^{1/m}$

S_{rd} = the allowable stress range

S_{rd} = $A\,N^{-1/m}$

α_i = number of cycles in the spectrum of the ith stress range divided by the total number of cycles.

S_{ri} = the ith stress range in the spectrum

A, m = constants from Table 4.8.1-1 and shown in Figure 4.8.1-1.

N_s = number of stress ranges in the spectrum.

N = the number of cycles to failure.

The summation developed by the Aluminum Association in equation 5.5 represents a Palmgren-Miner cumulative damage analysis. Using this procedure it is necessary to determine the allowable stress range, S_{rd}, from the tables and figures presented in the design manual and insure that the equivalent stress range, S_{re}, is below this level.

In order to use either the constant or variable loading approach presented by the Aluminum Design Manual it is necessary for the designer to determine the number of load cycles experienced by the detail and the level of stress associated with each of those cycles, i.e., the loading history. Determination of the number of load cycles and the intensity of the load associated with each of those cycles was found to be one of the biggest gaps in developing the fatigue design criteria for this task. It is interesting to note that the Aluminum Design Manual does not provide any guidance on this subject. Therefore, using the Aluminum Design Manual, it is incumbent upon the designer to develop the stress histogram without any guidance from the specifications.

Also, within Section 4.8 of the Aluminum Design Manual it explains that the minimum and maximum stresses to be used for the analysis are the nominal stresses determined by typical elastic analysis methods. This makes the method presented by the Aluminum Association a simple and straightforward stress and fatigue analysis once the loading environment has been determined.

The Aluminum Design Manual does not present any discussion on damage tolerance analysis.

Table 5–1 Copy of Table 4.8.1-1 From the Aluminum Design Manual.

Constants for S-N Curves[1]

Detail Category[3]	A		m	Fatigue Limit[2]	
	ksi	MPa	ksi and MPa	ksi	MPa
A	96.5	665	6.85	10.2	70
B	130	900	4.84	5.4	37
C	278	1920	3.64	4.0	28
D	157	1080	3.73	2.5	17
E	160	1100	3.45	1.8	13
F	174	1200	3.42	1.9	13

[1] Different constants are to be used for calculations in ksi, and MPa
[2] Fatigue limit is based on $N = 5x10^6$
[3] See Table 4.8-1

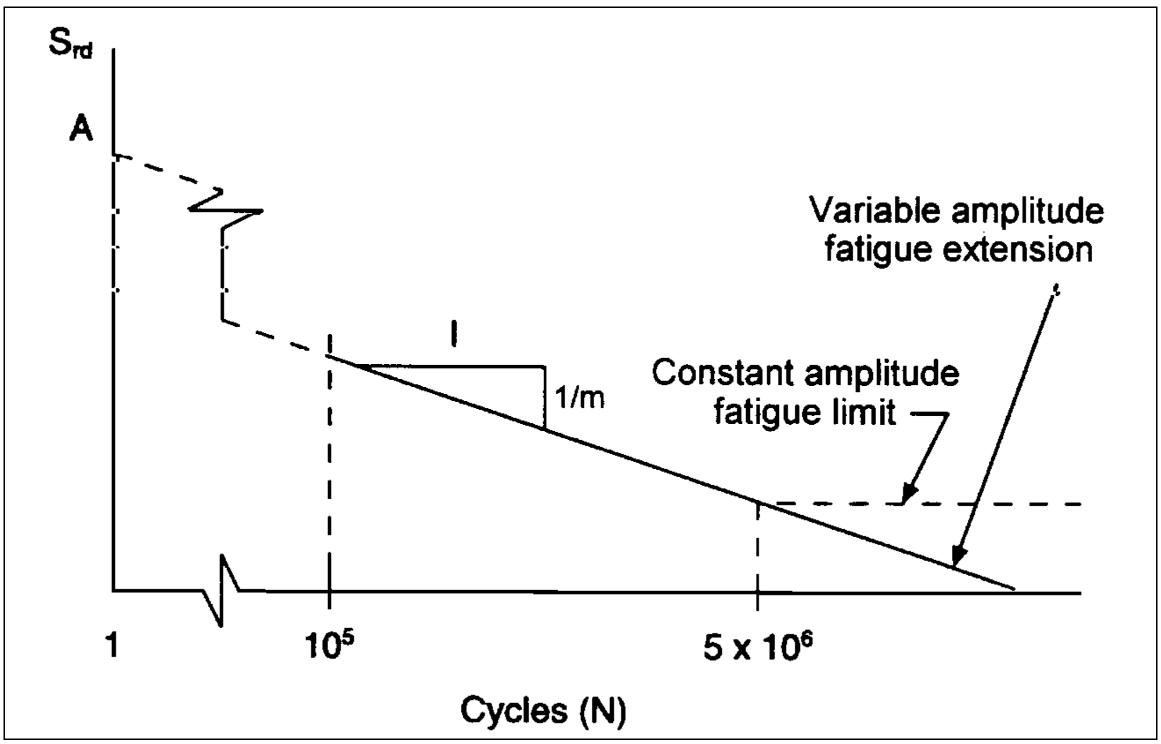


Figure 5-1 Copy of Figure 4.8.1-1 From the Aluminum Design Manual

5.4 European Committee for Standardization (CEN)

On 26 October 1997 the European Committee for Standardization, (Comit Europ en De Normalisation, CEN) approved the EuroCode 9 Prestandard as a prospective standard for provisional application. The prestandard has been distributed for preliminary use and is not yet a ratified Standard. It has been issued for a period of three years. After two years the members of the Comit are requested to submit their comments regarding the use of the prestandard, in particular, regarding the conversion of the document to a European Standard. EuroCode 9 addresses the Design of Aluminum Structures. Part 2 of this prestandard addresses Structures Susceptible to Fatigue.

The CEN is a consortium of European nations working collectively to develop a unified set of standards and practices regarding various aspects of engineering and engineering design. The member nations are, Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

As mentioned above, the EuroCode 9 is still in a preliminary state of development. After incorporation of any modifications, it is assumed the code will be issued in its final form as a European Standard.

In the meantime, there is a lot of good fatigue and damage tolerance design information contained within this code. The database of aluminum fatigue details initiated by Professor W.W. Sanders during the 1970's and 1980's was taken over by Professor Dimitris Kosteas who expanded the database greatly with significant large specimen testing since his inheritance. Professor Kosteas works at the Technical University of Munich and has been instrumental in the development of the EuroCode 9. The database forms the cornerstone of the fatigue and damage tolerance data used to develop the S/N curves and other data contained within this volume.

The EuroCode 9 is the only industry standard, identified by this report, that recognizes the effects of corrosive environments including varying degrees of marine exposure as well as immersion in seawater or freshwater. Similar to other codes, EuroCode 9 develops detail categories for the design being developed and recommends an applicable S/N curve based on a number of parameters.

5.4.1 Fatigue Design Philosophy in EuroCode 9

EuroCode 9 has two specific fatigue design categories:

1. Safe-Life Design.
2. Damage Tolerant Design.

A third option is included that is called "Design Assisted by Testing." It is expected that testing would not be proposed as the only method of solution but rather that test's would be used to supplement the analytical aspect of the design.

The Safe-Life and Damage Tolerant designs relate to the design philosophies discussed in Section 3.7 of this report regarding the crack-free life of the detail compared to the design service life of an application.

It is expected that most designs will be developed in accordance with the Safe-Life philosophy that develops a detail with a predicted crack-free life greater then the service life of the vessel, option 1 in Figure 3-16. Using the damage tolerant approach not only requires the fatigue analysis but a damage tolerance analysis and inspection plan as well. The plan requires inspection to be performed before the end of the predicted crack-free life. It also requires additional inspections to be performed at intervals not exceeding one-half of the predicted time to failure of the crack. If it is found that the crack is growing at a rate faster than predicted, the inspection schedule must be altered to account for the increased crack rate. This requires the crack growth rate calculations to be redone using the new information regarding the actual data from the detail.

The discussion of fatigue loads in EuroCode9 is very generic, requiring the designer to account for all sources of loading as well as the superposition of loads. Interesting discussion is provided regarding the confidence associated with the fatigue loads and associated partial factors of safety. When certain conditions exist it is not necessary to apply any factor to the loads. However, when confidence levels are lower, EuroCode9 defines the Partial Safety Factor for Fatigue Loading, γ_{Ff}, ranging anywhere from 1.1 to 1.5. These factors will increase the loads and resulting stress magnitudes acting in a detail with a corresponding decrease in the fatigue life. The high-speed craft designer should use similar ideas when developing load information or when using any data from design codes outside of the maritime industry.

EuroCode9 allows for the use of nominal, modified and hot spot stress considerations for the fatigue analysis. A nominal stress approach can be used for simple structures with details similar to those shown in the design code. Modified and/or hot-spot stress calculations are required for details that do not satisfy the nominal stress calculation criteria.

When all the stress and cycle data has been developed the designer uses the appropriate "detail category" and its associated fatigue curve to perform the Palmgren-Miner cumulative damage assessment of the detail.

5.4.2 Damage Tolerance Data and EuroCode 9

To allow the designer the ability to establish the crack growth rates and inspection schedules required for use with the damage tolerant design the EuroCode 9 also presents information and data relating to crack propagation rates in its Annex B, (Appendix B). Information regarding da/dN is presented for various aluminum alloys and load ratios, R. This represents the only design code uncovered by the research or this task with this type of information. It also reflects one of the largest gaps found during research for this task. That is, there is a lack of crack propagation rate information for aluminum alloys in the marine environment.

Appendix B of the EuroCode 9 presents a complete procedure for the damage tolerance analysis allowing prediction of time to failure after crack initiation.

More discussion is provided on this data in Section 6 of this report.

Please see Appendix C for complete presentation of certain portions of EuroCode9.

5.5 Association of American Railroads

Please see Appendix D for the complete presentation of the applicable portions of the AAR fatigue design procedures.

The Association of American Railroads, AAR, presents its fatigue design methodology in its Manual of Standards and Recommended Practices Section C – Part II. The information is presented in Chapter VII, Sections 7.1 through 7.5. The last of these sections presents the strain life method for fatigue analysis and will not be discussed in the main body of this report although it is reproduced in Appendix D for those interested in this analysis method. Section 7.3 of the AAR code presents a vast amount of Environmental Load Spectra data. While it is interesting and this is the only code uncovered for this task with such data, it is not reprinted in Appendix D due to the shear volume of data and the lack of applicability to the marine environment.

It is worth noting that the AAR design manual presents fatigue data for details constructed from both steel and aluminum. Discussion presented in paragraph 7.2.2.5 of the AAR design manual suggests the following interesting trend:

> *"If the data are insufficient to determine the fatigue strength of a member or detail in aluminum and the fatigue strength is available for the member or detail in steel, then it can be assumed that the aluminum fatigue strength (MGD y-axis intercept) is about equal to one-third (1/3) of the steel fatigue strength and the MGD has the same S-N slope, k, and the same MGD slope, m, with verification or adjustment of these strengths by comparison with other design codes. The one-third factor assumes that fatigue life consists of fatigue crack propagation only, which is a function of the modulus of elasticity."*

This recommendation reflects an observation in [5-8] and [5-9] where data and discussion are presented for fillet welded details constructed from steel and aluminum. This data also suggests that the fatigue strength of the aluminum details is about ½ to 1/3 that of the same detail in steel. Reference [5-8] also suggests that the fatigue life of butt-welded details constructed from aluminum is approximately 70% that of the same butt-welded detail in steel. These observations agree that the fillet weld details have fatigue strengths proportional to the modulus of elasticity while the butt weld details are more proportional to the tensile strengths of the steel and aluminum materials. Further investigation of these observations is strongly suggested. If this proves to be a valid assumption, with certain tolerable deviation, then it may be possible to use information developed for certain steel details when analyzing their aluminum counterparts. Factors of safety reflecting the use of this type of information could be included in the design.

The procedures outlined by these codes are somewhat more involved than those developed by either the Aluminum Association or CEN. They are presented here because of the use of the modified Goodman diagram in assisting with the fatigue calculations. Aside from using this somewhat different technique the AAR design code also has a lot of useful information and may assist the marine designer in certain applications.

Similar to the other two industry codes presented herein, the AAR fatigue design and analysis code is based upon the Palmgren-Miner cumulative damage technique. It utilizes the modified Goodman diagram to help evaluate the fatigue limit, S_e, of a given detail.

5.5.1 Modified Goodman Diagram

The modified Goodman diagram, MGD, presented in the AAR code is reprinted below as Figure 5-2. Used with the information in Section 7.4 of the AAR design manual, the MGD allows the user to determine the fatigue limit stress, S_e, for a given detail. If the maximum stress experienced by a detail is less then this value, the designer has a good degree of confidence that the detail will not develop any fatigue cracks during its service life. If the design stresses resulting from the environmental loads exceed the value of S_e then it will be necessary for the designer to continue with the fatigue analysis as outlined by the AAR design manual.

Since the fatigue limit, S_e, varies with different values of R, an equation for S_e may be obtained from the modified Goodman diagram.

IDEALIZED MODIFIED GOODMAN DIAGRAM

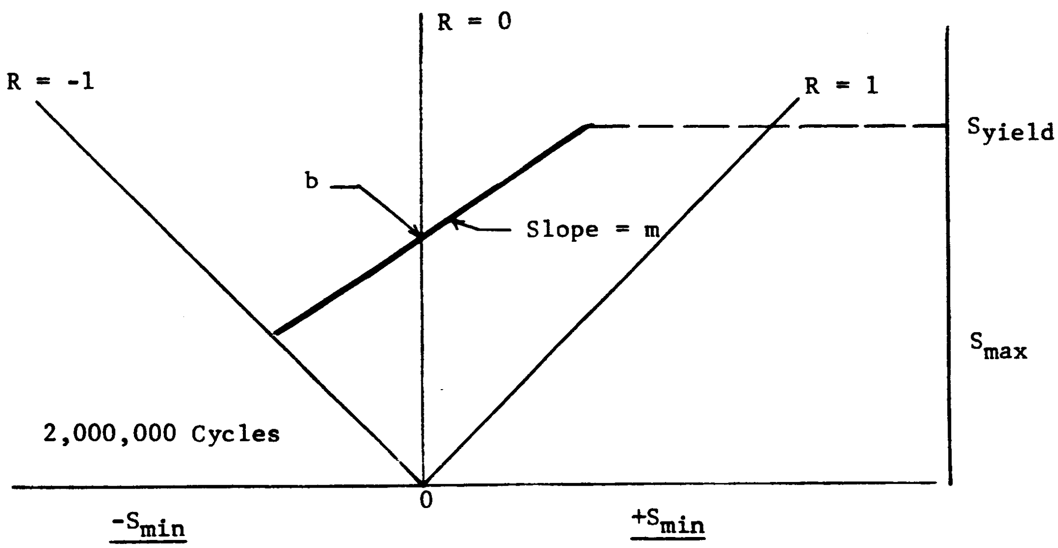


Figure 5-2 Copy of Modified Goodman Diagram from AAR

5.5.2 Stress Analysis Using AAR Design Manual

The AAR design manual provides for two different approaches to fatigue design and calculating the associated stresses. The first uses the nominal stress approach. These stresses and this approach can only be used if the detail being designed is the same, or very similar, to one of those presented in the AAR design code. The nominal stresses are determined in accordance with typical elastic stress analysis techniques, including finite element analysis if required. The obvious limitation on this approach relates to the relatively small number of details provided by the design code compared to the multitude of applications that can arise.

Regardless, this allows for a relatively simple set of calculations and does accommodate a fair number of details or those closely associated.

The second methodology used for stress calculation involves stress concentration factors acting upon the nominal stresses. This is used for details for which there is no corresponding detail provided in the design manual. The AAR design code does not provide any specific stress concentration factors. It does provide a number of references for the location of appropriate stress concentration values. These references are "Stress Concentration Design Factors", R. E. Peterson, Wiley and Sons, 1974 or "Stress and Strength of Manufactured Parts", Lipson, Noll, and Clock, McGraw-Hill Company, 1950. The AAR requires that the maximum stress be determined by multiplying the nominal stress by the appropriate stress concentration factor, either K_f or K_t. Peterson [5-10] defines these two factors as:

- K_f = fatigue notch factor for axial or bending load. (K_f is a factor determined by fatigue tests.)
- K_t = stress concentration factor for normal stress, $\sigma_{max}/\sigma_{nom}$. ($K_t$ is a theoretical factor .) Various expanded subscripts are used, such as K_{te} for elliptical notch, K_{th} for hyperbolic notch, K_{tA}, K_{t2}, $K_{t\alpha}$, etc., for special cases.

Regardless of the stress calculation, the designer uses the MGD as input to determine the acceptability of a given detail subjected to the loading environment under investigation.

5.6 Other Industry Design Codes

Appendix A provides a listing of various other design codes used around the world. Brief discussion of these codes, and others, are provided in [5-9].

5.7 References

[5-1] DNV Fatigue Analysis of High Speed Craft, Report No. 99-0551, 1999

[5-2] DNV Fatigue Assessment of Ship Structures, Classification Notes No. 30.7, September 1998.

[5-3] The Aluminum Design Manual, The Aluminum Association, Washington, D.C., 1994.

[5-4] EuroCode 9: Design of Aluminum Structures- Part 2: Structures Susceptible to Fatigue, Brussels, 1998.

[5-5] Manual of Standards and Recommended Practices Section C – Part II, Association of American Railroads, Washington, D.C., 1997

[5-6] Aluminum in the Marine Industry: Application to Fast Ferries. Collection of papers collated and presented by the Aluminum Association, Washington, D.C., 1997.

[5-7] Fredricksen, A., Fatigue Aspects of High Speed Craft. Paper presented at the FAST '97 symposium.

[5-8] Aluminum Company of America, ALCOA, Considerations for the Structural Detailing of Aluminum Ships, Hyattsville, MD., 1975

[5-9] Sharp, M. L., Nordmark, G. E., and Menzemer, C. G., Fatigue Design of Aluminum Components & Structures, McGraw-Hill, 1996

[5-10] Peterson, R. E., Stress Concentration Factors, Wiley Interscience, 1974

6. Fatigue Cracking and Damage Tolerance Analysis

6.1 Damage Tolerance Analysis

The major aspects of damage tolerance analysis are:

- Fatigue crack growth rate (FCGR) analysis - The methodology by which expected growth of a crack in a structural member is evaluated.
- Fracture or residual strength analysis –After a structure has begun to experience crack growth it can fail in one of two ways. First, the crack can grow to its critical size, exceed the fracture toughness of the material, and the structure will fracture. Second, the uncracked portion of the structure may lose its structural integrity and not be able to carry the loads to which it is subjected and it will fail from becoming structurally unstable or overstressed. Fracture analysis is developed using a methodology, either linear-elastic or elastic-plastic, by which the maximum allowable (critical) crack size is determined. The residual strength is determined through typical stress calculation procedures and is also discussed herein.

6.2 Fatigue Crack Growth Rate Analysis

In accordance with Anderson, [6-1], the procedures for analyzing constant amplitude crack propagation with small scale yielding at the crack tip are fairly well understood, although certain issues still remain. The procedures required for the study of crack propagation subjected to variable amplitude loading, large scale crack tip plasticity and short cracks are not as fully understood and require additional study. The operating scenario for high-speed aluminum craft generates a variable amplitude loading environment often with large zones of plasticity at the crack tip in the aluminum weldment. The large zone of plasticity defines the typical behavior of aluminum and represents an important departure from that of steel, which is characterized by small zones of plastic yielding at the crack tip. The “large” and “small” zones of crack tip plasticity are relative to the thickness of the specimen. They are depicted graphically in Figure 6-1, [6-1] and discussed below.

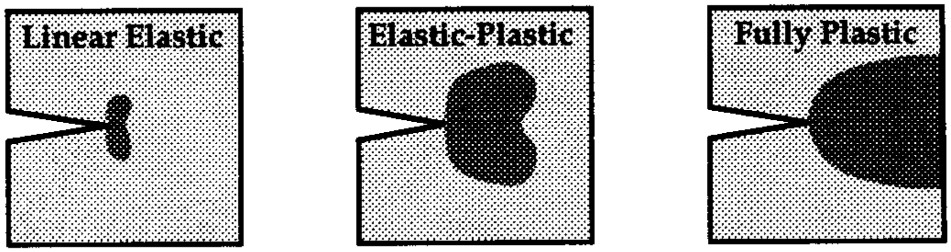


Figure 6-1 Relative Size of Plastic Zone at Crack Tip

Many of the well known theories used in the practice of fracture mechanics and crack growth simplify the analysis by assuming dependency of the event on a single variable, typically ΔK where K is the crack tip stress intensity factor and ΔK is defined as K_{max} - K_{min}. In fact, it is known that for various situations the value of ΔK is not sufficient to define crack propagation and that factors including the stress ratio R, and prior loading history experienced by the detail also influence the rate of crack growth. Regardless, the relationship first proposed by Paris and Erdogan depends only on ΔK. Known as the Paris equation and shown below as equation 6.1, it has gained wide acceptance for representation of the linear portion, region II, of the typical FCGR curve shown in Figure 6-2, [6-1].

$$\frac{da}{dN} = C\Delta K^{m} \tag{6.1}$$

Regions I and III shown in Figure 6-2, represent non-linear portions of the crack growth rate. At the beginning of a specimen's life it is assumed to be effectively intact. The crack growth rate is zero until the crack has been initiated at the threshold value of the stress intensity factor, ΔK_{th}. Near the end of the specimen life, the crack growth rate accelerates until the critical crack size is reached at which point fracture occurs. As discussed earlier, other damage mechanisms such as plastic collapse of the structure, tearing or buckling can also occur as the crack grows and may happen prior to fracture depending on the residual strength of the structure.

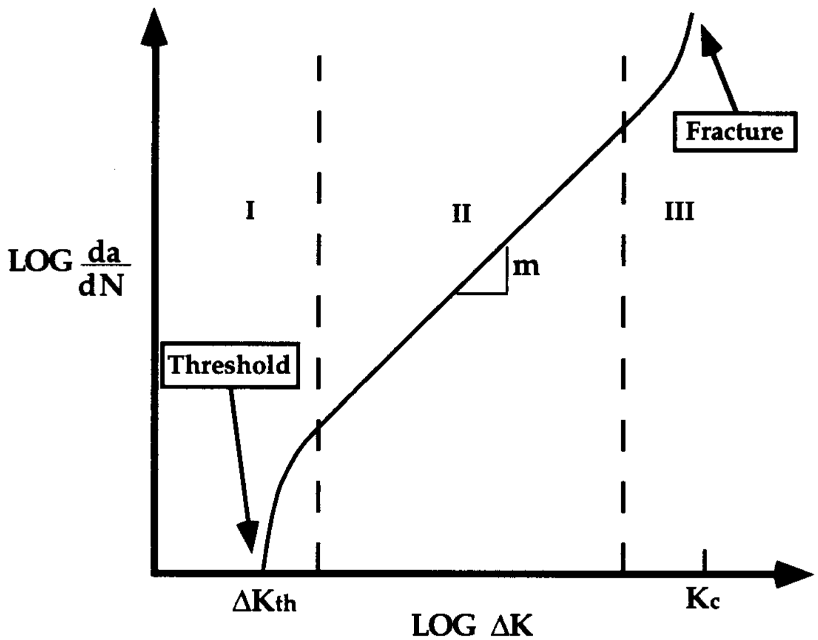


Figure 6-2 Typical FCGR Curve

Kosteas [6-2] and others [6-3], [6-4], however, note that the Paris equation should not be used for the marine grade aluminum alloys. These references state that the crack growth behavior varies with ΔK in Region II as the result of changes in crystallographic modes of crack propagation, and because crack propagation behavior can be quite different in the weld metal and HAZ. Thus, the crack growth behavior needs to be defined by polynomial equations, Figure 6-4, [6-2]. Figure 6-3,[6-4] also demonstrates the multi-linear step function for da/dN vice ΔK for aluminum in a salt water environment.

Figure 3-15 displays some crack growth rate data for a number of aluminum alloys in a benign environment where the linear FCGR through region II is shown to be more applicable.

The crack tip stress intensity factor, K, is a function of the applied stress, crack dimensions, the extent of plasticity at the crack tip and geometry. The general expression for K for crack growth in a linear-elastic material was presented in equation 3.5. Equation 6.2 presents the general expression for K as the size of the zone of plasticity at the crack tip increases, demonstrated in Figure 6-1, and can no longer be ignored (as done by equation 3.5). This applies as the crack grows through region III of Figure 6-2:

$$K = Y\sigma\sqrt{\pi\left(a + r_y\right)} \tag{6.2}$$

Where Y = geometric factor.

σ = applied global stress

a = crack length

r_y = crack tip plastic zone size = $r_y = \frac{1}{6\pi}\left(\frac{K}{\sigma_{YS}}\right)^2$

The equation for r_y was developed by Irwin [6-5] and reflects an effective crack length that accounts for the higher K values than predicted by the elastic stress distribution in the area of the crack.

Referring to Figure 6-1, linear elastic conditions apply for high strength, low toughness materials for which the crack tip plastic zone size is finite but small enough to be ignored in the above equation. Elastic plastic conditions apply for higher toughness materials for which the plastic zone size is larger and therefore needs to be considered, as in equation 6.2. Fully plastic conditions apply to materials with an even greater toughness. As discussed in Section 6.3, the extent of crack tip plasticity determines the fracture toughness criteria to be used to determine the critical crack size.

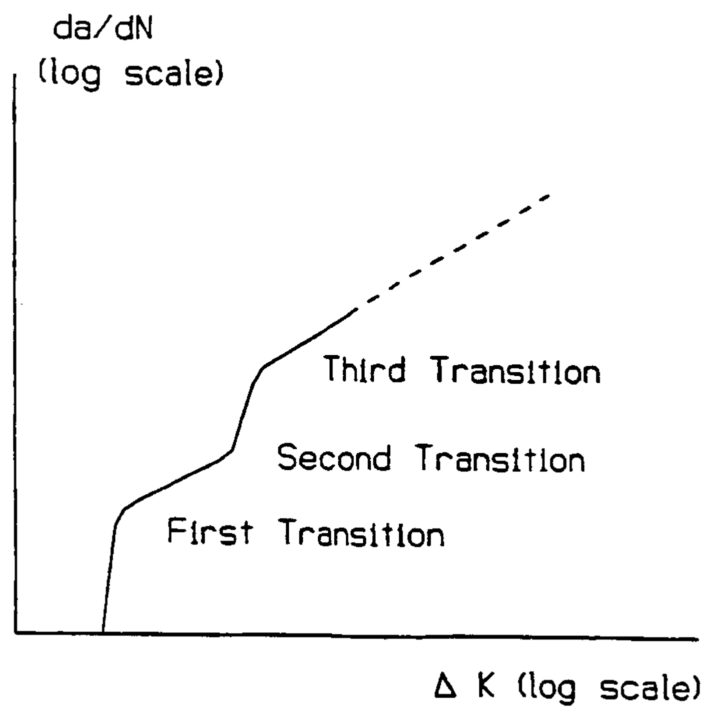


Figure 6-3 Schematic Diagram of Multi-Linear Segments of da/dN for Aluminum.

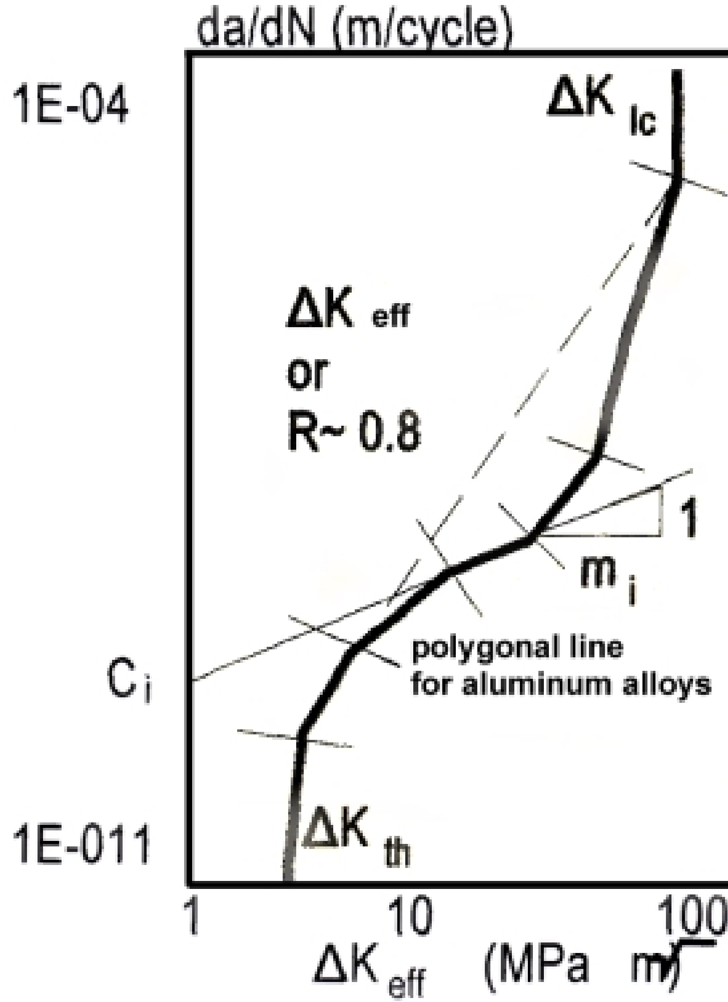


Figure 6-4 Polygonal da/dN curve for aluminum

6.2.1 Fatigue Crack Growth Rate and Aluminum High-Speed Craft

FCGR testing is typically performed under constant load (ΔK increasing), or constant K max (ΔK decreasing) conditions such that crack tip yielding is minimized. The FCGR curves are generated from axial or bend testing of base metal specimens, or welded specimens prepared so that the fatigue crack propagates through the weld metal or HAZ. Loading for high speed vessels, however, is variable and will include random high magnitude tensile loads that can cause significant crack tip yielding. Such yielding results in a region of compressive residual stress in front of the crack that slows subsequent growth until the crack passes through this region. This temporary reduction in crack growth rate is called retardation and may or may not be significant depending on the number and magnitude of overload cycles. This phenomenon is depicted graphically in Figure 6-5 and Figure 6-6, [6-1].

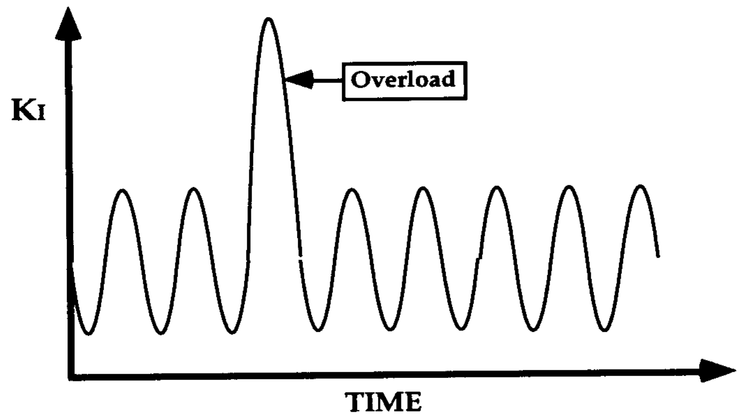


Figure 6-5 Peak Overload in Constant Amplitude Field

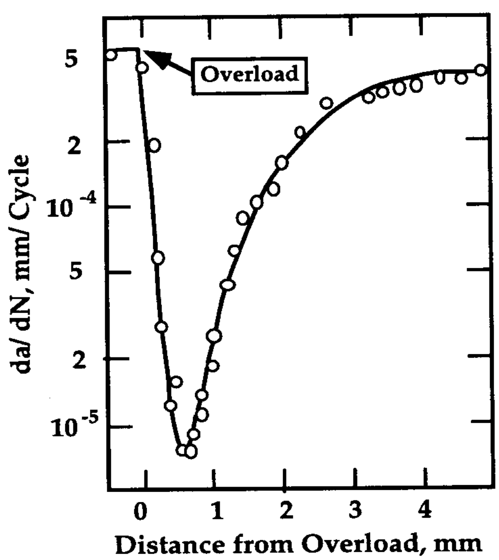


Figure 6-6 Crack Retardation as a Result of Peak Overload

Similar to crack retardation, the growth of a crack can be accelerated by a compressive overload that will result in tensile residual stresses upon release of the load. The crack growth will return to its "normal" rate once it has progressed through the area of tensile residual stresses resulting from the compressive overload.

Other factors to be considered are the effects of residual stresses, and higher crack growth rate for short cracks (resulting from reduced effects of crack closure that retard growth of larger cracks). EuroCode 9 uses a combination of constant load and constant K_{max} curves for conservatism to account for high residual stresses and short fatigue cracks. Specifically, high R ratio (R=0.8) or constant K_{max} curves for welds unless the specific residual stress pattern is known, and constant K_{max} curves for crack lengths less than 2mm, and constant load curves for crack lengths greater than 2mm.

As discussed below, some of the current fatigue/fracture software packages can accommodate polynomial crack growth curves and retardation effects.

6.3 Fracture Mechanics and Critical Crack Size

As noted previously, a growing crack will eventually reach a "critical" size that can no longer be tolerated in the structure. The critical crack size (length and depth) is determined using fracture mechanics analyses methods by comparison of the crack tip stress intensity (a measure of the crack driving force) to the materials fracture toughness (a measure of resistance to crack extension). The value of fracture toughness to be used for this analysis is material dependent, so the definition of critical crack size differs for different materials as follows:

- For high strength, low toughness materials, the fracture toughness parameter is determined using liner-elastic fracture mechanics, LEFM. A crack in such materials will propagate suddenly through a structure with essentially no prior plastic deformation (i.e., brittle fracture under elastic load) if it has grown (by fatigue or other mechanism) to a size at which the crack-tip stress intensity equals K_{Ic}. Thus, the critical crack size for these materials is the size at which brittle fracture will occur.
- For low strength, high toughness materials LEFM, cannot be used because the extent of crack tip plasticity in such materials is relatively large. Thus, brittle fracture without preceding plastic deformation is not a concern. There is still a "critical" crack size for these materials because other failure modes exist. These modes are most commonly defined by crack-tip-opening-displacement (CTOD) or 'J-Integral' values as determined by standard ASTM test methods. Structural steel and aluminum alloys used in the marine environment typify these materials which are analyzed using elastic-plastic fracture mechanics techniques, EPFM.

In accordance with American Society for Testing and Materials, ASTM, linear elastic conditions apply when the following relationship between specimen thickness, material fracture toughness and yield strength is satisfied:

$$B \geq 2.5\left(\frac{K_{Ic}}{\sigma_y}\right)^2 \tag{6.3}$$

Where B = specimen thickness. Typical nomenclature for the crack length and specimen thickness are shown in Figure 6-7.

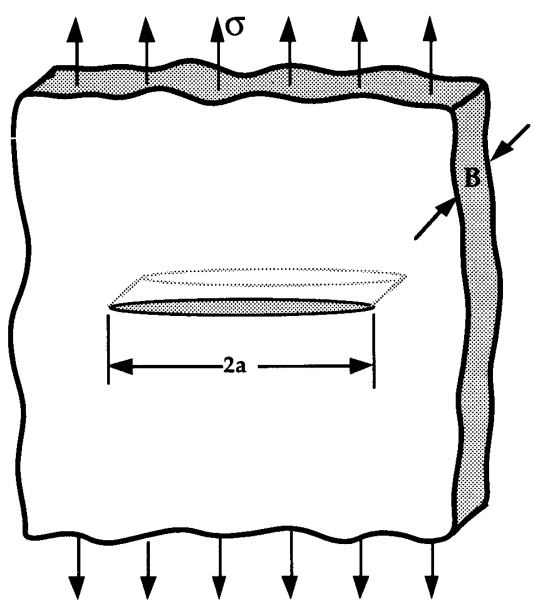


Figure 6-7 Crack Length and Thickness in Typical Specimen

For high strength, low toughness alloys the value of B is on the order of typical section thickness used in ship, and other, structural members so K_{Ic} can be used in conjunction with equation 6.3 to determine the critical crack size for fracture.

For low strength, high toughness materials, such as marine grade aluminum alloys, the value of B is relatively large and not representative of the thickness used for high-speed aluminum construction. For these materials it is necessary to use the CTOD or J integral values to obtain the critical crack size for fracture.

The values generated for CTOD and the J Integral using the ASTM tests are as follows [6-1]:

<u>CTOD</u> δ_u - CTOD at the onset of unstable fracture which has been preceded by more than 0.2 mm of stable crack growth.

δ_i - CTOD near the initiation of stable crack growth.
(analogous to J_{Ic} - see below)

δ_m - CTOD at the first attainment of maximum load plateau.
(crack tip displacement value corresponding to maximum load reached in specimens that display ductile tearing only)

NOTE The CTOD can also be used for low toughness materials for which the measured parameter is δ_c which is the CTOD value at the onset of unstable fracture with less than 0.2 mm of stable crack growth. This is analogous for K_{Ic}.

J Integral J_{Ic} - value of J integral near the initiation of slow, stable crack growth.

In addition to evaluation of the critical crack size, high toughness materials must also be evaluated for the possibility of plastic collapse of the remaining section as a crack propagates through a structure. Both criteria are covered by use of a failure-assessment-diagram (FAD) as illustrated in Figure 6-8, [6-1]. There are several forms of the FAD, and SSC-402, [6-6] recommends the material specific FAD, an example of which is shown in Figure 6-9, [6-6]. Note from Figure 6-9 that the equation for the material specific FAD curve is determined from the materials stress-strain behavior. The EuroCode 9 criteria are similar and read as follows: "The value of l_f [final crack length] shall be such that the net section, taking into account the likely shape of the crack profile through the thickness, shall be able to sustain the maximum static tensile forces without unstable crack propagation." This failure mode will occur when the remaining uncracked section is stressed into the plastic region.

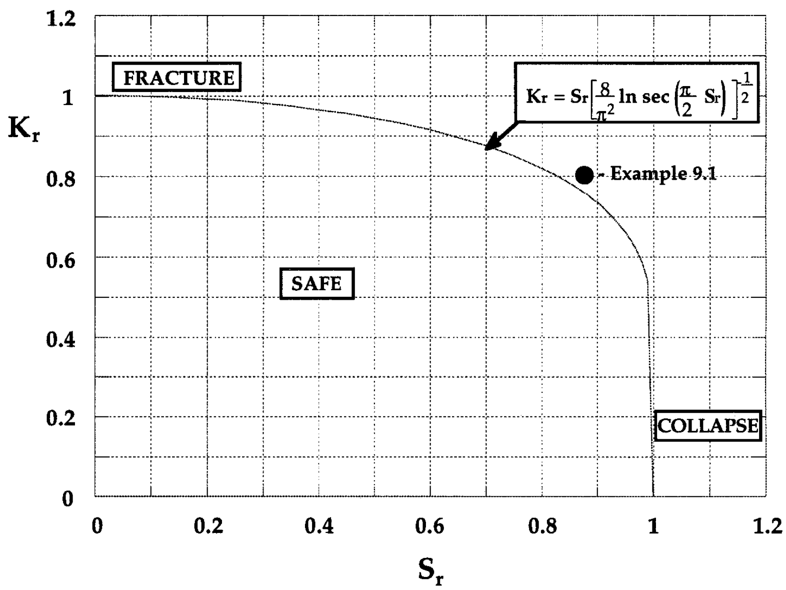


Figure 6-8 Typical Failure Assessment Diagram, FAD

The Y-axis in Figure 6-8 and Figure 6-9 is K_r which is the ratio of crack-tip stress intensity K_I in the structure being evaluated to K_{Ic}. As noted above, use of K_{Ic} is not appropriate for the marine grade aluminum alloys and must be replaced by the CTOD or J-integral criteria. SSC-402 recommends the CTOD criteria with the following conversion equation to K_{mat}:

$$K_{mat} = \sqrt{\frac{1.6\sigma_f \delta_{mat} E}{\left(1-\upsilon^2\right)}} \qquad (6.4)$$

Where:

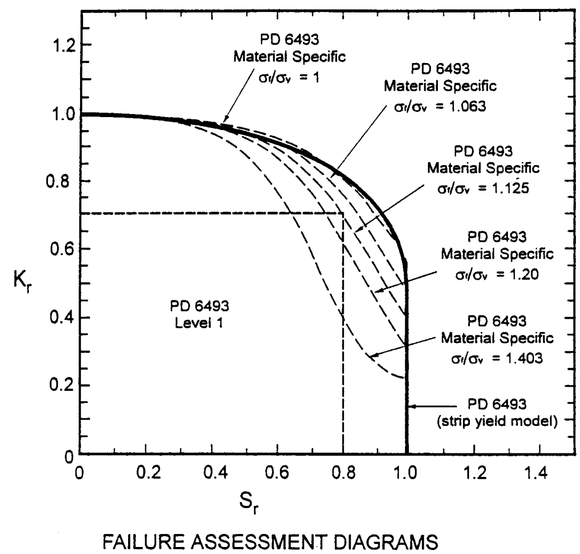
K_{mat} = value of fracture toughness to be used in lieu of K_{Ic}.

σ_f = flow stress = average of yield and ultimate tensile strengths.

δ_{mat} = critical CTOD value from ASTM test (specific criteria TBD).

E = Young's modulus.

ν = Poisson's ratio.



σ_f/σ_y	σ_y ksi	σ_u ksi
1.063	80	90
1.125	60	75
1.200	50	70
1.403	36	65

The Material Specific, FAC Curves represent: (1) elastic-perfectly plastic material, i.e., $\sigma_f/\sigma_y = 1$, (2) A 36, i.e., $\sigma_f/\sigma_y = 1.403$, (3) HSLA 50, i.e., $\sigma_f/\sigma_y = 1.200$ (4) HSLA 60, i.e., $\sigma_f/\sigma_y = 1.125$, and (5) HSLA 80 i.e., $\sigma_f/\sigma_y = 1.063$.

Figure 6-9 Material Specific FAD

For information, the conversion of J_{Ic} to K_{Ic} is as follows:

$$K_{Ic} = \sqrt{\frac{J_{Ic}E}{\left(1-\upsilon^2\right)}} \tag{6.5}$$

Other potential failure criteria that should be evaluated are:

- NASA criteria: [6-9]
  - crack-tip-opening-angle (CTOA).
  - Gurson-Tvergaard void growth and coalescence.
  - cohesive-zone-model.
- Energy dissipation rate. [6-10]

6.4 Failure Modes Associated with Fracture Mechanics

There are three principal modes of load application that can initiate or propagate a crack. They are illustrated in Figure 6-10, [6-1]. Mode I is a pure tensile load that tends to open the crack with principal stresses normal to the crack. Mode II is pure shear that tends to slide the two surfaces of the crack along its length and Mode III is an out of plane shear that extends the crack by the action of a moment generated at the base of the crack, i.e., at the crack tip. It is also possible to have stress or loading states that represent any combination of these three fundamental states.

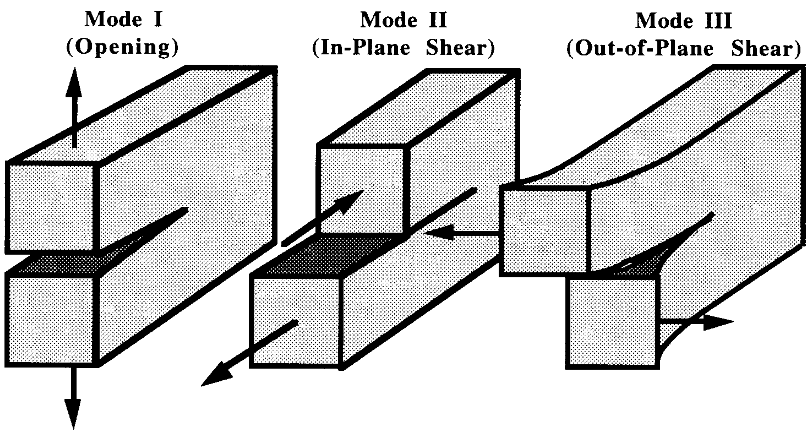


Figure 6-10 Three Modes of Loading for Crack Propagation

There is a critical crack tip stress intensity factor, or critical stress associated with each of these modes and they are denoted as, K_{Ic}, K_{IIc}, and K_{IIIc}, respectively. These stresses are typically above the yield strength of the material and represent the fracture toughness of the material for each of the three failure modes. For use with LEFM, they must be constrained to a small area around the crack tip opening. Generally, for metallic structures K_{Ic} is the critical stress intensity factor, i.e., it is smaller than either K_{IIc} or K_{IIIc}. Therefore, in order to take advantage of linear-elastic fracture mechanics, it is necessary to have good data for the K_{Ic} values associated with the material of interest and equation 6.2 is rewritten as:

$$K_{Ic} = Y\sigma\sqrt{\pi\left(a + r_y\right)} \qquad (6.6)$$

K_{Ic} is the fracture toughness of the material. It is constant for the material and independent of the size or geometry of the specimen. Marine grade aluminum alloys are typified as high toughness and low strength and, as previously discussed require unrealistically thick specimens compared to those used for high-speed craft to develop linear-elastic behavior, equation 6.3. Since the thickness of high-speed craft aluminum structures tend to be small this invalidates the use of the K_{Ic} values for this application and suggests that LEFM is not appropriate for the damage tolerance analysis of marine grade aluminum alloys. It also implies the use of the EPFM and CTOD or J Integral procedures as outlined above.

6.5 Fatigue Crack Growth Rate and Fracture Data

Table 6–1 summarizes the design information and material property data required for crack growth and fracture mechanics analyses of aluminum structures. A literature search was conducted to identify available data for the alloys listed in Table 1–1. The data are summarized in Table 6–2 which illustrates the fact that there are insufficient data for the analyses. This assessment is based on two primary factors:

1. There are insufficient data points to show the data spread and allow statistical analysis. That is, the designer should have sufficient information to permit selection of allowable values based on the mean, the minimum, or other statistical measure of the raw data depending on the criticality of the design. As discussed in SSC-402, a minimum of three specimens will be required for each test to ensure statistically valid results, and additional specimens may be required if scatter from the initial tests is too large.
2. There is insufficient documentation of data validity. It is often difficult from review of a technical paper to determine the exact test conditions. If such determination cannot be made it will be impossible to group data points together to meet the above statistical validity requirements.

One potential source of valid FCGR data that should be investigated further is EuroCode 9, specifically Appendix B covering damage tolerant design which contains numerous FCGR curves for aluminum alloys. Grade 5454 is the only grade from Table 1–1 currently included (see Table 6–2) but it is possible that other grades are being considered.

Material testing will be required if the EuroCode 9 data are not considered sufficient or would not be available for use by the U.S. Coast Guard. The required data are those listed in Table 6–2 and standard ASTM test methods are available for all the tests. Details of the test program, such as number of specimens and filler metal process and filler metal for welded specimens, will have to be developed. Another major issue will be identification of the most suitable fracture criteria for the aluminum alloys in question because this will determine which test method should be used.

A major advantage of a new test program as opposed to using literature data is that new data can be generated in electronic format and input directly into some of the fatigue and fracture software packages. Use of existing FCGR and other data in the form of curves will require data points to be picked-off the curves which can lead to errors. Complete control of the test set-up and execution is another advantage that would be realized by conducting new tests. Details and environments specific to the high-speed craft would be used for the test procedures instead of pre-existing tests with set-up parameters that may not correspond to the desirable variables in the high-speed craft industry. As further research is developed for the loads acting on high-speed craft it may also become desirable to perform these tests under bending loads rather than axial loads as the influence of primary and secondary loads on high-speed craft is assessed.

6.6 Fatigue and Fracture Software

Significant material testing will be required to generate the crack growth and fracture mechanics data listed in Table 6–1. It appears that CTOD data is the preferred property for fracture mechanics analysis but J Integral tests may have to be performed if meaningful CTOD results cannot be obtained. R-curve fitting will also be required if ductile tearing analysis needs to be performed.

Once sufficient material property data are generated, the question will be how best to use the data for damage tolerance analysis. It is highly recommended that currently available software packages be evaluated rather than attempt to development of a specific methodology for this application. Table 6–3 summarizes information on packages investigated for this report based on information from reference [6-7] and additional review of literature and contacts with the vendors. Other programs may exist and it is not suggested that the current list is exhaustive. The primary reason for the recommendation to evaluate these packages is that many can perform elastic-plastic analyses with consideration for polynomial FCGR curves, crack closure, crack retardation and other factors. Other programs can be or are being modified to address elastic-plastic analysis and other factors. In addition, many are Windows based, easy to use and can accept electronic input of material data. It must be emphasized that crack closure and other factors may turn out not to be major issues for the marine grade alloys, so any software package without the capability to address such factors should not be discounted at this stage.

The nSoft package listed in Table 6–3, contains a complete suite of interconnected software modules that can handle S/N and local strain approaches, includes BS 7608 for weldments and can handle analysis and synthesis of complex load and strain spectra. The nSoft package has been used in many fields world-wide and is easily integrated with the MSC/FATIGUE FEA package.

nSoft-E

Pre- and post-processor for measured field data. Range-mean counting algorithm. Statistical analysis of load amplitudes. Frequency analysis, filters. Randomized reconstruction of time histories from RainFlow matrices. DOS, WINDOWS, VMS, UNIX. Serves as gateway to FATIMAS-SN, FATIMAS-EN, KRAKEN, and FATIMAS-EDIT.

FATIMAS-SN

Stress-based life assessment for high-cycle fatigue, complex components, e.g., bearings, gears, etc. Uses base metal or component-test S-N curves. Weldment analysis follows BS 7608 and BS 8118. Variable amplitude analysis. Includes non-homogeneous materials such as cast iron.

FATIMAS-EN

Strain-based life assessment for crack initiation in safety-critical, non-welded components. Variable amplitude, accounts for load-sequence effects on mean and residual stresses. High-temperature applications. Smith-Topper-Watson and Morrow mean stress corrections.

FATIMAS-MULTIAXIAL

Strain-based multiaxial life assessment for proportional and non-proportional loading.

FATIMAS-SPECTRAL

Frequency domain life assessment based on power or amplitude spectra. Correction for surface finish and surface treatment.

KRAKEN

Linear elastic fracture mechanics analysis of crack growth in a component containing an initial crack-like discontinuity. RainFlow cycle counting. Crack closure, corrosion, material data and stress intensity factor libraries. Simple power relation of crack growth rate to range of stress intensity factor. Linear elastic fracture. Combined with FATIMAS-EN to estimate total life.

TESTLAB

Tools for analyzing monotonic tensile tests, strain-controlled fatigue tests, component fatigue tests, and strain gauge rosette data. Results in format for input to other nSoft modules.

One vendor stated that for an evaluation program they would supply their software to an independent activity and provide the necessary support. If the other vendors did likewise, a possible evaluation program would be as follows:

- Select a high use aluminum alloy and conduct testing to generate the necessary fatigue and fracture data (including welded samples and corrosive conditions).
- Prepare specimens of selected welded structural details in the same manner as is done to generate S/N data for new design. Prepare finite element models (FEM) for each detail that should be sufficiently detailed to allow modeling of weld details such as weld reinforcement angle and any undercut that may be present.
- Perform fatigue tests on these specimens using fatigue loading spectra typical of those that will be experienced in service in air and corrosive conditions (including seawater immersion and spray). Run the tests as normal S/N type tests until fatigue cracks initiate then measure all fatigue cracks in the test specimen and add the necessary details to the FEM model of the test specimen. Continue the test and monitor crack growth.
- Use the FEM model and material property test data with each software package to predict crack growth behavior in the test specimen. Accuracy of the packages can be determined by comparison of the calculated results of the crack extent and orientation to the actual test results.
- These tests should also be performed on details with simulated weld repairs because in some cases weld repairs may accelerate fatigue cracking as the result of poor quality and residual stresses. Such testing may provide guidance as to whether certain repairs should be made as normal maintenance, or should be delayed until periods of dry-docking when welding can be performed until more controlled conditions.

6.7 Conclusions

Except perhaps for the data in EuroCode 9, there are insufficient material data to support damage tolerance analysis of the known aluminum alloys used in high-speed vessels. A thorough review should be conducted to generate an up-to-date list of current aluminum alloy grades and filler metals. EuroCode 9 and related documents should be reviewed to determine the extent and validity of the material property data they contain, and testing programs should be undertaken to generate the necessary fatigue, fracture data, and other data as listed in Table 6.2. A prerequisite for the test program will be determination of which fracture criteria should be applied to these alloys.

There are numerous high quality, state-of -the-art fatigue and fracture software packages available. These should be evaluated to determine which are best suited for the damage tolerance analysis of the marine grade aluminum alloys used for the construction of high-speed craft.

Table 6–1 Summary of Design and Material Property Data Required for Crack Growth and Fracture Mechanics Analyses

ANALYSIS	REQUIRED DESIGN INFORMATION	REQUIRED MATERIAL PROPERTY DATA
Crack growth	• Finite Element Model (FEM) of the structural detail • Stress analysis showing crack tip stress intensity values • Fatigue loading spectrum	• Fatigue crack growth rate (FCGR) data in the form of da/dN vs delta K - Paris law or polynomial - air and seawater environment (immersion and spray) - base metal, weld metal, HAZ - constant amplitude testing
Fracture mechanics	• FEM and stress analysis from above	• Yield and ultimate tensile strengths • Flow strength (typically average of yield and ultimate tensile strength) • Stress strain curves • One of all of the following fracture toughness values (function of material): - Critical crack-tip-opening-displacement value (CTOD) - Critical J value - JIc - FAD curves - Other

Table 6–2 Number of Data Points From Published Literature for Material Properties Necessary to Conduct Aluminum Damage Tolerance Analyses (1)

	ALLOY	6061-T6		5083 (2)		5086		5454		5456 (2)		5356 weld metal	4043 weld metal	5183 weld metal
PROPERTY (ASTM TEST METHOD)	ENVIRONMENT/ CONDITION	Base Metal (BM)	Heat Affected Zone (HAZ)	BM	HAZ	BM	HAZ	BM	HAZ	BM	HAZ			
FCGR (E647)	Air	6	2	5 (H116) (3)	1 (H116)			4 (H24): (2 ΔK incr. for R=.1, .8, 2 K max for R=.1, .8) (8)		2 (H321) 1 (H117) 1 (H116)		3		1
	Corrosive Environment									3 (H116) 1 (H321)				
K_{Ic} (plane-strain) (E399)	Air	9					CTOD, J_{Ic} or other criteria should be used in lieu of K_{Ic} or K_c							
K_c (plane-stress) (E399)	Air			1 (H116)						1 (H117)				
CTOD (4) (E1290) (E1820)	Air													
J_{Ic} (5) (E1737) (E1820)	Air			4 (as rolled)	1							1	1	
R Curve (6) (E561) (E1737)	Air													4
Stress Strain Curves (7)	Air	Further literature searches will be conducted to locate stress strain curves												

1. Gray shaded boxes indicate no literature data available so testing will be required to generate the data.
2. Material condition is given parentheses.
3. The FCGR data points includes one from the NASA NASGRO database. The K_c data point for 5083 is also from this database. [6-11]
4. CTOD is crack-tip-opening-displacement
5. J_{Ic} is the value of J integral near the initiation of slow, stable crack growth. J-integral testing should only be performed is CTOD testing does not produce meaningful results.
6. R curves are crack-growth resistance curves. This testing should only be performed if ductile tearing analyses need to be performed.
7. Engineering stress strain curves are required to construct the material specific FAD.
8. The 5454 FCGR data are from EuroCode 9.

Table 6–3 Preliminary Summary of Fatigue and Fracture Software

PACKAGE	SOURCE	LINEAR ELASTIC OR ELASTIC-PLASTIC	FATIGUE CRACK GROWTH MODELS	FRACTURE CRITERIA	OTHER
The Fracture Mechanic	ASM International	N/A (no longer available)	N/A	N/A	N/A
PCFAD (current version 6A)	Babcock and Wilcox	Elastic-Plastic	N/A Fracture only	• Ductile tearing (uses CTOD or J) • Plastic collapse (FAD - CEGB R-6)	• Considers weld residual stresses • Includes 15 internal crack models
BEASY	Computational Mechanics	Linear elastic	• Paris • NASGRO with retardation	• KIc	Can interface with PATRAN and NASTRAN
NASGRO	NASA	Both	Wide range of crack growth models	• Crack tip opening angle (CTOA),	-----
ENDURE	Engineering Mechanics Research Corp.	Both	• Paris, Forman, Walker, Elberr, Collpriests • cycle-by-cycle, closure	• J, CTOD, K	• 15 built in crack models • can interface with NASTRAN or ANSYS
SmartCrack	Engineering Mechanics Technology	Linear elastic	• Paris, Walker, modified Forman	• KIc, FAD	-----
SmartCrack - Non-linear	Engineering Mechanics Technology	Elastic-plastic	• da/dN vs delta-J	• Tearing instability	-----
NASCRAC	Failure Analysis Associates	Both	• constant and variable amplitude • retardation	• KIc, J	-----
FALANCS	LMS	N/A S-N crack initiation analysis only	N/A	N/A	N/A
MSC/FATIGUE	MacNeal-Schwendler Corp	Linear elastic (with corrections - see next column)	• cycle-by-cycle • Paris corrected for closure and static fracture modes to produce da/DN vs delta K effective which is straight line over entire range	• KIc, plastic collapse • 35 built-in geometries plus ability to determine specific compliance functions	Integrated with MSC/PATRAN, MSC.NASTRAN, ABAQUS, ANSYS, and MARC
RPC III Extended Analysis	MTS Systems Corp	N/A Used only for generation of fatigue and fracture data	N/A	N/A	N/A
nSoft	Ncode International	Linear elastic	• Paris with crack closure	• TBD	-----
R6-Code	Nuclear Electric Ltd	Elastic-Plastic	• TBD	• CEGB R-6 FAD and British Standard PD 6493: 1991	-----
LifEst	SoMat Corp	TBD	• Accommodates mean stress, crack closure, constant and variable loading	• TBD	-----
mTAB FRACTURES	Structural Analysis, Inc.	TBD	• Constant and variable amplitude with retardation	• TBD	-----
pc-CRACK	Structural Integrity Associates	Both	• Paris with crack closure	• TBD	-----
CRACKWISE	The Welding Institute	Elastic Plastic	• TBD	• British Standard PD 6493: 1991	-----
FRACTURE GRAPHICS	Structural Reliability Technology	Linear Eleastic and ductile tearing	• Paris or polynomial • no retardation	• Level 3 FAD • ductile tearing analysis using crack growth resistance curve	Build in geometric models plus can use FEA Crack with library of K solutions

6.8 References

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7. Recommendations for Continued Research

The research conducted for this task has revealed a lack of information that is required for the consistent analysis of fatigue and damage tolerance of marine grade aluminum weldments in high-speed craft. In this sense, the term consistent means data that has been specifically developed to accurately reflect the intended analysis application. In particular, this relates to the loading environments of high-speed craft, the S/N curves for the appropriate aluminum alloys subjected to the marine environment and crack growth rate data for the same alloys reflecting the same environments. Information relating to other applications has been found and is reported herein. It is also reported that the factors of safety required for designs using this information need to be inflated to account for the differences between the intended and actual application of the data used for the analysis. Therefore, this report proposes various efforts to be undertaken to help generate consistent data for high-speed aluminum craft.

Before any of the recommendations put forward by this report are considered, it is imperative that review of the aluminum database that supports the EuroCode 9 be examined. It is apparent that this database contains extensive information regarding fatigue and damage tolerance/crack growth rate information for marine grade aluminum alloys. The applicability of the information in this database needs to be investigated for relevance to the high-speed craft industry. This database may have more applicable information than reported herein but it was not possible to review the database for this task. Discussion with Professor Kosteas conducted as part of the research for this task indicated a willingness to share the information contained within the database. Time and funding were not available for inclusion of this effort for the current report. Part of the effort required to review this database includes definition on the part of Professor Kosteas as to the proprietary nature of the various data included within the database and the organizations that funded specific tests. Time and funding should be made available for the USCG to review and contribute to this database which, through the efforts of Professor Sanders, had its origins here in the United States.(See Section 3.1 of this report). Also, there does appear to be an increasing amount of research underway leaving the impression that maritime organizations, classification societies and owners around the world are aware of the benefits in using aluminum and are starting to deal with some of the fatigue related obstacles that accompany its use.

Most of the data regarding fatigue in aluminum weldments originates from civil engineering applications and does not apply directly to the marine environment. Most of the fatigue tests have been conducted in laboratory air and not in seawater or exposed to the marine environment. The EuroCode 9 does discuss and present a series of factors to be applied for a fatigue analysis of aluminum alloys in environments other than air. These environments include marine and immersion in water and seawater and the factors all reduce the fatigue life compared to "in-air" behavior. The reduction of life is similar to that demonstrated in Figure 3-5 and reported in [7-1].

Regarding fatigue and damage tolerance, the particular areas that will require the development of data to support a consistent fatigue analysis are:

- Environmental loading and the number of loading cycles to be considered for design of High-Speed Craft. Also, the nature of the loading. Is primary loading the only important variable or do secondary loads also form a critical load component? How do ship size and length factor into the balance between primary and secondary loads? The answer to these questions may vary depending upon longitudinal location within the ship and the operational profile of a given vessel.
- Appropriate S/N curves for the structural details and aluminum alloys typically used for high-speed craft. The S/N curves should account for the marine environment and any other corrosive effects specific to a given application.
- Fatigue crack growth rate data for the appropriate aluminum alloys. The crack growth rate is also a function of the environment and tests need to reflect the effects of the marine environment. The crack growth rate tests may be developed in accordance with the fatigue, S/N tests. It may be possible to continue the S/N testing after crack initiation to determine the crack growth rate data. Any such tests need to insure the proper rate of loading is applied during the respective phases of the test. In particular, fatigue tests are often carried out at fairly high frequencies to reduce the time required to obtain high cycle count associated with these tests. The crack growth rate data must be obtained at load cycling frequencies that allow the corrodant of interest time to act upon the cracked detail, i.e., the load application frequency will be decreased to allow proper interaction between the corrodant and the aluminum.

The work outlined above forms the basis for the most critical data needed for the fatigue and damage tolerance analyses. Additional work will also be required to assess other factors. These include the effectiveness of coating systems and cathodic protection systems on the fatigue behavior and crack growth rate in the marine environment.

7.1 Environmental Loading for Fatigue Analysis

If it were possible to develop generic procedures for the loading environment applicable to high-speed craft, then this would be the first objective of future research and development in this area. It is possible that this type of information could be developed at a specific location of the ship and load factors developed to account for transverse and longitudinal distribution throughout the vessel. This information could be applied to specific designs to develop the stress and load cycle histories for the vessel and required for the fatigue analysis.

Alternatively, it may be possible to compile stress histograms through the direct instrumentation of high-speed craft over a period of time. The stress histograms could be related to the load profile experienced by the vessel and from this information design loading profiles could be developed for the design of high-speed craft. This information, although time consuming and expensive to obtain, provides reliable loading profiles for the design of future vessels. Of course, it would be necessary to modify this information to account for vessels to be used on trade routes that differ from those traveled by the instrumented craft.

The environmental load profiles currently available for commercial steel vessels include loads resulting from the payload carried onboard the vessel. The contribution of payload, such as vehicles carried upon passenger ferries, still needs to be investigated to evaluate the total loading environment. In general, the interaction of primary and secondary loads needs to be considered for high-speed craft. Secondary loads may be of particular importance for shorter craft as the stresses due to primary loads tend to be smaller for shorter vessels.

7.2 S/N Curves for Fatigue Analysis

Another area lacking information directly applicable to the marine environment are the S/N curves for the aluminum alloys used in the construction of high-speed craft. The information in Appendix E along with that shown in Figure 3-5 confirms the effect of seawater on the fatigue life of aluminum weldments. This data needs to be developed for the aluminum alloys and structural details typically used in this industry. The first priority would be to develop this information for the 5000 and 6000 series alloys and the details associated with each. It is expected that the long-term fatigue lives for these two families of alloys would approach the same value as discussed earlier in this report. Regardless, separate tests may be required for each series depending on the typical geometry, function and specific environments of the different details and their alloys. Series 6000 alloys are typically used in different environments than the 5000 series, i.e., the 5000 series alloys are the only alloys that are designed to be in contact with the seawater. The 6000 series are typically in air and possibly subject to the marine spray. Data for S/N curves of marine grade aluminum alloys do exist for other environments, typically laboratory air.

It is anticipated that future R&D programs would be developed to investigate structural details in a manner similar to that developed in SSC 318 for steel. The development of such an extensive database would require significant time and funding and it is not expected that this could be developed in the near term or through the efforts of any single task. Rather, it is expected that various R&D efforts over the years would address the more critical and commonly used details to best serve the high-speed industry. It may also be possible that information to this design database could be augmented from R&D conducted for programs not specifically connected to the Coast Guard or SSC. This could include research conducted at universities or other test facilities applicable to the high-speed ferry or high-speed craft industries.

7.3 Crack Growth Rate Data for Aluminum Alloys

It is critical to be able to develop FCGR curves similar to those shown in Figure 3-15 for the alloys and environments applicable to high-speed aluminum craft. Without this information it will not be possible to accurately determine the time to failure of damaged aluminum details. As suggested above, tests may be developed in conjunction with S/N tests or investigation may reveal that separate tests may produce the desired data more efficiently. One benefit of the dedicated crack growth rate tests is control of the experiment. If the tests were run as extensions of the fatigue tests then it is expected that random cracks would develop and require an extra degree of correlation not required with tests that start with existing cracks designed specifically to record the behavior of the sample relative to a known flaw. Once again, it is also imperative that efforts be made with the European Committee for Standardization to investigate the possibility of reviewing the database developed to support the fatigue crack growth rate data in EuroCode 9. The data used in the code does not reflect the marine environment but other information for the fatigue calculations suggests that there may be more data available for other environments. This is further substantiated because the EuroCode 9 is primarily developed for civil engineering applications but reference to other environments is made in various portions of the document.

7.3.1 Loading and Strain Rate Data for Damage Tolerance Analysis

Initially, it was expected that strain rate or loading rate would be an important variable in the damage tolerance analysis of aluminum weldments. Discussion with H. S. Reemsnyder confirmed that aluminum is not sensitive to strain-rate under 10,000 in/in/sec which exceeds any strain-rates to be experienced by high-speed craft and suggests that this variable is not critical for the damage tolerance assessment of marine grade aluminum alloys.

7.4 Fracture Toughness Criteria

It is clear that K_{Ic} is not suitable for the marine grade aluminum alloys, but it is not clear which of the other criteria identified in Section 6.3 should be used. Further literature searches and discussion with industry experts should be conducted to address this issue. Appropriate testing will then be required to generate the necessary data. Preliminary findings suggest that CTOD is the preferred method for elastic-plastic materials due to the simpler measurement techniques but additional research is still needed to confirm this conclusion.

7.5 Fatigue and Fracture Software for Damage Tolerance Analysis

It appears that many of the commercially available packages have the necessary sophistication to perform the elastic-plastic analysis required for the marine grade aluminum alloys considering such factors as crack retardation from periodic overloads. However, it is likely that some of the packages will produce results that may tend toward conservative or non-conservative estimates. This type of information must be evaluated before ship owners are required to perform damage tolerance analysis otherwise the results will not be meaningful. As such, a program is recommended to evaluate the software packages using welded specimens representative of actual structures and fatigue loading spectrums representative of actual service conditions.

7.6 Program to Gather the Necessary Data to Fill Gaps Identified Above

Before any program is addressed for future projects it is recommended that a survey of existing fatigue damage to aluminum structural details in high-speed craft be conducted. This will allow for the collection of a variety of information that should be obtained prior to further research. Resulting from this survey it should be possible to determine what type of information needs to be gathered by future research and the priorities associated with each. Among the information sought by preliminary surveys are:

- The type of details used in the construction of aluminum high-speed craft.
- The aluminum alloys, weld metals and welding procedures used for construction.
- Quality control procedures used during the construction of the vessel and the likelihood of introducing stress concentrations during construction. The quality of welding in aluminum fabrication is extremely important. Aluminum is not as forgiving as steel with regard to weld imperfections and fatigue/damage tolerance behavior. It would be important to know whether increased QA could help relieve some of the fatigue problems currently occurring throughout the high-speed craft industry.
- The type and location, i.e., longitudinal and transverse distribution of fatigue failures grouped according to the type of detail.
- Survey of the details that have experienced none or limited fatigue failures for comparison to those that seem more likely to crack.
- Preliminary calculations to determine whether analytic fatigue predictions would support the results of the surveys, i.e., are the analyses able to predict that some details will be more susceptible to fatigue cracking than others and do the analyses agree with the results of the surveys?

This type of information should be combined with the gaps in the data determined from this task in order to develop R&D tasks that could more fully support the industry. It does not appear that any survey of this type of information exists for aluminum high-speed craft. Typical repair practice for an aluminum boat appears to be very local and immediate, i.e., if a crack develops go repair it and be done with it. It appears that there are very little formal records and certainly no industry-wide database detailing this type of information.

The program to gather the necessary data would include work with one or more testing facilities capable of performing the fatigue tests and the crack growth rate tests. These two series of tests would develop the S/N curves and the da/dN vice ΔK curves typically used for these calculations. Including the appropriate environmental effects would be required of the test facilities. The work would have to include the notch effects to help quantify this aspect of the fatigue design problem and the reduction in life associated with such defects.

As suggested earlier, this work should also be integrated with the program to test the various software packages to determine how well they track with the results developed during the actual tests. An independent agent would be required to assess the quality of the software predictions to insure consistent modeling and use of the capabilities within each software package.

Additional work to help complete the program for gathering the necessary data would center on the loading environments and load histories appropriate to the high-speed craft. It is suggested that the definition of the loading spectra could be developed separately with model test facilities and through the use of loading algorithms such as those discussed for the spectral fatigue analysis in Section 2 of this report. Both procedures would need to account for the effects of speed and length on the loading histories and would have to assess the specific importance of the primary and secondary load components typically associated with ship design. The results of the two procedures would be compared to help determine the inaccuracies associated with load prediction methodologies and associated corrections for future design practice.

Along with the load spectra development would be the investigation of the applicability of using probability distribution functions to represent the long-term distribution of various load components on the high-speed craft.

As a summary, the program to gather the necessary data to fill the gaps is:

1. Conduct survey of existing details used in the construction of high-speed craft. Identify shipyards, boat builders and owners that would be willing to cooperate with the spirit of this program and offer access to their records and/or vessels.
2. Quantify and catalog the details and note fatigue resistant details as well as those with failure histories. Record the material, design and welding procedures used to develop the details.
3. Perform preliminary calculations to determine the capability of existing methodologies for prediction of fatigue failures.

4. Investigate the database compiled for the development of EuroCode 9 and determine its applicability to the current subject matter. If access to this database becomes available then the steps outlined below will probably need to be redefined.
5. Define the fatigue, fracture and crack growth tests that need to be developed. This includes the aluminum alloys that need to be investigated and the corresponding environments and protection or coating, i.e., painting systems. Also included in these tests will be notched specimens to help quantify the effects of such notches and explicit stress concentrations on aluminum in the marine environment.
6. Identify test facilities capable of performing the fatigue and crack growth experiments required for the data collection identified in this report. Investigate their capability to simulate the marine environment during the testing procedures. Also obtain cost estimates to perform the various tests.
7. Assess and compare the various software packages available for the fatigue and damage tolerance analyses. Work with the software vendors to determine the limits of each package's applicability and the willingness of the vendor to contribute to the comparison effort.
8. Identify resources capable of developing the loading histories for the various classes of high-speed craft. Investigate the analytical and testing methodologies available to develop this data. Also need the ability to assess the relative magnitude and phasing of the primary and secondary loading components and account for the length and speed effects of the high-speed craft.
9. Identify resources capable of working with the loading histories and investigating the applicability of probability distribution functions to define long-term loading profiles. This needs to address both primary and secondary loads.
10. Identify new alloys and fabrication processes such as and friction stir welding which are currently undergoing significant study for application to high-speed craft.

7.7 Detail Improvement Techniques

Along with the information presented in this report and the prospect for the development of fatigue design procedures for aluminum high-speed craft it is also recommended that designers of such craft review some of the fundamental techniques currently available to reduce fatigue induced cracking. These include the design philosophies associated with the selection of details inherently more fatigue resistant and utilization of appropriate welding procedures during fabrication. Designers of high-speed aluminum craft should remember the basic guideline that procedures used to improve the fatigue resistance of a steel detail will also work to improve the resistance of an aluminum detail. Minimize stress concentrations and simplify the geometry of details. These are two of the primary causes of fatigue crack initiation.

This section lists a number of references dealing with the concept of improved detailing to help minimize or reduce fatigue problems. By no means is this intended to be an exhaustive collection, merely a number of references to help the designer with this aspect of the design. The SSC reports listed in this section were primarily developed for application to steel vessels. Regardless, the concepts put forward by these reports establish good techniques for the reduction of stress concentration or crack initiation cites. Many of the same philosophies apply to both steel and aluminum and it may benefit the designer to see some of the improved details recommended by previous efforts. As suggested in Appendix A, further information regarding these and other SSC reports may be obtained from their site at www.shipstructure.org.

- SSC 405 “Fatigue Resistant Detail Design Guide for Ship Structures.”
- SSC 400 “Weld Detail Fatigue Life Improvement.”
- SSC 379 “Improved Ship Hull Structural Details Relative to Fatigue.”
- SSC 372 “Maintenance of Marine Structures; A State of the Art Summary.”
- SSC 367 “Fatigue Technology Assessment and Strategies for Fatigue Avoidance in Marine Structures.”
- SSC 318 “Fatigue Characterization of Fabricated Ship Details for Design.”
- Lloyd’s Register “Guidance Notes for the Classification of Special Service Craft” Version 1.0 Design Details.
- ALCOA Report for Project Serial No. S4633 Task 18126 “Considerations for the Structural Detailing of Aluminum Ships” November 1974

In addition to these references, it is also suggested that the designer investigates techniques for fatigue improvement using stress-relieving techniques. These could include thermal treatment, peening, grinding or other applicable techniques. Appropriate maintenance schedules and plans for aluminum vessels also need to be developed and administered.

Together, these practices can lead to the development of more fatigue resistant aluminum weldments in high-speed craft.

7.8 Variation on the Safe-Life Design Philosophy

As discussed earlier in this report the factors of safety typically associated with a Safe-Life design are in the range of 3 to 4. These factors also include the use of conservative loading and S/N data for the fatigue analysis. These factors represent practice developed by the aircraft industry to insure crack-free service lives of details whose failure would result in the catastrophic collapse of the structure. The failure of one of these details could result in the crash of an aircraft and the associated loss of life and property.

While the structural integrity of a ship is certainly critical, it is also recognized that there is significant redundancy within the structure of most ships. It is anticipated that most details that experience fatigue cracking could lose their entire load carrying capacity without threatening the structural integrity of the hull or endangering the vessel, its crew, passengers or payload.

Therefore, this report would like to suggest the possibility of a third design option associated with the Safe-Life and Fail-Safe designs. These structural components would be addressed as Service-Life components and would be part of the structurally redundant envelope that forms the basic structure for so many vessels. A Service –Life component would be defined as:

- Service-Life – An individual structural component that forms a portion of a more complex, redundant structural system such as the hull girder or supporting systems of a ship. The loss of load carrying capacity of the individual component will not threaten the global capacity of the system or its contents.

It is intended that Service-Life components have crack free service lives at least 50% greater than the service life of the vessel.

These components would be typified as longitudinal stiffeners on decks, shell or longitudinal bulkheads, vertical stiffeners on transverse bulkheads and the brackets or details associated with their fabrication.

The reason for developing this classification is to allow for the design of details that have a time to crack initiation that exceeds the service life of the vessel but does not have the same large factor of safety associated with the typical Safe-Life design. This is justified by the consequences of failure associated with the component and the inherent redundancy of ship structural systems. Indeed, there may be details that should be designed in accordance with the strict interpretation of the Safe-Life design and it is not intended that this new classification interfere with those details. It is also intended that the use of the Service–Life classification be developed with appropriately conservative load and S/N data similar to the conservative nature of data used for Safe-Life classification.

7.9 Conclusion

This report has identified numerous gaps in the data that need to be filled before a complete and consistent fatigue analysis can be developed for high-speed aluminum craft. It has also defined techniques that can be used until such time that all this data has been developed. These techniques include the use of aluminum fatigue design procedures developed by DNV and other industries. The conservative application of the information in these codes to account for the marine environment and its particular demands will allow the designers of high-speed craft the flexibility of including the fatigue design problem during the early stages of development. This will change the attitude of fatigue in aluminum weldments to "solution during design" rather than the constant "repair and maintenance" problem throughout the life of the craft.

Market demands and increasing fatigue problems will continue to focus attention on the concerns addressed by this report. Significant and interesting efforts should be undertaken to help support this industry and provide for safer passage of all fare paying customers enjoying the use of these aluminum high-speed vessels while simultaneously reducing the operating expenses of Owners.

7.10 References

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APPENDIX A

1.0 Introduction

This appendix includes numerous references for fatigue and damage tolerance analysis. They have been segregated into categories that roughly address each of these two topics. Obviously, these two subjects are closely related and many of the references cited below contain information regarding both.

During the research for this database a scan of all previous SSC reports was conducted through their web site at www.shipstructure.org. Once inside the home page for this site, two separate searches were performed using the “Search the database by Subject” option. The first search was performed on “fatigue” and the second on “fracture”. A search of the database utilizing “damage tolerance” only hit upon two SSC reports, one of which had been captured by each of the other searches. The SSC database includes numerous reports that were identified by the search with these two keywords. It appeared that only one of these reports dealt with aluminum, SSC 218 “Design Considerations for Aluminum Hull Structures Study of Aluminum Bulk Carrier” and the summary of this report is included in the present database. It appeared that all the other previous SSC reports dealt with steel and it was decided not to include them in the current database. However, the reader is invited to review all these earlier reports to investigate the magnitude of the work done with marine grade steel compared to that developed for aluminum.

It is also suggested that many of these earlier SSC reports contain information regarding good practices for the development of fatigue resistant structures. Although written for application to steel, many of these practices also relate to good detailing for aluminum and will benefit the designer of high-speed aluminum craft.

2.0 Adequacy of the Database for Fatigue Design Criteria

The philosophy behind the development of fatigue design criteria is well established and reflected in many of the references cited in the present database. This philosophy is also reflected in the body of the report. However, as discussed in the report, there are a number of gaps in the data required to perform a consistent fatigue for aluminum weldments in the marine environment. These gaps apply to the loading cycles and magnitudes of secondary loads as well as the primary loads acting on high-speed craft. In addition, it will be necessary to establish phasing between the different types of loads to establish the overall stresses acting in the vessel’s structure. Data on the crack growth rate of marine grade aluminum that is required for the damage tolerance analysis has also not been found for the current project and reflects another area that requires additional test and evaluation.

The database does present a lot of good references for classical fatigue analysis. The database also cites various references that have recently been developed in the area of fatigue of aluminum weldments in the marine environment. It allows the reader to realize that there is a growing recognition of this problem and that various organizations have begun to address it. These organizations include classification societies, educational institutions and private industry.

Before proceeding to the general database developed for this task, a few specific references are listed separately. These references were selected from the rest because of the current, broad-based information they contain. In addition to the design codes cited in this report a number of others are listed below to help the designer recognize other potential sources of information.

General References

Anderson, T. L., Fracture Mechanics, CRC Press 1995.

Barsom, J. M., and Rolfe, S.T. Fracture & Fatigue Control in Structures, Prentice-Hall, Englewood Cliffs, New Jersey, 1987.

Sharp, M. L., Nordmark, G. E., and Menzemer, C. G., Fatigue Design of Aluminum Components & Structures, McGraw-Hill, 1996.

Maritime Design Codes

DNV Fatigue Analysis of High Speed Craft, December, 1999 (Proposal)

DNV Fatigue Assessment of Ship Structures, Classification Notes, No. 30.7, September, 1998.

Lloyd’s Register Rules and Regulations for the Classification of Special Service Craft, Volume 5, Part 7, Hull Construction in Aluminum, 1996.

Lloyd’s Register Guidance Notes for the Classification of Special Service Craft, Version 1.0, Design Details. 1996.

Other Industry Design Codes

Aluminum Design Manual from the Aluminum Association, Washington, D.C., 1994.

EuroCode 9: Design of Aluminum Structures – Part 2: Structures Susceptible to Fatigue, from the European Committee for Standardization, revision 2, 1999.

Manual of Standards and Recommended Practices Section C – Part II, from the Association of American Railroads, Washington, D.C., 1998.

AASHTO Guide Specification for Aluminum Highway Bridges, from the American Association of State Highway Transportation Officials, Washington, D.C., 1991.

BS 8118, from the British Standards Institution, 1992. Section 7 of Part I provides information on fatigue design of aluminum components.

European Recommendations for Aluminum Alloy Structures Fatigue Design, from the European Convention for Constructional Steelworkers (ECCS).

Papers Presented at the 4th International Forum on Aluminum Ships, May 2000

In addition to the papers referenced below, further information may be available on the website of the forum organizers at www.quantic.co.uk. The individual listed with each of the papers was the presenter at the conference. Additional contributors were often cited for complete authorship. Readers may also wish to access the website referenced above to review the titles presented at the 3rd International Forum on Aluminum Ships held in 1998.

Effects of Impact on Aluminum Shell Plating, Professor Bart Boon, Delft University of Technology.

Hull Structural Damage and Repairs, Mr. Oyvind Wilhelmsen, Det Norske Veritas.

Structural Design, Production and Operational Experience of Superseacat Fast Ferries, Mr. Stefano Ferraris, Fincantieri C.N.I Naval Vessels Business Unit.

Aluminum SWATH Pilot Tender for the German Bight, Mr. Victor Beltran, Germanischer Lloyd.

ABS Developments Related to the Requirements for Aluminum Vessels, Mr. Derek Novak, American Bureau of Shipping.

Practical Considerations for Aluminum Ship Construction, Mr. J. Polderman, Lloyd’s Register of Shipping.

Aplications of the ALUSTAR Alloy AA5059 in the Marine Industry, Dr. Desikan Sampath, CORUS RD&T.

Application of Friction Stir Welding for the Manufacture of Aluminum Ferries, Mr. Stephan Kallee, The Welding Institute.

Influence of Welding Conditions and Configurations on Microstructure and Static Properties of AA5383 Weldments, Mr. R. Dif, Pechiney Centre de Recherches de Voreppe.

Proof Strength of Aluminum Alloy 6N01/6005A-T5 Extrusion Butt-Welded Joint, Dr. Kazuyoshi Matsuoka, Toshiaki Iwata Ship Research Institue.

Fatigue Behavior of 5383 Aluminum Alloy Weldments, Mr. R. Dif, Pechiney Centre de Recherches de Voreppe.

Fatigue Life of a Typical Construction Detail for Aluminum High-Speed Ships, Mr. J. Vink, Delft University of Technology.

Application of Pre-Fabricated Friction Stir Welded Panels in Catamaran Building, Mr. Ole Terje Midling, Hydro Aluminum Maritime.

Development of Valu Added Aluminum Extrusions for the Marine Market, Mr. Johannes G nner, CORUS Aluminum Extrusions

Possibilities with Aluminum Extrusions Joined by Friction Stir Welding, Mr. Jan Backlund, Sapa Profiler AB

Fatigue Database

Ref ID 1

Author Tveiten, Bard Wathne

Title Fatigue Assessment of Welded Aluminum Ship Details

Source NTNU, Trondheim

Volume NA

Summary The purpose of this work has been to improve methods for the fatigue strength assessment of welded aluminum ship details. Three main areas were investigated: 1) Verify and improve the design principles and design approaches for the fatigue assessment of welded aluminum ship details. 2) Investigate the affect of local weld treatment as a means for improving the fatigue strength of existing aluminum ship details. 3) Investigate the affect of low stress levels on the prediction of fatigue lives of welded aluminum ship details subjected to variable amplitude loading. Nominal, structural and a notch stresses were used for this evaluation.

Ref ID 2

Author Menzemer, C.C.

Title Fatigue Behavior of Welded Aluminum Structures

Source Alcoa Technical University

Volume NA

Summary A study was undertaken to extend the full scale fatigue database for aluminum weldments, examine differences in behavior of small specimens and large beams, investigate various life prediction techniques, quantify the fracture resistance of typical structural alloys, and propose design rules.

Ref ID 3

Author Paauw, A.J., Fredheim, S., Engh, B.

Title Konstruksjonsdata for dynamisk belastade aluminium sveiseforbindelser

Source Norges Tekniske Naturvitenskaplige Forskningsrad

Volume 82-595-3082-1

Summary As aluminum becomes more important it is highly relevant to find out more about it's fatigue properties. This paper addresses this problem and provides test data for aluminum weldments and alloys such as AlMg2.5, AlMg4.5, AlMgSi1 and AlZn4.5Mg. The tests are conducted on butt-, T-, K- and on reinforced V weldments and these specimens are exposed to air, vapor and seawater.

Ref ID 4

Author Beach, J.E., Johnson, R. E., Kohler, F.S.

Title Fatigue of 5086 Aluminum Weldments

Source Second International Conference on Aluminum Weldments, Munich, F.R.G., 24 to 26 May 1982

Volume NA

Summary Full size welded 5086 aluminum details were fatigue tested to study the geometric effects on fatigue life. They were comprised of an extruded tee fillet welded to a bottom plate (shell plate with longitudinal stiffener) with a centrally located intersecting or passing plate and tee stiffener (transverse bulkhead with vertical stiffener). A total of

46 specimens were laboratory tested under constant amplitude axial loads, variable amplitude axial loads and variable amplitude bending loads.

Ref ID 5

Author Sanders, W.W. and McDowell, K. A.

Title Fatigue Behavior of 5000 Series Aluminum Alloy Weldments in Marine Environment

Source NA

Volume NA

Summary This report presents the results of a study of the fatigue behavior of 5086-H116, 5456-H116 and 5456-H117 aluminum alloys. The weldments are analyzed both in air and submerged in seawater for 30 days before and during the tests (ASTM D1141-52.) The specimens are full thickness plates (3/4 in. and 1 in. thick) axially fatigued under a zero-to-tension stress cycle. Sixty fatigue tests are conducted including thirty-nine tests on specimens in marine environment with the remainder in air. Results are presented in both tabular and graphical form. S-N diagrams show the significant reduction in fatigue life for both plain plates and weldments at all stress levels as a result of submergence in seawater.

Ref ID 6

Author James, M.N., Paterson, A.E. and Sutcliffe, N.

Title Constant and variable amplitude loading of 6261 aluminum alloy -beams with welded

Source Sixth International Conference of Welded Structures

Volume NA

Summary A study of the constant and variable amplitude fatigue performance of 6261-T6 aluminum I-beams with a welded rectangular cover plate is conducted. The test involved over 100 specimens and considered the effect of weld 'quality' (in terms of toe angle, leg length and heat input), and thermal and vibratory stress relief on stress life curves under simple repeated two level block loading.

Ref ID 7

Author Reemsnyder, H. S.

Title Development and Application of Fatigue Data for Structural Steel Weldments.

Source ASTM, Special Technical Publication 648, 1978

Volume N/A

Summary Presents a good overview for many of the basic parameters effecting the fatigue environment. Discussion on testing and test set-up, notches residual stresses and the welding process all provide good information for the introduction to the subject matter. Additional discussion on mean stress and stress range introduce the effects of these variables. Also presents introductory discussion on crack initiation and propagation.

Ref ID 8

Author Wolfgang, F., and Petershagen, H.

Title Detail design of welded ship structures based on hot-spot stresses

Source Germanischer Lloyd, Institute fur Schiffbau der Universitat Hamburg

Volume N/A

Summary Details of ship structures are characterized by a relatively complex geometry, showing a large variety in shape and plate thickness. The paper can assist the designer in determining the stress concentrations at different details.

Ref ID 9

Author Orjasaeter, O.

Title Environmental Behavior of Aluminum and new Design Rules

Source Stahlbau Spezial-Aluminum in Practice/Dimitris Kosteas

Volume memo..!

Summary

Ref ID 10

Author Atzori, B., and Tovo, R.

Title Comparison of fatigue strength in light alloy welded joints

Source Welding International 1998

Volume p. 884-889

Summary This paper deals with the experimental investigation of fatigue strength of AA 5083 and AA 6009 aluminum alloy welded joints. Test pieces consist of 3 mm plates with different welded joints: butt welds and lap fillet joints, both MIG welded. Fatigue tests under constant amplitude loading, as well as tension tests and reverse bend tests were conducted.

Ref ID 11

Author Orjaset, O.

Title Variable amplitude loading of aluminum weldments

Source SINTEF, Norway. Report number: STF20 A90099

Volume NA

Summary A series of butt welds and fillet welds of AlMgSi1 and AlMg4.5Mn, were subjected to tests carried out under two types of random loading spectra. Both air and seawater environments were investigated. The test results were re-calculated using Miner sum of 0.6 and that proved to give a satisfactory safety level.

Ref ID 12

Author Aabo, S., Paauw, A.J., Engh, B., Solli, O.

Title Utmattning av sveiste aluminiumforbindelser

Source SINTEF, Norway. Report number: STF34 A85024

Volume NA

Summary A test series of butt welds and fillet welds of AlMgSi1 and AlMg4.5Mn, were performed. Different weld procedures were compared in relation to fatigue. Also differences in R-value have been investigated subjected to bending loads. The report is written in Norwegian.

Ref ID 13

Author Paauw, A.J., Fredheim, S., Engh, B.

Title Konstruksjonsdata for dynamisk belastade aluminium sveiseforbindelser

Source SINTEF, Norway; Report number: STF34 A83042

Volume NA

Summary A test series of butt welds and fillet welds of AlMgSi1, AlMg4.5Mn, AlMg2.5 and AlZn4.5Mg have been performed in considering dynamic loading. The tests have also been conducted in air, sea water and sea water vapor. The report is written in Norwegian.

Ref ID 14

Author Atzori, B., and Tovo, R.

Title Comparison of fatigue strength in light alloy welded joints

Source Welding International

Volume 1998-12, p.884-889

Summary Experimental investigation of fatigue strength of AA 5083 and AA 6009 welded joints. Butt welds and fillet welds considered. Tension tests and reverse bend tests, taking into account both as-welded bead and the leveling of the weld bead.

Ref ID 15

Author Cottignies, L., Ehrstrom, J. C., Pillet, G., Cialti, F.

Title Fatigue behavior of sub-scaled specimens and full size welded and non-welded AA6082

Source Int. Conference on fatigue of welded components and structures

Volume Seventh International Spring Meeting

Summary Fatigue tests on full size AA6082 profiles in welded and non welded condition. Results compared.

Ref ID 16

Author Partanen, T., and Niemi, E.

Title Hot spot S-N curves based on fatigue tests of small mig welded aluminum specimens

Source IIW, International Institute of Welding

Volume No: XIII-1636-96

Summary Fatigue tests of MIG welded aluminum joints based on the hot spot approach. 87 aluminum specimens included. This reference consist of 4 different papers that have been incorporated and put together into one document.

Ref ID 17

Author Sanders, W.W., and McDowell, K. A.

Title Fatigue behavior of 5000 series aluminum alloy weldments in marine environment

Source Welding Research Council

Volume NA

Summary Tests studying small-specimen fatigue behavior. The weldments are analyzed both in air and in sea-water. Specimens are full thickness plates. Axial tension tests with 39 specimens in the marine environment. R = 0.

Ref ID 18

Author Raynaud, G. M., and Gomiero, Ph.

Title The Potential of 5383 Alloy in Marine Applications

Source Pechiney Rhenalu

Volume NA

Summary Discusses the potential fatigue and other properties of this new alloy recently developed for specific application to the marine environment.

Ref ID 19

Author Wohlfahrt, H., Th Nitschke-Pagel, Zinn, W.

Title Improvement of the fatigue strength of welded joints by post-weld treatment

Source IIW, International Institute of Welding

Volume NA

Summary A comparison between steel and aluminum. Improvement of the materials have been made by, shot penning and/or improvement of the weld seam profile by TIG welding of the last passes or TIG dressing.

Ref ID 20

Author Berge, S.,

Title The Plate Thickness Effect in Fatigue Design – Again.

Source Norwegian Institute of Technology

Volume

Summary Paper discusses the effects of specimen thickness on fatigue behavior and way in which this needs to be modeled using finite element analysis.

Ref ID 21

Author Heggelund, S. E., Tveiten, B. W., and Moan, T.

Title Fatigue analysis of high speed catamarans

Source Norwegian University of Science and Technology

Volume NA

Summary It is shown that fatigue is governing the design of the investigated midship stiffener/web frame connections at the top and bottom of a high speed craft aluminum catamaran. A direct computation method for estimating the fatigue damage on structural details in a high-speed large catamaran is established.

Ref ID 22

Author Heggelung, S. E., Moan, T., and Oma, S.

Title Global structural analysis of large catamarans

Source Norwegian University of Science and Technology

Volume NA

Summary Simple methods for determining global loads and load effects in catamarans are compared with direct calculation procedures, with particular references to a 60 m catamaran.

Ref ID 23

Author Berstad, A. J., Larsen, C. M.

Title Fatigue crack growth in the hull structure of high-speed vessels

Source Norwegian University of Science and Technology

Volume NA

Summary Fatigue crack growth in the hull structure is considered. The procedure takes global as well as local effects into account. A case study on a realistic ship structure is also carried out. Procedure for calculating accumulated damage on a high-speed craft is outlined.

Ref ID 24

Author Mikkola, T. P. J.

Title Hot spot approach for fatigue analysis of ship structures

Source TT Manufacturing Technology, Espoo, Finland

Volume NA

Summary Fatigue analysis of ship structures hot spot stresses is described. Tools developed for effective finite element modeling for hot spot stresses are also discussed.

Ref ID 25

Author Reemsnyder, H. S.

Title Constant Amplitude Fatigue Life Assessment Models

Source SAE Transactions, Volume 91, 1983

Volume

Summary

Ref ID 26

Author Fayard, J. L., Bigonnet, A., Dang Van, K.

Title Fatigue design criterion for welded structures

Source Fatigue Fracture of Engineering Meterials Structures Ltd

Volume Vol. 19, No. 6, pp. 723-729, 1996

Summary This work presents a fatigue design criterion for continuously welded thin sheet structures based on a unique S-N curve. In practice, the geometrical stress state is calculated by means of the finite element method (FEA) using thin shell theory.

Ref ID 27

Author Di, S., Kelly, D., Kastak, D., Chwdhury, M., Goss, P Berkovitz, A.

Title Development of a generic ship model for the study of fatigue in welded aluminum

Source Australian Marine Design, Australia

Volume NA

Summary This paper proposes a general procedure to determine the effects of fatigue cracks in welded aluminum ship structures. A 68 meter aluminum catamaran has been modeled and is capable of determining the overall response of the vessel including the stress intensity factors.

Ref ID 28

Author Hughes, O.

Title Two First Principles Structural Designs Of A Fast Ferry - All-Aluminum and All-Composite

Source Virginia Polytechnical Institute and State University, FAST 97

Volume NA

Summary Presents a strategy for a first structural design using modern computer tools. Example provided for a 100 meter fast monohull ferry. Both aluminum and composite materials are investigated.

Ref ID 29

Author Russel, J. D., Jones, R. L.

Title Developments in Welding Techniques for Aluminium Alloys

Source TWI, The Welding Institute UK, FAST97

Volume NA

Summary The increased use of aluminum alloys in high-speed craft has led to a reappraisal of welding techniques. New methods, such as laser welding are reviewed in this article.

Ref ID 30

Author Ranes, M., Kluken, A. O., Midling, O. T.

Title Fatigue Properties of AS-Welded AA6005 and AA6082 Aluminum Alloys in T1 and T5

Source The 4 Int. Conference on Trends in Welding. Tenn., USA, 5-8 June 1995

Volume NA

Summary An investigation to determine the fatigue properties of as-welded AA6005 and AA6082 aluminum alloys in T1 and T5 temper conditions is presented. Extruded flat bars were welded with MIG, friction stir and plasma key hole techniques.

Ref ID 31

Author Fredriksen, A.

Title Fatigue Aspect of High Speed Craft

Source Det Norske Veritas, FAST 97-Intenational Conference on fast sea transportation

Volume NA

Summary Investigates and reports upon the experience, design philosophy and examples of fatigue on high-speed craft. DNV's in-service experience with respect to hull, waterjet and machinery are presented. Important factors that affect fatigue on high-speed craft are also presented. Also presents and outline of DNV's fatigue procedure for HSC. Fredricksen is the author of the DNV Fatigue Analysis of High Speed Craft listed under the Maritime Design Codes of this appensix.

Ref ID 32

Author Fyfe, A., Hawkins, G. L., Shenoi, R. A., Price, W. G., Temarel, P.,P.J.C.L. Read, Kescmar, J.

Title Fatigue Performance of Welded Aluminum Tee Connections

Source FAST'97- International Conference on fast sea transportation

Volume NA

Summary Addresses fatigue performance of aluminum structures subjected to production variability. The particular focus is on tee connections. Specimens have been produced. Tested in a 45-degree pull-off configuration. This occurs when the bulkhead, floor or web frame is vibrating.

Ref ID 33

Author Niemi, E.

Title Random Loading Behavior of Welded Components

Source Lappeenranta University of Technology, Finland;IIW- International Institute of welding

Volume NA

Summary Random loading fatigue testing and design of welded components are briefly discussed in this paper. Focus is put on the damage caused by the small stress-cycles below the constant amplitude fatigue limit. Damage distributions are calculated and compared, using both the S-N curve approach and fracture mechanics.

Ref ID 34

Author Bannantine, J. A., Comer, J. J., Handrock, J. L.

Title Fundamentals of metal fatigue analysis

Source Prentice Hall Englewood Cliffs, New Jersey 07632

Volume NA

Summary This book presents basic theory and information for fatigue analysis. It addresses the fundamentals of stress-life and strain-life approaches and fracture mechanics. It also addresses notches, variable amplitude and multi-axiai fatigue.

Ref ID 35

Author Niemi, E.

Title Stress determination for fatigue analysis of welded components

Source IIW-International Institute of welded components

Volume IIW-1221-93

Summary This document introduces definitions of the terminology relevant to stress determination for fatigue analysis of welded components. The various stress concentrations, stress categories and fracture mechanics approaches are defined.

Ref ID 36

Author Lyngstad, O. A.

Title Strength reduction in heat affected zone (Technical report)

Source Det Norske Veritas

Volume Rep. No. 96-0251

Summary This report give some background for the allowable static stresses for welds in aluminum according to DNV's present rules. The extent and the severity of the HAZ is reviewed.

Ref ID 37

Author Berge, S.

Title The plate thickness effect in fatigue design-again

Source Norwegian University of Science and Technology

Volume Vol.3, 1990

Summary The scientific background for the plate thickness effect in fatigue of welded joints is reviewed. Effects of post welded treatment and weld profiling are summarized.

Ref ID 38

Author Mikkola, T. P. J.

Title Calculation of the hot spot stresses by thick shell elements for longitudinal stiffener

Source Technical Research Centre of Finland (VTT).

Volume NA

Summary Thick shell elements were used to derive the structural stress concentration at critical locations of welded plate structures. The program HOREX was developed for the stress extrapolation. The P/Fatigue program was applied for the numerical fatigue analysis.

Ref ID 39

Author Blom, A. F.

Title Welded high-strength steel structures

Source North European Engineering and Conference Series

Volume NA

Summary FEM calculations of the stress concentration factor K using shell and solid elements are presented. Two cases are studied: a non-load carrying fillet welded specimen and rectangular tube-to-plate joint.

Ref ID 40

Author Jordan, C. R., and Krumpen, Jr, P.

Title Performance of ship structural details

Source AWS-American Welding Society

Volume Vol. 63

Summary Data on the observed performance of ship structural details are presented and evaluated, with emphasis on design, fabrication, welding, maintenance and service.

Ref ID 41

Author Sharp, M. L., Nordmark, G. E., Menzemer, C. C.

Title Hot-spot fatigue design of aluminum Joints

Source ASCE

Volume NA

Summary This paper shows that the hot-spot design method is applicable for aluminum structures. Included are definitions of general fatigue curves applicable to all types and procedures for establishing the local stress (Hot spot stress) consistent with these curves.

Ref ID 42

Author Menzemer, C. C.

Title Fatigue behavior and design of aluminum structures

Source University of Akron, USA

Volume NA

Summary Basic aspects of the fatigue behavior of aluminum components and structures are discussed, beginning with an examination of material coupons and progressing to full-scale structural systems.

Ref ID 43

Author Menzemer, C. C.

Title Fatigue design of aluminum structures

Source University of Akron, USA

Volume NA

Summary This paper examines some of the items which should be considered in the fatigue design process and the trends in behavior for various types of joint details.

Ref ID 44

Author Menzemer, C. C., Fisher, J. W.

Title Revisions to the Aluminum Association fatigue design specifications

Source Alcoa Technical Center, USA

Volume NA

Summary Discussion of pertinent test and analytical results that necessitated some of the changes are included. Comparisons to other aluminum fatigue design codes are made.

Ref ID 45

Author Pettersen, O., Wiklund, K. M.

Title Det Norske Veritas requirements for direct calculation methods of high speed and light craft

Source Det Norske Veritas

Volume NA

Summary This paper presents background information, and aims at giving an overview of the new rules for direct calculation of loads on a high speed light craft. The different levels of direct calculations applicable for various sizes and types of craft are explained.

Ref ID 46

Author Kosteas, D., Editor

Title Aluminum in practice

Source University of Munich, Germany (Stahlbau)

Volume NA

Summary This reference is a collection of papers and articles about various subjects, all related to aluminum. The topics in this reference include: fatigue, environmental impacts, structural design, buckling and bolted connections, etc. A number of the articles are written in German, the remaining are written in English.

Ref ID 47

Author Petersen, R. I., Agerskov, H., Askegaard, V., Martinez, L. L.

Title Fatigue life of high-strength steel plate elements with welded attachment

Source SSAB, Sweden; technical University of Denmark

Volume NA

Summary The primary purpose of this project is to study the fatigue life of off-shore steel structures under various types of stochastic loading. It also provides a good example of how to use the Palmgren-Miner cumulative damage analysis method.

Ref ID 48

Author Faltinsen, O. M. and Zhao, R.

Title Numerical prediction of ship motions

Source Phil. Trans. Royal Soc., London.

Volume Vol. A334

Summary This is an extension of the strip theory performed in 1970 by Faltinsen, Salvesen and Tuck. The theory will include high forward speed, which it did not do in its original state.

Ref ID 49

Author Salvesen, N., Tuck, E. O., Faltinsen, O. M.

Title Ship motions and sea loads

Source SNAME Transaction

Volume 78: pp 250-287

Summary Formulation of the strip theory that is used to derive sea loads on a ship hull.

Ref ID 50

Author Grant, J. E., Dickerson, P. B., Sharp, M. L., Wolff, N. P., Yanok, G. P.

Title Considerations for the structural detailing of aluminum ships

Source Naval Ship Engineering Center, USA

Volume Serial No. S4633 Task 18126

Summary This report was initiated to improve the program CASDOS to be useable on aluminum as well as steel. The report also provides a lot of background information in aluminum ship design and construction, with all its implications.

Ref ID 51

Author Myklebost, I., Oma, S.

Title Aluminium catamarans; material, design and hull fabrication technology

Source The Third International Forum on Aluminum Ships

Volume NA

Summary This paper describes various aspects of development of new aluminum catamarans. Three main activities are dealt with: Aluminum Material technology, Catamaran design and fabrication technology.

Ref ID 52

Author Bjorneklett, B. I., Frigaard, O., Grong, O., Myhr, O. R., Midling, O. T.

Title Modelling of local melting during friction stir welding of Al-ZN-Mg alloys

Source International Conference on Aluminum Alloys (ICCA-6)

Volume NA

Summary The conditions for local melting at high angle grain boundaries during rapid heating of an Al-Zn-Mg alloy have been modeled. Local melting is discussed in relation too friction stir welding.

Ref ID 53

Author Fostervoll, H.

Title GT-MIG Welding: A new technique for increased productivity in arc welding of aluminum

Source SINTEF, Norway

Volume NA

Summary A new technique for arc welding of aluminum alloys, given the name T-MIG (Gas Tungsten-Metal Inert Gas) welding, is presented and tested. The conventional MIG(Metal Inert Gas) and TIG(Tungsten Inert Gas) processes are combined into one process.

Ref ID 54

Author Frigaard, O., Grong, O., Bjorneklett, B., Midling, O. T.

Title Modeling of the thermal and microstructure fields during friction stir welding of aluminum

Source Hydro Aluminum, Norway

Volume NA

Summary The paper presents a process model for friction stir welding of Al-ZN-Mg alloys. Framework for handling complex problems of this kind is outlined. The results are illustrated in different numerical examples and case studies.

Ref ID 55

Author Hval, M., Sande, V.

Title A new high strength aluminum alloy for marine application

Source Hydro Aluminum Maritime, Raufoss Technology, Norway

Volume NA

Summary This paper presents the background for the development of a new high strength aluminum alloy suitable for marine application and shipbuilding. The alloy that is a variant of AA7108 is an AlZnMgZr- based alloy.

Ref ID 56

Author Midling, O. T., Osterkamp, L. D., Bersaas, J.

Title Friction stir welding aluminum-process and applications

Source 7:th Int. Conference On Joints in aluminum (INALCO'98)

Volume NA

Summary This paper addresses the most recent advances in process technology, basic understanding of the process itself and new applications. Corrosion behavior of joints welded within the processing window is evaluated.

Ref ID 57

Author Frigaard, O., Bjorneklett, B., Grong, O., Midling, O. T.

Title Process modeling applied to friction stir welding of Al-Mg-Si alloys

Source 6:th Int. Conference On Aluminum Alloys (ICAA-6)

Volume NA

Summary In the present investigation a 3-D numerical heat flow model for friction stir welding of aluminum alloys has been developed.

Ref ID 58

Author Myhr, O. R., Klokkehaug, S., Fjaer, H. J., Grong, O., Kluken, A. O.

Title Modeling of microstructure evolution and residual stresses in processing and welding of

Source 5:th Int. Conference On trends in Welding Research, 1998

Volume NA

Summary This paper illustrates the applications of process modeling for prediction of microstructure evolution and residual stresses in welding of age hardened aluminum alloys. Three components: heat flow, microstructure and mechanical models are all considered.

Ref ID 59

Author Mousavi, M. G., Cross, C. E., Grong, O., Hval, M.

Title Controlling weld metal dilution for optimized weld performance in aluminum

Source Hydro Aluminum, Norwegian University of Science and technology

Volume NA

Summary It is demonstrated how the current trend towards high speed, narrow groove welding, and the corresponding shift towards high base metal dilution may result in decreased weldability for 6XXX and 7XXX aluminum alloys.

Ref ID 60

Author Myhr, O. R., Klokkehaug, S., Fjaer, H. J., Grong, O., Kluken, A. O.

Title Process model for welding of Al-Mg-Si extrusions

Source The Institute of Materials

Volume

Summary Model based alloy design and optimization of welded conditions for Al-Mg-Si extrusions, with particular emphasis on how changes in the base metal chemical composition and thermal history affect the heat affected zone microstructure evolution.

Ref ID 61

Author Menzemer, C. C., Srivatsan, T. S.

Title The effect on environment on fatigue crack growth behavior of aluminum alloy 5456

Source Material Science and Engineering: An Int. Journal

Volume

Summary The effect of laboratory air, water vapor and oxygen on fatigue crack propagation behavior of aluminum alloy 5456 have been investigated over a range of growth rates spanning five orders of magnitude.

Ref ID 62

Author Newman, Jr, J. C.

Title Prediction of crack growth under variable-amplitude loading in thin-sheet 2024-T3

Source NASA Langley Research Center, USA

Volume

Summary This paper is concerned with the application of a "plasticity-induced" crack closure model to study fatigue crack growth under various load histories on thin-sheet 2024-T3 aluminum alloys.

Ref ID 63

Author James, M. N., Paterson, A. E.

Title Fatigue performance of 6261-T6 aluminium alloy - constant and variable amplitude

Source In. Journal of Fatigue

Volume Vol. 19, pp S109-S118

Summary This work is a summary of the results to examine the fatigue strength of extruded 6261-T6 I-beams with centrally located, welded cover plates under constant and variable amplitude loading.

Ref ID 64

Author James, M. N., Paterson, A. E., Sutcliffe, N.

Title Constant and variable amplitude loading of 6261 aluminum alloy I-beams with welded

Source In. Journal of Fatigue

Volume Vol. 19, pp125-133

Summary A study investigating the constant amplitude and variable amplitude fatigue performance of 6261-T6 aluminum I-beams with a rectangular cover plate is reported.

Ref ID 65

Author Bretschneider, C. L.

Title Review of practical methods for observing and forecasting ocean waves by means of

Source Trans. American Geophysical Union

Volume April, 1957

Summary Together with information from Ref ID 66 Bretschneider derives his wave spectra that are different from Pierson-Moskowitz spectrum. It can be used with finite fetch which is more suited to the high-speed craft.

Ref ID 66

Author Bretschneider, C. L.

Title The generation and decay of wind waves in deep water

Source Trans. American Geophysical Union

Volume Vol. 37, 1952

Summary See Ref. 65.

Ref ID 67

Author Pierson, W. J., Moskowitz, L.

Title A proposed spectral form for fully developed wind seas based on the similarity theory of

Source Journal of Geophysical Research

Volume Vol. 69, 1964

Summary In this report Pierson and Moskowitz formulate their wave spectra that is based on real time measurements and addresses fully developed sea states.

Ref ID 68

Author Yee, R. D., Malik, L., Basu, R., Kirkhope, K.

Title Guide to damage tolerance analysis of marine structures

Source National Technical Info. Service, US Dept. of Commerce

Volume SSC-402

Summary This guide is intended to provide naval architects and structural engineers with detail guidance on the application of damage tolerance analysis to ship structures.

Ref ID 69

Author Conference proceedings

Title Short course on fatigue and fracture analysis of ship structures

Source Fleet Technology Limited (FLT), Kanata, Ontario, Canada

Volume August 18-21, 1998, Troy, Michigan

Summary The course provide basic information in a number of ship structure related topics, such as material properties, fatigue, fracture mechanics, loads on ships, stress analysis, residual stresses, environmental effects etc.

Ref ID 70

Author Stambaugh, K. A., Lawrence, F., Dimitriakis, S.

Title Improved ship hull structural details relative to fatigue

Source National Technical Information Service. US Dept. of Commerce

Volume Report No. SSC-379

Summary This report presents a fatigue design strategy for welded ship structural details. The fatigue design is based on cumulative damage theory using nominal stress. Guidance is provided showing designers how to improve the fatigue life of details.

Ref ID 71

Author Kirkhope, K. J., Bell, R., Caron, L., Basu, R. I.

Title Weld detail fatigue life improvement techniques

Source National Technical Information Service. US Dept. of Commerce

Volume Report No. SSC-400

Summary Key elements of this project were to compile available data on fatigue life improvements techniques, assess the feasibility and practicality for their application to ship details, identify gaps in the technology, and finally to recommend design, construction and repair requirements. Steel is the material considered, but some methods might be applicable on alternative materials.

Ref ID 72

Author American Society for Materials

Title Metals Handbook: Nondestructive inspection and quality control, 8th Edition

Source American Society for Metals

Volume Vol. 11

Summary This volume covers a variety of testing and inspection procedures, such as hardness testing, ultrasonic inspection, leak testing, radiographic testing. It also covers quality inspections, e.g. weldments, forgings, castings, adhesive-bonded joints.

Ref ID 73

Author Reemsnyder, H. S.

Title Stress Analysis

Source SAE Transactions, Volume 91, 1983

Volume

Summary

Ref ID 74

Author US Navy Sea Systems Command

Title Superstructure cracking repair.

Source Ingalls Shipbuilding, Inc.

Volume

Summary This is a manual on guideline for repairs of cracks in the CG 47 superstructure.

Ref ID 75

Author American Bureau of Shipping

Title Guide for Building and Classing High-Speed Craft, (Feb. 1997)

Source American Bureau of Shipping

Volume

Summary This guide has been prepared to update the requirements of the ABS "Guide for Building and Classing High-Speed Craft October 1990". The guide specifies machinery requirements and hull construction requirements based on steel, aluminum alloys and fiber reinforced plastics (FRP). It does not address fatigue.

Ref ID 76

Author Fuchs, H. O., Stephens, R.I.

Title Metal fatigue in engineering

Source John Wiley & Sons, New York

Volume

Summary This textbook provides general information about fatigue, fracture mechanics, design methods and details, but mostly for steel applications.

Ref ID 77

Author Ferdinand, P. B., Johnston, Jr., E. R.

Title Mechanics of Materials

Source McGraw-Hill, New York

Volume

Summary Textbook about general strength assessment specifically addressing basic beam theory.

Author Altenburg, C. J., and Scott, R. J.

Title SSC 218 Design Considerations for Aluminum Hull Structures Study of Aluminum Bulk Carriers.

Source Ship Structure Committee

Volume **SSC 218**

Summary The fabrication of a large aluminum hull with state of the art materials and construction techniques is shown to be technically feasible. Present 5000 series alloys have adequate properties, though additional research is required, particularly into fatigue characteristics. Experience to date with existing aluminum ships has been good, though instances of cracking at welds and corrosion have been noted. Criteria for the design of the aluminum hull structure are presented and justified. Methods of fire protection and system/equipment installation are evaluated, and operational characteristics of an aluminum bulk carrier are reviewed. The designs of a large aluminum bulk carrier and an equivalent steel ship are presented and compared. The aluminum ship's structure weighs 43 per cent less than the steel ship, and its hull is about 50 per cent more flexible. Cargo deadweight is increased 7-1/2 per cent. Cost studies indicate that for the same return on investment the required freight rate of the aluminum bulk carrier is higher than the equivalent steel ship, for all levels of procurement, assumed hull life, or voyage length considered. Areas for further research are presented and further investigations of large aluminum ships are proposed.

Damage Database

Ref ID 1
Author K.
Title Revisions to the Aluminum Association Fatigue Design Specifications
Source FAST '97 Papers
Volume p. 11
Summary 1) 1985 Aluminum Association aluminum fatigue design rules used S/N curves approximated by step curves - used data from tests and the literature in database developed at Iowa State - forerunner of the ALFABET database developed and maintained at Technical University of Munich

2) 1994 design rules use straight line S/N curves based on numerous tests by Alcoa and others from 1892-1986 on 5 details - lower bound curves were established to provide 95% confidence limit for 97.7% probability of failure - the design curves were set at two standard deviations from the mean

Ref ID 2
Author K.
Title A Comparison of Design Codes for Aluminum Structures
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 25
Summary

Ref ID 3
Author J.
Title Fatigue Behavior and Design of Welded Aluminum Hollow Shapes
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 197
Summary

Ref ID 4
Author K.
Title Safety and Reliability in Aluminum Design
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 1
Summary

Ref ID 5
Author J.
Title Design Review of an Aluminum Alloy Railway Coach
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 37
Summary Fatigue assessment using BS8118 and detailed evaluation of hot spots

Ref ID 6
Author K.
Title Fatigue of Aluminum Stiffener-Girder Connection
Source FAST '97 Papers
Volume p. 637
Summary See attached

Ref ID 7
Author
Title Development of a Generic Ship Model for the Study of Fatigue in Welded Aluminum Catamaran
Source FAST '97 Papers
Volume p. 629
Summary 1) S/N response of many welded joints in catamaran structure is imprecise and largely unreliable function of weld type geometry and weld technique

2) further work includes generating the wave loading based on a selected route and sea-state, including slamming and other dynamic effects

Ref ID 8
Author
Title Fatigue Aspects of High Speed Craft
Source FAST '97 Papers
Volume p. 217
Summary See attached

Ref ID 9
Author
Title Fatigue Performance of Welded Aluminum Tee Connections
Source FAST '97 Papers
Volume p. 209
Summary 1) S/N for 5083 for fillet welds of varying size and gap - results show different weld toe HAZ properties from differences in welding voltage and amperage have more effect than the weld size and gaps in these tests

2) the "hot-spot" using peak stresses from FEMA at the crack initiation site is preferable to the use of nominal stresses because it is not always possible to define the nominal stress at a given detail because of the complexities of most designs, suitable fatigue tests results are not always available for each structural detail

Ref ID 10
Author
Title Fatigue Crack Growth in the Hull Structure of High Speed Vessels
Source FAST '97 Papers
Volume p. 255
Summary 1) crack growth is governed by time varying local stresses in the detail where the crack is developing - these stresses are influenced by global moments in the ship hull from waves and ship motions, and also variations of the local pressure on the plates near the actual detail

2) slamming loads which may increase local pressure, whipping, and springing response have not been taken into account - for some sea states these effects may be of great importance and should be considered in a more refined analysis

Ref ID 11
Author
Title Guide to Damage Tolerance Analysis of Marine Structures
Source Ship Structure Committee SSC-402, August 97.
Volume
Summary 1) fracture toughness data are required at higher loading rate simulating that from wave impacts (see 3.5.2)

2) key properties are yield strength, tensile strength, fracture toughness (3.5)

3) gives fracture toughness lower bound values for several steels without Charpy impact data, from conversion of Charpy impact data, and from conversion of crack tip opening displacement (CTOD) data

4) ship structural members are usually subject to intermediate strain rates of 5x10-3 in/in/s which is higher than the quasi-static loading rate of normal fracture toughness tests (3.5.2)

5) gives some crack growth rate data for steel in air and seawater (4.4)

Ref ID 12
Author
Title Hydrodynamic Impact on Displacement Ship Hulls

Source Ship Structure Committee SSC-402, August 97.
Volume
Summary 1) transient hydrodynamic impulsive loads (HIL) from slammings, wave slap, and frontal impact effects must be combined with those from slow varying wave induced loads

2) impact loads involve extreme pressure acting over very short time periods relative to the natural rate of response of the structure

3) structure response to the HIL is high transient and non-linear - damage varies from deformed shell plating, to distorted and buckled longitudinals and frames, to fatigue cracking - most damage is sustained by tertiary structure at location of impact, but secondary structure can be damaged by direct action of impulse loads or by high frequency forces - primary structure is usually only affected by whipping forces

4) under slamming during forward bottom impact, duration is milliseconds and excites dynamic response of local structure and hull girder

5) impact loads of high performance vehicles are basically of same nature as on conventional ships but HPV's have special features: usually aluminum which generally has lower ratio of allowable fatigue stress to yield strength than steel, and high hydrodynamic loads due to high speed and unconventional geometry of means of support cause unusual load distributions (3.2.4.1)

Ref ID 13
Author
Title Fatigue and Damage Tolerance Design Philosophies: an Aerospace Perspective with Applications to High
Source SNAME FAST 99 - 5th Int. Conf. On Fast Sea Transportation,
Volume
Summary 1) starting point for damage tolerance analysis is to assume a defect is present - the major question is what size defect to use

2) need Structural Integrity Program (SIP) to address cracks found during inspection - this program will include inspection intervals, inspection methods, etc

3) should also include Corrosion Prevention and Control Program (CPCP)

4) typically weldment fracture toughness is less than the base metal - weld repair can further decrease fracture toughness by 20-30%

Ref ID 14
Author
Title The Evolution of Structures for Fast Craft and Ships

Source 15th Fast Ferry International Conference, 2/16-17/99, Hynes
Volume
Summary See attached

Ref ID 15
Author
Title Physical, Mechanical Properties and Corrosion Resistance of Alustar Alloy Rolled Materials
Source 15th Fast Ferry International Conference, 2/16-17/99, Hynes
Volume
Summary Alustar is modified 5083 with improved as welded strength, ductility, corrosion resistance, fatigue strength, and toughness (as measured by notched tensile and impact tests)

Ref ID 16
Author
Title Developments in Welding Techniques for Aluminum Alloys
Source FAST '97 Papers
Volume p. 559
Summary

Ref ID 17
Author
Title Two First Principles Structural Designs of a Fast Ferry - All-Aluminum and All-Composite
Source FAST '97 Papers
Volume p. 91
Summary analysis is performed per DNV Rules for High Speed and Light Craft

Ref ID 18
Author
Title Data Basis for Fracture Mechanics Analysis of Aluminum Weldments
Source Source and date unknown
Volume
Summary 1) tests on 7020 (AlZn4, 5Mg1), 5083 (AlMg4, 5Mn), and 6082 (AlMgSi1) base metal, HAZ, and weld metals 5183 (S-AlMg4, Mn), 5556 (S-AlMg5), and 4043 (S-AlSi5) - welding parameters are given in references 1 and 2 of this report

2) fracture toughness per ASTM E399: no valid results because of high toughness

3) R-curves per ASTM E589: no valid results because of extended

plasticity - this methods is based on linear-elastic analysis

4) CTOD: calculated Kc values are 40% above KJc from J-integral

5) J-Integral per ASTM E813: 1149-2161 N/mm 3/2 - a thickness dependency is present up to 20mm

6) fracture toughness and mechanical properties are reduced in the HAZ but less so for fracture toughness: unstable crack will not occur with these alloys - elastic KIc at the onset of stable crack growth and KJc values should be used as lower bounds of fracture toughness

7) FCGR: three regions of different microscopic features - Data are only presented for AlMg4, 5Mn (5083) - behavior of the other alloys is similar - use of K effective values eliminates effects of R ratio - propose to use the effective crack growth behavior as a lower bound for computations - must use polynomial FCGR curve because straight line Paris curve not valid for entire delta K range

Ref ID 19
Author
Title Damage Tolerant Design Handbook
Source WL-TR-94-4052 Compiled bv University of Dayton Research
Volume
Summary fatigue and fracture properties for 2XXX, 6000, 7000 series aluminum alloys

Ref ID 20
Author
Title A Guide for the Use of Aluminum Alloys in Naval Ship Design and Construction Volume I: Material Characteristics,
Source David Taylor Naval Ship Research and Development
Volume
Summary S/N curves for base metal, welded, and notched 5083-H113, 5086-H32, 5456-H321 - 5083-H113 in seawater spray

Ref ID 21
Author
Title A Guide for the Use of Aluminum Alloys in Naval Ship Design and Construction Volume II: Design for Shipbuilding
Source David Taylor Naval Ship Research and Development
Volume
Summary Probability based S/N curves for as-welded 5456 and 5086 butt welds in air

for R=-1

Ref ID 22
Author
Title A Guide for the Use of Aluminum Alloys in Naval Ship Design and Construction Volume III: Fabrication for Shipbuilding
Source David Taylor Naval Ship Research and Development
Volume
Summary

Ref ID 23
Author
Title A Guide for the Use of Aluminum Alloys in Naval Ship Design and Construction Volume IV: Maintenance and Repair
Source David Taylor Naval Ship Research and Development
Volume
Summary

Ref ID 24
Author
Title Methods for Assessing the Significance of Weld Defects and Repair Welding on the Fatigue Performance of Thin 5000
Source David Taylor Naval Ship Research and Development
Volume
Summary 1) S/N curves and initial stress intensity vs cycles to failure for 5083 and 5456-H116 with LOP, LOF, and porosity defects - the fatigue life depend on stress intensity calculated from initial defect width, maximum stress, and plate thickness

2) S/N curve for repair welded 5456-H116 - fatigue life of weld repairs with embedded repair welds is less than original sound welds and can be less than original welds containing the above defects - this reduction appears primarily to result from weld residual stresses and geometric discontinuities

Ref ID 25
Author
Title European Research on Fatigue of Aluminum Structures
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 53
Summary Evaluation of welded, adhesive-bonded, and friction-grip bolted joints

Ref ID 26
Author
Title European Research on Fatigue of Aluminum Structures
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 65
Summary Evaluation of welded and adhesive-bonded joints

Ref ID 27
Author
Title Scale Effect in Fatigue of Fillet Welded Aluminum Alloys
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 77
Summary Use of TWI Fatigue Wise software to predict S/N curves and initial flaw size using FCGR data

Ref ID 28
Author
Title Fatigue Strength of Longitudinally Welded Aluminum Alloy Structures
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 95
Summary

Ref ID 29
Author
Title Preliminary Fatigue Comparison of Transverse Butt Welded Joints to Three Row Flush Riveted Aircraft Lap Joints
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 267
Summary
1) Welded 5456-H116 vs riveted 2024-T3 for aircraft structure

2) good corrosion resistance of 5456 might allow it to be used

Ref ID 30
Author
Title Application of Fracture Mechanics to the Assessment of Aluminum Weldments
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 423
Summary
1) 6082-0 and T6

2) 5083 annealed

Ref ID 31
Author
Title Elements, Background and Evaluations on Fatigue and Fracture Behavior of Aluminum Components
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 463
Summary 1) Addresses 1992 European Recommendations for Aluminum Alloy Structures - Fatigue Design (ERAAS)

2) S/N curves based on full scale component tests most to 2x106 cycles

3) 5083 base metal S/N design curve and welded S/N design curves

Ref ID 32
Author
Title Correlating Design and Quality Classifications of Welded Structural Details in Fatigue
Source Proceedings, Sixth International Conference on Aluminum
Volume p. 487
Summary 1) BS 8118 provides only correlation between strength classification and quality criteria

2) Analytical prediction of S/N behavior using FCGR curves from Graf (ref. [33])

3) Results of this study will contribute to Eurocode 9: Design of Aluminum Structures

Ref ID 33
Author
Title Fracture Mechanics Data and Procedures for the Calculation of Fatigue Behavior of Welded Aluminum Joints
Source Report of the Department of Constructional Engineering,
Volume
Summary (need to review)

Ref ID 34
Author
Title Selecting Aluminum Alloys to Resist Failure by Fracture Mechanisms
Source Engineering Fracture Mechanics, Pergamon Press,

Volume Vol. 12, pp. 407-441
Summary Summary of fatigue and fracture data for 2XXX, 3XXX, 5XXX, 6XXX, and 7XXX alloys

Ref ID 35
Author
Title Effect of Weld Discontinuities on Fatigue of Aluminum Butt Joints
Source Welding Research Supplement, June 1987.
Volume p. 162s
Summary 1) the levels of incomplete penetration and gross porosity present in these specimens did not affect the fatigue strength of reinforcement intact welds

2) removing the weld reinforcement doubles the lives of sound welds, but greatly reduced the lives of transverse specimens containing incomplete penetration

3) high residual stresses, such as would be found in actual structures, had more effect on longitudinal joints than on transverse joints

4) repaired welds had lives only 40% to 75% of sound welds, unless the repairs were suitably ground or peened

5) for relatively short fatigue cracks, insertion of interference bolts in holes at the ends of the cracks produced lives equivalent to those of sound welds - stoppage holes, even expanded holes, did not delay propagation much

6) reinforcement intact repair welding of fatigue cracks was more effective for transverse joints than for longitudinal joints - bonded or welded patches were as effective as repair welds for transverse joints.

Ref ID 36
Author
Title Effects of Flowing Natural Seawater and Electrochemical Potential on Fatigue-Crack Growth in Several Hihg-Strength
Source Naval Research Lab Report 8042, 8/30/76
Volume
Summary

Ref ID 37
Author
Title Fatigue And Corrosion-Fatigue Crack Propagation in Intermediate-Strength Aluminum Alloys
Source ASME Paper 73, MAT-N 1973
Volume
Summary

APPENDIX B

Excerpts from

Aluminum Design Manual from the Aluminum Association

1.0 Copyright Release and Limitations on Liability

The information contained in this appendix is reprinted from the Aluminum Design Manual published by the Aluminum Association. The Ship Structure Committee has obtained the written permission of the Aluminum Association to use this information in accordance with the guidance for preparation of SSC reports. Users of the information contained in this appendix assume all responsibilities and liabilities associated with its use unless other contractual arrangements are made directly with the Aluminum Association.

2.0 Introduction

This first portion of the Aluminum Design Manual reprinted herein comes from Part IA, Specifications for Aluminum Structures – Allowable Stress Design. The same information is contained in Part IB of the design code but is not repeated herein. Part IB of the rules is entitled Specifications for Aluminum Structures – Building Load and Resistance Factor Design. It contains the exact same formulation of the fatigue design procedure as Part IA except for elimination of discussion regarding the 1/3 increase in allowable stress values as provided in Section 2.3.2 of the design code.

The portions of the design code concerning fatigue contained in Part IIA and Part III are presented after the information from Part IA. Part IIA is entitled "Commentary on Specifications for Aluminum Structures – Allowable Stress Design." Part III is entitled "Design Guide."

From Part IA:

4.8 Fatigue

Welded details, mechanically fastened joints and base material of aluminum alloys subjected to repeated fluctuations of stress shall meet all the static requirements of this specification as well as the fatigue requirements of this section. Fatigue design of castings and associated details shall be made by testing in accordance with Section 8.

There shall be no 1/3 increase in allowable stress values determined in this section as provided by Section 2.3.2.

Categories of details for fatigue design parameters shall be chosen from Figure 4.8-1 and Table 4.8-1.

The maximum and minimum stresses used to calculate the stress range are nominal stresses determined by standard elastic methods. Stresses perpendicular to the expected plane of cracking shall be used.

4.8.1 Constant Amplitude Loading

For constant amplitude loading

$$S_{ra} \leq S_{rd} \qquad \textit{(Eq. 4.8.1-1)}$$

where

S_{ra} = applied stress range, the algebraic difference between the minimum and maximum calculated stress in the member or detail

S_{rd} = the allowable stress range

S_{rd} = $AN^{-1/m}$ *(Eq. 4.8.1-2)*

A, m = constants from Table 4.8.1-1 and shown in Fig. 4.8.1-1

N = the number of cycles to failure

If the applied stress range, S_{ra}, is less than the constant amplitude fatigue limit as given in Table 4.8.1-1, then no further fatigue consideration shall be needed. The allowable stress range, S_{rd} shall not be less than the value from Eq. 4.8.1-2 when N = 5 x 10^6 cycles and shall not be greater than the value from Eq. 4.8.1-2 when $N = 10^5$ cycles.

4.8.2 Variable Amplitude Loading

If the maximum stress range in the spectrum is less than the fatigue limit, then no further fatigue assessment shall be needed.

For variable amplitude loading:

$$S_{re} \leq S_{rd} \qquad \textit{(Eq. 4.8.2-1)}$$

where

S_{ra} = equivalent stress range

$$S_{re} = \left| \sum_{i=1}^{N_S} \alpha_I S_{ri}^m \right|^{\frac{1}{m}} \qquad \textit{(Eq. 4.8.2-2)}$$

S_{rd} = the allowable stress range

S_{rd} = $AN^{-1\backslash m}$ *(Eq. 4.8.2-3)*

α_i = number of cycles in the spectrum of the ith stress range divided by the total number of cycles

S_{ri} = the ith stress range in the spectrum

A, m = constants from Table 4.8.1-1 and shown in Fig. 4.8.1-1

N_s = number of stress ranges in the spectrum

N = the number of cycles to failure

The allowable stress range S_{rd} shall not be greater than the value from Eq. 4.8.2-3 when $N = 10^5$ cycles.

Table 4.8-1
STRESS
CATEGORY

General Condition	Detail	Detail Category[(1)]	Fatigue Design Details[(2)]
Plain Material	Base metal with rolled or cleaned surfaces.	A	1,2
Built up Members	Base metal and weld metal in members, without attachments, built-up of plates or shapes connected by continuous full- or partial-penetration groove welds or continuous fillet welds parallel to the direction of applied stress.	B	3,4,5
	Calculated flexural stress, f_b, in base metal at toe of welds on girder webs or flanges adjacent to welded transverse stiffeners.	C	6,21
	Base metal at end of partial-length welded cover plates having square or tapered ends, with or without welds across the ends.	E	5
Mechanically Fastened	Base metal at net section of mechanically fastened joints which do not induce out-of-plane bending in connected material, where		
	Stress ratio, the ratio of minimum stress to maximum stress, SR is:**		
	SR < 0	C	7
	0 ≤ SR < 0.5	D	7
	0.5 ≤ SR	E	7
	Base metal at net section of mechanically fastened joints which induce out-of-plane bending in connected material.	E	8
Fillet Welded Connections	Base metal at intermittent fillet welds.	E	
	Base metal at junction of axially loaded members with fillet welded end connections. Welds shall be disposed about the axis of the members so as to balance weld stresses.	E	15,17
	Weld metal of continuous or intermittent longitudinal or transverse fillet welds.	F	5,15,18
Groove Welds	Base metal and weld metal at full-penetration groove welded splices of parts of similar cross section ground flush, with grinding in the direction of applied stress and with weld soundness established by nondestructive inspection.	B	9
	Base metal and weld metal at full-penetration groove welded splices at transitions in width or thickness, with welds ground to provide slopes no steeper than 1 to 2.5, with grinding in the direction of applied stress, and with weld soundness established by nondestructive inspection.	B	11,12
	Base metal and weld metal at full-penetration groove welded splices, with or without transitions having slopes no greater than 1 to 2.5, when reinforcement is not removed and/or weld soundness is not established by nondestructive inspection.	C	9,10,11,12

General Condition	Detail	Detail Category[1]	Fatigue Design Details[2]
Attachments	Base metal detail of any length attached by groove welds subject to transverse and/or longitudinal loading, when the detail embodies a transition radius, the radius of an attachment of the weld detail, R, not less than 2 in. (50 mm) and with the weld termination ground smooth:		
	R ≥ 24 in. (610 mm)	B	13
	24 in. > R ≥ 6 in. (150 mm)	C	13
	6 in. > R ≥ 2 in. (50 mm)	D	13
	Base metal at detail attached by groove welds or fillet welds subject to longitudinal loading, with transition radius, if any, less than 2 in. (50 mm):		
	2 in. (50 mm) ≤ a ≤ 12b or 4 in. (100mm)	D	14
	a > 12b or 4 in. (100mm) where	E	14,19,20
	a = detail dimension parallel to the direction of stress b = detail dimension normal to the direction of stress and the surface of the base metal		
	Base metal at a detail of any length attached by fillet welds or partial-penetration groove welds in the direction parallel to the stress, when the detail embodies a transition radius, R, not less than 2 in. (50 mm) and weld termination ground smooth:		
	R ≥ 24 in. (610 mm)	B	16
	24 in. (610 mm) > R ≥. 6 in. (150 mm)	C	16
	6 in. (150 mm) > R ≥ 2 in. (50 mm)	D	16
	Base metal at a detail attached by groove welds or fillet welds, where the detail dimension parallel to the direction of stress, a, is less than 2 in. (50 mm)	C	19

(1) See Table 4.8.1-1. All stresses are T and Rev., where "T" signifies range in tensile stress only; "Rev." signifies a range involving reversal of tensile or compressive stress; except Category F where stress range is in shear including shear stress reversal.

(2) See Fig. 4.8-1. These examples are provided as guidelines and are not intended to exclude other reasonably similar situations.

(**) Tensile stresses are considered to be positive and compressive stresses are considered to be negative.

Figure 4.8-1
FATIGUE DESIGN DETAILS

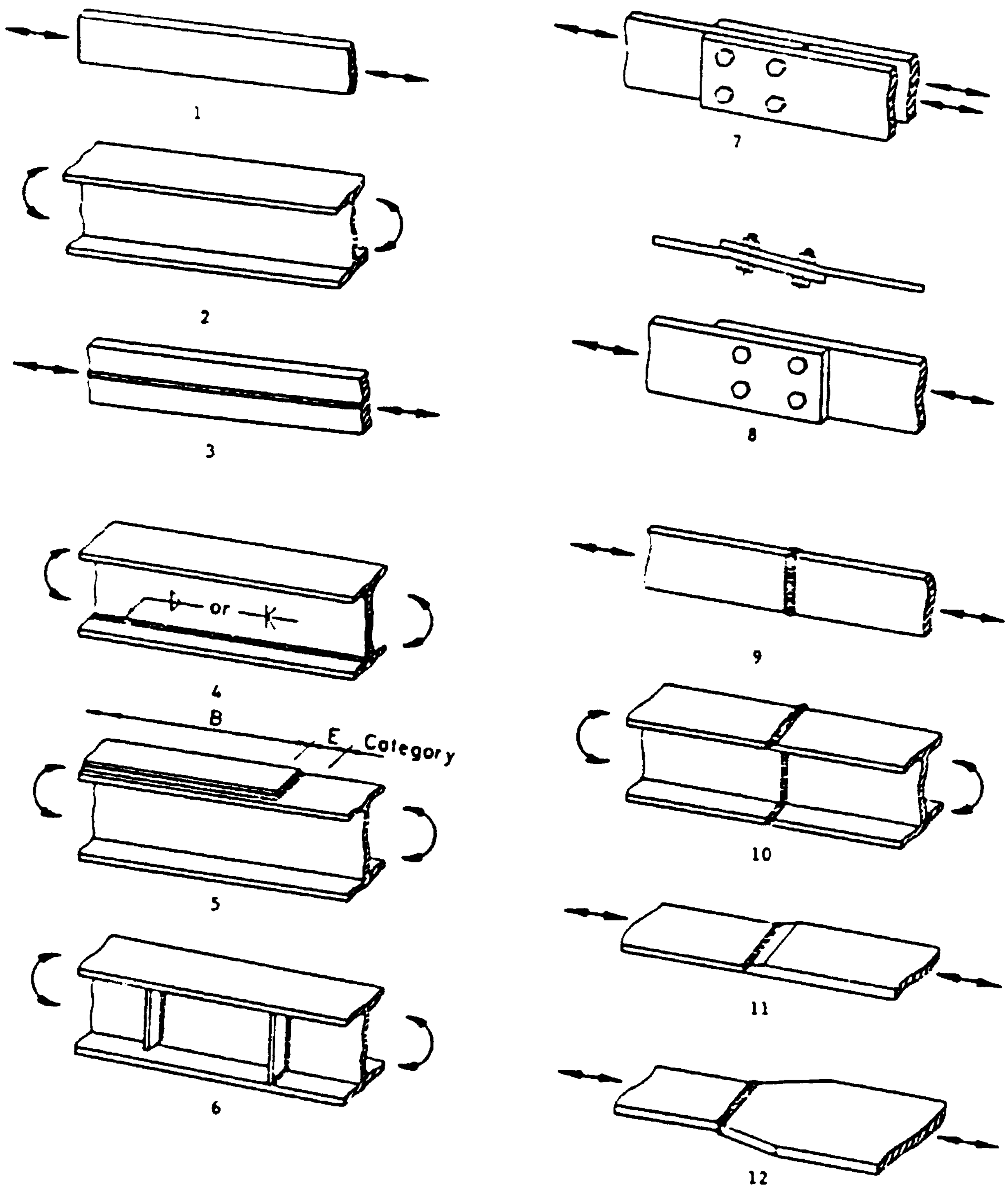


Figure 4.8-1
FATIGUE DESIGN DETAILS
(Continued)

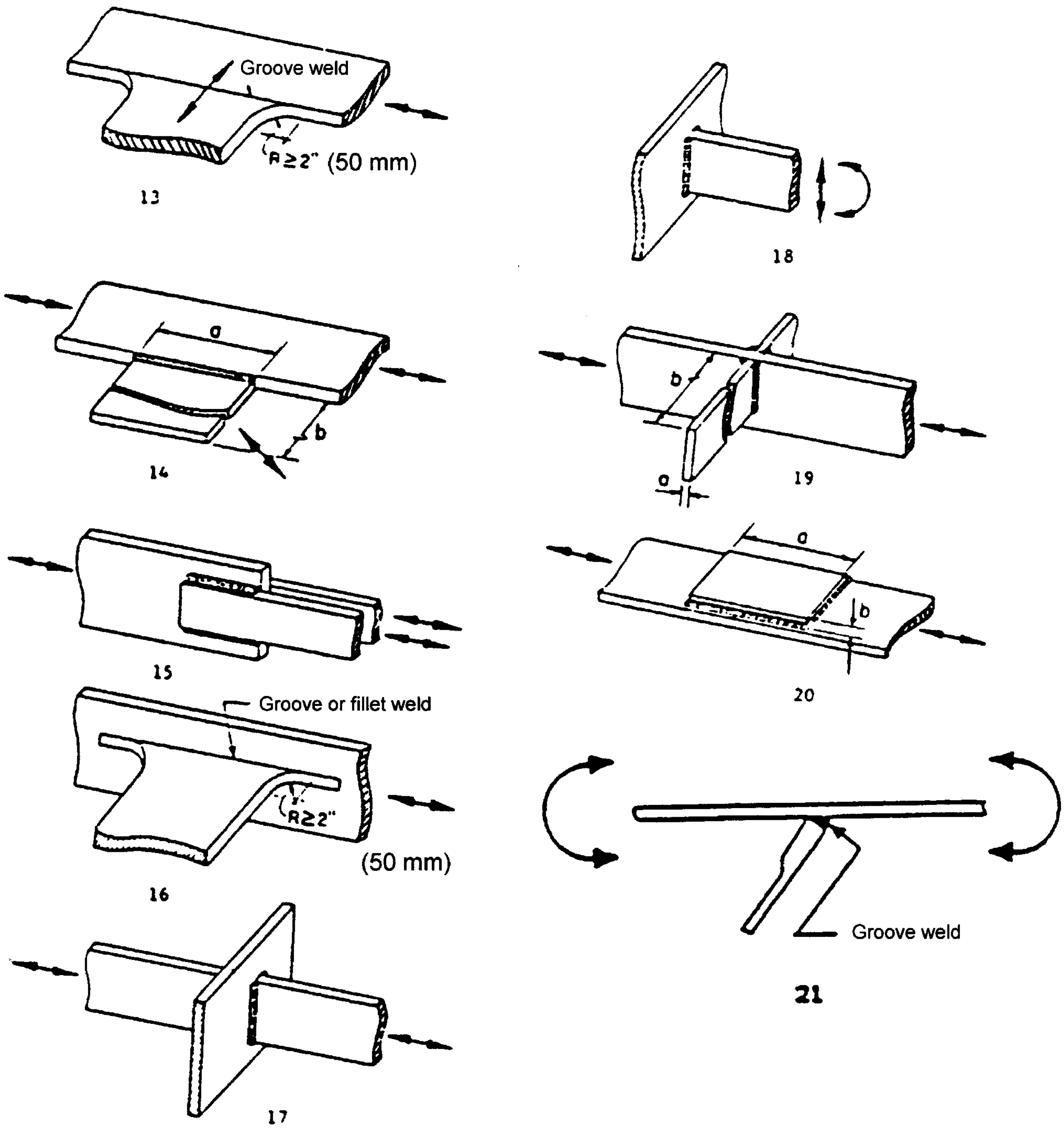


Table 4.8.1-1

Constants for S-N Curves[1]

Detail Category[3]	A		m	Fatigue Limit[2]	
	ksi	MPa	ksi and MPa	ksi	MPa
A	96.5	665	6.85	10.2	70
B	130	900	4.84	5.4	37
C	278	1920	3.64	4.0	28
D	157	1080	3.73	2.5	17
E	160	1100	3.45	1.8	13
F	174	1200	3.42	1.9	13

[1] Different constants are to be used for calculations in ksi, and MPa

[2] Fatigue limit is based on N = $5x10^6$

[3] See Table 4.8-1

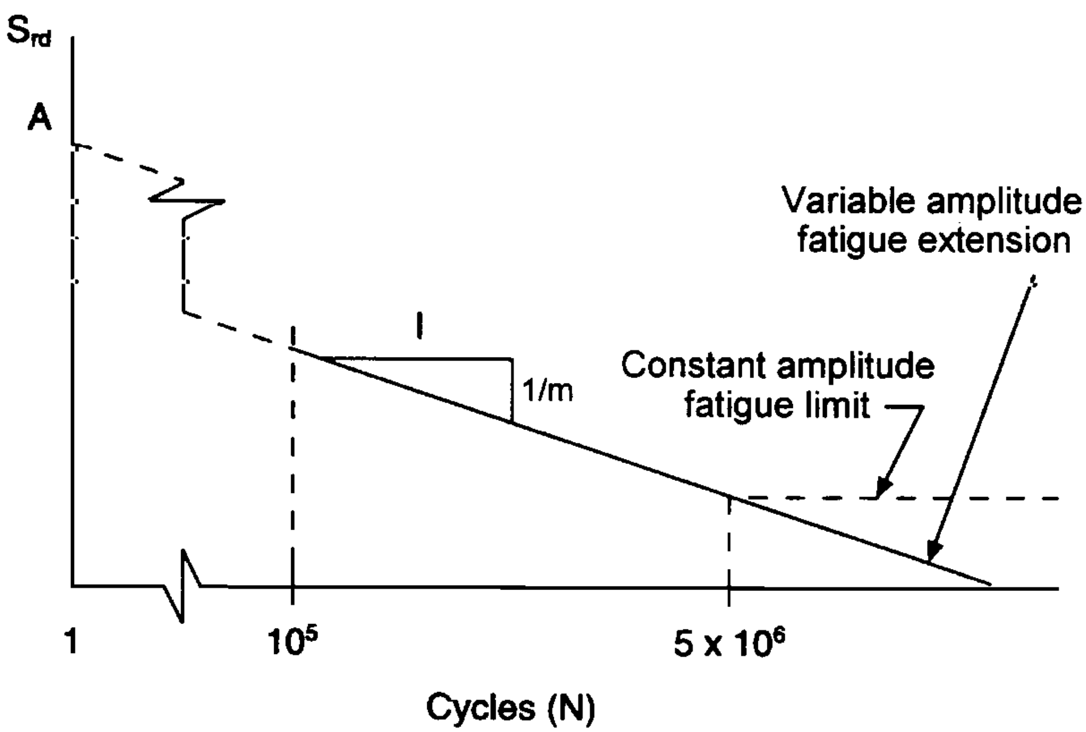


Figure 4.8.1-1

SCHEMATIC FATIGUE CURVE

The following information is from Part IIA of the Aluminum Design Manual, “Commentary on Specifications for Aluminum Structures – Allowable Stress Design.”

4.8 Fatigue

The provisions of this section are modifications of the original fatigue specifications (44). The modifications include changes to the fatigue strength curves and the addition of a method to determine life of parts under spectrum loading. The changes are based on recent tests of full scale welded beams in the United States (45) and Europe (46).

The analyses consider that the major factors affecting fatigue behavior are the number of stress cycles, the magnitude of the stress range and the type and location of the member or detail. The fatigue crack will generally grow perpendicular to the plane of maximum stress. This section of the Specifications uses a nominal stress range determined by elastic analysis. The effect of stress concentrations are accounted for through the proper selection of fatigue details. Many other factors, including environment, detrimental weld quality, and post-weld mechanical treatment can have an effect, but are not considered within the scope of this document. Special analysis or tests are required for details and conditions not specifically covered by the specifications.

Loads and number of load applications are not covered. If the information exists for structures of other materials, the same values may be used for aluminum structures of the same type. Wind induced vibrations of undamped structures or components can cause large numbers of cycles and high stresses and thus need to be avoided. Alternatively, vibration dampers may be used to limit wind induced vibrations.

4.8.1 Constant Amplitude Loading

The equations for allowable stress are based on the 95% confidence for 97.7% probability of survival. The results of the recent beam tests account for the revision of the previous values. The fatigue limit was assumed to occur at 5×10^6 cycles for each detail. Static strength provisions in the other sections of the specification limit the design fatigue strength for low numbers of cycles.

4.8.2 Variable Amplitude Loading

Real load histories are frequently more complicated than the constant amplitude loading discussed in the previous section. This section provides a method by which the engineer may design for more random variable amplitude loadings experienced by many structures. The equivalent stress method is based on nominal stress ranges, linear damage accumulation, and no sequencing effects. The engineer should also use a standard cycle counting algorithm, such as rainflow counting (72,73) to determine the equivalent stress range.

The equation for the equivalent stress range is derived directly from Miner's Rule when the S-N curve is a straight line in log-log space. Miner's rule is given by

$$\frac{n_i}{N_i} \leq 1.0$$

where

n = number of cycles of the i^{th} stress range

N_i. = number of cycles constituting failure at the i^{th} stress range

The equation states that when this fraction approaches unity, some of the details within the group have begun to fail. The engineer may wish to use the Miner's rule formulation over the equivalent stress range when assessing the remaining life of an existing structure or when fatigue data is not linear in the Log(stress)-log(life) space.

The analysis is made as specified in Section 4.8.1 except that the fatigue limit is not used. In this case, the equations for allowable stress are also used for number of cycles greater than 5×10^6 because available data for spectrum loads show continuing decrease at long lives.

The following information is from Part III of the Aluminum Design Manual, "Design Guide."

4.0 Fatigue

Design of components for fatigue is covered by *Equations 4.8.1-1 and 4.8.1-2* for constant amplitude loadings and by *Equations 4.8.2-1 and 4.8.2-3* for spectrum loadings. Various standard details are provided and stress/number of cycle (S-N) curves are given for all the details. The S-N curves are based on the curve providing 97.7% probability of survival with 95% confidence level. There is no factor of safety applied to the curves. The procedure for design is to use the fatigue strength of the standard detail that most closely approximates the new detail being designed.

When designing for fatigue there are defined or assumed cyclic loads and a number of cycles. Joints or geometrical discontinuities, such as holes, are usually areas in which fatigue cracks originate. The designer must establish the geometry and joining method such that the resulting stresses are within those given by *Equations 4.8.1-1 and 4.8.2-1*.

The aluminum component generally must be different from the steel component for the same load spectrum. Figure 4.0-1 shows fatigue strengths for aluminum and steel for groove welds (a Category C detail). For long lives the fatigue strength of aluminum groove welds is about 40% that for steel. There is a smaller difference at short lives. The design of the aluminum component must be consistent with the fatigue strength curves for aluminum.

There are a number of factors that should be considered when designing for fatigue.

1. The light weight of the aluminum structure may result in reduced design loads. Examples are automotive frames and some ship structures in which the loading is proportional to the mass of the structure. In cases in which the imposed loads are large compared to the mass of the structure, the design loads are about the same for all materials.

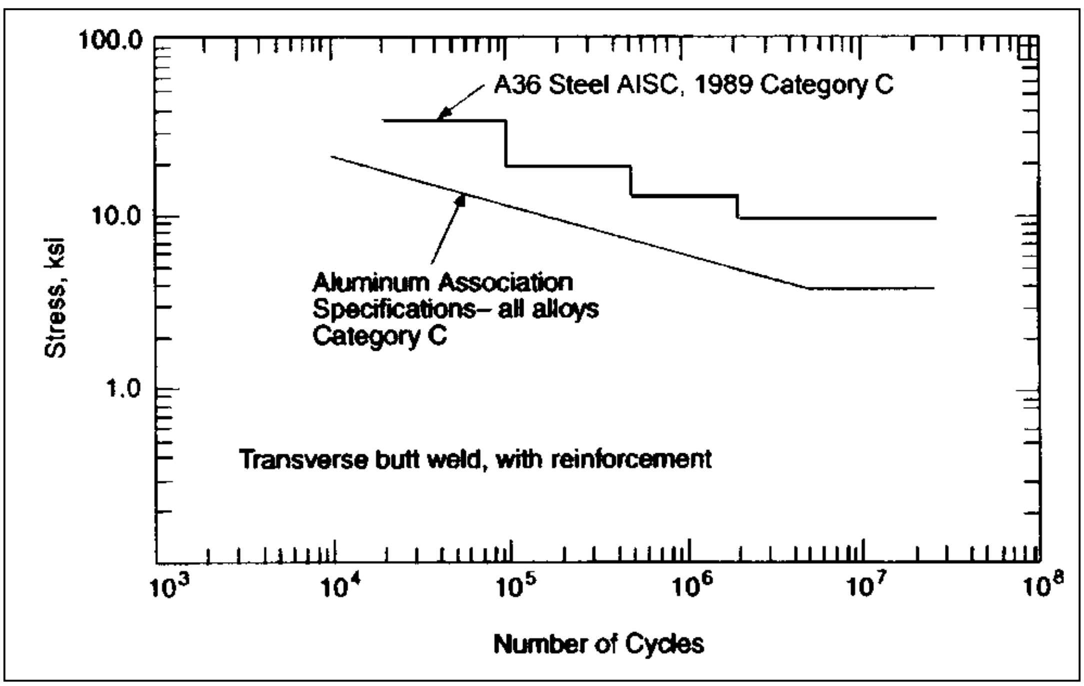


Figure 4.0-1
FATIGUE DESIGN CURVES
FOR ALUMINUM AND STEEL

2. There are some general guidelines (as compared to steel design) that will provide for more efficient aluminum structures. Aluminum members in bending should be deeper than those of steel. The spacing of stiffeners on plates

should be smaller for aluminum components compared to that for steel components. These geometrical differences will help meet any deflection requirements for the aluminum component and will lower the stresses in the parts, helping with any fatigue requirements.

3. Joints may be eliminated by the use of extrusions and castings, thus removing sites for fatigue crack initiation. In some cases the designer can locate joints or discontinuities in areas of low stress, thus improving fatigue resistance.

4. The type of joint affects fatigue strength significantly, whether welded, mechanically fastened or adhesively bonded. The designer should select the joint that best meets the need.

5. There are enhancements to joints that can improve fatigue strength. These include shaping the weld toes and peening the edges of the welds. Adhesives can be employed in mechanically fastened (and spot welded) joints. All of these enhancements increase fatigue strength. Tests will be needed to establish fatigue strength.

Much more information is available on designing for fatigue (1,3,8). In many cases the cause of fatigue behavior has to be minimized or eliminated. Wind induced vibration of members can be prevented by proper design or by the addition of damping. Vibration of structures caused by unbalanced forces from machinery, can be minimized by the use of properly designed vibration mounts and proper design of the structure (natural frequency less than 1/2 or more than 2 times the exciting frequency). Design for fatigue would not be possible without the control of the forces in these cases.

Fatigue resistant joints should always be employed. Gradual changes in geometry of components and joints and avoiding areas of concentrated load and stress are two of many good design practices. Because most fatigue failures initiate at areas of localized high stress, particularly joints, these details need to be designed carefully. Environment, temperature, air quality and corrosive substances can influence fatigue strength in some cases.

The use of S-N curves is the most common but only one of perhaps four methods of designing for fatigue. The others are hot spot, strain-life, fracture mechanics and good practice design methods. All of the techniques have merit and can be applied to most types of structures(8).

Components under constant amplitude loading generally have a fatigue endurance limit, a stress below which failure should not occur. Components of variable amplitude loading may not exhibit an endurance limit, because a crack can be initiated by the higher stress cycles of the spectrum and propagate at stresses below the constant amplitude endurance limit. Miner's rule is generally used for spectrum loading with the straight-line portion of the fatigue curves (assuming no endurance limit)(8). There also may not be an endurance limit in mechanical connections that fail by fretting. Tests may be required to evaluate the possibility of fretting failures.

The stress amplitudes in a spectrum usually are difficult to determine unless a cycle-counting procedure is employed. Of the several procedures that are available(8), the rainflow counting method is commonly used.

APPENDIX C

Excerpt from

EuroCode 9: Design of Aluminum Structures –Part 2: Structures Susceptible to Fatigue

The European Committee for Standardization

1.0 Copyright Release and Limitations on Liability

The information contained in this appendix is reprinted from the EuroCode 9: Design of Aluminum Structures –Part 2: Structures Susceptible to Fatigue by the European Committee for Standardization. The Ship Structure Committee has obtained the written permission of the European Committee for Standardization to use this information in accordance with the guidance for preparation of SSC reports. Users of the information contained in this appendix assume all responsibilities and liabilities associated with its use unless other contractual arrangements are made directly with the European Committee for Standardization.

2.0 Introduction

The information in the EuroCode 9 presents unique guidance for the fatigue and damage tolerance analyses of aluminum weldments. Similar to the other two non-maritime codes discussed in this report, the primary focus of the EuroCode 9 is civil engineering applications. However, unlike any of the other codes, EuroCode 9 presents guidance for the use of their fatigue and S/N curves for details in various environments other then air. Included in these other environments are marine and immersion in water and seawater. This portion of the EuroCode 9 is included in this appendix.

The EuroCode 9 is also the only design code with any information relating to the damage tolerance analysis of cracked details. Information is presented on crack growth rate with a variety of FCGR curves for various alloys and R ratios although all information is developed for the in-air environment.

The unique nature of the information presented in EuroCode 9 and discussion with Professor Kosteas strongly suggest that further investigation of the aluminum database developed to support this code needs to be investigated before further research is conducted for subsequent to this task.

Designers considering the use of the information contained in this code should contact CEN at +32 2 550 08 11 and obtain a complete copy of the EuroCode 9 standard.

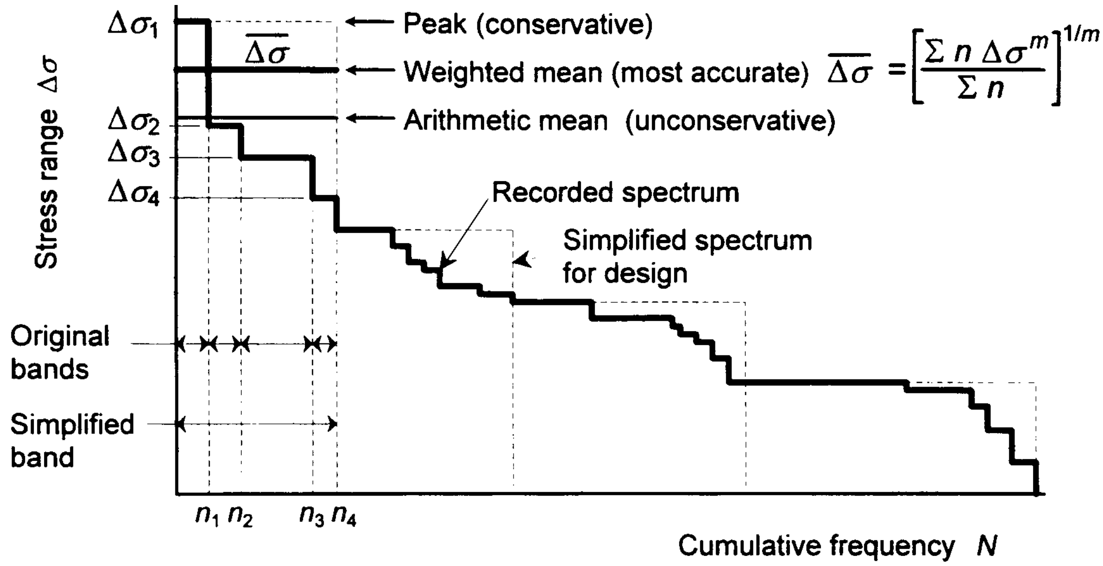


Figure 4.5.2. Simplified Stress Range Spectrum

5 Fatigue strength

5.1 Detail Categories

5.1.1 Factors affecting detail category

(1)P The fatigue strength of a detail shall take into account the following factors:

a) the direction of the fluctuating stress relative to the detail;
b) the location of the initiating crack in the detail;
c) the geometrical arrangement and relative proportion of the detail.

(2) The fatigue strength may also depend on the following:

d) the product form;
e) the material (unless welded);
f) the method of fabrication;
g) the degree of inspection after fabrication;
h) the quality level (in the case of welds and castings).

5.1.2 Detail Category tables

(1) The detail categories for more commonly used details have been divided into five basic groups, namely:

a) non-welded details in wrought and cast alloys (see table 5.1.1)
b) welded details on surface of loaded member (see tables 5.1.2(a) and 5.1.2(b))
c) welded details at end connections (see table 5.1.3)
d) mechanically fastened joints (see table 5.1.4)
e) adhesively bonded joints (see table 5.1.5)

5.2 Fatigue Strength Data

5.2.1 Classified details

(1)P The generalised form of the Δσ-N relationship is shown in figure 1.5.2, plotted on logarithmic scales. The design curve represents a mean minus 2 standard deviation level below the mean line through experimental data.

(2)P The basic fatigue design relationship for endurances less than 5 x 10^6 cycles is defined by the equation:

$$N_i = 2 \times 10^6 \times \left(\frac{\Delta\sigma_c}{\Delta\sigma_i} \frac{1}{\gamma_{Ff}\,\gamma_{Mf}} \right)^{m_l} \tag{5.1}$$

where:

N_i is the predicted number of cycles to failure of a stress range $\Delta\sigma_i$
$\Delta\sigma_c$ is the reference value of fatigue strength at 2 x 10^6 cycles, depending on the category of detail;
$\Delta\sigma_i$ s the principal stress range at the detail and is constant for all cycles;
m_l is the inverse slope of the Δσ-N curve, depending on the detail category;
γ_{Ff} is the partial safety factor allowing for uncertainties in loading spectrum and analysis of response (see 3.4);
γ_{Mf} is the partial safety factor for uncertainties in materials and execution (see 5.2.1(3)).

(3) For normal applications where the design conforms with this Prestandard, including the manufacturing requirements of Annex D, a value of γ_{Mf} = [1,0] may be applied (but see 5.2.3(3) in the case of adhesively bonded joints).

(4) The constant amplitude fatigue limit, $\Delta\sigma_D$, occurs at 5x10^6 cycles, below which constant amplitude stress cycles are assumed to be non-damaging. However, even if occasional cycles occur above this level, they will cause propagation which, as the crack extends, will cause lower amplitude cycles to become damaging. For this reason the inverse logarithmic slope m_2 of the basic Δσ-N curves between 5 x 10^6 and 10^8 cycles should be changed to m_2 for general spectrum loading conditions, where $m_2 = m_l + 2$.

(5)Any stress cycles below the cut-off limit $\Delta\sigma_L$, which occurs at 10^8 cycles, should be assumed to be non-damaging.

(6) The Δσ-N relationship is fully described by the double number detail category $\Delta\sigma_c$ - m_l where $\Delta\sigma_c$ is an integer expressed in units of N/mm^2. Their values are given in tables 5.1.1 to 5.1.5. The Δσ-N curves are given in figures 5.2.1 to 5.2.5.

(7) For the purpose of defining a finite range of categories and to enable a category to be increased or decreased by a constant geometric interval, a standard range of $\Delta\sigma_c$ values is given in table 5.2.6. An increase (or decrease) of 1 category means selecting the next larger (or smaller) $\Delta\sigma_c$ value whilst leaving m_l and m_2 unchanged.

8)P The detail categories are safe for all values of mean stress (see 5.3) but do not allow for environments other than ambient (see 5.4).

9) The use of the $m_2 = m_1 + 2$ inverse slope constant may be conservative for some spectra. Where a design is critically dependent on this region and where maximum economy is sought it may be appropriate to consider using component testing (see Annex C.3.1) or applying fracture mechanics analysis (see Annex B).

(10)P The detail category values in tables 5.1.2(b) and 5.1.3 shown in brackets are attainable only with high weld quality levels which are not readily verifiable by normal non-destructive testing techniques. In order to meet the needs of quality assurance, bracketed values should only be used where special inspection procedures are applied which have been demonstrated to be capable of detecting and evaluating critical sizes of weld discontinuity which shall have been established by fracture mechanics or testing (see Annex B and C).

5.2.2 Unclassified details

(1)Details not fully covered by tables 5.1.1 to 5.1.5 should be assessed by reference to published data where available. Alternatively fatigue acceptance tests may be carried out in accordance with Annex C.3

5.2.3 Adhesively bonded joints

(1) Design of adhesive joints should consider the following:

- Peel loading should be reduced to a minimum.
- Stress concentrations should be minimised.
- Strains in the parent metal should be kept below yield.
- Chemical conversion or anodizing of the surfaces generally improves fatigue life compared to degreasing or mechanical abrasion.
- Aggressive environments usually reduce fatigue life.

(2)The reference fatigue strength of an adhesively bonded lap joint which fails in the bond line is defined by the equation:

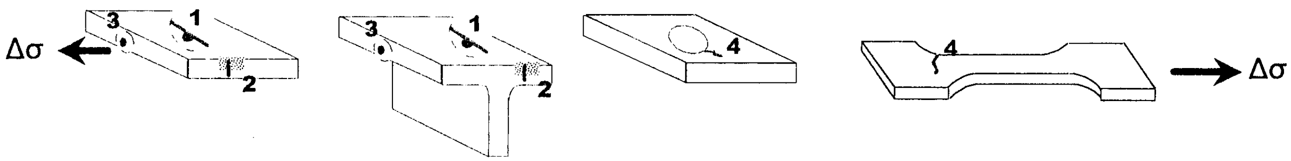
$$\Delta\sigma_c = k_{c,adh} \cdot f_{v,adh} \qquad (5.2)$$

where

$k_{c,adh}$ is the value of the adhesive joint fatigue strength factor k_{adh} at $N = 2x10^6$ cycles
$f_{v,adh}$ is the characteristic shear strength of the adhesive obtained from a standard static lap shear test (see Part 1.1 of this Prestandard).

(3)Testing under representative conditions of geometry, workmanship and environment is recommended for critical applications. Otherwise a high value of γ_{Mf} should be used.

Table 5.1.1* Detail Categories for Plain Material



Product Forms		Simple Extruded Rod and Bar, Machined Parts		Sheet, Plate, Extrusions, Tubes, Forgings		Notches, Holes		Castings	
Initiation Site	Reference No.	1, 2		1, 2		4		1	3
	Location	Small surface irregularity						Cast material	
Stress orientation (see 4.3.4)		PARALLEL or NORMAL[1] to rolling or extrusion direction						-	-
Alloys		7020	As table 1.1.1 (except 7020)	7020	As table 1.1.1 (except 7020)	7020	As table 1.1.1 (except 7020)	As Table 1.1.2	
Particular Requirements	Dimensional	Surfaces free of sharp corners unless parallel to stress direction; Edges free of stress raisers							
		No re-entrant corners in profile, No contact with other parts		-					
	Fabrication	Machining only by high speed milling cutters		Hand grinding not permitted unless parallel to stress direction		Holes drilled and reamed		Casting as per Table 1.1.2 Machining only by high speed milling cutters	
	Inspection/Testing	Visual						Dye Penetrant	Radiography
								see Chapter 6*	
	Quality Standard	Surface finish (R_a < 0.5mm)		No score marks transverse to stress direction		-		see Chapter 6*	
Stress Analysis	Stress parameter	Principal structural stress at initiation site				Account for stress concentration Annex A.4		Principal structural stress at initiation sit	
	Stress concentrations already allowed for	Surface texture							Permitted interna porosity
Type Number		1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
Detail Category $\Delta\sigma$ **-** m_1 [2]		**130 - 7**	**95 - 7**	**85 - 7**	**70 - 7**	as Types 1.1 to 1.4		**70 - 7**	**70 - 7**

[1] The manufacturer shall be consulted concerning the quality assurance in case of extrusions by port hole or bridge die

[2] $m_1 = m_2$, constant amplitude fatigue limit at 2×10^6 cycles

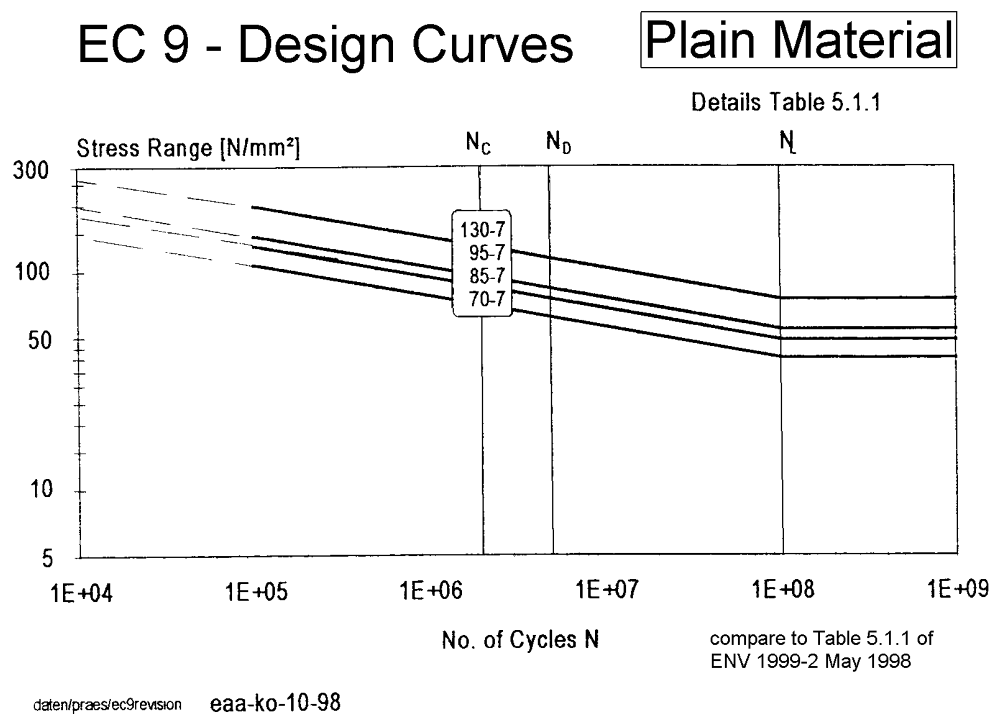
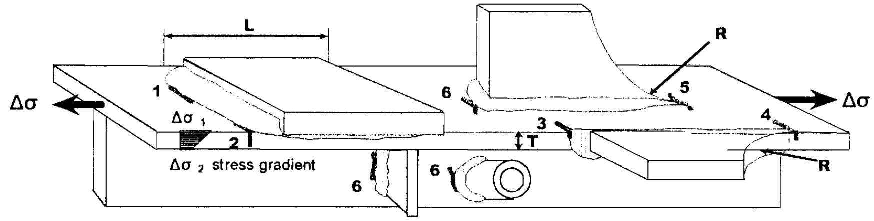


Fig. 5.2.1* Design Curves Δσ - N for plain material detail categories in Table 5.1.1*

Table 5.2.1* Numerical values of Δσ (N/mm²) for plain material

Detail Category	slope		Cycles N						
2E+06	m_1	m_2	1E+04	1E+05	1E+06	5E+06	1E+07	1E+08	1E+09
130,0	7,0	7,0	277,1	199,4	143,5	114,0	103,3	74,3	74,3
95,0	7,0	7,0	202,5	145,7	104,9	83,3	75,5	54,3	54,3
85,0	7,0	7,0	181,2	130,4	93,8	74,6	67,5	48,6	48,6
70,0	7,0	7,0	149,2	107,4	77,3	61,4	55,6	40,0	40,0

Table 5.1.2* Detail Categories for Members with Welded Attachments - Transverse Weld Toe



Product Forms			Rolled, extruded and forged products						
Initiation Site	Reference No.		1		2	3	4	5	6
	Location		At transverse weld toe on stressed member				At longitudinal weld end	At transverse weld toe on stressed memb	
			On surface away from edge		At corner	On edge	In ground weld toe on edge	On surface away from edge	
Stress orientation (see 4.3.4)			Normal to transverse weld toe				Parallel to weld axis		Normal to weld tc
Alloys			As table 1.1.1						
Particular Requirements	Dimensional	Joint Geometry	Attachment on member surface			Attachment on member edge		Attachment on member surface	
			Weld on surface away from corner		Welded round corner	Weld on edge		Weld on surface away from corner	
		Length L (mm)	L ≤ 20	L > 20	L and T as for	No radius	R ≥ 50	R ≥ 50	No radius
		Thickness T (mm)	see table below		Types 2.1 and 2.2				
	Fabrication				Grind undercut smooth		Grind radius parallel to stress direction [1]		
	Inspection/Testing		see chapter 6*						
	Quality in acc. to EN 30 042	internal	C						
		geometrical	C						
Stress Analysis	Stress parameter		Nominal stress at initiation site						
	Stress concentrations already allowed for		Discontinuities permitted as given in EN 30042						
			Stiffening effect of attachment						
Type Number			2.1	2.2	2.3	2.4	2.5	2.6	2.7
Detail Category $\Delta\sigma$ m_1 = 3,4 , m_2 = 5,4 for all Types		$T \leq 4$ $4 < T \leq 10$ $10 < T \leq 15$	**31** **31** **31**	**25** **22** **20**	As Types 2.1 to 2.2, but reduced by 12%	**18**	**35**	**35**	**23**
Adjustment for stress gradient			Where $\Delta\sigma_1$ and $\Delta\sigma_2$ are of opposite sign increase by 2 Categories where $T \leq 15$ mm						

[1] Weld toe shall be fully ground out

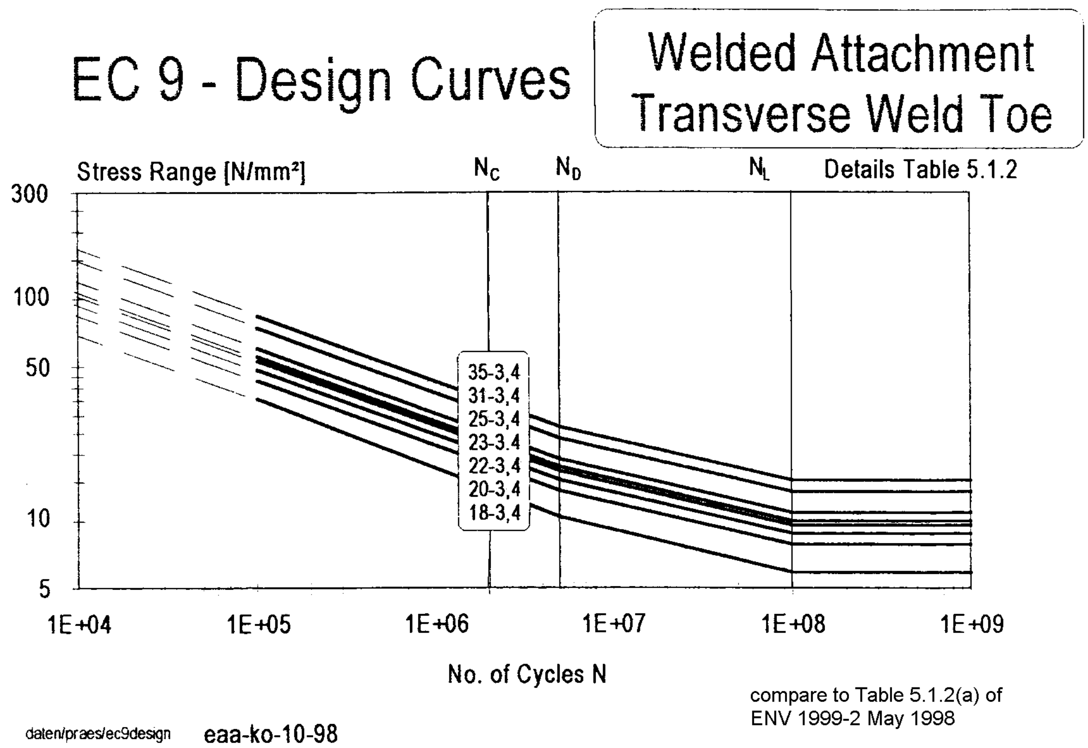
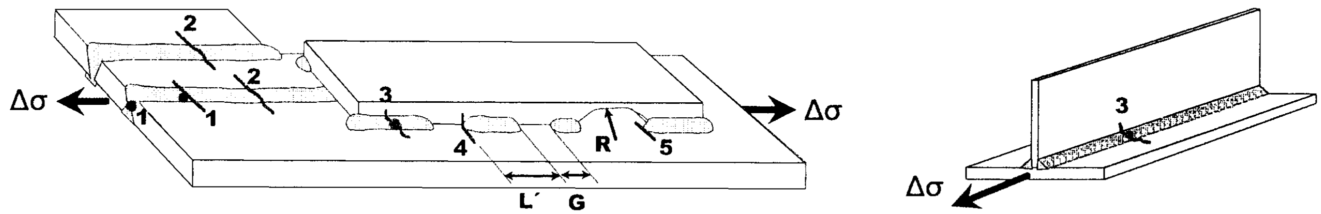


Fig. 5.2.2* Design Curves $\Delta\sigma$ - N for members with welded attachments / transverse weld toe detail categories in Table 5.1.2*

Table 5.2.2* Numerical values of $\Delta\sigma$ (N/mm²) for members with welded attachments / transverse weld toe

Detail Category	slope		Cycles N						
2E+06	m_1	m_2	1E+04	1E+05	1E+06	5E+06	1E+07	1E+08	1E+09
35,0	3,4	5,4	166,3	84,5	42,9	26,7	23,5	15,3	15,3
31,0	3,4	5,4	147,3	74,8	38,0	23,7	20,8	13,6	13,6
25,0	3,4	5,4	118,8	60,3	30,7	19,1	16,8	11,0	11,0
23,0	3,4	5,4	109,3	55,5	28,2	17,6	15,5	10,1	10,1
22,0	3,4	5,4	104,5	53,1	27,0	16,8	14,8	9,6	9,6
20,0	3,4	5,4	95,0	48,3	24,5	15,3	13,4	8,8	8,8
18,0	3,4	5,4	85,5	43,4	22,1	13,7	12,1	7,9	7,9

Table 5.1.3* Detail Categories for Members with Welded Attachments - Longitudinal Welds



Product Forms			Rolled, extruded and forged products						
Initiation Site	Reference No.		1		2	3		4	5
	Location		A weld discontinuity					Weld toe or crater	
Stress orientation (see 4.3.4)			Parallel to weld axis						
Alloys			As Table 1.1.1						
Particular Requirements	Dimensional		Full penetration butt weld			Continuous fillet weld		Intermittent fillet weld	Cope hole centred on weld axi
								G ≤ 2.5L	R ≤ 25mm
	Fabrication		Continuous automatic welding						
			Weld caps ground flush in direction of Δσ			2)			
			Any backing bars (and attachment welds) to be continuous						
	Inspection/Testing		see Chapter 6*						
	Quality in acc. to EN 30 042	internal	B	C	C	B	C	C	C
		geometrical	C	C	D	C	D	D	D
		add. requirements			1)	3)			
Stress Analysis	Stress parameter		Nominal stress at initiation site						
	Stress concentrations already allowed for		Weld discontinuities as permitted by EN 30 042						
									Presence of cope hole
Type Number									
Detail Category Δσ - m_1 ($m_2 = m_1 + 2$)			**60 - 4,3**	**55 - 4,3**	**45 - 4,3**	**45 - 4,3**	**40 - 4,3**	**35 - 4,3**	**28 - 3,4**

1) Ripple/imperfection no. 504/EN 30 042:B 2) imperfection due to stop-start effect shall be checked 3) Discontinuity in direction of longitudinal weld shall not be higher than 1/10 of plate thickness or exhibit slope steeper than 1:4

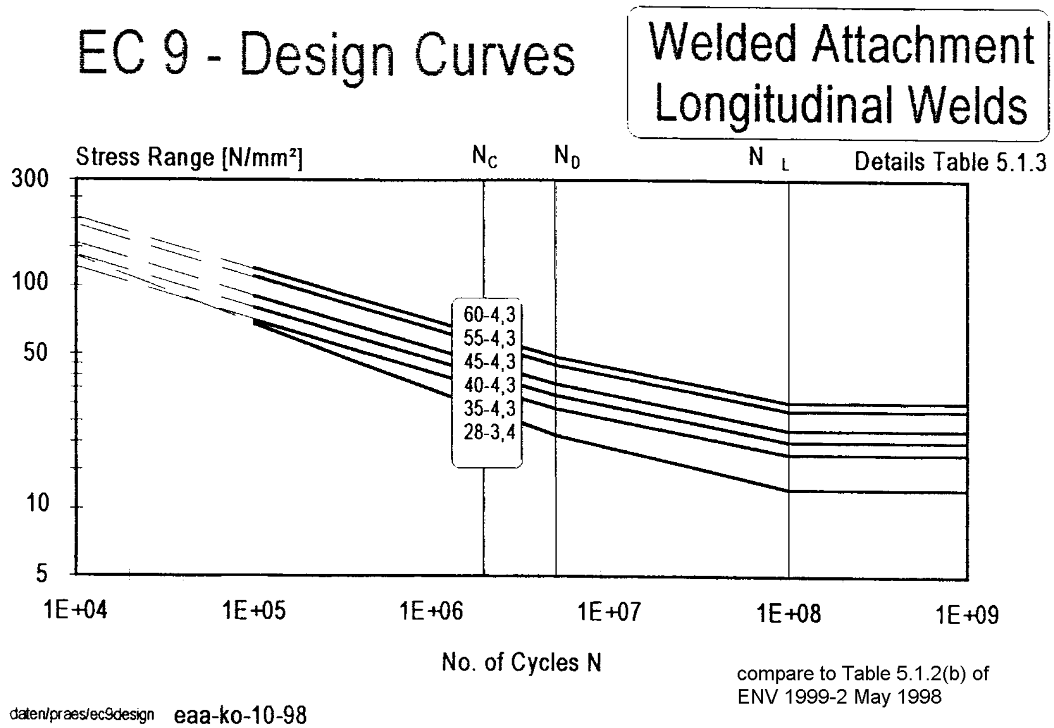
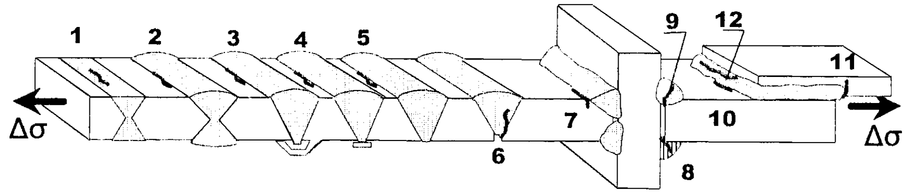


Fig. 5.2.3* Design Curves Δσ-N for members with welded attachments / longitudinal welds

Table 5.2.3* Numerical values of Δσ (N/mm²) for members with welded attachments / longitudinal welds

Detail Category	slope		Cycles N						
2E+06	m_1	m_2	1E+04	1E+05	1E+06	5E+06	1E+07	1E+08	1E+09
60,0	4,3	6,3	205,7	120,4	70,5	48,5	43,4	30,1	30,1
55,0	4,3	6,3	188,6	110,4	64,6	44,4	39,8	27,6	27,6
45,0	4,3	6,3	154,3	90,3	52,9	36,4	32,6	22,6	22,6
40,0	4,3	6,3	137,1	80,3	47,0	32,3	29,0	20,1	20,1
35,0	4,3	6,3	120,0	70,2	41,1	28,3	25,3	17,6	17,6
28,0	3,4	5,4	133,0	87,6	34,3	21,4	18,8	12,3	12,3

Table 5.1.4* Detail Categories for Welded Joints between Members



Product Forms			Rolled, extruded and forged products																		Castings
Initiation Site	Reference No.		1		2			3, 4		5			6	7		8	9	10	11	12	
	Location		weld, base material										weld	base material		weld		base material		weld	
Stress orientation (see 4.3.4)			Normal to weld axis																		
Alloys			As table 1.1.1																		
Particular Requirements	Dimensional	Joint type	In-line-butt											Cruciform or Tee				Lap			
		Weld type	Butt												Double fillet 1)		One sided fillet	Fillet			
		Preparation	Double sided					Single sided						edge preparation							
		Penetration	Full										Partial	Full	Partial						
		Transition	Taper slope < 1:4 at width or thickness change																		
	Manufacturing	Root	Ground					Backed		Unbacked				Ground							
		Cap	Ground flush																		
		Ends	Extension plates used on ends, cut off and ground flush in direction of Δσ																		
	Inspection/Testing		see Chapter 6*																		
	Quality in acc. to EN 30 042	internal	B	C	B	B	C	C	C	B	C	C	D	B	C	C	C	C	C	C	
		geometrical	B	C	C	B	C	C	C	B	C	C	C	B	C	C	C	C	C	C	
		add. requirements		3)	3)	3)	3)	3)	3)	2) 3)	2) 3)	2) 3)	3)	2) 3)	3)	3)	3)	3)	3)	3)	
Stress Analysis	Stress parameter		net section										net throat	net section		net throat		net section		net throat	
	Stress concentrations already allowed for													Stiffening effect of transverse element				stress peaks at weld ends			
Type Number			4.1 fl	4.1 op	4.2 fl	4.2 op		4.3 fl	4.3 op/ho	4.4 fl		4.4 op/ho	4.5	4.6	4.7	4.8	4.9	4.10	4.11	4.12	
Detail Category	Δσ - m_1		55-7	45-7	50-4,3	40-3,4	35-3,4	40-4,3	30-3,4	45-4,3	40-4,3	30-3,4	18-3,4	35-3,4	30-3,4	25-3,4	12-3,4	23-3,4	18-3,4	14-3,4	

1) Round tubes one sided fillet 2) Imperfection no. 402 / EN 30 042 not allowed

fl: Flats, Solids / op: Open Shapes / ho: Hollow, Tubular

3) Discontinuity in direction of longitudinal weld shall not be higher than $^1/_{10}$ of plate thickness or exhibit slope steeper than 1:4

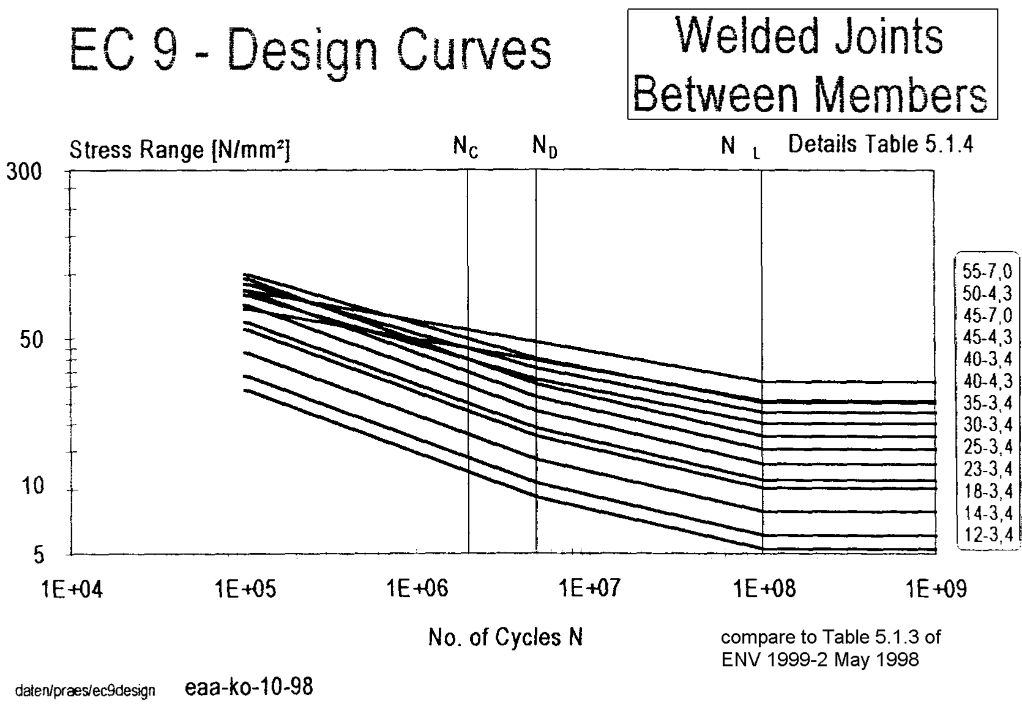
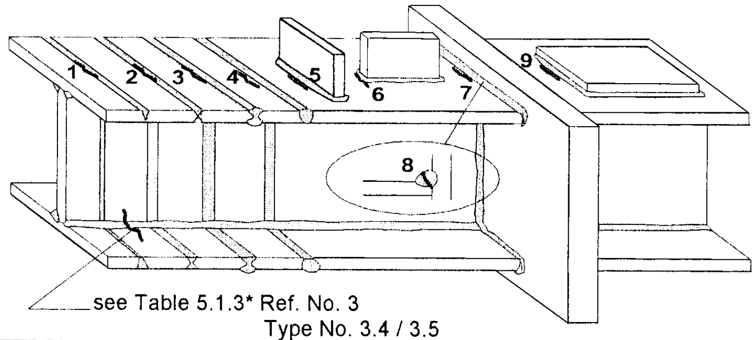


Fig. 5.2.4* Design Curves $\Delta\sigma$-N for welded joints between members

Table 5.2.4* Numerical values of $\Delta\sigma$ (N/mm²) for welded joints between members

Detail Category	slope		Cycles N						
2E+06	m_1	m_2	1E+04	1E+05	1E+06	5E+06	1E+07	1E+08	1E+09
55,0	7,0	7,0	117,2	84,4	60,7	48,3	43,7	31,5	31,5
45,0	7,0	7,0	95,9	69,0	49,7	39,5	35,8	25,7	25,7
50,0	4,3	6,3	171,4	100,4	58,7	40,4	36,2	25,1	25,1
45,0	4,3	6,3	154,3	90,3	52,9	36,4	32,0	22,6	22,6
40,0	3,4	5,4	187,5	95,8	49,0	30,6	27,0	17,6	17,6
40,0	4,3	6,3	137,1	80,3	47,0	32,3	28,9	20,2	20,2
35,0	3,4	5,4	166,3	84,5	42,9	26,7	23,5	15,3	15,3
30,0	3,4	5,4	142,5	72,4	36,8	22,9	20,2	13,2	13,2
25,0	3,4	5,4	118,7	60,3	30,6	19,1	16,7	11,0	11,0
23,0	3,4	5,4	109,2	55,5	28,2	17,6	15,5	10,1	10,1
18,0	3,4	5,4	85,5	43,4	22,1	13,7	12,0	7,9	7,9
14,0	3,4	5,4	66,5	33,8	17,2	10,7	9,4	6,1	6,1
12,0	3,4	5,4	57,0	29,0	14,7	9,2	8,1	5,3	5,3

Table 5.1.5* Detail Categories for Crossing Welds / Built-up Beams



Product Forms											
Initiation Site	Reference No.		1	2	3	4	5	6	7	8	9
	Location		Weld						Base Material	Weld	On surface aw from edge
Stress	orientation	(see 4.3.4)									
Alloys											
Particular Requirements	Dimensional	Joint type				In-line-butt		Attachment		Cruciform or tee	Coverplate
		Weld type				Butt					Fillet
		Preparation	Single sided	Double sided	Double sided	Single sided				Double sided	
		Penetration				Full					
		Transition	Taper slope < 1:4 at width or thickness change								
	Manufacturing	Root	Ground flush	Ground							
		Cap	Ground flush	Ground							
		Ends ??				1)					
	Inspection/Testing		see Chapter 6*								
	Quality in acc. to EN 30 042	internal	B	B	B	C	C	C	C	C	C
		geometrical	B	B	C	C	C	C	C	C	C
		add. requirements	for web-to-flange fillet welds ⇒ 2)								
Stress Analysis	Stress parameter		net section							net throat	net section
	Stress concentrations	already allowed for					Stiffening effects of attachment				
Type Number			5.1		5.2	5.3	5.4	5.5	5.6	5.7	5.8
Detail Category	$\Delta\sigma$ - m_1		40-3,4		35-3,4	30-3,4	18-3,4	23-3,4	30-4,3	25-4,3	20-4,3

1) Transverse web and flange butt joint before final assembly of beam with longitudinal welds 2) see Table 5.1.3* Reference No. 3 / Type No. 3.4 or 3.5

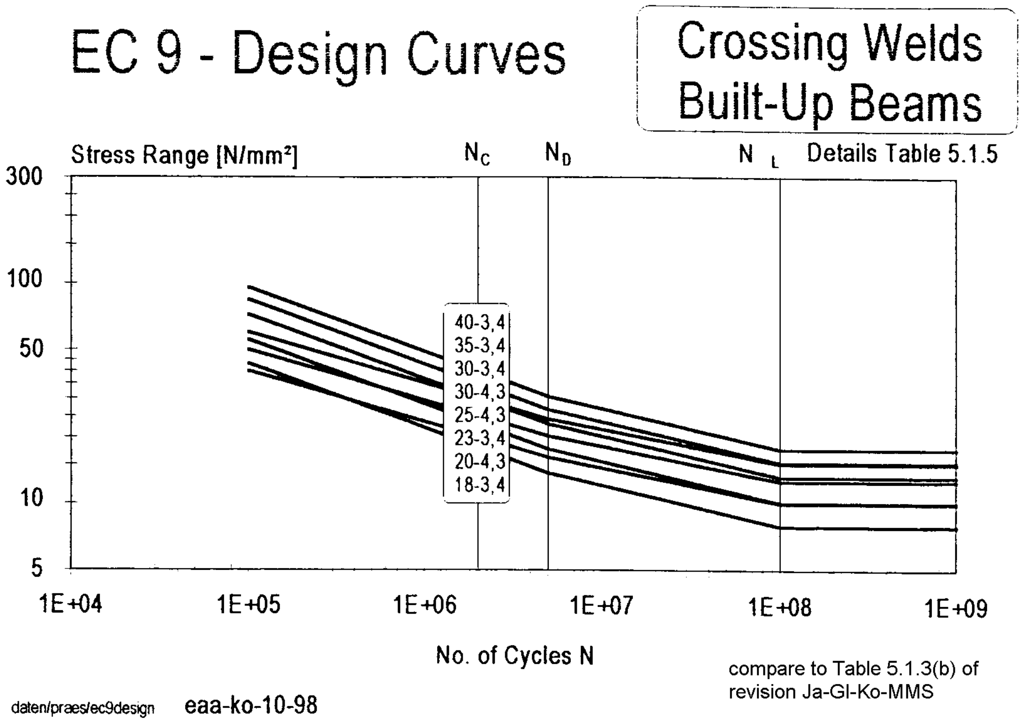


Fig. 5.2.5* Design Curves Δσ-N for crossing welds and built-up beams

Table 5.2.5* Numerical values of Δσ-N for crossing welds and built-up beams

Detail Category	slope		Cycles N						
2E+06	m_1	m_2	1E+04	1E+05	1E+06	5E+06	1E+07	1E+08	1E+09
40,0	3,4	5,4	187,5	95,8	49,0	30,6	27,0	17,6	17,6
35,0	3,4	5,4	166,3	84,5	42,9	26,7	23,5	15,3	15,3
30,0	3,4	5,4	142,5	72,4	36,8	22,9	20,2	13,2	13,2
30,0	4,3	6,3	102,9	60,2	35,2	24,2	21,7	15,1	15,1
25,0	4,3	6,3	85,7	50,2	29,4	20,2	18,7	12,6	12,6
23,0	3,4	5,4	109,3	55,5	28,2	17,6	15,5	10,1	10,1
20,0	4,3	6,3	68,6	40,1	23,5	16,2	14,5	10,0	10,0
18,0	3,4	5,4	85,5	43,4	22,1	13,7	12,1	7,9	7,9

(2) For certain details higher fatigue strengths may be used for negative R ratios for $N<10^5$ cycles (see Annex F).

5.3.6 Cycle counting for R-ratio calculation

The method of obtaining the maximum, minimum and mean stress for individual cycles in a spectrum using the Reservoir counting method shall be as shown in Fig.4.5.1.

5.4 Effect of Environment

(1)P The detail category $\Delta\sigma_c$ given in Tables 5.1.1 to 5.1.5 and 5.2.2 shall be reduced in accordance with Table 5.4.1 for certain combinations of alloy and environment where the average ambient temperature during the life does not exceed 65°C.

NOTE: For marine environment the average ambient temperature during the life should not exceed 30°C.

Table 5.4.1 Number of detail categories by which $\Delta\sigma_c$ shall be reduced according to environment and alloy [1)]

Alloy			Environment							
Series	Basic Composition	Protec-tion ratings (see Part 1.1)	Rural	Industrial/Urban		Marine			Immersed	
				Moderate	Severe	Non-Industrial	Moderate	Severe	Fresh Water	Sea Water
3000[3)]	AlMnCu	A	-	-	(P)	-	-	-[5)]	-	-[5)]
5000	AlMg	A	0	0	(P)[4)]	0	0	0[5)]	0	0[5)]
5000	AlMgMn	A	0	0	(P)[4)]	0	0	0[5)]	0	1[5)]
6000	AlMgSi	B	0	0	(P)[4)]	0	0	1[5)]	0	2[5)]
7000	AlZnMg	C	0	0	(P)[4)]	0	0	2[5)]	1	3[5)]

Note 1:See Table 5.2.1. (7)
Note 2: For conditions where table 5.4.1 requires a reduction in detail category and the average temperature exceeds 30°C specialist advice should be sought.
Note 3: Data not available
Note 4: (P) very dependent on chemistry of environment. Regularly maintained protection may be required to avoid risk of local exposures which may be particularly detrimental to crack initiation.
Note 5 :The value of N_D should be increased from $5x10^6$ to 10^7 cycles.
The value of N_L should be increased from 10^8 to $2x10^8$ cycles

5.5 Improvement Techniques

(1) The fatigue strength of certain detail types shown in tables 5.1.1 to 5.1.5 may be improved by the application of special manufacturing techniques. These are generally expensive to apply and present quality control difficulties. They should not be relied upon for general design purposes, unless fatigue is particularly critical to the overall economy of the structure, in which case specialist advice should be sought. They are more commonly used to overcome existing design deficiencies.

(2) The following techniques have been used on aluminium alloys and are most effective for high cycle applications.

a) Introduction of compressive residual stresses at the location of crack initiation. This may be carried out at transverse weld toes by peening. At bolt holes the cold expansion method may be used.

(b) Reduction of stress concentration effect at the location of crack initiation. This may be carried out by grinding transverse weld toes to a smooth profile.

(3) Further information on improvement techniques is given in Annex E.

6 Quality requirements

6.1 Determination of Required Quality Level

(1)P The detail categories in tables 5.1.1 to 5.1.5 represent the maximum fatigue strength permitted by this code for the detail in question when manufactured to the quality requirements of Annex D, and shall not be exceeded without further substantiation by test (see Annex C).

(2)P The higher class details often require additional inspection and demand higher workmanship standards (see Annex D), which can have an adverse effect on the economy of manufacture. Inspection and workmanship standards shall be determined by the quality level appropriate to the particular fatigue performance requirements and not by the maximum potential fatigue resistance.

(3)P The required quality level at a detail shall be obtained by determining the lowest fatigue strength curve from where Miner's summation D_L does not exceed unity (see 2.2.2(2)g). Where stress fluctuations occur in more than one direction at a detail different class requirements may be found for each direction.

(4)P The quality level for welded joints shall be determined from table 6.1.1.

Table 6.1.1. Determination of quality level for welded joints

Lowest detail category $\Delta\sigma_c$ for which $\Delta_L \leq 1$ [1)]	Required quality level
62, 55	Fat 62
49, 44	Fat 49
39, 35	Fat 39
31, 28	Fat 31
25, 22	Fat 25
20 and below	Normal
Note 1: assuming m_1 and m_2 remain constant	

6.2 Designation of Quality Levels on Drawings

(1)P In order that inspection can be particularly concentrated on those parts of the structure which are critical for fatigue the following actions shall be taken:

a) Determine by calculation those regions of the structure where the fatigue strength requirement exceeds detail Category 20.
b) Indicate on the detailed drawings at all details in these regions the required quality level from table 6.11 and the direction of stress fluctuation as shown in figure 6.2.1.

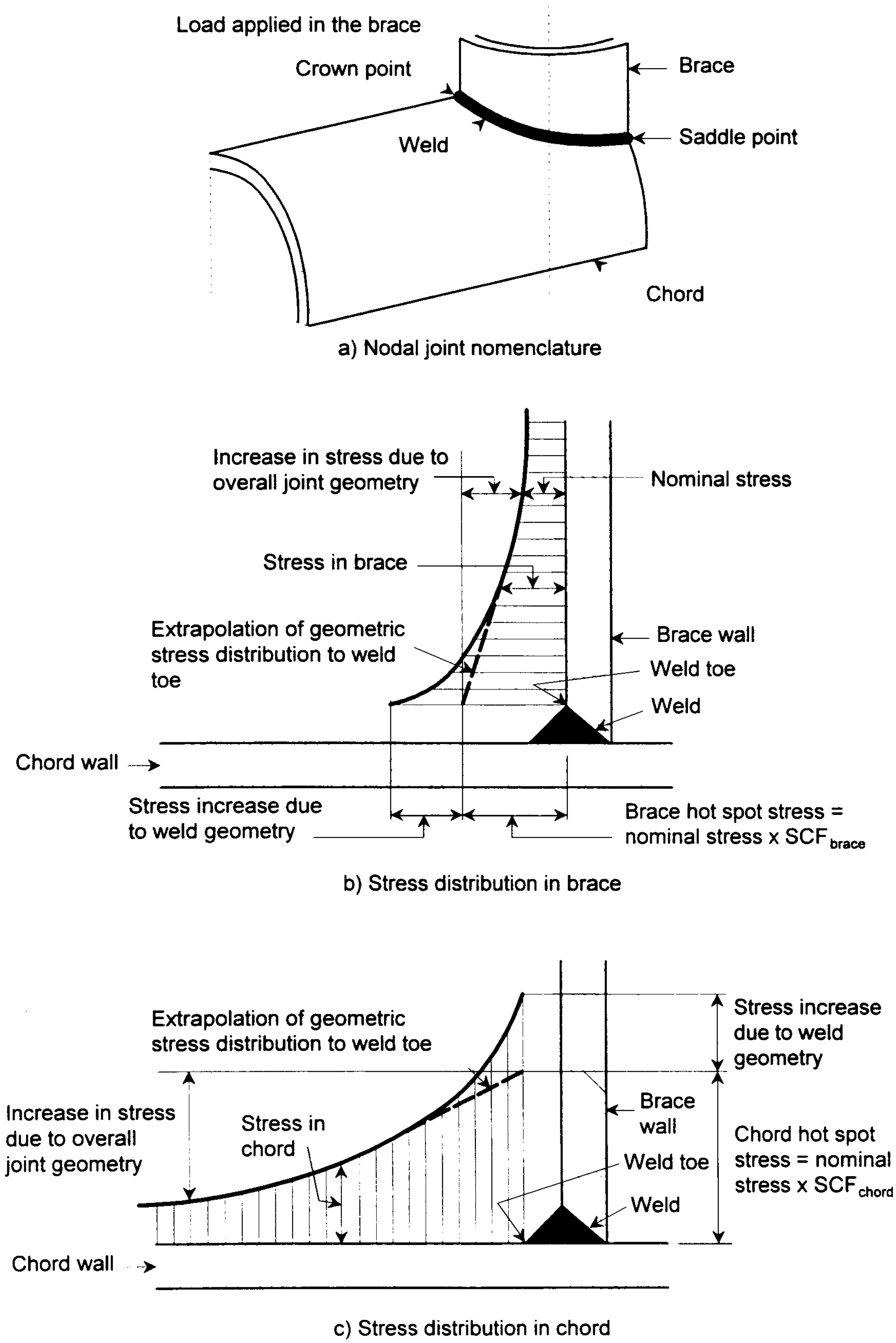


Fig.A.3.1 Example of hot spot stresses in a tubular lattice joint

Annex B [informative]:

Guidance on Assessment by fracture mechanics

B.1 Scope

(1) The objective of the annex is to provide information on the use of fracture mechanics for assessing the growth of fatigue cracks from sharp planar discontinuities. Main uses are in the assessment of:

- known flaws (including fatigue cracks found in service).
- assumed flaws (including consideration of the original joint or NDT detection limits).
- tolerance to flaws (including fitness for purpose assessment of fabrication flaws for particular service requirements).

(2) The method covers fatigue crack growth normal to the direction of principal tensile stress (Mode 1).

B.2 Principles

B.2.1 Flaw dimensions

(1) Fatigue propagation is assumed to start from a pre-existing planar flaw with a sharp crack front orientated normal to the direction of principle tensile stress fluctuation $\Delta\sigma$ at that point.

(2) The dimensions of the pre-existing flaws are shown in Figure B.2.1 depending on whether they are surface breaking or fully embedded within the material.

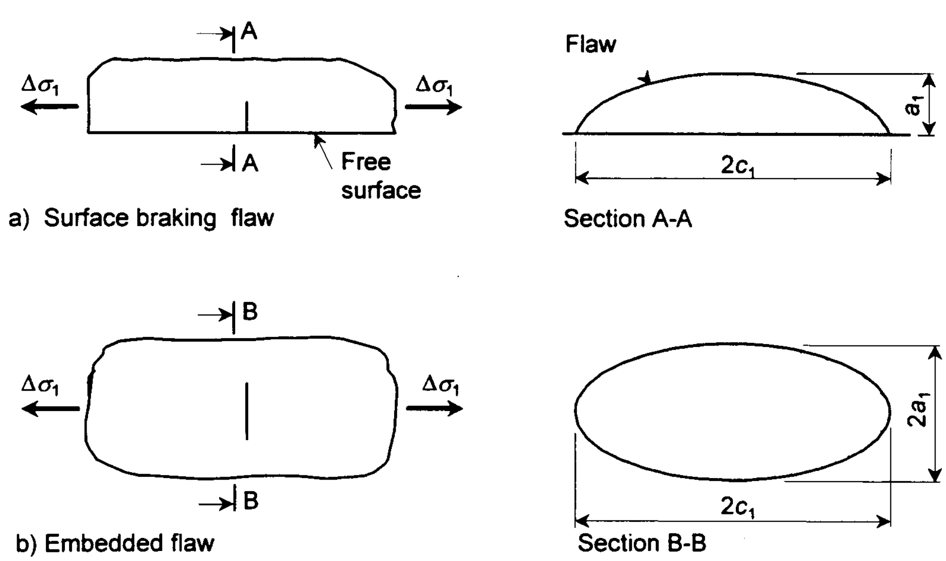


Figure B.2.1 Pre-existing planar flaws

B.2.2 Crack growth relationship

(1) Under the action of cyclic stress range $\Delta\sigma$ the crack front will move into the material according to the crack propagation law. In the direction of 'a' the rate of propagation is given by:

$$da/dN = A\,(\Delta\sigma\, a^{0,5}\, y)^{m} \qquad \text{(B.1)}$$

where A is the fatigue crack growth rate (FCGR) material constant
m is the crack growth rate exponent
y is the crack geometry factor depending on the crack shape, orientation and surface boundary dimensions.

NOTE: The most common units for stress intensity factors ΔK are $MPam^{0,5}$ ($Nmm^{-2}\, m^{0,5}$) and for crack growth rate da/dN is m/cycle. Data given in B.3. are only valid for these units.

(2) This can be rewritten in the form
$$da/dN = A\,\Delta K^{m} \qquad \text{(B.2)}$$
where ΔK is the stress intensity range and equals $\Delta\sigma\, a^{0,5}\, y$.

(3) After the application of N cycles of stress range $\Delta\sigma$ the crack will grow from dimension a_1 to dimension a_2 according to the following integration:

$$N = \int_{a_1}^{a_2} \frac{da}{A(\Delta K)^{m}}\, 1 \qquad \text{(B.3)}$$

(4) For the general case A, ΔK and m are dependent on 'a'.

(5) For further information on fracture mechanics techniques, particularly for welded structures, see References B.8.1 and B.8.2.

B.3 Crack growth data A and m

(1) A and m are obtained from crack growth measurements on standard notched specimens orientated in the LT, TL or ST direction (e.g. see Figure B.3.1) using standardised test methods (e.g. see Reference B.8.3). The specimen design must be one for which an accurate stress intensity factor (K) solution (i.e. the relationship between applied load and crack size 'a') is available.

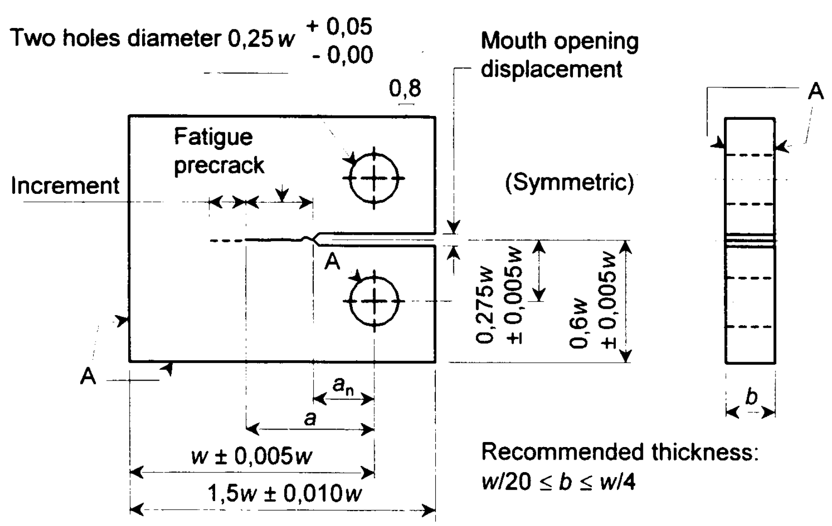


Fig.B.3.1. Typical crack growth specimen (example from ref.B.8.3)

(2) The test entails computer controlled cyclic loading of the specimen at constant applied stress intensity ratio (K_{min}/K_{max}), R, for R^c - testing conditions or at constant K_{max} for K_{max}^c - testing conditions (see ref. B.8.7) and accurate measurement of the growth of the crack from the notch.

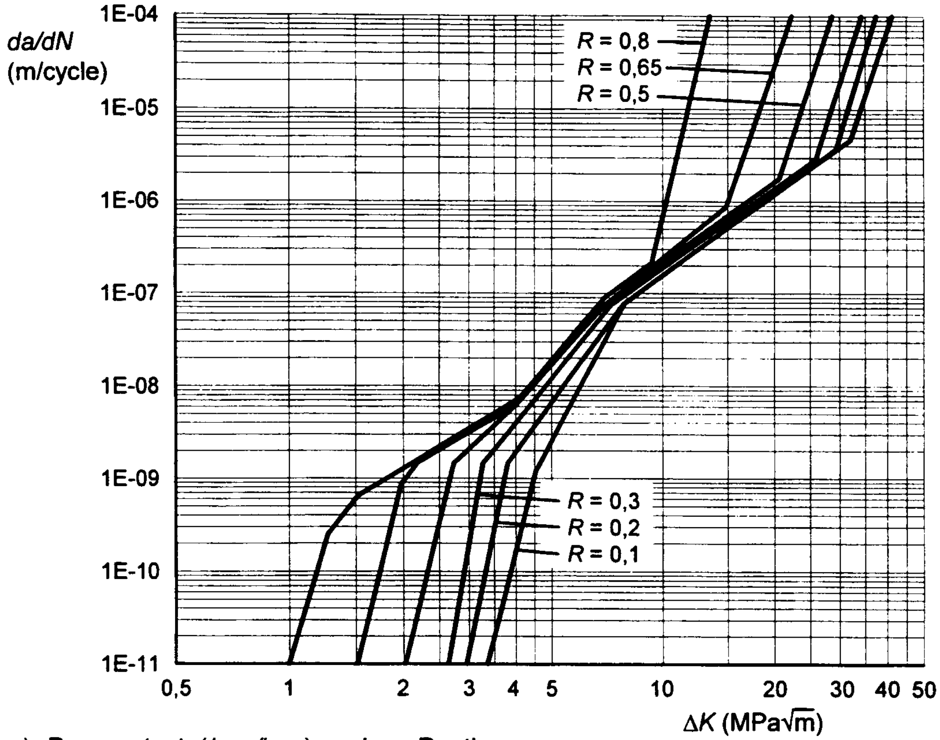
(3) If discrete values of crack length 'a' are obtained, a smooth curve is fitted to the data using the method specified in the test Standard. The crack growth rate, da/dN, at a given crack length is then calculated as the gradient of the curve at that 'a' value.

(4) The corresponding value of the stress intensity factor range, ΔK, is obtained using the appropriate K solution for the test specimen, in conjunction with the applied load range. The results da/dN versus DK are plotted using logarithmic scales.

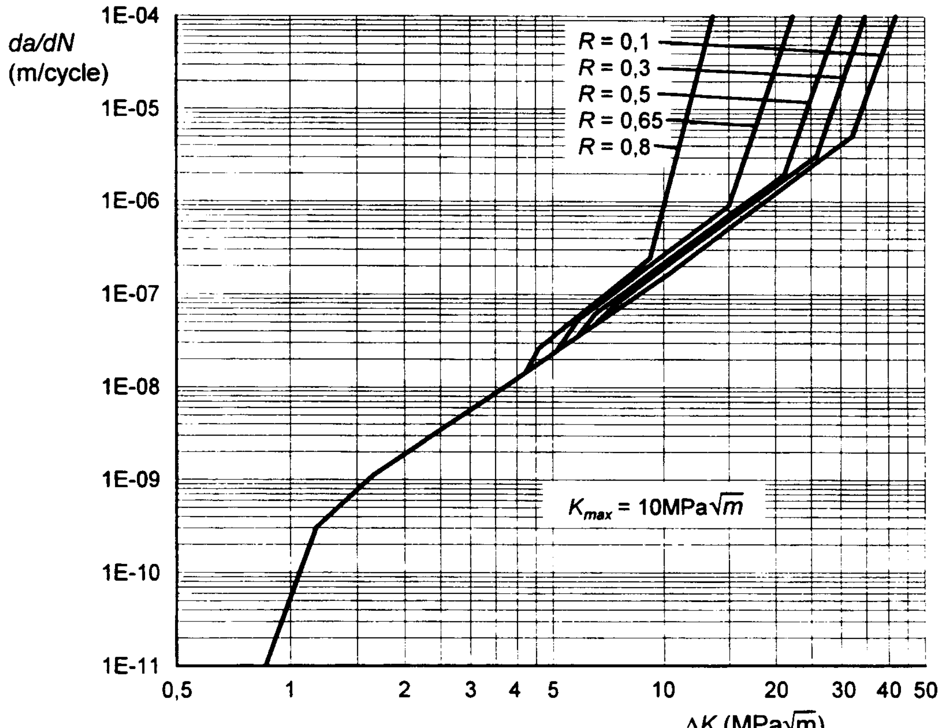
(5) For general use, crack growth curves may be required for different R values. Figure B.3.2 shows a typical set of da/dN vs ΔK curves for the aluminium extrusion alloy AA6005A-T6 (AlMgSi0.7). In Fig.B.3.2(a) the testing condition was constant ratio of stress intensity K_{min}/K_{max}, R^c, and in Fig.3.2(b) the result of a K_{max}^c - test at a constant K_{max} of 10MPa(m)$^{1/2}$ is combined with the conservative branches of the curves from Fig.B.3.2(a). This combination of the results of the R^c and the K_{max}^c data is a conservative engineering approximation and can be used for the fatigue life prediction in case of high residual tensile stresses or short fatigue crack evaluations. The values of m and A for Fig. B.3.2. are given in tables B.3.2(a) and (b).

(6) The assumption made in ref. B.8.1, equation A4-11, that the fatigue crack propagation rates of metals are proportional to the cube of the ratio of the Young's moduli with respect to steel is used as a scale to compare the FCGR of different aluminium alloys. In Fig.B.3.3(a) the R^c-FCGR of wrought aluminium alloys of R=0.1 are plotted and in Fig.B.3.3(b) the corresponding data for R=0.8 are added. Figure B.3.4 shows the set of R^c-FCGR curves of three gravity die cast alloys at R=0.1 and R=0.8. Figure B.3.5 represents the combined data of R^c and K_{max}^c - tests of wrought aluminium alloys for R=0.1 and R=0.8. The values of m and A of the upperbound FCGR envelopes for Figs.B.3.3 to B.3.5 are given in tables B.3.3 to B.3.5 respectively.

(7) Corrosive environments can effect A and m. Test data obtained under conditions of ambient humidity will be adequate to cover most normal atmospheric conditions.



a) R = constant (k_{min}/k_{max}) various R-ratios



b) k_{max} = constant (10MPa$\sqrt{m}$) various R-ratios

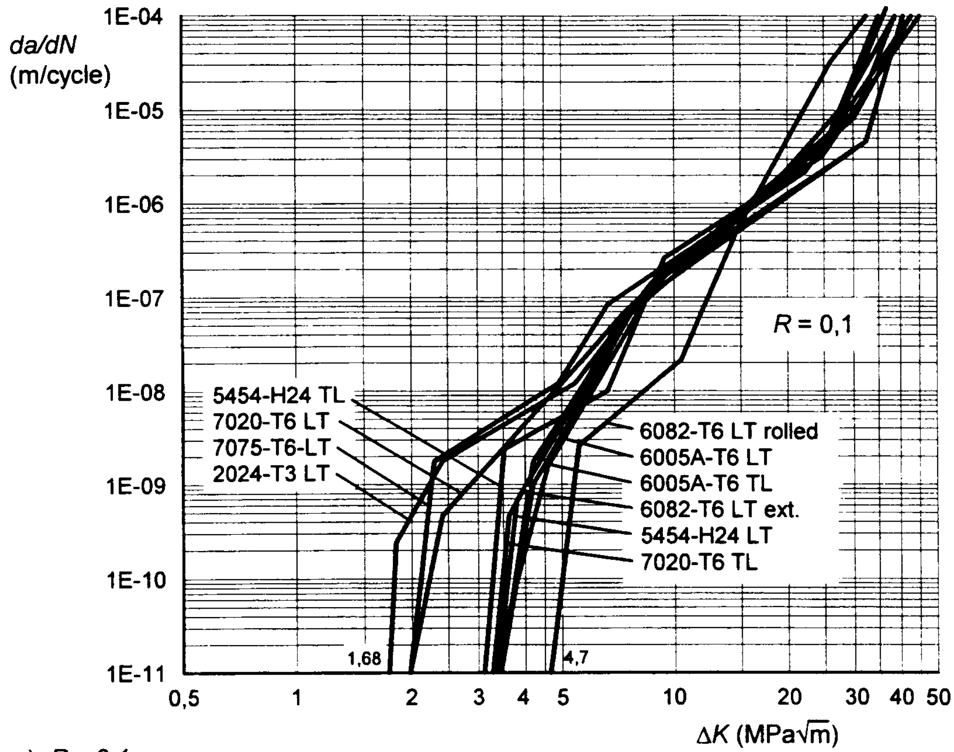
Figure B.3.2. Typical fatigue crack growth curves for aluminium alloy 6005A T6LT

Table B.3.2(a) Fatigue crack growth rate data for EN AN 6005-T6 LT, R-K_{min}/K_{max}=constant

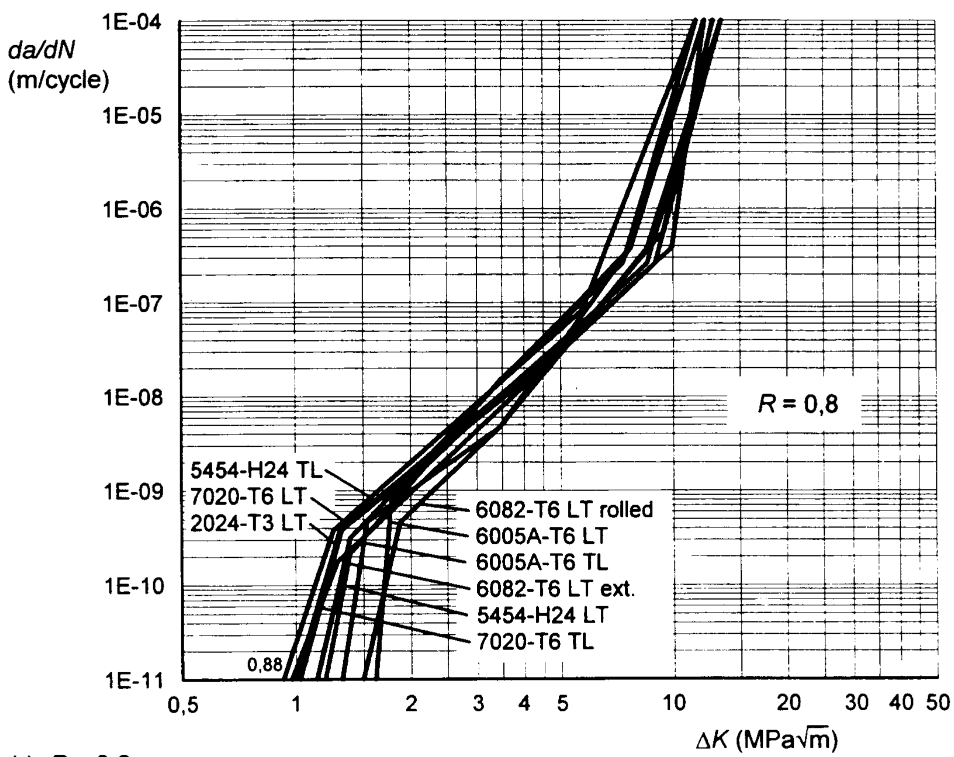
R-ratio	Stress Intensity ΔK MPam^{0,5}	m	A	R-ratio	Stress IntensityΔ ΔK MPam^{0,5}	m	A
0,100	3,30	15,00	0,1657E-18	0,500	2,00	16,29	0,1243E-15
	4,50	7,51	0,1293E-13		2,72	3,85	0,3174E-10
	8,00	2,96	0,1673E-09		4,20	4,86	0,7414E-11
	32,4	11,97	0,4100E-23		6,50	2,80	0,3406E-09
	41,61	11,97	0,4100E-23		21,00	12,23	0,1211E-21
	60,00	11,97	0,4100E-23		29,16	12,23	0,1211E-21
					42,50	12,23	0,1211E-21
0,200	2,90	18,53	0,2679E-19	0,650	1,50	16,93	0,1042E-13
	3,80	5,86	0,5949E-12		1,95	4,42	0,4418E-10
	7,50	2,92	0,2227E-09		2,20	2,38	0,2206E -09
	29,60	12,43	0,2253E-23		3,55	4,76	0,1068E-10
	37,98	12,43	0,2253E-23		6,00	3,05	0,2326E-09
	55,00	12,43	0,2253E-23		15,00	12,00	0,6084E-20
					22,17	12,00	0,6084E-20
0,300	2,60	18,67	0,1774E-18	0,800	1,00	13,03	0,9999E-11
	3,40	5,23	0,2470E-11		1,28	4.99	0,7289E-10
	7,35	2,82	0,3060E-09		1,55	2,50	0,2168E-09
	26,00	12,40	0,8411E-23		3,50	6,03	0,2611E-11
	34,49	12,40	0,8411E-23		4,60	3,11	0,2225E-09
	50,00	12,40	0,8411E-23		9,20	15,93	0,9830E-22
					13,48	15,93	0,9830E-22

Table B3.2.(b) Fatigue crack growth rate data for EN AA-6005A-T6 LT, K_{max}-100MPa(m)^{0,5} = constant

R-ratio	Stress Intensity ΔK MPam^{0,5}	m	A	Ratio	Stress Intensity ΔK MPam^{0,5}	m	A
0,100	0,85	11,09	0,6069E-10	0,500	0,85	11,09	0,6069E-10
	1,16	3,74	0,1807E-09		1,16	3,74	0,1807E-09
	1,60	2,68	0,2969E-09		1,60	2,69	0,2960E-09
	8,00	2,96	0,1673E-09		5,55	4,76	0,1081E-11
	32,40	11,97	0,4103E-23		6,50	3,05	0,2326E-09
	41,61	11,97	0,4103E-23		21,00	12,04	0,6081E-21
					29,16	12.04	0,6081E-21
0,300	0,85	11,09	0,6069E-10	0,650	0,85	11,09	0,6069E-10
	1,16	3,74	0,1807E-09		1,16	3,74	0,1807E-09
	1,60	2,71	0,2935E-09		1,60	2,69	0,2960E-09
	6,70	5,51	0,1413E-11		4,95	4,76	0,1081E-10
	7,35	2,82	0,3060E-09		6,00	3,05	0,2326E-09
	26,00	12,40	0,8421E-23		15,00	12,04	0,6081E-20
	34,49	12,40	0,8421E-23		22,17	12,04	0,6081E-20
				0,800	0,85	11,09	0,6069E-10
					1,16	3,74	0,1807E-09
					1,60	2,71	0,2927E-09
					4,15	6,01	0,2689E-11
					4,60	3,11	0.2225E-09
					9,20	15,93	0,9819E-22
					13,48	15,93	0,9819E-22

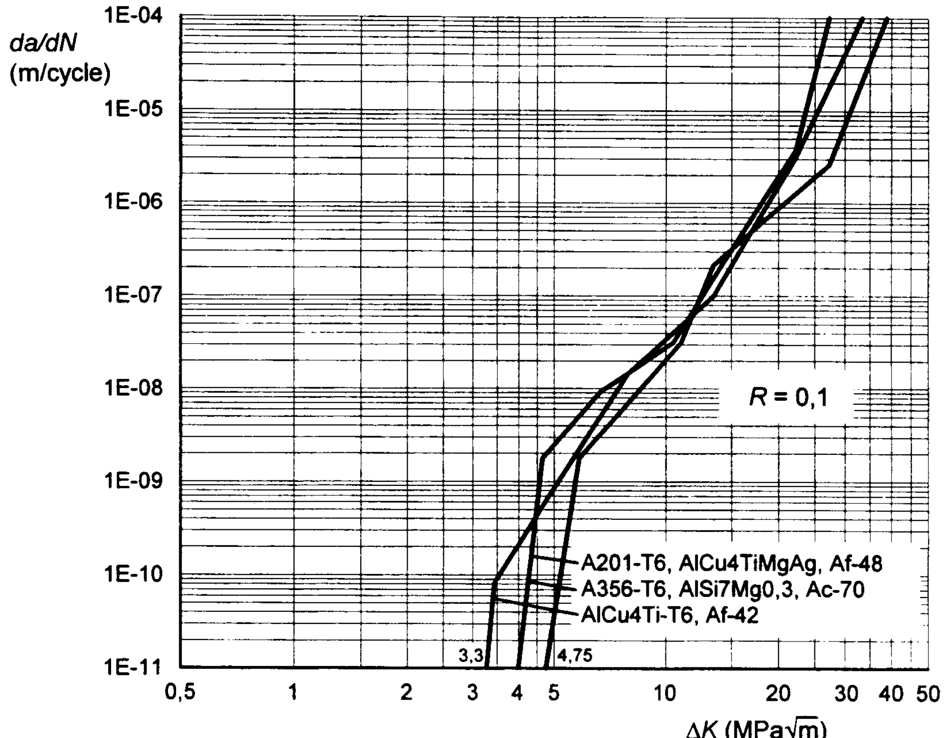


a) $R = 0{,}1$

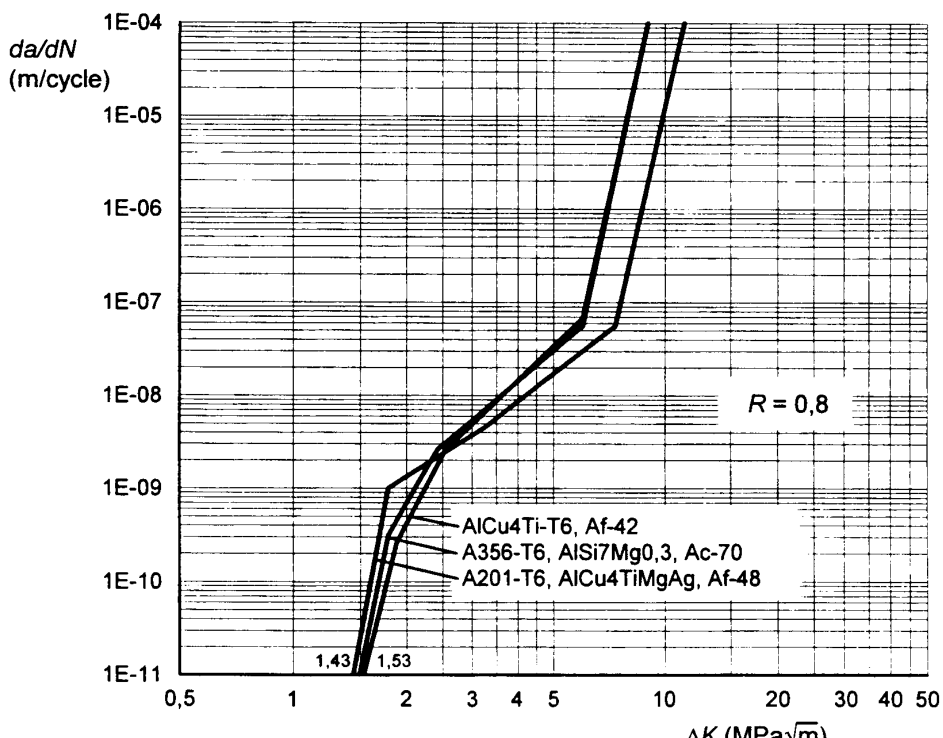


b) $R = 0{,}8$

Figure B.3.3 Typical crack growth rate curves for various wrought alloys

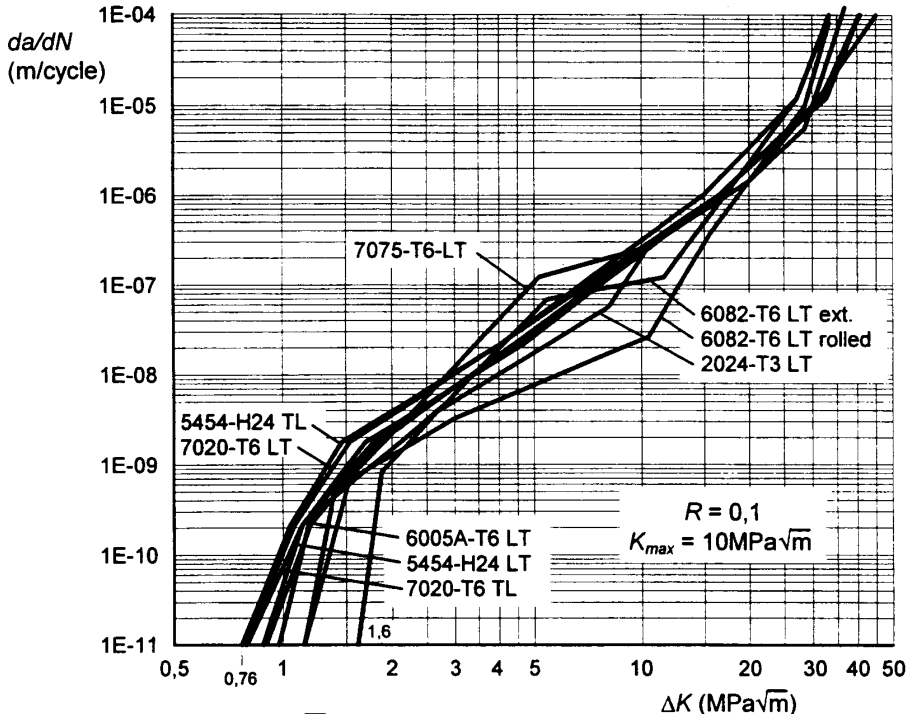


a) $R = 0{,}1$

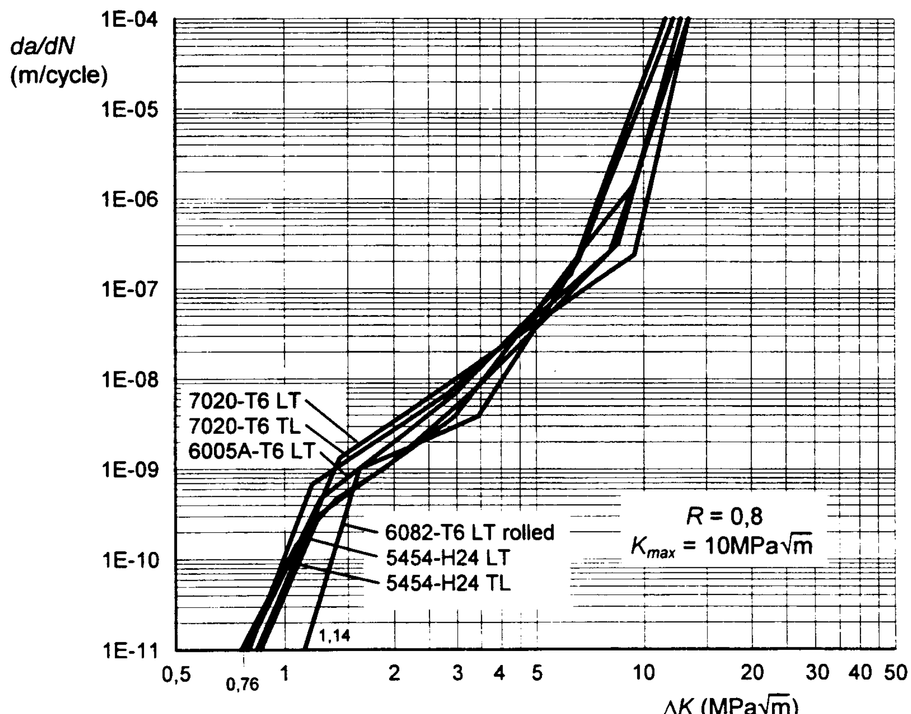


b) $R = 0{,}8$

Figure B.3.4. Typical fatigue crack growth curves for various cast alloys



a) $R = 0,1$; $k_{max} = 10 \text{MPa}\sqrt{m}$



b) $R = 0,8$; $k_{max} = 10 \text{MPa}\sqrt{m}$

Figure B.3.5 Typical fatigue crack growth curves for various wrought alloys (K_{max}) = 10 MPa $\sqrt{m}$

Table B3.3. Fatigue crack growth rate data for wrought alloys, $R = K_{min}/K_{max}$=constant

R-ratio	Stress Intensity ΔK $MPam^{0,5}$	m	A
a) 0,100	1,68	3,3	0,2541E-18
	1,89	3,4	0,4065E-10
	2,96	4,1	0,4886E-09
	4,75	6,6	0,2951E-12
	6,70	2,8	0,4838E-09
	19,51	5,9	0,4080E-13
	28,71	9,8	0,3072E-17
b) 0,800	0,87	10,43	0,4276E-10
	1,24	3,33	0,1959E-09
	2,27	2,98	0,2603E-09
	3,40	6,36	0,4155E-11
	5,44	8,34	0,1454E-12
	11,45	8,34	0,1454E-12
Note: These values are upperbound envelopes derived from the curves shown in Fig.B.3.3(a) and (b)			

Table B3.4. Fatigue crack growth rate cast alloys $R=K_{min}/K_{max}$ = constant

R-ratio	Stress Intensity ΔK $MPam^{0,5}$	m	A
a) 0,100	3,28	35,46	0,5102E-29
	3,45	11,01	0,7184E-16
	4,60	6,50	0,7051E-13
	8,85	3,85	0,2260E-10
	23,07	19,12	0,3475E-31
	27,30	19,12	0,3475E-31
b) 0,800	1,42	21,24	0,6086E-14
	1,76	5,47	0,4520E-10
	5,82	12,34	0,2537E-15
	8,70	12,34	0,2537E-15

Table B.3.5 Fatigue crack growth rate data for wrought alloys, $K_{max}=10MPa(m)^{0,5}$ constant

R-ratio	Stress Intensity ΔK $MPam^{1/2}$	m	A
0,100	0,76	9,13	0,1211E-09
	1,26	2,77	0,5266E-09
	19,50	5,95	0,4190E-13
	28,71	8,79	0,3072E-17
	34,48	8,79	0,3072E-17
0,800	0,76	9,30	0,1268E-09
	1,22	2,84	0,4560E-09
	4,37	5,28	0,1243E-10
	6,76	11,02	0,2128E-15
	11,45	11,02	0,2128E-15

B.4 Geometry Function y

(1) The geometry function y is dependent on the crack dimension (shape and size), the boundary dimensions of the surface of the surrounding material and the stress pattern in the region of the crack path.

(2) This information can be obtained from finite element analyses of the detail using crack tip elements. The stress intensity for different crack lengths is calculated using the J integral procedure. Alternatively it can be calculated from the displacement or stress field around the crack tip, or the total elastic deformation energy.

(3) Published solutions for commonly used geometries (plain material and welded joints) are an alternative source of y values. Standard data are often given in terms of Y where $Y = y\pi^{-0,5}$. A typical example for a surface breaking crack in a plain plate is shown in Figure.B.4.1.a. If the crack is located at a weld toe on the plate surface then a further adjustment for the local stress concentration effect can be made using the magnification factor M_K (see Figure.B.4.1.b).

(4) The product of Y for the plain plate and M_K for the weld toe gives the variation of y as the crack grows through the thickness of the material (see Figure.B.4.1.c).

(5) For further information on published y solutions see References B.8.1, B.8.3 and B.8.5.

B.5 Integration of crack growth

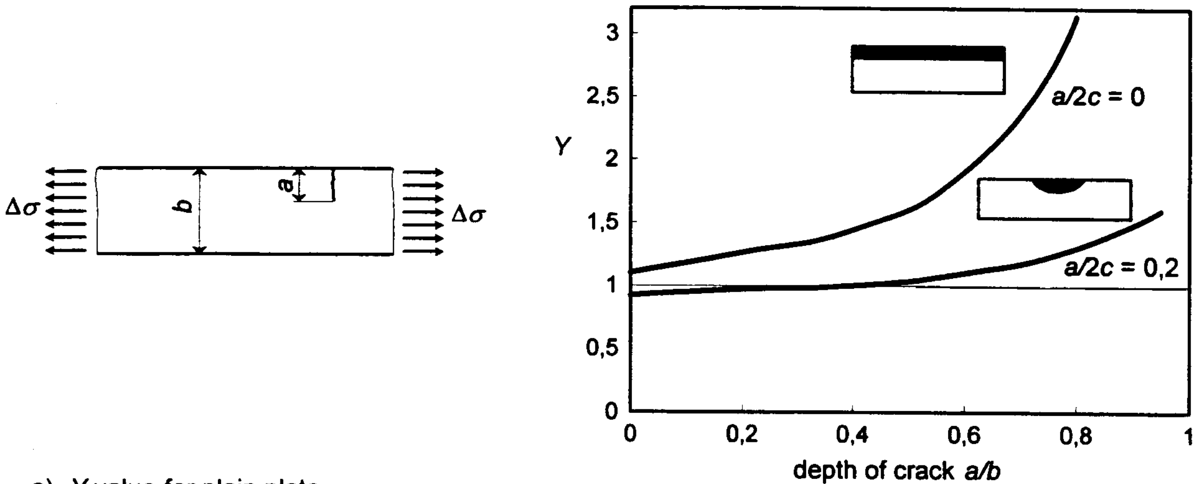
(1) For the general case of a variable amplitude stress history, a stress spectrum has to be derived (see 2.2). In practice the complete spectrum should be applied in at least 10 identical sequences with the same stress ranges and R ratios, but with one tenth of the number of cycles. The block with the greatest amplitude should be applied first in each sequence (see Figure.4.5.1). The incremental crack growth is calculated using the crack growth polygon for the appropriate R ratio, for each block of constant amplitude stress cycles.

(2)In the region of welds, unless the residual stress pattern is actually known, either a high R-ratio ($R = 0,8$) or a K_{max} constant crack growth curve should be used.

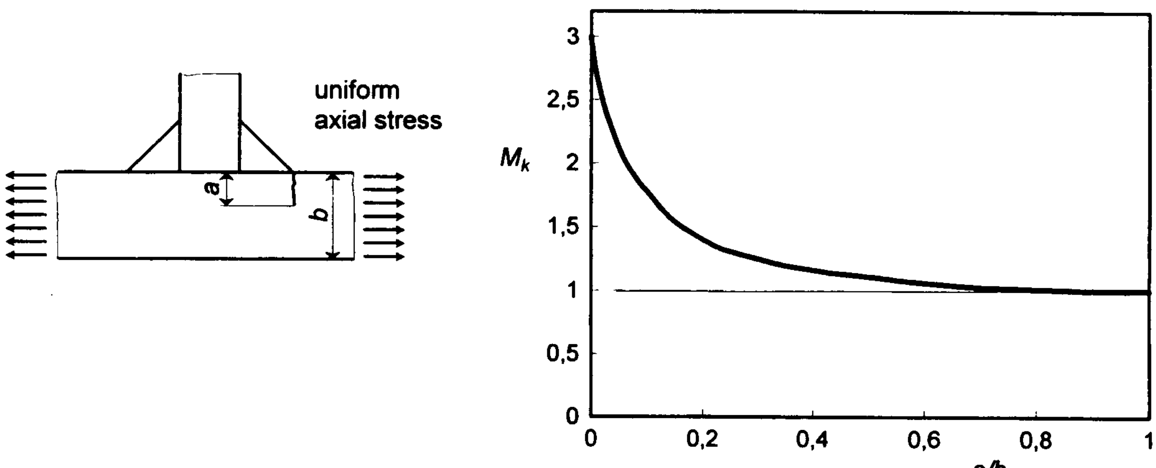
(3) The crack length 'a' is integrated on this basis over until the maximum required crack size a_2 is reached and the numbers calculated.

B.6 Assessment of maximum crack size a_2

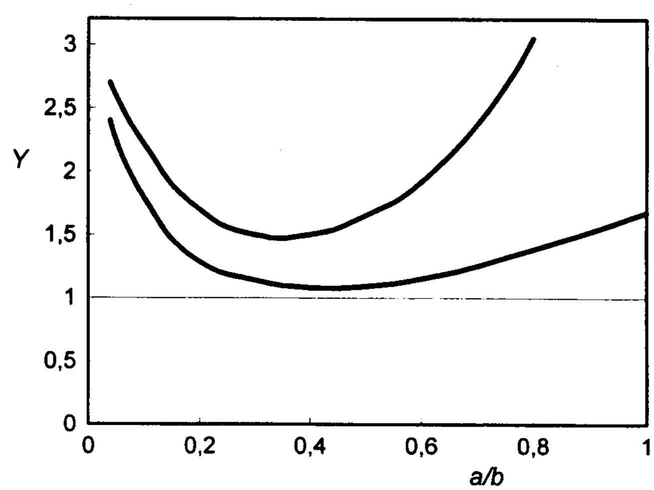
(1) This will usually be determined on the basis of net section ductile tearing under the maximum applied tensile load with the appropriate partial factor (see Part 1 of this Prestandard). For further information on fracture toughness see References B.8.1 and B.8.2.



a) *Y* value for plain plate



b) M_k value for weld toe stress concentration



c) *Y* for welded joint

Figure B.4.1. Use of typical standard geometry solutions for y

B.7 Calculations for initial crack length, a_i, based on Annex B fatigue crack growth rate data FCGR and the fatigue reference stresses at 2 Million Cycles for a semi-circular surface crack

(1) The calibrated initial fatigue crack length, a_i, were determined for the fatigue reference stress ranges at 2 million cycles in case of (1) a uniform tension and (2) a stress gradient. The proposed conservative envelope of the fatigue crack growth curves as shown in Figs.B.3.3-B.3.5 and listed in tables B.3.3 to B.3.5 were used. The fracture mechanics model was a half disk surface crack in a 12mm thick and 200mm wide plate subjected to the two loading cases (see Fig.B.7.1).

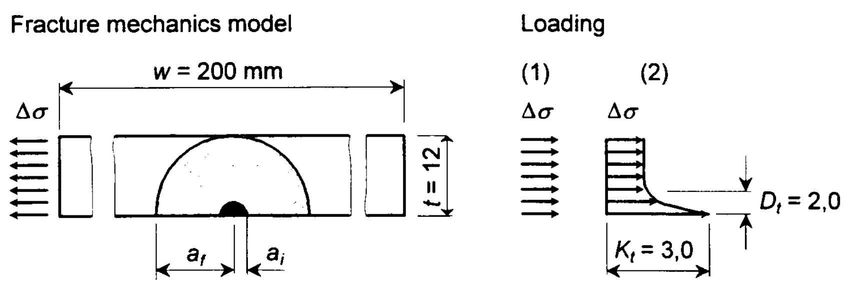


Figure B.7.1. Crack geometry and stress distributions for calculation of crack lengths for a semi-circular surface crack

(2) The two loading cases were:

Loading case 1: Uniform Tension Stress Range, $\Delta\sigma$= 80N/mm^2
(reference stress range at 2 x 10^6 cycles)

Loading case 2:Stress Gradient, K_t = 3,0, D_t = 2,0mm, $\Delta\sigma$ = 80N/mm^2
(K_t at surface 3,0 and 2.0mm below surface, 1,0, decay parabolic, DCF5)

(3) The following fatigue crack growth rate curves (FCGR) were used:

1) WAA Wrought alloy	$R = K_{min}/K_{max}$ = const.,	R = 0,1 and R = 0,8
2) WAA Wrought alloy	K_{max} = 10MPa(m)^{0,5} const.,	R = 0,1 and R = 0,8
3) Cast alloy	$R = K_{min}/K_{max}$ = const.,	R = 0,1 and R = 0,8
4) AA6005A-T6LT	$R = K_{min}/K_{max}$ = const.,	R = 0,1 and R = 0,8
5) AA6005A-T6LT	K_{max} = 10MPa(m)^{0,5} const.,	R = 0,1 and R = 0,8

(4) Fatigue crack propagation was studied in two phases:

Phase 1: Initial crack length a_i = 0,05mm, final crack length, a_f = 2,05mm
Phase 2: Initial crack length a_i = 2,0mm, final crack length, a_f = 12,mm

(5) The surface stress of three times the global stress decreases parabolically, reaches the global stress 2mm below the surface and remains constant through the rest of the thickness at the same reference stress range as in the first case. The fatigue life is equal to the fatigue crack growth from the initial crack length, a_i, to the final crack length, a_f, given by the plate thickness. The phenomenon of short crack fatigue crack propagation is approximated by using the K_{max} constant FCGR curves in the region, where the crack length is smaller than 2mm. From 2mm upwards the FCGR curves corresponding to the applied R ratio ($R=K_{min}/K_{max}$) are used. In the case of the cast aluminium alloys the K_{max} constant curves were approximated by the R = 0,8 curve of the R constant FCGR set.

(6) Tables B.7.1.(a) and (b), for wrought and cast alloys respectively, show variations in predicted maximum tolerable initial crack size as a function of fatigue reference stress range, R-ratio and stress pattern.

(7) Tables B.7.2 to B.7.5. show the variations in predicted fatigue life under a stress range of 80N/mm^2 as a function of initial crack length a_i, fatigue crack growth curve. R-ratio and stress pattern have been used.

B.8 References

B.8.1 IIW guidance on assessment of the fitness for purpose of welded structures. IIW Draft for Development doc. SST-1157-90.

B.8.2 Guidance on some methods for the derivation of acceptance levels for detects in fusion welded joints. British Standard Published Document 6493:1991.

B.8.3 Standard test method for measurement of fatigue crack growth rates, ASTM E647-93.

B.8.4 Fatigue crack propagation in aluminium, IIW Document XIII-B77-90.

B.8.5 Stress intensity factor equations for cracks in three-dimensional finite bodies. ASTM STP 791, 1983, ppI-238 - I-265.

B.8.6 Graf, U: 'Fracture mechanics parameters and procedures for the fatigue behaviour estimation of welded aluminium components', 1992.

B8.7`Simulations of short crack and other low closure loading conditions utilising contact K_{max} ΔK-decreasing fatigue crack growth procedures. ASTM STP 1149-1992, pp.197-220.

Table B.7.1. Predicted inital crack length a_i for various stress ranges at 2 x 10^6 cycles

a) Wrought aluminium alloys
Upperbound fatigue crack growth data from tables B.3.3 and B3.5.

Stress Range	Uniform Tension		K_t=3.0, Dt=2.0mm, DCF5]	
Stress intensity ratio R:	0,1	0,8	0,1	0,8
N/mm²	mm	mm	mm	mm
16	8,57	6,68	6,28	4,06
20	6,63	4,79	4,00	1,99
25	4,82	3,00	2,19	0,266
25 1)	-	-	0,11	0,11
31	3,22	1,42	0,44	0,07
31 1)	-	1,42	0,051	0,051
39 1)	1,24	0,52	0,025	0,025
49 1)	0,30	0,26	0,014	0,014
62 1)	0,14	0,13	0,0073	0,0073
77 1)	0,078	0,075	-	-
96 1)	0,042	0,042	-	-
121 1)	0,023	0,023	-	-

Note 1: FCGR: WAA K_{max} 10MPa(m)^{0,5} one single phase, i.e. FCG from a_i up to the plate thickness of 12mm

b) Cast aluminium alloys
Upperbound fatigue crack growth rate from table B.3.4.

Stress Range	Uniform Tension		K_t=3.0, Dt=2.0mm, DCF5]	
Stress intensity ratio R:	0,1	0,8	0,1	0,8
N/mm²	mm	mm	mm	mm
16	11,99	6,46	11,99	3,33
20	11,88	4,49	11,56	1,83
25	10,99	2,97	9,09	0,391
31	8,87	1,92	5,90	0,200
39	6,51	1,17	3,32	0,1067
49	4,48	0,71	0,072	0,062
62	2,86	0,42	0,036	0,035
77 1)	1,80	-	-	-
77	0,295	0,259	0,022	0,0219
96 1)	1,082	-	-	-
96	0,162	0,159	-	-
121 1)	0,621	-	-	-
121	0,096	0,095	-	-

Note 1: FCGR CAA R constant, R = 0,1, 1 single phase, ie FCG from a_i up to the plate thickness of 12mm

Table B.7.2 Fatigue life predictions based on upperbound fatigue crack growth data for wrought aluminium alloys from tables B.3.3 and B3.5

a) Uniform tension - Phase 2					
Type of FCGR:		$R=K_{min}/K_{max}$ = constant		K_{max} = 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress intensity range, MPam^{0,5}	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life cycles
12,00	13,88	-	-	-	-
11,00	12,97	1 428	3	1 411	2
10,00	12,03	3 172	8	3 131	6
9,00	11,08	5 347	17	5 271	15
8,00	10,12	8 123	37	7 996	40
7,00	9,16	11 749	80	11 545	110
6,00	8,20	16 614	185	16 293	336
5,00	7,25	23 258	464	22 854	1 163
4,00	6,30	33 728	1 312	32 319	4 295
3,00	5,31	61 317	3 452	46 887	12 007
2,00	4,25	149 999	16 791	71 997	33 860

b) Stress gradient - Phase 2					
Type of FCGR:		$R=K_{min}/K_{max}$ = constant		K_{max} = 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress Intensity Range, MPam^{0,5}	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles
12,00	15,61	-	-	-	-
10,00	14,65	2 027	2	2 009	1
9,00	14,00	3 214	3	3 184	2
8,00	13,26	4 580	6	4 535	3
7,00	12,42	6 196	10	6 130	6
6,00	11,51	8 166	17	8 070	12
5,00	10,51	10 655	31	10 516	28
4,00	98,42	13 950	64	13 745	77
3,00	8,19	18 618	158	18 303	275
2,00	6,72	26 049	547	25 524	1 590

Table B.7.3. Fatigue life predictions based on upperbound fatigue crack growth data for cast aluminium alloys from table B.3.4 and wrought alloy AA 6005A-T6 from table B.3.2(a)

a) Uniform tension - Phase 2

Type of FCGR:		CAA $R=K_{min}/K_{max}$ = constant		AA6005A $R=K_{min}/K_{max}$ = constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress intensity range, $MPam^{0,5}$	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life cycles
12,00	13,88	-	-	-	-
11,00	12,97	2'016	0	2 725	11
10,00	12,03	4'670	0	6 092	47
9,00	11,08	8'267	0	10 346	172
8,00	10,12	13'294	1	15 849	681
7,00	9,16	20'552	4	23 148	3 031
6,00	8,20	32'302	16	33 107	8 369
5,00	7,25	57'146	63	50 251	16 049
4,00	6,30	116'025	312	96 452	27 648
3,00	5,31	279'046	1'692	246 958	46 490
2,00	4,25	938'072	6'154	997 170	83 056

b) Stress gradient - Phase 2

Type of FCGR:		CAA $R=K_{min}/K_{max}$ = constant		AA6005A $R=K_{min}/K_{max}$ = constant	
Stress intensity ratio R:		0.1	0.8	0.1	0.8
Crack length, a_i mm	Stress intensity range, $MPam^{0,5}$	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles
12,00	15,61	-	-	-	-
11,00	15,19	1 182	0	1 808	1
10,00	14,65	2 517	0	3 793	3
9,00	14,00	4 081	0	6 035	7
8,00	13,26	5 978	0	8 636	16
7,00	12,42	8 367	0	11 742	38
6,00	11,51	11 505	0	15 572	109
5,00	10,51	15 835	1	20 477	383
4,00	9,42	22 202	3	27 074	1 776
3,00	8,19	33 164	13	36 609	6 769
2,00	6,74	64 980	94	59 496	15 333

Table B.7.4. Fatigue life predictions based on upperbound fatigue crack growth data for wrought aluminium alloys from table B.3.3. and wrought alloy AA 6005A-T6 from table B.3.2.(b)

a) Uniform tension - Phase 1					
Type of FCGR:		WAA K_{max} 10MPa(m)^{0,5} const.		AA6005A K_{max} 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress intensity range, MPam^{0,5}	Fatigue life, cycles	Fatigue life cycles	Fatigue life, cycles	Fatigue life, cycles
2,05	4,30	-	-	-	-
1,85	4,07	7 139	7 527	14 355	13 409
1,65	3,83	15 518	16 395	31 119	29 712
1,45	3,58	25 527	27 031	51 031	49 116
1,25	3,32	37 759	40 089	75 212	72 732
1,05	3,03	53 169	56 627	105 451	102 341
0,85	2,72	73 424	78 502	144 855	141 042
0,65	2,38	101 802	109 388	199 471	194 885
0,45	1,98	146 015	158 005	283 365	278 004
0,25	1,47	231 455	253 422	444 329	438 619
0,05	0,66	5 561 901	5 604 650	19 522 952	19 515 242

b) Stress Gradient - Phase 1					
Type of FCGR:		WAA K_{max} 10MPa(m)^{0,5} const.		AA6005A K_{max} 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress itensity range, MPam^{0,5}	Fatigue life, cycles	Fatigue life cycles	Fatigue life, cycles	Fatigue life, cycles
2,05	6,82	-	-	-	-
1,85	6,70	1 905	673	3 995	2 335
1,65	6,61	3 877	1 395	8 124	4 760
1,45	6,55	5 923	2 170	12 405	7 290
1,25	6,48	8 015	2 978	16 778	9 883
1,05	6,36	10 188	3 847	21 316	12 591
0,85	6,08	12 553	4 869	26 240	15 567
0,65	5,71	15 315	6 243	31 964	19 112
0,45	5,14	18 765	8 350	39 063	23 666
0,25	4,10	24 176	13 294	50 033	31 961
0,05	1,99	42 254	32 843	85 148	66 467

Table B.7.5. Fatigue life predictions based on upperbound fatigue crack growth data for cast aluminium alloys from table B.3.4.

a) Uniform tension - Phase 1			
Stress intensity ratio R:		0,1	0,8
Crack length, a_i mm	Stress intensity range, $MPa(m)^{0,5}$	Fatigue life, cycles	Fatigue life, cycles
2,05	4,30	-	-
1,85	4,07	398 937	1 736
1,65	3,83	1 154 022	4 119
1,45	3,58	2 688 305	7 506
1,25	3,32	7 563 667	12 541
1,05	3,03	99 972 200	20 495
0,85	2,72	3,630109E+09	34 172
0,65	2,38	3,462941E+11	60 895
0,45	1,98	1,719760E+14	125 648
0,25	1,47	3,335859E+18	1 3278 202
0,05	0,66	1,680181E+30	6,315015E+12

b) Uniform tension - Phase 1			
Stress intensity ratio R:		0,1	0,8
Crack length, a_i mm	Stress intensity range, $MPa^{0,5}$	Fatigue life, cycles	Fatigue life, cycles
2,05	6,82	-	-
1,85	6,70	11 723	47
1,65	6,61	24 415	101
1,45	6,55	38 268	165
1,25	6,48	52 852	235
1,05	6,36	68 809	319
0,85	6,08	88 282	442
0,65	5,71	116 339	685
0,45	5,14	163 937	1 100
0,25	4,10	335 864	2 136
0,05	1,99	1,638740E+13	17 145

Annex C (Informative)

Testing for Fatigue Design

C.1 Derivation of loading data

C.1.1 Fixed structures subject to mechanical loading

(1) This includes structures such as bridges, crane girders and machinery supports. Existing similar structures subject to the same loading sources may be used to obtain the amplitude, phasing and frequency of the applied loads.

(2) Strain, deflection or acceleration transducers fixed to selected components which have been calibrated under known applied loads can record the force pattern over a typical working period of the structure, using analog or digital data acquisition equipment. The components should be selected in such a way that the main loading components can be independently deduced using the influence coefficients obtained from the calibration loadings.

(3) Alternatively load cells can be mounted at the interfaces between the applied load and the structure and a continuous record obtained using the same equipment.

(4) The mass, stiffness and logarithmic decrement of the test structure should be within 30% of that in the final design and the natural frequency of the modes giving rise to the greatest strain fluctuations should be within 10%. If this is not the case the loading response should be subsequently verified on a structure made to the final design.

(5) The frequency component of the load spectrum obtained from the working period should be multiplied by the ratio of the design life to the working period to obtain the final design spectrum. Allowance for growth in intensity or frequency, or statistical extrapolation from measured period to design life should also be made as required.

C.1.2 Fixed structures subject to environmental loading

(1) This includes structures such as masts, chimneys, and offshore topside structures. The methods of derivation of loading spectrum are basically the same as in C.1.1 except that the working period will generally need to be longer due to the need to obtain a representative spectrum of environmental loads such as wind and wave loads. The fatigue damage tends to be confined to a specific band in the overall loading spectrum due to effects of fluid flow induced resonance. This tends to be very specific to direction, frequency and damping. For this reason greater precision is needed in simulating both the structural properties (mass, stiffness and damping) and aerodynamic properties (cross-sectional geometry).

(2) It is recommended that the loading is subsequently verified on a structure to the final design if the original loading data are obtained from structures with a natural frequency or damping differing by more than 10%, or if the cross-sectional shape is not identical.

(3) A final design spectrum can be obtained in terms of direction, intensity and frequency of loading, suitably modified by comparing the loading data during the data collection period with the meteorological records obtained over a typical design life of the structure.

C.1.3 Moving structures

(1) This includes structures such as travelling cranes and other structures on wheels, vehicles and floating structures.

APPENDIX D

Excerpts from
Manual of Standards and Recommended Practices Section C – Part II
Association of American Railroads

1.0 Copyright Release and Limitations on Liability

2.0 Introduction

The fatigue design information is contained within Chapter VII of the design code published by the AAR. In addition to the information contained in this appendix, the AAR design manual also contains information for the fatigue design of steel details. This is similar to the information for the aluminum details. Unlike any of the other design codes investigated for this report, the AAR design manual also contains a tremendous amount of environmental loading data for various types of railroad cars. Contained in nearly 200 pages, this provides the railroad designer with consistent data for the development of details subjected to fatigue.

Chapter VII
FATIGUE DESIGN OF NEW FREIGHT CARS
SECTION 7.1 ADMINISTRATIVE PROVISIONS

7.1.1. PURPOSE AND SCOPE

7.1.1.1. GENERAL

This interim specification is a guideline for fatigue analysis of freight cars and is not intended to supersede or make obsolete any existing AAR design requirement. In general, existing, specifications are concerned with static and high impact loads. However, when a member or connection is subjected to fluctuating stresses, failure can occur under stresses considerably lower than those that would cause failure under steady conditions. This guideline gives the designer or analyst a method for estimating the fatigue life of a freight car or component when subjected to fluctuating stresses. The accuracy of fatigue analysis is however not as high as that of static stress analysis. While fatigue analysis methods give an indication of the adequacy of the design from a fatigue viewpoint, the actual life estimates must be utilized with caution.

7.1.1.2. RELATED SPECIFICATIONS AND PUBLICATIONS

Portions of the following specification and publications form a part of this guideline where applicable:

1. ASTM Standards
2. AWS welding symbols
3. AAR Specification for Tank Cars

7.1.2. ANALYSIS REQUIREMENTS

7.1.2.1. MILEAGE CRITERIA FOR ANALYSIS

The purpose of this fatigue design specification is to provide assurance that a proposed car design that is not similar to an approved design in service, or has modifications not contemplated in the original design, will meet the high utilization or full-interchange mileage criteria specified below. In addition to the basic strength requirements for modifications or "new appurtenances" discussed in Section 1.2, a demonstration of satisfactory fatigue strength or life relative to an approved design, detail or modification already in satisfactory service is required. Generally, the demonstration of basic strength of appurtenances or structural modifications under static and/or impact loading alone is not sufficient.

The following mileage criteria are to be used to determine the acceptability of fatigue life estimates:

Unit train and high utilization cars—3,000,000 miles

General interchange—1,000,000 miles

7.1.2.2. CAR TYPES REQUIRING FATIGUE ANALYSIS

This specification will ultimately apply to all car types. In order to perform the analysis, it is necessary to have relevant environmental data. If these data are not available, then a fatigue review or analysis based on a comparison to a similar car type which has demonstrated satisfactory field performance in similar service is acceptable. For a radically new car design, it must be demonstrated that fatigue life has been considered. Application of fatigue analysis to the following car types is mandatory: 70 ton boxcars, 100 ton special service high side gondola cars, 100 ton open top hopper cars and 100 ton tank cars.

7.1.2.3. COMPONENTS REQUIRING FATIGUE ANALYSIS

Based on a survey of fatigue failures, the following components and their attachments require fatigue analysis. This does not preclude fatigue analyses of other possible critical components in new designs.

1. Bolsters
2. Center sills and stub center sills
3. Buff and draft attachments and supports
4. Box car doorway area
5. Side sills on center sill-less cars
6. Covered hopper car roofs
7. Covered hopper car interior partitions
8. Automobile rack car side sills
9. Flat car trailer hitch supports

7.1.3. ANALYSIS METHODS

The fatigue analysis methods used in the guideline are not considered the only methods available. Many other methods have been proposed, but only those generally accepted and proven over a wide range of test cases will be accepted in place of these methods. Those wishing to use methods other than these must be able to verify the methods' general acceptance in the field of fatigue analysis.

7.1.4. GLOSSARY OF TERMS

α — Fraction of the total number of cycles applied at given stress levels $S_{max\ i}$ and $S_{min\ i}$.

β — Total number of spectrum cycles per mile.

b — Fatigue limit for stress ratio R = o; The y-axis intercept on modified Goodman diagram curve.

k — Absolute value of the slope of the S-N curve.

m — Slope of the modified Goodman diagram curve.

N' — Number of cycles applied at a given level of stress.

N_e — Number of cycles to produce failure at a given level of stress.

N — Number of cycles which produces failure at a stress level of S_e.

N_T — Fatigue life (total number of cycles to failure) under a given spectrum loading.

N'_i — Number of cycles applied at each level of $S_{max\ i}$ and $S_{min\ i}$.

N_i — Number of cycles to produce failure at each level of $S_{max\ i}$ and $S_{min\ i}$.

R — Stress ratio, S_{min}/S_{max}.

S_e — Fatigue limit or stress which produces failure in N_e cycles (N_e assumed 2 x 10^6 cycles for steel).

S_i — Fatigue limit computed for failure at N_i cycles.

S_{max} — Maximum or highest algebraic applied stress.

S_{min} — Minimum or lowest algebraic applied stress.

S_r — Range of stress. The algebraic difference between the maximum and minimum stress in one cycle, that is, $S_r = S_{max} - S_{min}$

K_i — Theoretical stress concentration factor.

K_f — Fatigue notch factor.

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SECTION 7.2 FATIGUE ANALYSIS METHODS

7.2.1. GENERAL

The methodologies presented in this section provide two generally acceptable approaches to fatigue analysis. The preferable of the two is to use nominal stresses and an applicable member detail. One shortcoming of this approach is the limited number of details available. However, the selection of details should be broad enough to allow their use to be expanded for analysis of similar but not exactly matching details. Great care will be required in the selection of the "closest" detail. When doubt exists among several choices, the more conservative properties should be used or the second approach should be taken.

The second approach should be used when a member detail cannot be found to match even approximately the detail under analysis. This method involves determining the local stresses or strains thru the use of concentration factors in combination with basic material fatigue properties. Since great care is required in establishing notch factors and material properties in the weld region, this method is not recommended for use with welds.

7.2.2. ANALYTICAL METHOD USING APPLICABLE FATIGUE PROPERTIES OF MEMBERS AND DETAILS

7.2.2.1. ASSUMPTIONS

1. Miners linear cumulative damage rule using nominal stresses and experimental data applies.
2. Nominal stresses are below the yield strength of the material.
3. Nominal stresses are accurately determined analytically or experimentally.
4. Detail being analyzed corresponds realistically to the detail chosen from Section 7.4.
5. S-N curve is a straight line on log-log paper from 100,000 cycles to 2,000,000 cycles for steels and 100,000 cycles to 10,000,000 cycles for aluminum alloys, with a slope independent of the stress ratio, R.
6. Fatigue limit, S_e, for steels is reached at 2,000,000 cycles, and for aluminum alloys at 10,000,000 cycles.
7. Order of load application for environmental spectrums will not affect fatigue damage accumulation.
8. The modified Goodman diagrams have constant slope and are truncated at the yield point of the material.
9. If the minimum stress has greater absolute value than the maximum stress for a given cycle, the cycle is considered as a complete reversal (R = –1.0) cycle with a maximum stress equal to ½ the range of stress. For example, if the actual maximum stress of a cycle is –5,000 psi and the minimum stress is –20,000 psi, then the maximum stress will be taken as [–5,000 – (–20,000)] ÷ 2 = 7,500 psi.
10. The values of the stress ratio, $R = S_{min}/S_{max}$ vary from –1.0 to +1.0 inclusive.
11. No previous fatigue damage has occurred in the detail being analyzed.
12. Failure in fatigue has occurred when a crack is detected by the unaided eye.

7.2.2.2. DERIVATION OF EQUATIONS

According to the linear cumulative damage hypothesis, every time a component is stressed to a given level above the fatigue limit for the detail at the applied stress ratio, a known amount of damage is incurred. Consequently, it is assumed that failure from fatigue will result when the summation of the "increments of damage" equals unity. If N' represents the number of cycles applied at some damaging stress level and N represents the number of cycles at that same stress level which would result in failure, then failure occurs when:

$$\frac{N_i'}{N_i} = 1 \quad \text{.......(1)}$$

If N_T represents the total number of cycles to failure of a component under a spectrum of loads, it is convenient to denote the fraction of the total number of cycles applied at each stress level by a. Therefore $N_i = \alpha_I N_T$ and equation (1) may be rewritten:

$$N_T \quad \frac{\alpha_i}{N_i} = 1 \quad \text{.......(2)}$$

A relationship for the fatigue life under spectrum loading may now be expressed as:

$$N_T = \frac{1}{\frac{\alpha_i}{N_i}} \quad \text{.......(3)}$$

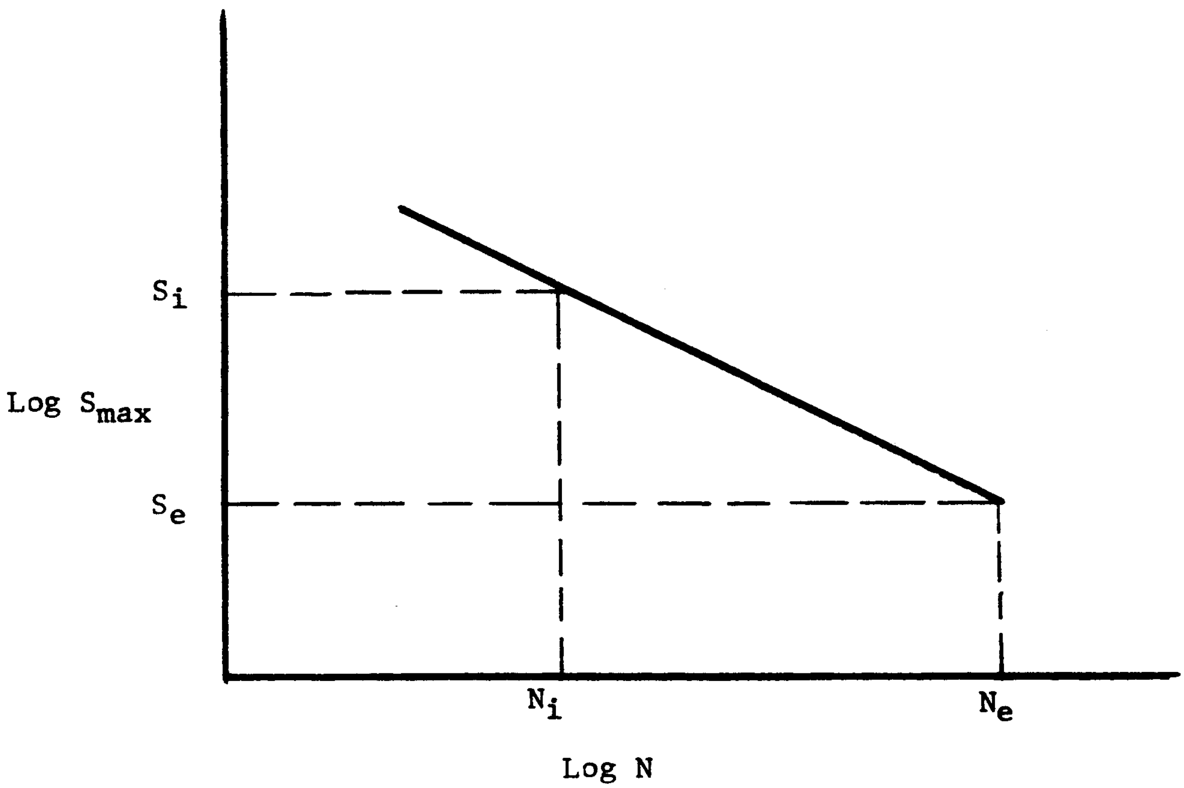
where N_T is the total number of spectrum cycles and not just cycles at damage producing stress levels. In actual calculations, however, only the cycles at damage producing levels (above the fatigue limit) are included in the summation of equation (3). Cycles at stress levels below the fatigue limit are not included since they are assumed to do no damage.

The fatigue limit stresses shown in the fatigue properties table of Section 7.4 can be used to determine the damaging stress levels. From the stress spectrums derived from the load spectrums of Section 7.3, the fraction of total loaded cycles, α, falling into any range can be obtained for use in equation (3).

The fatigue properties of members and details presented in Section 7.4 of this specification are used to determine the fatigue limit, S_e (assumed to occur at 2,000,000 cycles), for a specific design detail and stress ratio, R. This fatigue limit represents the maximum stress, S_{max}, which may be introduced to this component an infinite number of times at that stress ratio without producing a fatigue failure. The application of maximum stresses of any greater value would, if applied often enough, eventually result in the fatigue failure of the component. This maximum stress is the algebraic total of the static stress and the dynamic stress. The fatigue properties presented were developed for average quality workmanship and were obtained from available literature.

It is noted that the fatigue property tables are all based on infinite life, or fatigue limit stresses. They cannot be used directly to indicate the number of cycles at some higher stress level that would produce a fatigue failure. Experimental evidence has been collected which indicates that the classical S-N curve is essentially a straight line on log-log paper between 100,000 cycles and the number of cycles corresponding to the fatigue limit for the material under study (2×10^6 cycles for steel). By knowing the slope of this curve, it is possible to predict the life N_i (number of cycles to failure) of a component subjected to a stress S_i exceeding the fatigue limit. Slopes of curves are presented as 'k' values in Section 7.4 of this specification. An equation for life, N„, may be derived from a S-N diagram as follows:

IDEALIZED S-N DIAGRAM



Let k = absolute slope of S-N line.

$$\frac{\log S_i - \log S_e}{\log N_e - \log N_i} = k \quad \text{(4)}$$

$$k \log \frac{N_e}{N_i} = \log \frac{S_i}{S_e} \quad \text{(5)}$$

$$\frac{N_e}{N_i} = \left(\frac{S_i}{S_e}\right)^{\frac{1}{k}} \quad \text{(6)}$$

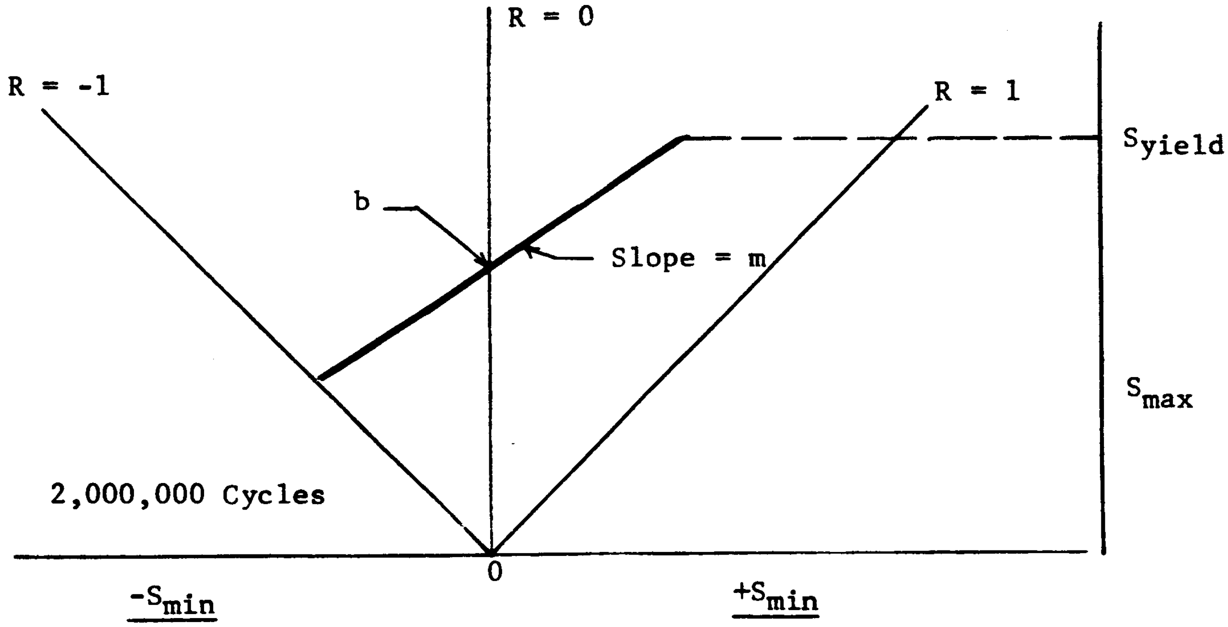
$$N_i = \frac{N_e}{\left(\frac{S_i}{S_e}\right)^{\frac{1}{k}}} \quad \text{(7)}$$

In practice, S_{max_i} replaces S_i giving the equation:

$$N_i = \frac{N_e}{\left(\frac{S_{max_i}}{S_e}\right)^{\frac{1}{k}}} \quad \text{(8)}$$

Since the fatigue limit, S_e, varies with different values of R, an equation for S_e may be obtained from the modified Goodman diagram.

IDEALIZED MODIFIED GOODMAN DIAGRAM



Equation of MGD Curve:

$$S_{max} = mS_{min} + b \quad (9)$$

$$S_{min} = \frac{S_{max} - b}{m} \quad (10)$$

By definition, $R = \frac{S_{min}}{S_{max}} = \frac{\frac{S_{max} - b}{m}}{S_{max}}$, but $S_{max} = S_e$ at fatigue limit, therefore:

$$R = \frac{\frac{S_e - b}{m}}{S_e} \quad (11)$$

or,

$$S_e = \frac{b}{1 - mR} \quad (12)$$

where b is the fatigue limit at R = O and m is the slope of the Goodman curve.

Using equations 3, 8 and 12, it is possible to predict the number of cycles to failure of any component for which fatigue properties (Section 7.4) are available.

Finally, to determine the life of a component:

$$\text{Life (in miles)} = \frac{N_T}{\beta}$$

where NT is total cycles to failure,

β is total spectrum cycles per mile.

7.2.2.3. APPLIED STRESSES

Locations of likely crack initiation sites are shown for each detail in the diagrams of Section 7.4. In the case of welded connections, the stresses required are nominal stresses without consideration of stress concentrations of the detail. The nominal stresses such as those based on simple beam formulas serve as indices of load intensity. They permit use of modified Goodman properties derived from fatigue tests of applicable structural details which are assumed to include the same local state of stress and stress concentrations at the fatigue critical locations. This approach was chosen since the actual stresses at the concentrations associated with weldments are extremely difficult if not impossible to accurately determine either analytically or experimentally.

For analysis of members which do not include welds (and associated concentrations), the maximum stress levels must be determined analytically or experimentally and modified Goodman properties for the basic material used. Care must be used here to include the effect of all stress concentrations. Even with the nominal stress approach, there are situations in which a simple uniaxial stress concept is inadequate for the prediction of a fatigue life based on the applicable modified Goodman diagram. In such cases, usually involving combined loadings that produce biaxial stress states with significant shear loading and reversals, a fatigue equivalent, uniaxial stress cycle should be derived. For biaxial stress states in which the signs of the principal stresses are the same, the stress having the larger absolute value and/or range can be used as the fatigue equivalent stress. When the signs of the principal stresses are opposite, a fatigue equivalent stress that has a value equal to the sum of the magnitudes of the principal stresses can be used as an approximation.

7.2.2.4. ENVIRONMENTAL LOAD SPECTRA

Several environmental load spectra are given in Section 7.3 for specific car types. The spectra are to be used to derive an appropriate stress spectrum for use in a fatigue analysis. Spectra are provided for various force components acting on the car body structure. Considerable emphasis must be placed on an accurate conversion of the load spectra into stress spectra. The stress analysis, whether analytical or experimental, is the foundation upon which the fatigue analysis is based. Since the fatigue analysis predictions are not linear relative to the stress level inputs, errors in the stress analysis can make any method of fatigue life prediction grossly inaccurate.

Two or more force component spectra may act sequentially or simultaneously to produce fatigue damage at the critical location. Completely accurate treatment of such combined spectra situations is not possible in many circumstances because of the usual uncertainty in force component time phase relationship and local stress directional effects, etc. Nevertheless, some guidelines may be obtained by analogy from the relationship for fatigue life given in equation (3) for a single spectrum loading.

The situation is most straightforward for the case of sequential histories. In most cases:

$$\text{Life} = \frac{1}{\frac{1}{\text{Life 1}} + \frac{1}{\text{Life 2}} + \ldots\ldots\ldots\ldots}$$

where life 1, life 2, etc., are lives under the different force component spectra.

If analysis requires a spectrum of a car type that is not available, a "best" estimate may be made by choosing a spectrum of a car type which would exhibit similar dynamic characteristics. As examples, comparisons could be made of the car body bending stiffness, height of center of gravity, torsional stiffness, types of draft gear or cushioning, etc.

Users are cautioned that selecting a "worst case" or most conservative load spectrum may result in completely unrealistic life estimates.

Dimensional, structural, and suspension characteristics of specific cars for which environmental load spectra are available are presented in Section 7.3.

A complete evaluation is required of factors which affect the stress spectrum for the analysis being made. Only in the most simple instances could a single load spectrum be converted directly to a representative stress spectrum. In most cases, the effect of the empty to loaded car miles ratio should be considered in order to accurately describe the life of a freight car. Additional factors which could modify the basic spectrum are items of varying load distribution. As an example, the distribution of trailer length carried may affect the actual stress cycles of an area being analyzed on a piggyback flat car.

Sections 4.1.3.1., 4.1.3.2., 4.1.3.2.1., 4.1.3.2.2. and 4.1.3.3. show distributions of loading to be used in the static stress analysis of the car body. They represent worst cases and may be too conservative for fatigue analysis. Fatigue analysis requires typical loading distributions.

The three-dimensional spectrum could be simply described as an elaboration of the conventional histogram. It is put in the form of a modified Goodman diagram using similar coordinates; that is, maximum load versus minimum load. Thus, for each maximum-minimum load combination there is entered the percent occurrences (the third dimension) that the cycles are encountered in the environment. These percent occurrence distributions are determined from actual environmental test records reduced to the three dimensional format. Reduction of the test data (basically cycle counting) could be done using one of many methods; however, the Rainflow counting method is currently considered the best available and should be used in obtaining load spectrum information.

NOTE: A description of the Rainflow counting method with application to freight car fatigue life analysis is provided in "User's Guide to Rainflow Counting Program," AAR report R-274, July 1977.

The load spectra presented in Section 7.3 are folded to provide a condensed format. Folding of these spectra refers to the operation of transferring the counts of occurrences into the upper left diagonal portion of the spectrum from the corresponding location in the lower right diagonal portion. This action is taken since it is considered that no difference in damage is caused by a cycle that starts at a negative value and goes positive versus a cycle (of equal maximum-minimum values) that starts at a positive value and goes negative. While this may not be true for very high stress values, this assumption is made for long-life prediction analysis.

Use of these folded spectra requires the reading of the percent occurrences for each increment or box and determining the coordinates (max and min) of that box. Since each increment relates to two maximum values and two minimum values, a conservative approach is used to choose a single max and min value representing each increment. The maximum value is chosen as the value which provides the larger maximum stress, S_{max}. The minimum value is chosen to provide the greater range between S_{max} and S_{min}.

In addition to the selection of spectra based on dynamic characteristics, the empty-loaded ratios given in Section 7.3 should be used when applicable (i.e., vertical load spectra). These ratios should be used as listed unless more specific information is available for the car being analyzed.

7.2.2.5. MATERIAL PROPERTIES FOR FATIGUE ANALYSIS

The modified Goodman diagram or MGD given in Section 7.2.2.2. is a convenient means of indicating the allowable stresses for dynamic stress cycles of various mean stress levels. The horizontal scale shows the minimum stress for the cycle and the vertical scale shows the maximum stress (positive or tensile stress). A vertical line is drawn through zero on the horizontal scale representing all points for zero-to-tension cycles; i.e., the minimum stress is zero with any selected maximum tensile stress. This line is denoted as the R = 0 line, where R is the stress ratio $R = S_{min}/S_{max}$. Cycles to the right of the R = 0 line will be tension-to-tension cycles while to the left will be compression-to-tension cycles. The line to the right inclined at 45 degrees is the R = +1 line representing a static stress condition. A similar line to the left is the R = –1 line representing complete stress reversal.

The modified Goodman diagrams constants are presented in tabular form in Section 7.4. The tabular data are conservative estimates which are not rigidly based on statistical analysis of the test data. The tabulated values have been factored from the mean values. This was necessary due to significant differences in sample sizes for various details and corresponding ranges in scatter of data. A factor of 0.70 was generally used to obtain representative MGD y-axis-intercept values at 2×10^6 cycles for steels and 10,000,000 cycles for aluminum, based on the mean fatigue strengths. These values correspond to a value approximately 2 standard deviations below the mean fatigue strength. The intercept values at 10×10^6 cycles were generally obtained by multiplying the 2×10^6 cycles values by a factor of 0.85. This corresponds to the reduction factor that would be obtained for an S-N slope of 0.20. Thus, the tabulated values make use of engineering judgements to provide a reasonable and compatible set of data.

If the data are insufficient to determine the fatigue strength of a member or detail in aluminum and the fatigue strength is available for the member or detail in steel, then it can be assumed that the aluminum fatigue strength (MGD y-axis-intercept) is about equal to one-third (1/3) of the steel fatigue strength and the MGD has the same S-N slope, k, and the same MGD slope, M, with verification or adjustment of these strengths by comparison with other design codes. The one-third factor assumes that fatigue life consists of fatigue crack propagation only, which is a function of the modulus of elasticity.

The use of the modified Goodman diagram details is desirable, since this data represents tests of an actual construction; however, the test samples do not necessarily represent the actual connections as built in a freight car. While the details account for concentrations associated with average quality welding, influences such as residual stresses, welding variation, temperature and corrosion are not considered. When choosing a detail to approximate a similar detail for analysis, care must be used to consider the geometry of the members and the resulting concentrations. A convenient approach is to compare the stress flow path through the detail being analyzed and the available details.

7.2.2.6. ANALYSIS OUTLINE

1. Determine nominal stress-load relationship for all applicable load inputs.
2. Select an appropriate load spectrum.
3. Select appropriate modified Goodman diagram constants for the detail to be analyzed.
4. Determine whether or not stress levels exceed the fatigue limit (check all values of R).
5. When the maximum stress levels exceed the fatigue limit and infinite life is not predicted, determine which portion of spectrum exceeds Se.
6. Tabulate $\frac{\alpha_i}{N_i}$ including all factors such as empty-loaded ratio and multiple load spectra.
7. Determine β for the chosen spectrum and calculate the life = N_T/β in miles.

7.2.3. ANALYTICAL METHOD USING MAXIMUM STRESS

7.2.3.1. ASSUMPTIONS

The same assumptions (7.2.2.1) made in the nominal stress method apply.

7.2.3.2. ANALYSIS OUTLINE

1. Determine nominal stress-load relationship for all applicable load inputs.
2. Obtain maximum stresses by multiplying nominal stresses by appropriate fatigue notch factor, K_f. If the value of K_f cannot be obtained, then use K_t the theoretical stress concentration factor. The use of K_t will always result in a conservative analysis for ductile steels.

NOTE: K_f and K_t can be obtained from textbooks such as "Stress Concentration Design Factors", R. E. Peterson, Wiley and Sons, 1974 or "Stress and Strength of Manufactured Parts", Lipson, Noll and Clock, McGraw-Hill Company, 1950.

3. Use fatigue properties for base material Section 7.4.1.1.1.
4. Calculate fatigue life from formulas previously developed for nominal stress method.

7.2.4. MANUAL CALCULATION EXAMPLE

7.2.4.1. MANUAL CALCULATION—ANALYTICAL METHOD USING APPLICABLE FATIGUE PROPERTIES OF MEMBERS AND DETAILS

The following fatigue calculation is based on single spectrum loading. The member analyzed is assumed to be part of a body bolster for a 100 ton cushioned underframe auto parts box car. Since the detail being analyzed is a beam reinforced by a partial cover plate, the design stresses will be the nominal stresses at the end of the cover plate and not the true maximum stresses that would be used if we were doing a basic material analysis. The nominal maximum and minimum stresses developed are fictitious and are used only for purposes of illustration. All calculations are made by "long hand"; however, the computing time required can be considerably reduced by use of a computer.

DATA REQUIRED FOR CALCULATIONS

1. Environmental stresses (S_{max} and S_{min})

The dynamic stresses are determined from the road environment-percent occurrence spectrum for vertical g's at bolster, 100 ton auto parts box car, fully loaded, reference page 148. The static (1.0g) stress due to dead and live loads is assumed to be 10,000 psi tension, and the dynamic stress is assumed for this example to vary in direct ratio to the static stress. For example, for a ± 0.2g acceleration, the dynamic stress is ± 0.2(10000) = ± 2000 psi. The actual co-ordinates, S_{max} and S_{min}, for each increment or box in the spectrum must be chosen to produce the greater value of S_{max} and to produce the value S_{min} which yields the greater range.

2. Total cycles per mile (β)

The average cycles per mile is 354.661 (Ref: Page 148)

3. Material

The material is assumed to be ASTM A441 having Sy = 50000 psi.

4. Fatigue properties of detail

The detail chosen to represent this case is a beam reinforced with a partial length cover plate applied with longitudinal and transverse fillet welds. The intercept (b) is 7400, the slope of the MGD (m) is 1.00, and the S-N slope k is 0.35.

5. Ratio of Empty to Loaded Miles

Referring to Table 7.3.1. for the ratios of empty to loaded freight car miles by type of car, the ratio for equipped box cars is 0.93.

CALCULATIONS

Tables I, II and III present the calculated results. In Table I, column 1, the dynamic stresses are calculated using the g values from the spectrum. From the spectrum, column II, row 10, the accelerations are 0.1g up (maximum) and 0.0g down (minimum) for 1.415% occurrences. It is assumed acceleration up creates tensile stresses and acceleration down causes compressive stresses. Therefore, S_{max} = 0.1(10000) = 1000 psi and S_{min} = 0 psi.

For column 7, row 8, the accelerations are 0.3g up and 0.4g down for 0.067% occurrences. The corresponding stresses are 0.3(10000) = 3000 psi and 0.4(10000) = –4000 psi. In column 2, of Table I, the static stress of 10000 psi tension is added to the dynamic stresses of column I resulting in S_{max} and S_{min}.

Column 3, Table I, lists the fraction of total loaded cycles, α_i. These are obtained from the percent boxes of the spectrum and divided by 100. Column 4, Table I, is the calculation of $R = S_{min}/S_{max}$. The value of S_e in column 5, Table I, is $S_e = b/l–mR = 7400/1-1.0R$. N_i in column 6, Table I, is computed in Table II and is obtained by the equation $N_i = N_e/(S_{max}/S_e)^{1/k}$. If S_e is greater than S_{max}> no fatigue damage is assumed to occur. The value of $N_T = l/(\Sigma\ \alpha_i/Ni)$ is tabulated in Table III and the fatigue life in miles = N_t/β, where β is cycles per mile = 354.661.

TABLE I

1		2		3	4	5	6
Dynamic Stress		Static Plus Dynamic Stress		α_1 Fraction Of Total Loaded Cycles	R $\frac{S_{min}}{S_{max}}$	S_e Endurance Limit	N_i No. of Cycles to Failure (See Table II)
S_{max}	S_{min}	S_{max}	S_{min}				
1000	0	11000	10000	.014150	.909	50000	No Damage $S_e > S_{max}$
2000	0	12000	10000	.000130	.833	44300	No Damage $S_e > S_{max}$
3000	0	13000	10000	.000010	.769	32000	No Damage $S_e > S_{max}$
1000	−1000	11000	9000	.381790	.818	40700	No Damage $S_e > S_{max}$
2000	−1000	12000	9000	.007750	.750	29600	No Damage $S_e > S_{max}$
3000	−1000	13000	9000	.000180	.692	24000	No Damage $S_e > S_{max}$
4000	−1000	14000	9000	.000010	.643	20700	No Damage $S_e > S_{max}$
1000	−2000	11000	8000	.054630	.727	27100	No Damage $S_e > S_{max}$
2000	−2000	12000	8000	.016290	.667	22200	No Damage $S_e > S_{max}$
3000	−2000	13000	8000	.001160	.615	19200	No Damage $S_e > S_{max}$
4000	−2000	14000	8000	.000060	.571	17200	No Damage $S_e > S_{max}$
1000	−3000	11000	7000	.002520	.636	20300	No Damage $S_e > S_{max}$
2000	−3000	12000	7000	.004530	.583	17700	No Damage $S_e > S_{max}$
3000	−3000	13000	7000	.001740	.539	16100	No Damage $S_e > S_{max}$
4000	−3000	14000	7000	.000140	.500	14800	No Damage $S_e > S_{max}$
5000	−3000	15000	7000	.000020	.467	13900	1,610,000
1000	−4000	11000	6000	.000090	.546	16300	No Damage $S_e > S_{max}$
2000	−4000	12000	6000	.000470	.500	14800	No Damage $S_e > S_{max}$
3000	−4000	13000	6000	.000670	.462	13800	No Damage $S_e > S_{max}$
4000	−4000	14000	6000	.000260	.429	13000	1,618,000
5000	−4000	15000	6000	.000040	.400	12300	1,134,000
1000	−5000	11000	5000	.000010	.455	13600	No Damage $S_e > S_{max}$
2000	−5000	12000	5000	.000030	.417	12700	No Damage $S_e > S_{max}$
3000	−5000	13000	5000	.000170	.385	12000	1,593,000
4000	−5000	14000	5000	.000190	.357	11500	1,141,000
5000	−5000	15000	5000	.000020	.333	11100	847,000
2000	−6000	12000	4000	.000010	.333	11100	1,601,000
3000	−6000	13000	4000	.000020	.308	10700	1,147,000
4000	−6000	14000	4000	.000030	.286	10400	856,000
5000	−6000	15000	4000	.000040	.267	10100	646,000
6000	−6000	16000	4000	.000020	.250	9900	508,000
2000	−7000	12000	3000	.000010	.250	9900	1,155,000
4000	−7000	14000	3000	.000010	.214	9400	641,000
5000	−7000	15000	3000	.000020	.200	9300	510,000
0	−1000	10000	9000	.498420	.900	50000	No Damage $S_e > S_{max}$
0	−2000	10000	8000	.013630	.800	37000	No Damage $S_e > S_{max}$
−1000	−2000	9000	8000	.000010	.889	50000	No Damage $S_e > S_{max}$
0	−3000	10000	7000	.000070	.700	24700	No Damage $S_e > S_{max}$
0	−4000	10000	6000	.000010	.600	18500	No Damage $S_e > S_{max}$
−1000	−4000	9000	6000	.000010	.667	22200	No Damage $S_e > S_{max}$
−2000	−4000	8000	6000	.000010	.750	29600	No Damage $S_e > S_{max}$
−2000	−7000	8000	3000	.000010	.375	11800	No Damage $S_e > S_{max}$

NOTE: S_{Static} = 10,000 psi and is the stress due to dead and live loads. All stress values are in psi.

CALCULATION OF N_i:

$$N_i = \frac{N_e}{\left(\frac{S_{max}}{S_e}\right)^{\frac{1}{k}}} = \frac{2,000,000}{\left(\frac{S_{max}}{S_e}\right)^{\frac{1}{.35}}}$$

TABLE II

1	2	3	4
S_{max}	S_e	$\left(\frac{S_{max}}{S_e}\right)^{\frac{1}{.35}}$	N_i Number of Cycles To Failure
15000	13900	1.2426	1,610,000
14000	13000	1.2361	1,618,000
15000	12300	1.7629	1,134,000
13000	12000	1.2558	1,593,000
14000	11500	1.7526	1,141,000
15000	11100	2.3620	847,000
12000	11100	1.2492	1,601,000
13000	10700	1.7444	1,147,000
14000	10400	2.3371	856,000
15000	10100	3.0947	646,000
16000	9900	3.9402	508,000
12000	9900	1.7321	1,155,000
14000	9400	3.1186	641,000
15000	9300	3.9193	510,000

CALCULATION OF N_T:

$$N_T = \frac{1}{\sum \frac{\alpha_i}{N_i}}$$

TABLE III

1 α_i From Col. 3 Table I	2 N_i From Col. 4 Table II	3 $\frac{\alpha_i}{N_i}$
2×10^{-5}	1.610×10^6	1.242×10^{-11}
26×10^{-5}	1.618×10^6	16.069×10^{-11}
4×10^{-5}	1.134×10^6	3.527×10^{-11}
17×10^{-5}	1.593×10^6	10.672×10^{-11}
19×10^{-5}	1.141×10^6	16.652×10^{-11}
2×10^{-5}	$.847 \times 10^6$	2.361×10^{-11}
1×10^{-5}	1.601×10^6	$.625 \times 10^{-11}$
2×10^{-5}	1.147×10^6	1.744×10^{-11}
3×10^{-5}	$.856 \times 10^6$	3.505×10^{-11}
4×10^{-5}	$.646 \times 10^6$	6.192×10^{-11}
2×10^{-5}	$.508 \times 10^6$	3.937×10^{-11}
1×10^{-5}	1.155×10^6	$.866 \times 10^{-11}$
1×10^{-5}	$.641 \times 10^6$	1.560×10^{-11}
2×10^{-5}	$.510 \times 10^6$	3.922×10^{-11}

$$\sum \frac{\alpha_i}{N_i} = 72.874 \times 10^{-11}$$

$$N_T = \frac{1}{72.874 \times 10^{-11}} = 13.722 \times 10^8 \text{ cycles}$$

$$\text{Life} = \frac{N_T}{\beta} = \frac{13.722 \times 10^8}{354.661} = 3{,}869{,}000 \text{ Miles (Loaded Only)}$$

EFFECT OF EMPTY TO LOADED RATIO:

As stated for this example:

$$\frac{\text{empty mileage}}{\text{loaded mileage}} = 0.98$$

or empty mileage = 0.98 loaded mileage
or total mileage = 1.98 loaded mileage

1. Recalculate life for loaded portion of usage as:

$$\text{Life}_{LD} = \frac{N_T}{\beta_{LD}} \text{ where } \beta_{LD} = \text{ no. of loaded occurrences per mile.}$$

$$\beta_{LD} = \beta \times \frac{\text{loaded mileage}}{\text{total mileage}}$$

$$\text{For this example } \beta_{LD} = 354.661\frac{1}{1.98} = 354.661 \times 0505$$

$$\beta_{LD} = 179.122 \text{ loaded cycles per mile}$$

2. Calculate empty car stresses:

In the example, empty car stresses are obtained by ratio of car weights,

$$\text{empty car stress} = \text{loaded car stress x } \frac{\text{car body wt.}}{\text{max. wt. on rails minus truck weight}}$$

$$\text{In this example, } S_{EMP} = S_{LD} \times \frac{90{,}000}{240{,}000}$$

$$S_{EMP} = .375 \text{ SLD}$$

3. Referring to Table I, and applying this reduction factor to S_{MAX} and S_{MIN}, all values are below the endurance limits, S_i, and therefore the empty car cycles produce no damage.

4. Had the empty car stresses exceeded S_e, a summation would have to be done to find Life_{EMPTY} and then combined as independent spectra to calculate total life as shown in Section 7.2.4.2.

5. Calculate total life (loaded and empty):

Total Life = 1.98 Loaded Life
= 3,869,000 x 1.98
= 7,661,000 miles

ROAD ENVIRONMENT PERCENT OCCURRENCE SPECTRUM

VERTICAL G'S @ BOLSTER

100 TON AUTO PARTS BOX CAR

UP—DOWN | COLUMN NUMBER | UP—UP

MAXIMUM PEAK VERTICAL ACCELERATION G'S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	ROW NUMBER
1.0																					1
0.9																					2
0.8																					3
0.7																					4
0.6					0.0020																5
0.5				0.0020	0.0040	0.0020	0.0040	0.0020													6
0.4				0.0010	0.0030	0.0190	0.0260	0.0140	0.0060	0.0010											7
0.3					0.0020	0.0170	0.0670	0.1740	0.1160	0.0180	0.0010										8
0.2				0.0010	0.0010	0.0030	0.0470	0.4530	1.6290	0.7750	0.0130										9
0.1						0.0010	0.0090	0.2520	5.4630	38.1790	1.4150										10
0							0.0010	0.0070	1.3630	49.8420											11
−0.1							0.0010		0.0010												12
−0.2				0.0010			0.0010														13
−0.3																					14
−0.4																					15
−0.5																					16
−0.6																					17
−0.7																					18
−0.8																					19
−0.9																					20
−1.0																					

−1.0 −0.9 −0.8 −0.7 −0.6 −0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

DOWN—DOWN

MINIMUM PEAK
VERTICAL ACCELERATION G'S

ROAD TEST OF: 100 TON AUTO PART BOX CAR (CUSHION UNDERFRAME)
CROSS RAIL Wt.: 235,500 lbs. TEST DATE:
FROM-TO:
ON: RR
SIZE TRAIN:
TEST CAR LOCATED:
MAX. MPH: 60-70 AVG. MPH: 32.3
RECORDED MILEAGE: 157.7
RECORDING TIME: 5.0 Hrs.

SPECTRUM TOTAL: 99.9489
POSITIVE FORCE IS: UP
NEGATIVE FORCE IS: DOWN

TOTAL OCCURRENCES: 111.856
AVG. OCCURRENCES/MILE: 709.322
AVG. CYCLES/MILE: 354.661

7.2.4.2. MANUAL CALCULATION—MAXIMUM STRESS METHOD

The following fatigue calculations illustrate the maximum stress method of determining fatigue life. The member analyzed is assumed to be a center sill of a covered hopper subjected to a single spectrum loading.

DATA REQUIRED FOR CALCULATIONS

1. Environmental Stress (S_{max} and S_{min})

The static stress for this example is assumed to be zero. The dynamic stresses are determined from the road environment percent occurrence spectrum for longitudinal coupler force—100 ton hopper car, reference page 152. The stresses are assumed to apply for both empty and loaded cars. The nominal stress for a 100,000 pound draft coupler force is assumed to be 9000 psi and for a 100,000 pound buff force is –9000 psi. At the location of the above nominal stresses in the center sill, a sharp groove with a very small radius exists. It is assumed this notch creates a fatigue notch factor K of 3.0 and is similar to the detail shown in chart 77, page 135; Lipson, Noll and Clock; "Stress and Strength of Manufactured Parts"; McGraw-Hill; 1950.

2. Total Cycles per Mile ()3)

The average cycles per mile from the Repos is 105.03.

3. Material The material is assumed to be ASTM A242 having S_y = 50000 psi.

4. Fatigue Properties

The fatigue properties applicable for this analysis are in Section 7.4, Table I, as-rolled base material. The intercept is 31000 psi, the slope of the MOD (m) is 0.86 and the S-N slope, k, is 0.10.

CALCULATIONS

Table IV shows the computation to determine the number of cycles to failure, N_i. The coupler force in column 1 and the fraction of total cycles, α_i, are obtained from the load spectrum. The maximum dynamic stresses in column 2, Table IV, includes a fatigue notch factor of 3.

TABLE IV

1		2		3	4	5	6
Coupler Force (pounds) From Repos		Maximum Dynamic Stresses (psi) $\frac{\text{Coupler Force} \times 3 \times 9000}{100000}$		α_i Fraction of Total Cycles From Repos	$R = \frac{S_{min}}{S_{max}}$	S_e $\frac{31,000}{1-.86R}$ (PSI)	N_i No. of Cycles to Failure $\frac{2,000,000}{\left(\frac{S_{max}}{S_e}\right)^{1/0.10}}$
Tension	Tension or Compression						
20000	0	5400	0	.436560	0	31000	No damage $S_e > S_{max}$
40000	0	10800	0	.268660	0	31000	No damage $S_e > S_{max}$
60000	0	16200	0	.000910	0	31000	No damage $S_e > S_{max}$
80000	0	21600	0	.000900	0	31000	No damage $S_e > S_{max}$
100000	0	27000	0	.000010	0	31000	No damage $S_e > S_{max}$
40000	20000	10800	5400	.248080	.500	54400	No damage $S_e > S_{max}$
60000	20000	16200	5400	.019790	.333	43400	No damage $S_e > S_{max}$
80000	20000	21600	5400	.000220	.250	39500	No damage $S_e > S_{max}$
100000	20000	27000	5400	.000070	.200	37400	No damage $S_e > S_{max}$
120000	20000	32400	5400	.000020	.167	36200	No damage $S_e > S_{max}$
60000	40000	16200	10800	.017730	.667	72800	No damage $S_e > S_{max}$
80000	40000	21600	10800	.002350	.500	54400	No damage $S_e > S_{max}$
100000	40000	27000	10800	.000040	.400	47300	No damage $S_e > S_{max}$
140000	40000	37800	10800	.000020	.285	41100	No damage $S_e > S_{max}$
80000	60000	21600	16200	.001830	.750	87300	No damage $S_e > S_{max}$
100000	60000	27000	16200	.000150	.600	64000	No damage $S_e > S_{max}$
180000	60000	48600	16200	.000020	.333	43400	645,000
20000	-20000	5400	-5400	.001460	-1.000	16700	No damage $S_e > S_{max}$
40000	-20000	10800	-5400	.000020	-.500	21700	No damage $S_e > S_{max}$
60000	-20000	16200	-5400	.000020	-.333	24100	No damage $S_e > S_{max}$
20000	-40000	8100 1/	-8100	.000190	-1.000	16700	No damage $S_e > S_{max}$
40000	-40000	10800	-10800	.000010	-1.000	16700	No damage $S_e > S_{max}$
40000	-60000	13500 1/	-13500	.000010	-1.000	16700	No damage $S_e > S_{max}$
40000	-80000	16200 1/	-16200	.000010	-1.000	16700	No damage $S_e > S_{max}$
40000	-100000	18900 1/	-18900	.000010	-1.000	16700	580,000
20000	-120000	18900 1/	-18900	.000010	-1.000	16700	580,000

1/ Referring to assumption (9) of 7.2.2.1., "If the minimum stress has greater absolute value than the maximum stress for a given cycle, the cycle is considered as a complete reversal cycle with a maximum stress equal to ½ the range of stress." For example, load 20000 lbs. gives S_{max} = 5400 psi; load − 40000 lbs. gives S_{min} = −10800 psi. Column 2 S_{max} equals $\frac{[5400 - (-10800)]}{2}$ = 8100 psi.

CALCULATION OF N_T:

$$N_T = \frac{1}{\sum \frac{\alpha_i}{N_i}}$$

$$N_T = \frac{1}{\frac{.000020}{645,000} + \frac{.00001}{580,000} + \frac{.00001}{580,000}}$$

$$N_T = 152.67 \times 10^8 \text{ cycles}$$

$$\text{Life} = \frac{N_T}{\beta} = \frac{152.67 \text{ x } 10^8}{105.03} = 145,000,000 \text{ miles}$$

ROAD ENVIRONMENT PERCENT OCCURRENCE SPECTRUM

LONGITUDINAL COUPLER FORCE

100 TON COVERED HOPPER

DRAFT—BUFF | COLUMN NUMBER | DRAFT—DRAFT

Row number (vertical axis: MAXIMUM PEAK KIPS, LONGITUDINAL COUPLER FORCE, 200 to −200); column number (horizontal axis: MINIMUM PEAK KIPS, LONGITUDINAL COUPLER FORCE, −200 to 200)

Row	Max. peak kips	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	200 / 180																				
2	180 / 160														0.0020						
3	160 / 140																				
4	140 / 120													0.0020							
5	120 / 100												0.0020								
6	100 / 80											0.0010	0.0070	0.0040	0.0150						
7	80 / 60											0.0090	0.0220	0.2350	0.1830						
8	60 / 40										0.0020	0.0910	1.9790	1.7730							
9	40 / 20						0.0010	0.0010	0.0010	0.0010	0.0020	26.8660	24.8080								
10	20 / 0					0.0010				0.0190	0.1460	43.6560									
11	0 / −20								0.0040	0.0350	0.1010										
12	−20 / −40						0.0010	0.0010	0.0020	0.0130											
13	−40 / −60							0.0020	0.0020												
14	−60 / −80																				
15	−80 / −100						0.0010														
16	−100 / −120				0.0010																
17	−120 / −140		0.0010		0.0010																
18	−140 / −160																				
19	−160 / −180		0.0020																		
20	−180 / −200																				

Minimum peak kips: −200, −180, −160, −140, −120, −100, −80, −60, −40, −20, 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200

BUFF—BUFF

MINIMUM PEAK KIPS
LONGITUDINAL COUPLER FORCE

ROW NUMBER

ROAD TEST OF: 100 TON COVERED HOPPER CAR

CROSS RAIL Wt.: 254,150 lbs. TEST DATE:

FROM-TO:

ON: RR

SIZE TRAIN:

TEST CAR LOCATED:

MAX. MPH: 70-80 AVG. MPH: 44.0

RECORDED MILEAGE: 374

RECORDING TIME: 8.5 Hrs.

SPECTRUM TOTAL: 99-9969

POSITIVE FORCE IS: DRAFT

NEGATIVE FORCE IS: BUFF

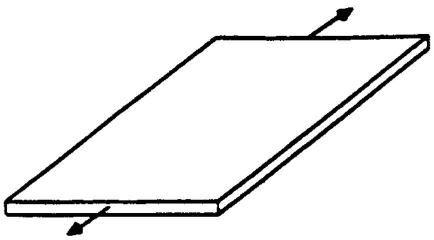
TOTAL OCCURRENCES: 78.566

AVG. OCCURRENCES/MILE: 210.07

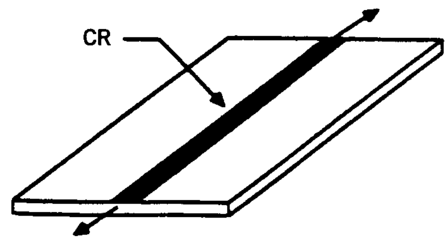
AVG. CYCLES/MILE: 105.03

7.4.2.1

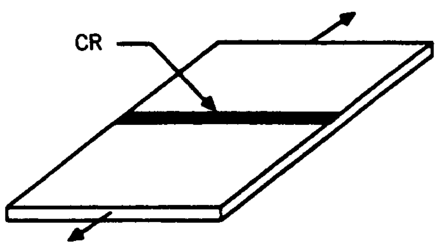
DETAIL SUMMARY FOR MATERIAL FATIGUE PROPERTIES — ALUMINUM



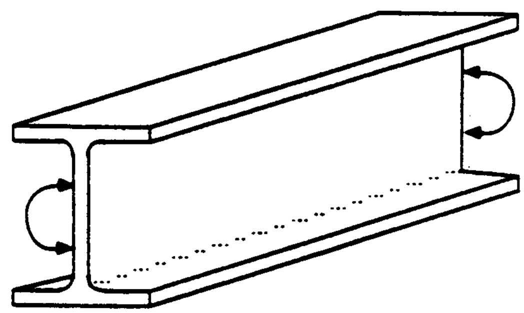
1.1.1(A) — SHEET OR PLATE (AXIAL LOAD)
1.1.2(A) — EXTRUSIONS (AXIAL LOAD)



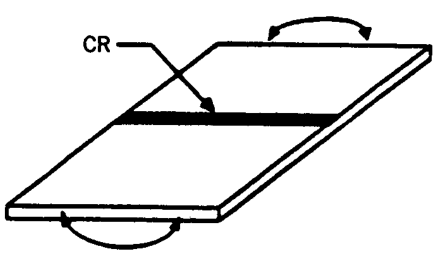
BUTT JOINTS — LONGITUDINAL (AXIAL LOAD)
2.1.5(A) — WELD REINFORCEMENT INTACT
2.1.6(A) — WELD REINFORCEMENT REMOVED



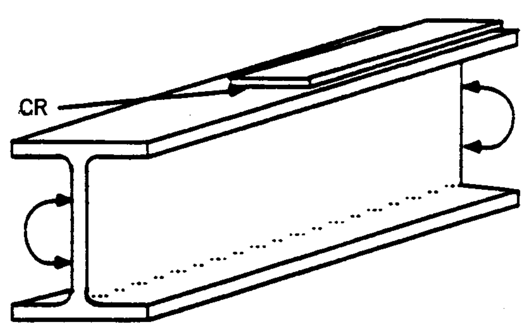
BUTT JOINTS — TRANSVERSE (AXIAL LOAD)
2.1.1(A) — WELD REINFORCEMENT INTACT
2.1.2(A) — WELD REINFORCEMENT REMOVED



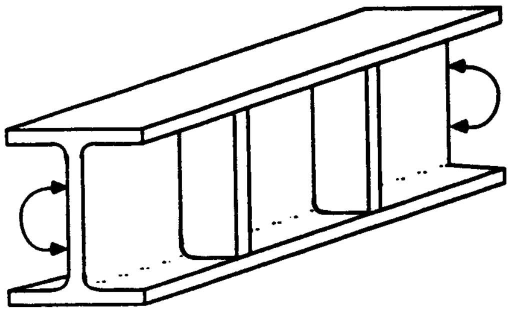
3.1(A) — EXTRUDED BEAM (FLEXURAL LOADING)



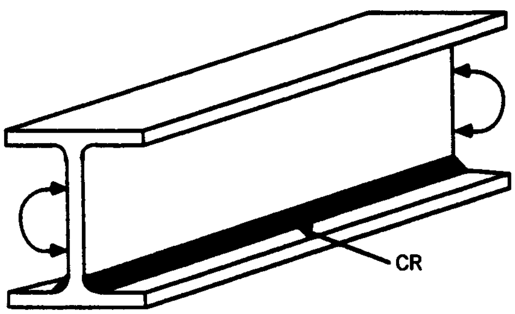
BUTT JOINTS — TRANSVERSE (FLEXURAL LOADING)
2.1.3(A) — WELD REINFORCEMENT INTACT
2.1.4(A) — WELD REINFORCEMENT REMOVED



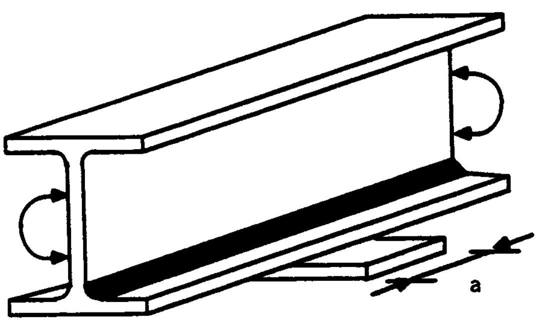
3.1.5(A) — PARTIAL LENGTH COVER PLATES ON EXTRUDED OR FABRICATED BEAM (FLEXURAL LOADING)



3.1.7(A) — STIFFENERS ON EXTRUDED OR FABRICATED BEAM (FLEXURAL LOADING)

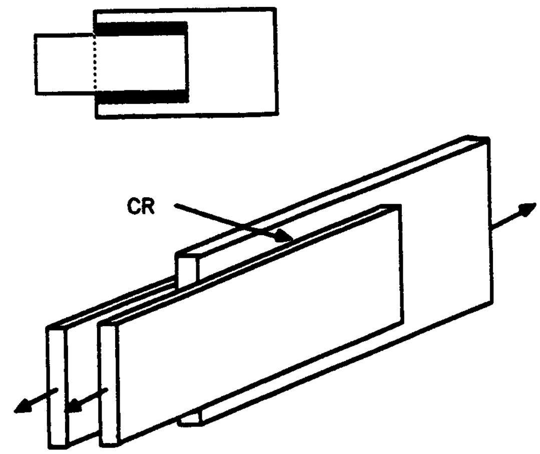


3.2.1(A) — FABRICATED BEAM (FLEXURAL LOADING)

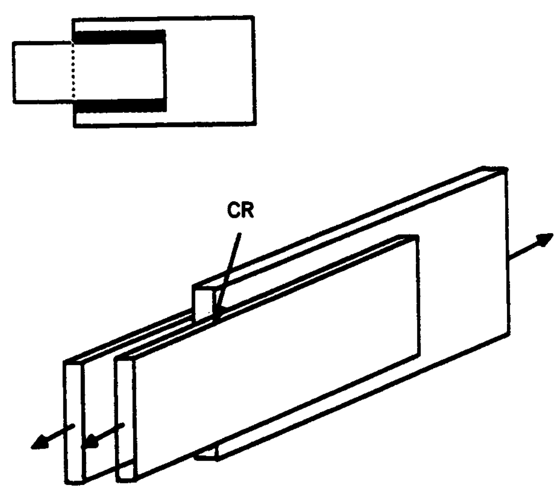


3.2.9 & 10(A) — LATERAL PLATE ATTACHMENT TO FLANGE OF EXTRUDED OR FABRICATED BEAM (FLEXURAL LOADING)

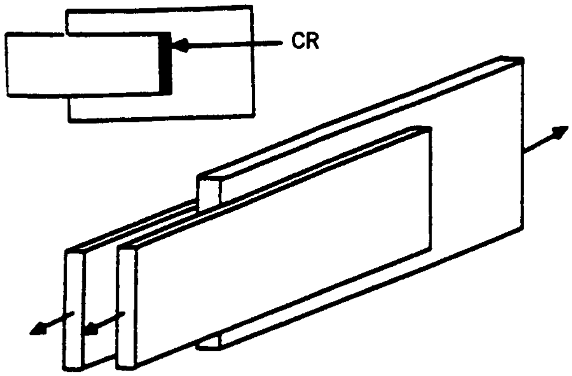
3.2.9(A): $a < 2''$
3.2.10(A): $a \leq 4''$



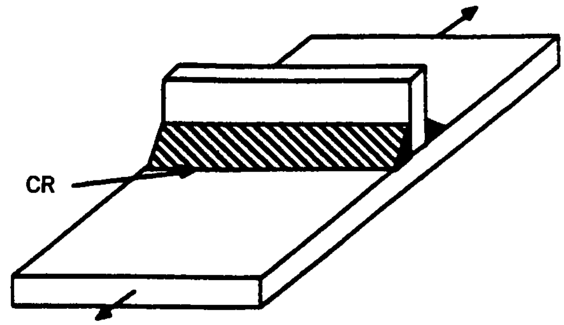
4.1.1(A) — LAP WELDED JOINT — WELD STRESS CRITICAL (AXIAL LOAD)



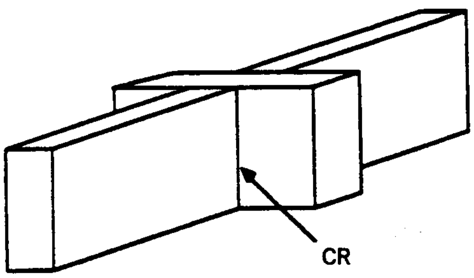
4.1.2(A) — LAP WELDED JOINT — PLATE STRESS CRITICAL (AXIAL LOAD)



4.2.2(A) — LAP WELDED JOINT — WITH TRANSVERSE WELD ONLY (AXIAL LOAD)



5.2.1.1(A) — PLATE WITH TRANSVERSE FILLET WELDED RIB — ONE SIDE (AXIAL LOAD)



TEE JOINTS (AXIAL LOAD)

5.1.1.1(A) — FULL PENETRATION GROOVE WELD — PLATE STRESS CRITICAL

5.1.1.2(A) — PARTIAL PENETRATION GROOVE WELD — PLATE STRESS CRITICAL

5.1.1.3(A) — PARTIAL PENETRATION GROOVE WELD — WELD STRESS CRITICAL

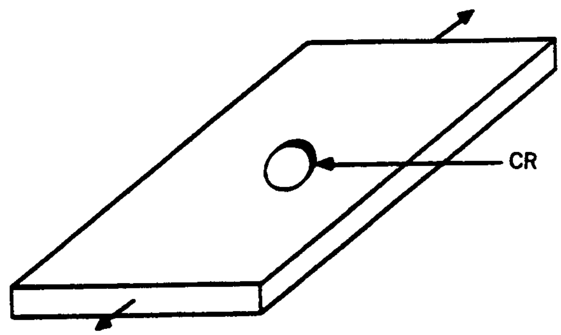
5.1.2(A) — FILLET WELDED — WELD STRESS CRITICAL

5.1.3(A) — FILLET WELDED — PLATE STRESS CRITICAL

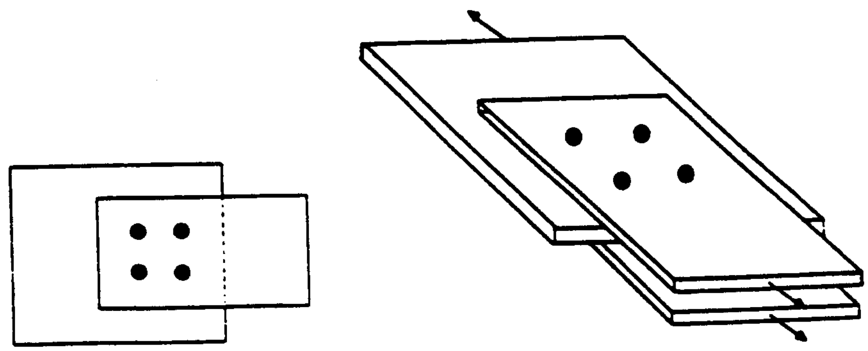
TEE JOINTS (FLEXURAL LOADING)

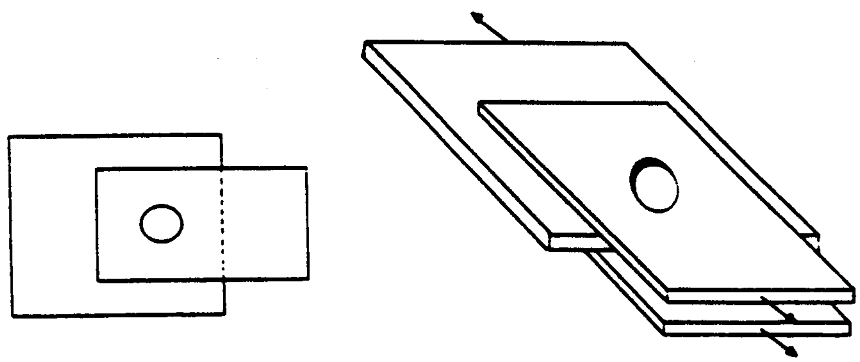
5.1.4(A) — FULL PENETRATION GROOVE WELDS — PLATE STRESS CRITICAL

5.1.5(A) — PARTIAL PENETRATION GROOVE WELDS — PLATE STRESS CRITICAL



7.1.1(A) — PLATES WITH HOLES (AXIAL LOAD)

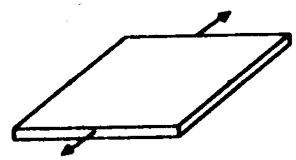
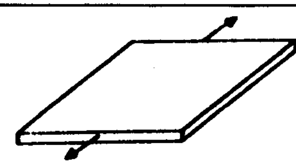
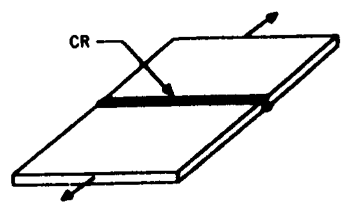




8.1(A) — RIVETED OR NON-FRICTION BOLTED JOINT
— NET SECTION STRESS (AXIAL LOAD)

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

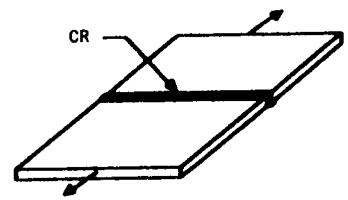
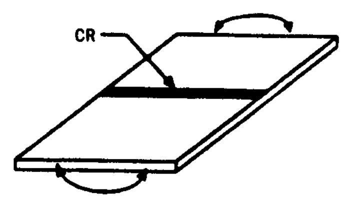
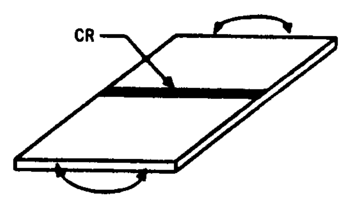
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
1.1.1(A)	Sheet or Plate. — Axial load.		7.3	0.80	0.16
1.1.2(A)	Extrusions. — Axial load.		7.3	0.80	0.16
2.1.1(A)	Butt joint, transverse, full penetration, reinforcement intact. — Axial load.		3.7	0.95	0.24

*y-intercept at 10×10^6 cycles.

(   ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

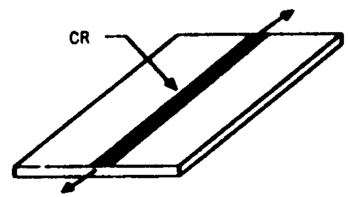
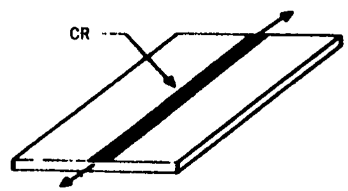
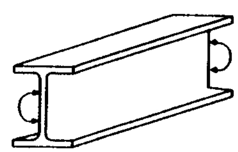
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
2.1.2(A)	Butt joint, transverse, full penetration, reinforcement removed. — Axial load.		4.6	0.87	0.21
2.1.3(A)	Butt joint, transverse, full penetration, reinforcement intact. — Flexural loading.		3.7	(1.0)	0.24
2.1.4(A)	Butt joint, transverse, full penetration, reinforcement removed. — Flexural loading.		4.6	0.87	0.21

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

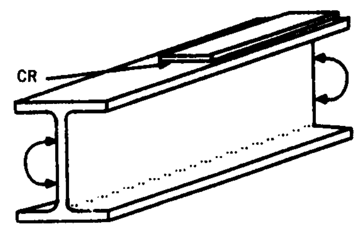
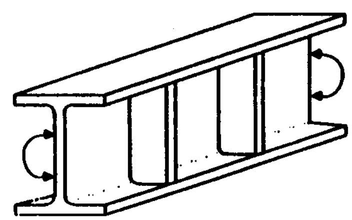
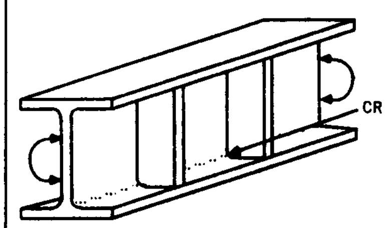
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
2.1.5(A)	Butt joint, longitudinal, full penetration, reinforcement intact. — Axial load.		5.1	(1.0)	0.24
2.1.6(A)	Butt joint, longitudinal, full penetration, reinforcement removed. — Axial load.		6.0	0.87	0.21
3.1(A)	Beam, extruded. — Flexural loading.		7.3	0.80	0.16

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

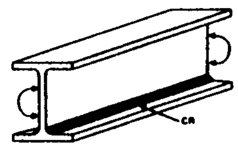
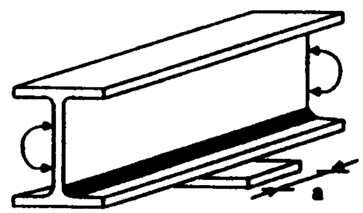
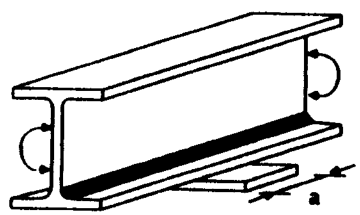
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
3.1.5(A)	Beam, extruded or fabricated, with partial length cover plate or attachment more than 4″ in length. — Flexural loading.		1.6	(1.0)	0.29
3.1.6(A)	Beam, extruded or fabricated, with fillet welded stiffeners, bending stress at extreme fiber of beam. — Flexural loading.		3.1	(1.0)	0.24
3.1.7(A)	Beam, extruded or fabricated, with fillet welded stiffeners, principle tensile stress at end of weld to web. — Flexural loading.		2.7	(1.0)	0.24

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

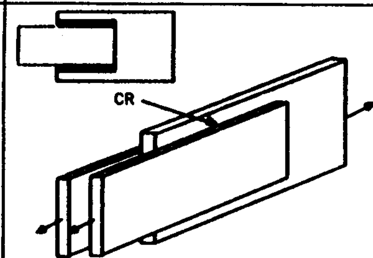
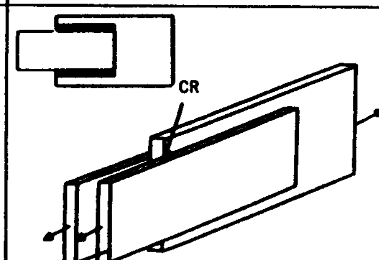
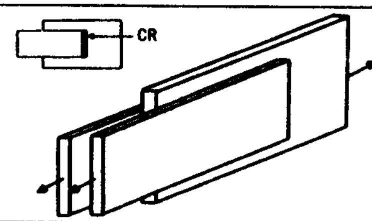
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
3.2.1(A)	Beam, fabricated. — Flexural loading.		4.3	(1.0)	0.16
3.2.9(A)	Beam, extruded or fabricated, with lateral plate attachment to flange, plate attachment length of 2″ or less. — Flexural loading.		2.5	(1.0)	0.29
3.2.10(A)	Beam, extruded or fabricated, with lateral plate attachment to flange, plate attachment length of 4″ or less. — Flexural loading.		(2.3)	(1.0)	0.25

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

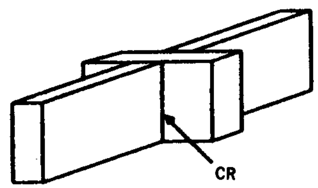
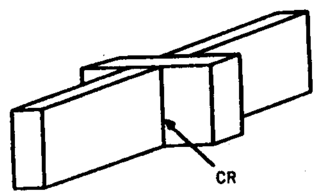
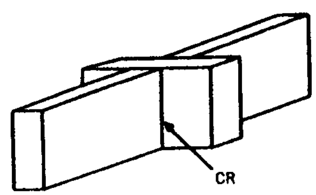
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
4.1.1(A)	Lap welded joints, longitudinal or longitudinal with transverse fillet weld, weld throat shear stress. — Axial load.		2.3	(1.0)	0.25
4.1.2(A)	Lap welded joints, longitudinal or longitudinal with transverse fillet weld, plate stress at end of longitudinal weld. — Axial load.		1.6	(1.0)	0.29
4.2.2(A)	Lap welded joints, transverse fillet weld, plate stress at toe of weld. — Axial load.		2.4	(1.0)	0.24

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

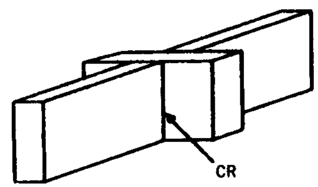
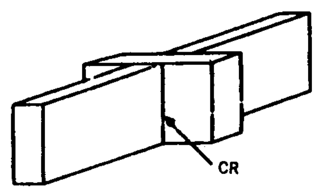
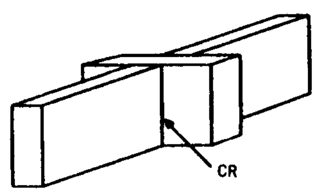
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
5.1.1.1(A)	Tee joint, full penetration groove weld, stress in plate. — Axial load.		2.4	(1.0)	0.24
5.1.1.2(A)	Tee joint, partial penetration groove welds, stress in plate. — Axial load.		(1.9)	(1.0)	0.29
5.1.1.3(A)	Tee joint, partial penetration groove welds, stress in throat of weld. — Axial load.		(1.6)	(1.0)	0.29

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

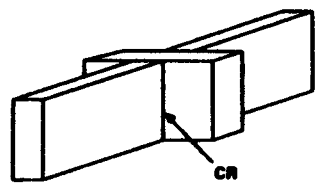
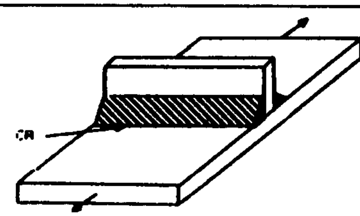
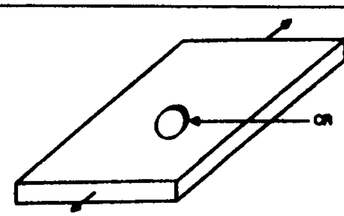
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
5.1.2(A)	Tee joint, continuous fillet welds, weld throat shear stress. — Axial load.		3.0	(1.0)	0.25
5.1.3(A)	Tee joint, continuous fillet welds, plate stress. — Axial load.		2.4	(1.0)	0.24
5.1.4(A)	Tee joint, continuous full penetration groove weld, plate stress. — Flexural loading.		2.3	(1.0)	0.27

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

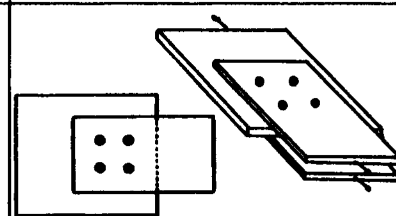
DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
5.1.5(A)	Tee joint, continuous partial penetration groove weld, plate stress. — Flexural loading.		2.0	(1.0)	0.27
5.2.1.1(A)	Plate with transverse fillet welded rib, one side. — Axial load.		(2.3)	(1.0)	0.26
7.1.1(A)	Plate with hole at centerline, net section stress. — Axial load.		4.6	(1.0)	0.21

*y-intercept at 10×10^6 cycles.

( ) = estimated value

TABLE 7.4.3

FATIGUE PROPERTIES OF MEMBERS AND DETAILS — ALUMINUM

DETAIL NO.	DESCRIPTION OF MEMBER	MEMBER DETAILS	MGD Intercept (*b*)*	MGD Slope (*m*)	S-N Slope (*k*)
8.1(A)	Riveted joints or non-friction bolted joints, net section stress. — Axial load.		4.3	(0.9)	0.21

*y-intercept at 10×10^6 cycles.

( ) = estimated value

APPENDIX E

Appendix E contains a few S/N diagrams that have been copied from the sources cited below and in Section 4 of the report. It is recognized that significant information must still be gathered before relevant S/N diagrams can be developed for design purposes. The curves presented in this appendix represent raw data for the series of tests represented by the curves. There is insufficient data to confirm the statistical acceptability of the data and the use of these curves needs to incorporate safety factors that consider this condition. For purposes of design, it is recommended that the information in the various codes presented in appendices B, C and D be used until additional data can be gathered for compilation of design curves.

Reference (1) shown below addresses details 20 through 24 in Section 4 of the report and reference (2) addresses details 25 through 28. More information regarding the testing used to generate these S/N curves is available through these references.

(1) Paauw, A. J., Fredheim, S., and Engh, B., Konstruksjonsdata for dynamisk belastede aluminum sveiseforbindelser (Construction data for dynamic testing of aluminum weldments), SINTEF Report No. STF34 A83042, 1983

(2) Tveiten, B. W., Fatigue Assessment of Welded Aluminum Ship Details, Doctoral Thesis, Department of Marine Structures, Norwegian University of Science and Technology, Trondheim, 1999.

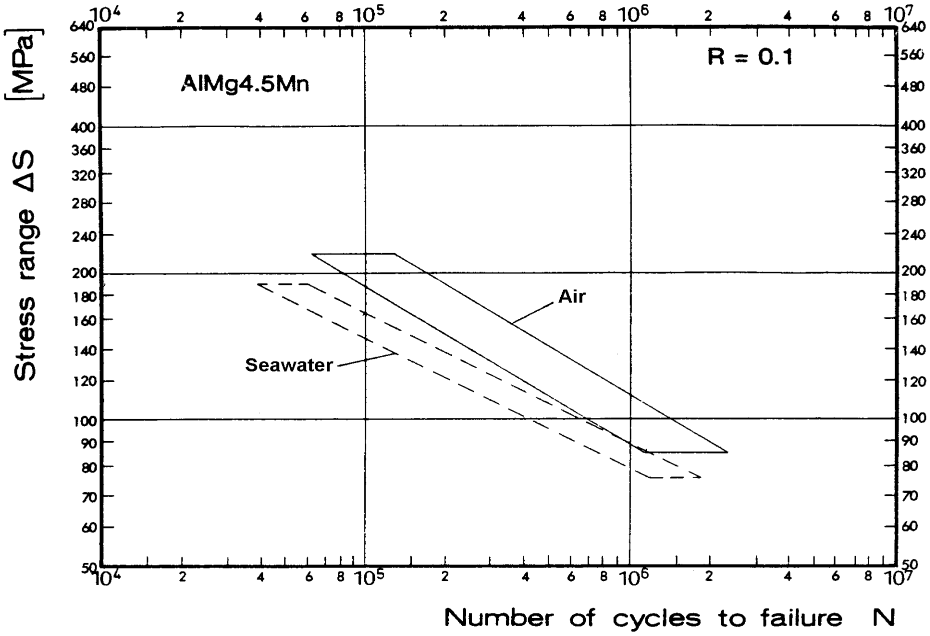


Figure E-1; Transversely welded plate; Alloy AlMg4.5Mn; R = 0.1;

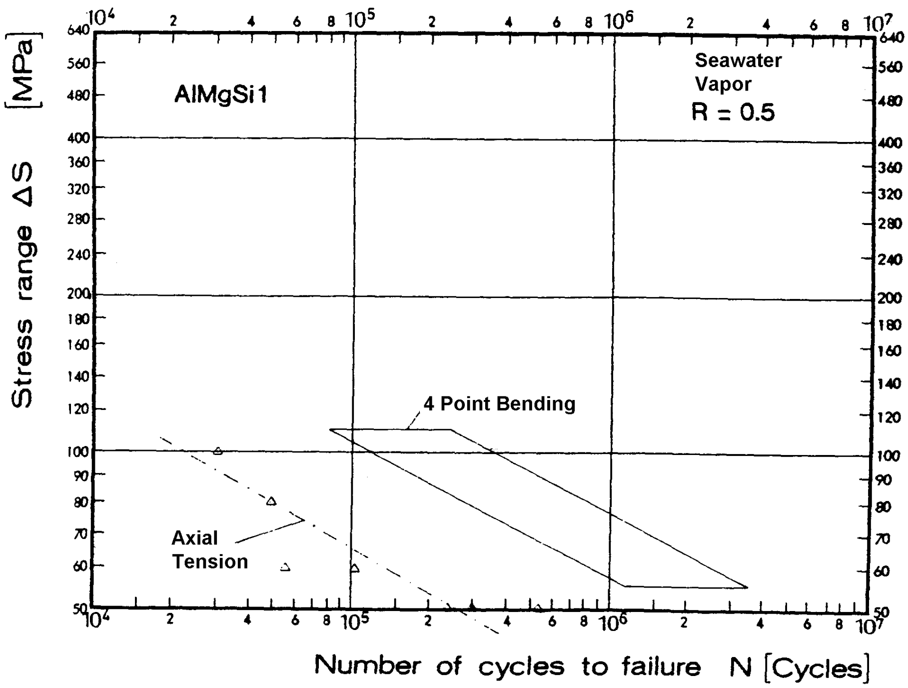


Figure E-2; Transversely welded plate subjected to both axial tension and 4 point bending; Alloy AlMgSi1; R-ratio = 0.5;

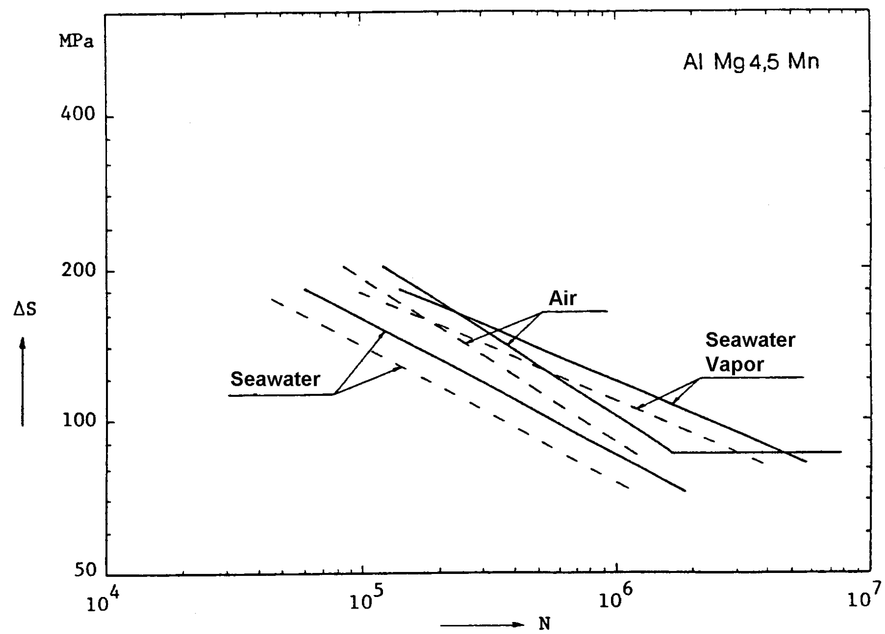


Figure E-3; Transversely welded plate; Alloy AlMg4.5Mn; R = 0.1;Error! Reference source not found.

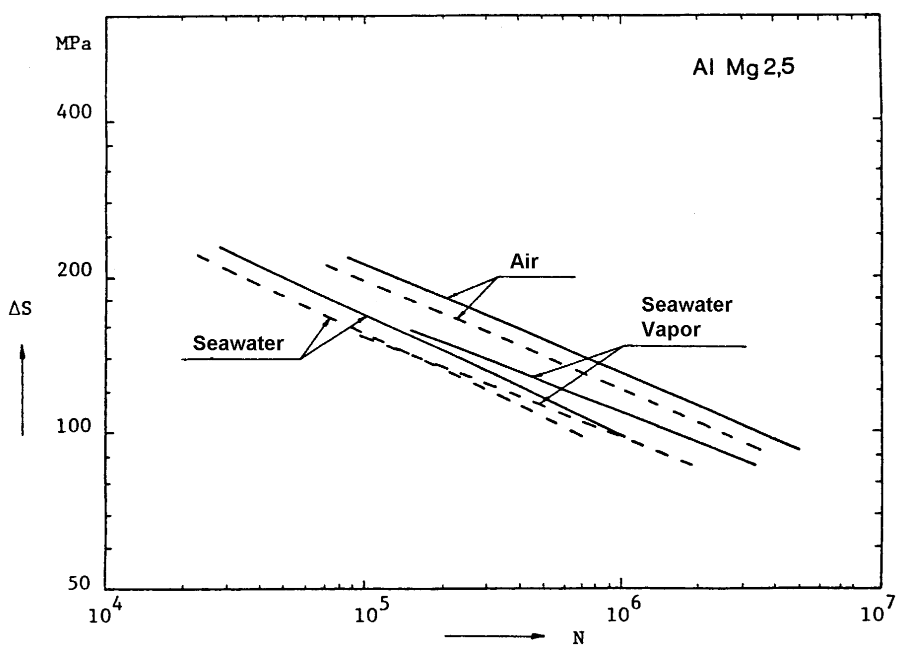


Figure E-4; Transversely welded plate; Alloy AlMg2.5; R-ratio = 0.1;

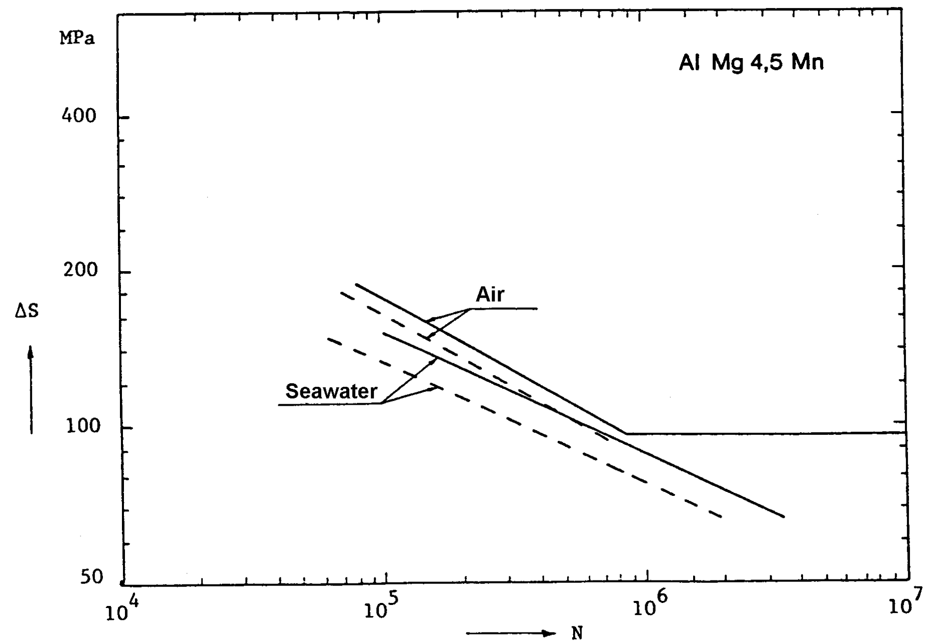


Figure E-5; T-Joint connection; Alloy AlMg4.5Mn; R = 0.1;

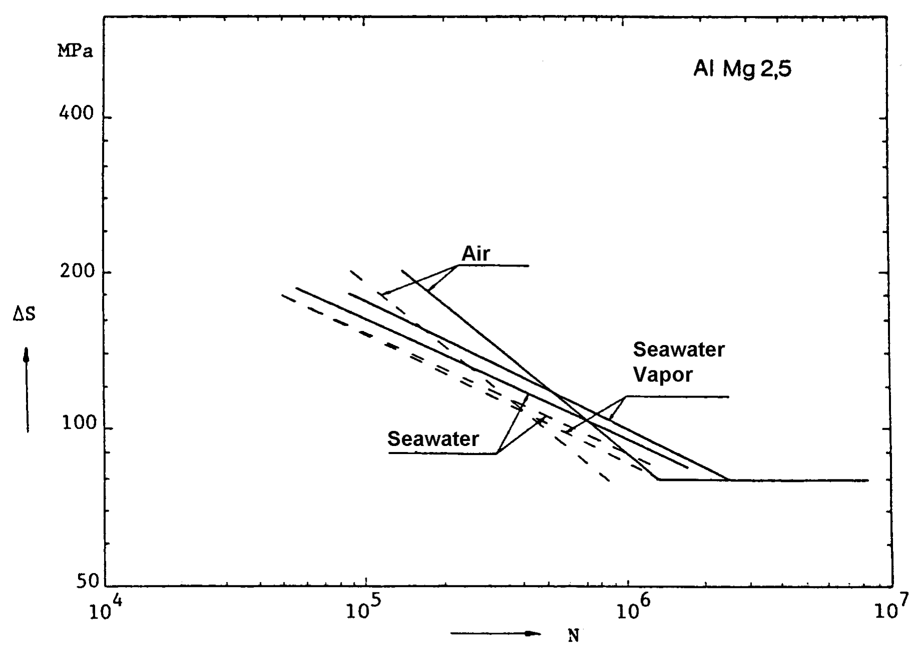


Figure E-6; T-Joint connection; Alloy AlMg2.5; R = 0.1; g);

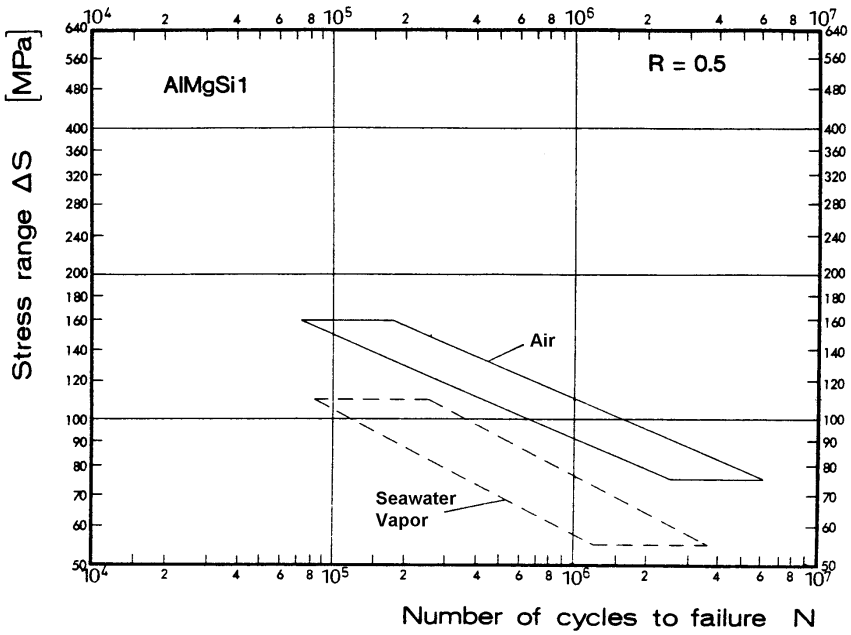


Figure E-7 Transversely welded plate; Alloy AlMgSi1; R = 0.5;

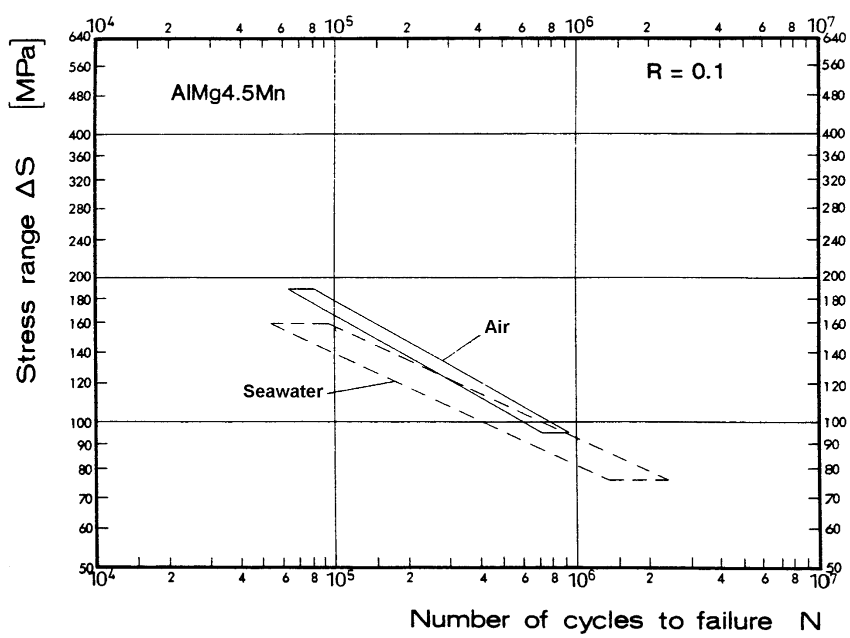


Figure E-8; T-Joint connection; Alloy 5083; R = 0.1;

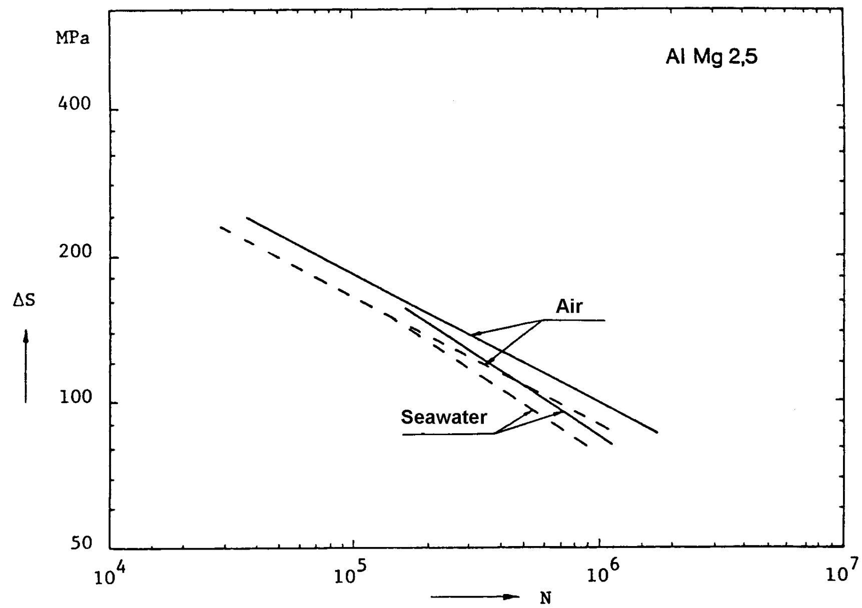


Figure E-9; Transversely welded plate with V- connection; Alloy AlMg2.5; R = 0.1;

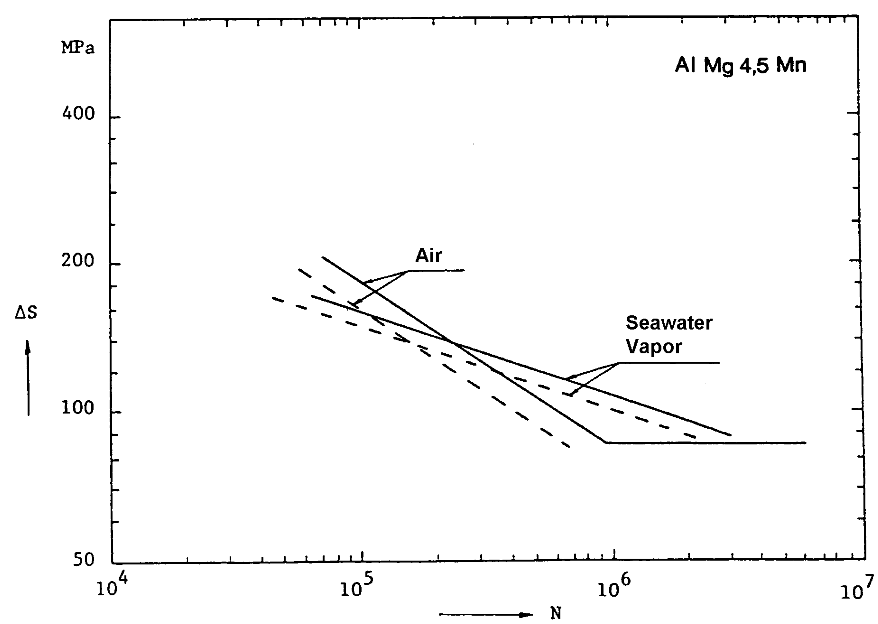


Figure E-10; Transversally welded plate with V-connection; Alloy AlMg4.5Mn; R = 0.1;

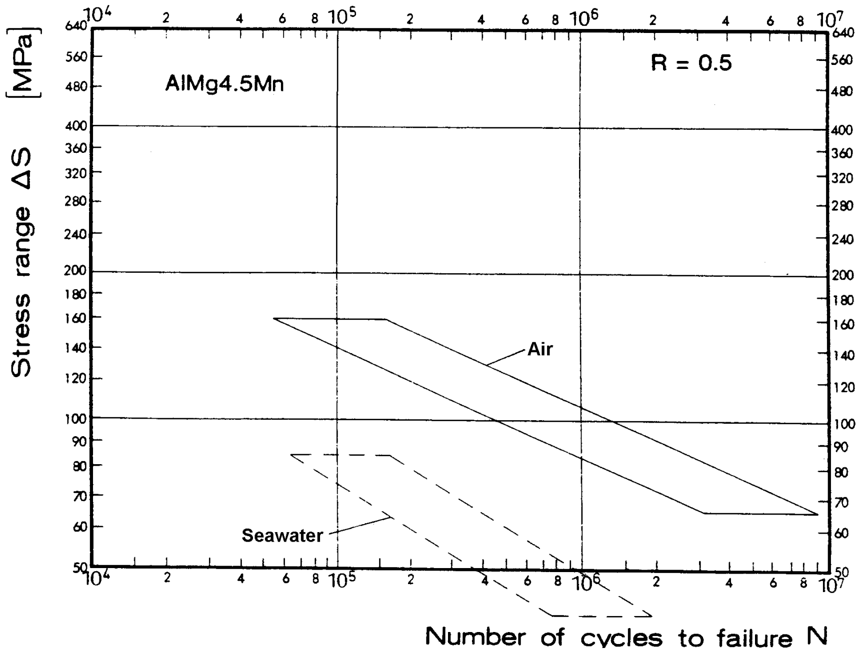


Figure E-11; T-Joint connection; Alloy AlMg4.5Mn; R = 0.5;

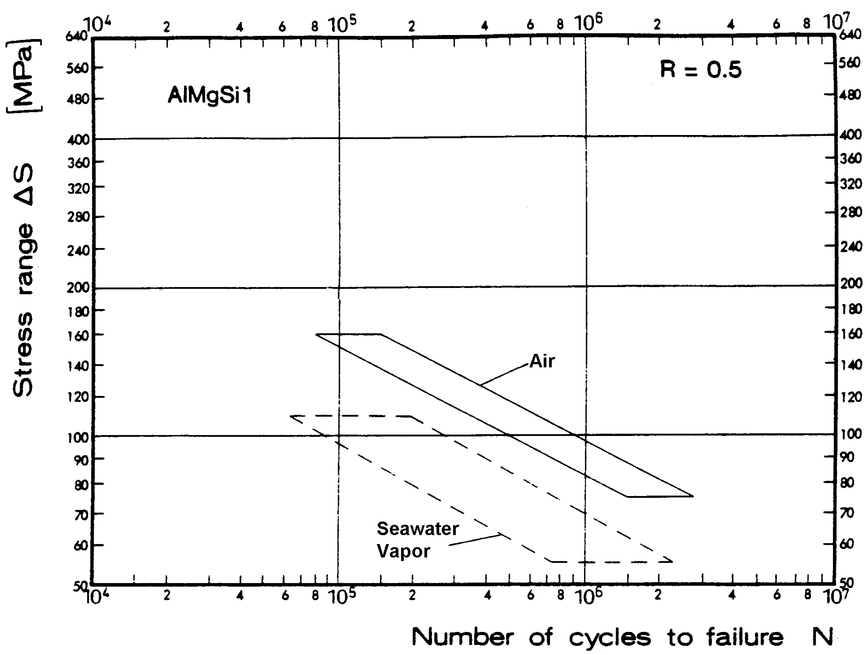


Figure E-12; T-Joint connection; Alloy AlMgSi1; R = 0.5;

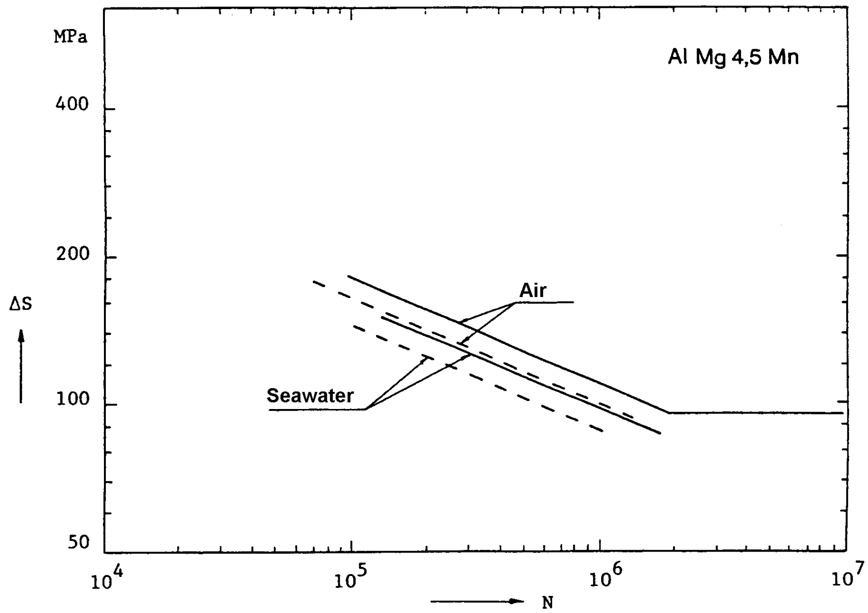


Figure E-13; Cruciform Joint; Alloy AlMg4.5Mn; R = 0.1;

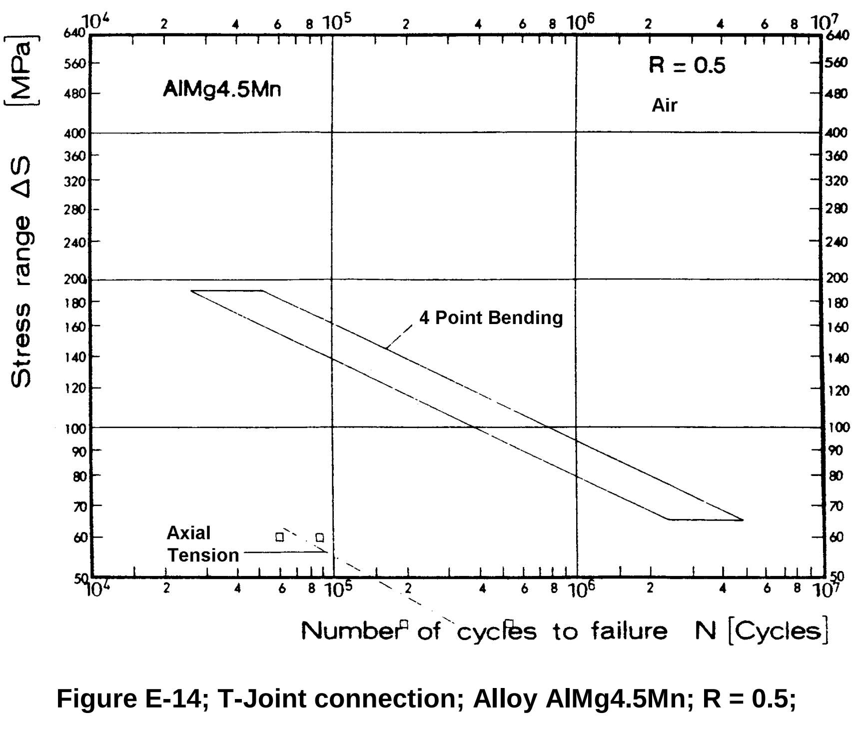


Figure E-14; T-Joint connection; Alloy AlMg4.5Mn; R = 0.5;

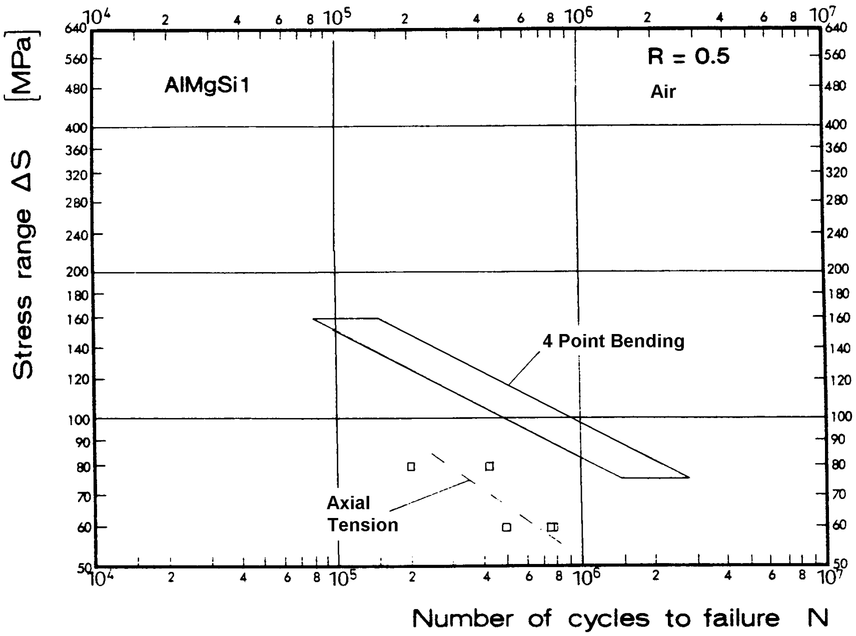


Figure E-15; T-Joint; Alloy AlMgSi1; R = 0.5;

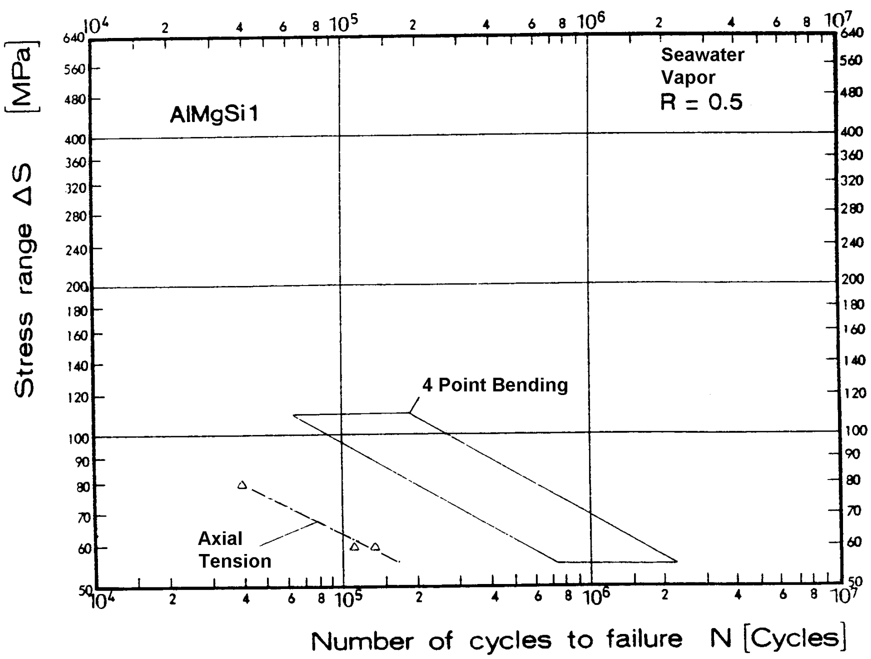


Figure E-16; T- Joint; Alloy AlMgSi1; R = 0.5;

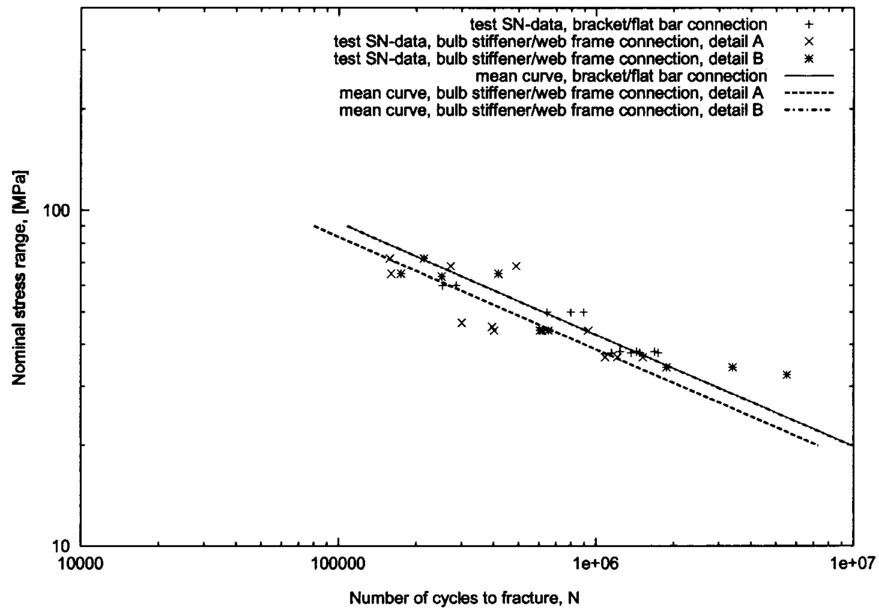


Figure E-17 Flatbar/bracket (Joint 25) connection and bulb stiffener/web frame connection (Joint 26); Nominal stress range; Alloy 5083; R = 0.44; Tension;

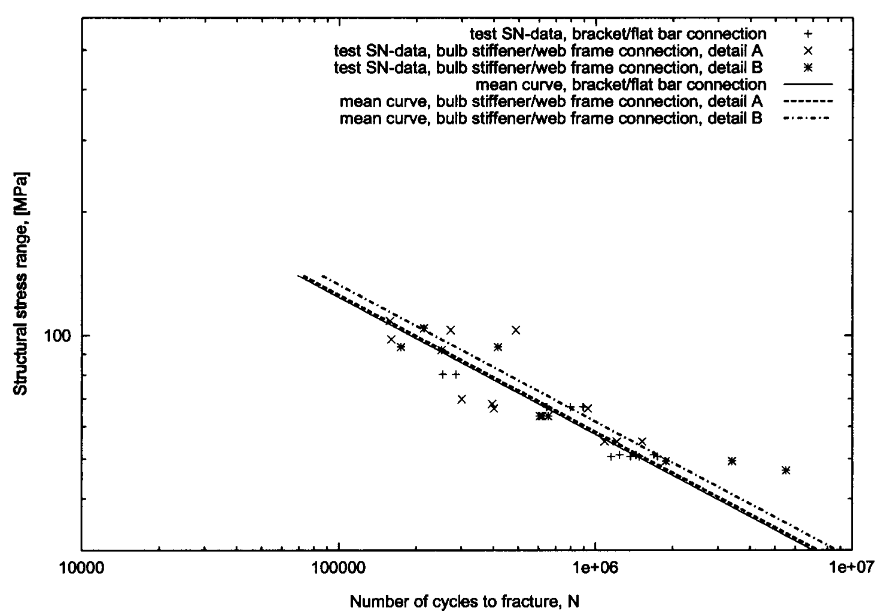


Figure E-18; Flatbar/bracket connection (Joint 25) and the longitudinal stiffener/web frame connection (Joint 26); Structural stress range; Alloy 5083; R = 0.44; Tension;

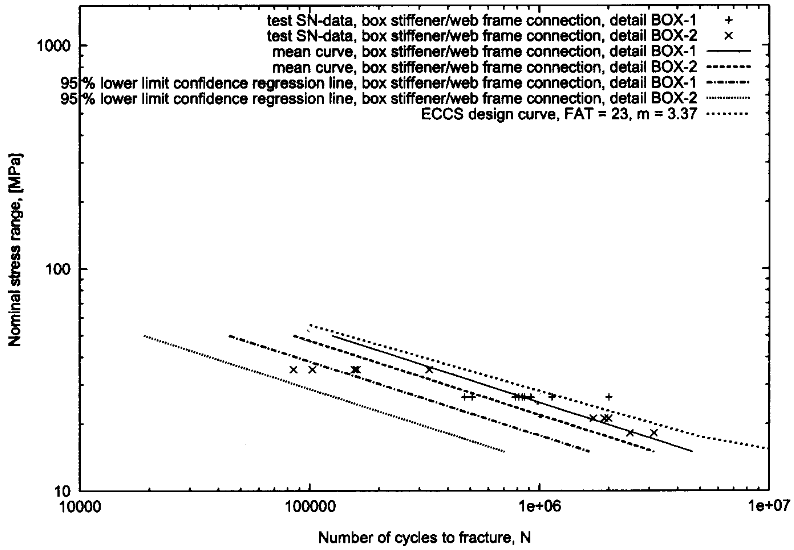


Figure E-19; Box 1 (Joint 27) and Box 2 (Joint 28); Alloy 5083; R = 0.44; Tension;

APPENDIX F

List of Contacts

1.0 Introduction

In order to develop the database and gather the information necessary for the development and completion of this report it was necessary to speak to individuals and organizations recognized as authorities in the field. This appendix contains a listing of the contacts made for this effort. Many of the individuals and organizations were contacted on more than one occasion. It is not intended that this record reflect a "log-book" of all calls and contacts, rather an index to be used in conjunction with this report. It is suggested that interested parties contact any of these references for further information.

FATIGUE OF ALUMINUM STRUCTURAL WELDMENTS

Organization	Individual	Date of contact	Telephone number	Email address	Summary of discussion
NAVSEA	Alan Manuel	3/25/99	703-602-9402		Recommended calling of T. Montemarano & E. Czyryca
NSWCCD	Tom Montemarano	3/25/99	301-227-5071		Recommended various volumes, articles and publications & call E. Duncan.
NSWCCD	Ernie Czyryca		301-227-5073		
NAVSES	Eric Duncan	3/25/99	215-897-1287		Only performed maintenance on displacement hulls, CG47, FFG7. Recommend to call C Cheeseman.
NAVSES	Chris Cheeseman	3/26/99	215-897-7652		Suggested Tech Manual for CG 47 Superstructure Cracking Repair. We agree that Jim Bourne at NAVSEA may have copy.
NAVSEA	Jim Bourne	4/1/99	703-602-5959		Will provide Tech Manual for CG47 Superstructure Cracking Repair.
NAVSEA	Charles Null	3/26/99	703-602-0143		Welds very sensitive to imperfections, inclusions, etc. Need strict definition for design of details and fabrication controls. Aluminum deckhouse in USN abandoned as much for fatigue & material problems as for survivability.
NSWCCD	Jeff Beach	3/26/99	301-227-1742		Referred to same 4 volume set as T Montemarano "Guide for use of Al Alloys in D&C of Naval Vessels." This is not in public domain and cannot be referred to in report. Also suggest to call Prof. W. Sanders @ Iowa St.
Retired (Iowa State University)	Prof. Wallace Sanders	3/26/99	515-232-7184	WSanders@IASTATE .edu	Significant source of information. Will provide CV of experience and willing to help with questions. Worked with AASHTO, Canadian DOT, Craig Menzemer (ALCOA fatigue guru currently @ Univ of Akron), Aluminum Assoc. in D.C., Welding Research Council, Work in Europe (ECCS), Prof. Dimitris Kosteas
Aluminum Association	Peter Pollak	3/26/99	202-862-5124		Recommended ASM Fatigue Data: Light Structural Alloys ASM @ 440-338-5151, Cleveland, OH. All data from Aluminum Assoc pertains to civil engr apps, not marine. Regardless, will pursue Aluminum Design Manual, 1994.
ASM		3/26/99			Investigated "Fatigue Data: Light Structural Alloys" @ www.asm-intl.org
JJMA	Joe Koelbel	3/25/99	703-933-6773		Recommended numerous contacts @ CG, NAVSEA, NSWC & papers, etc.
JJMA	John Hollingsworth	3/26/99	703-933-6733		Recommend PMS 325 personnel and aluminum boat builder personnel.
JJMA	Dave Little		703-933-6652		Provided contacts @ National Center for Excellence in Metalworking Technology (NCEMT) & Navy Joining Center (NJC).
NSWCCD det Norfolk	Mark Hoggard	4/7/99	757-686-7160		Use existing NAVSEA stress level std's. Does not have any data for fatigue of aluminum.
AWS	Hardy Campbell	4/5/99	800-443-9353		Didn't think that AWS would have useful information for aluminum weldments in marine environment. Recommended to contact Paul Dickerson.
Retired	Paul Dickerson		724-339-9807		Repeated reference to Iowa State, University of Munich & Aluminum Assoc.
AASHTO	Kyung Kyu Lim	4/5/99	202-624-8918		Only info would be in 2nd Edition of LRFD Bridge Design Specs, 1998. Technical inquires to Dr. John Kulieki @ Modjeski & Masters. 2nd call: Can go and review specs @ AASHTO in DC 8:30 to 4:30 @ 444 N Capitol St, NW, Suite 249.
Modjeski & Masters	Dr. John Kulieki	4/5/99	717-790-9565		Not able to provide much precise information without infringing upon AASHTO rights. Says that Specs contain series of details with allowable stress ranges. Suggest call back to AASHTO to get release of info.

FATIGUE OF ALUMINUM STRUCTURAL WELDMENTS

Organization	Individual	Date of contact	Telephone number	Email address	Summary of discussion
ABS NY	Jack Spencer	4/6/99	212-839-5274		Mr. Spencer used to be Chief of Hull Structures Group at USCGHQ. He has been out of touch with this work for a long time and could not provide any references or contacts to help with current task.
USCG HQ	Steven Cohen	4/6/99	202-267-0467		No specific references or contacts however, he did recommend Fincanterri and Don Blunt (Navy Small Boat Group). Involved with 47 MLD that used fatigue practice parallel to steel, i.e., low nominal stress, continuity/load path.
USCG ELC	Debu Ghosh	4/7/99	410-762-6736		Mr. Ghosh is the Boat Branch Chief at ELC. He does not have any specific information that would help in this task at this time but would be interested in attending the PTC Meetings in the future.
Navy Joining Center (EWI)	Matt White	4/8/99	614-688-5241		Sent the task statement to Mr. White. He will review and return listing of applicable documents from NJC.
Association American Railroads	Charlie Powell	6/10/99	719-585-1883		Cited the section of the AAR Code that is applicable to Aluminum fatigue. In the Manual of Standards & Recommended Practices it is Section C, Part 2, Volume 1. Also cited car producer Trinity or Johnson America for specific grades of Al used in construction. AAR only produces performance specs.
Concurrent Technologies Corp.	Gary Miller	4/19/99	814-269-2874		Spoke to Richard Henry @ CTC who is PM for NCE in Metalworking Technology. Gary Miller ret'd call. He recommends speaking to SAE. Not much info at NCEMT. Also recommend John Cammett at NAVFAC Cherry Point (Helicopter refurbishment.)
SAE	Phyllis Roessler	4/19/99	724-772-7154		
NSWCCD	David Kihl	4/19/99	301-227-1956		Mr. Kihl is a member of the PTC for this task with a great deal of experience relating to fatigue. We had an informal discussion relating to this task and he suggested that he had little experience with aluminum and that all such experience at the Model Basin would be available through Jeff Beach.
Technical University of Munich	Prof. Dimitris Kosteas	4/20/99	011-49 89 64 27 04 24		Established connection with Prof. Kosteas through a letter I FAXED him. He responded via email and does indeed seem to be a very good source of information. Also appears willing and able to assist in the current effort.
NAVSEA	Gene Mitchell	4/21/99	703-602-0205		Will be able to supply a copy of ASM "Fatigue Data: Light Structural Alloys." Need to obtain and make copy of applicable information.
Technical University of Munich	Prof. Dimitris Kosteas	5/20/99	011-49 89 64 27 04 24		Met with Prof. Kosteas @ JJMA NYO. Discussed European works, EuroCode #9, ECCS and the database of information available thru Kosteas. Need to determine how database can be accessed for review for this task. Rec'd copy of EC9 after requesting from Prof. Kosteas.

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Organization	Individual	Date of contact	Telephone number	Email address	Summary of discussion
Lehigh University	John Fisher	6/10/99	610-758-3535		Most of his work is in steel. Only real work was with his grad student, Craig Menzemer. Their work led to a lot of the input in the Aluminum Design Manual.
Bethlehem Steel	Harold S. Reemsnyder	6/10/99	610-694-6737		Mr. H. S. Reemsnyder was selected by the PTC as the Technical Advisor to this report. He provided invaluable commentary to the report and guidance during its development. His insight and knowledge of the subject helped the entire PTC to better understand the mechanics of fatigue and fracture.
University of Akron	Dr. Craig Menzemer	6/10/99	330-972-7291		Confirmed that the work he and Prof. Fisher developed formed basis for fatigue data in Aluminum Design Manual. Also confirmed that Kosteas is the primary authority for current work and database supervision. He will search for papers he wrote with Fisher regarding full size specimen work they did at Lehigh.
NTNU, Trondheim, Norway	Svein Erling Heggelund	9/17/99	(735) 9 55 47	She@ntnu.marin.no	Svein is a Dr. Ing. Student He Wrote an article entitled "Fatigue Analysis Of High Speed Aluminium Catamarans" together with Bard Wathne Tveiten and Torgeir Moan.It could be worth going through. And check up the other authors. Fax no. (735) 9 55 28
DNV, Norway	Magnus Lindgren	9/24/99		magnus.lindgren@dnv.com	Magnus was going to send me DNV Class. Notes 30.7. Magnus was project leader for the project Aluminium in Ships which just were concluded. He seemed very helpful and he might be in a position to help with additional material. Phone no. is available at DNVs homepege.
DNV, Norway	Albert Fredriksen	9/24/1999	+4767577508	Albert.fredriksen@dnv.com	He on the contrary to Magnus Lindgren did not seem as helpful to provide additional material. He recommended me to talk to Magnus and Bard Wathne Tveiten at NTNU in Trondheim.
Halliburton??, Stavanger, Norway.	Bard Wathne Tveiten	10/5/1999	+4751838179	Bardwathne.tveiten@halliburton.com	Former Phd student that now is working in Stavanger for a company called Halliburton??. He has done some work together with Torgeir Moan at NTNU in Trondheim. His paper is called, "Fatigue of Welded Joints in Aluminium". He was going to send it and was very helpful. He had been with Torgeir Moan on both FAST 97 and 99.
Chalmers, Goteborg, Sweden	Anders Ulfvarson	Constant		Au@na.chalmers.se	Prof. at Chalmers University of Gothenburg. A profound knowledge in ship design and in aluminium. A lot of good connections at DNV and Lloyds.
Hydro Aluminium	Ole Terje Midling	10/6/1999	+4752845019	Ole.terje.midling@hydro.com	Ole has been working in the project "Aluminium in Ships" together with Kvaerner & DNV. OT Midling has extensive knowledge in materials and he had been involved in most preojects that had to do with welding. But he had most of papers from the project that were "opened" to the public and were going to send those. Could be a good resource in material properties?
NTNU	Torgeir Moan	10/7/1999	+4773595541	Tormo@marin.ntnu.no	Torgeir Moan is Prof. at the department of marine structures at NTNU in Trondheim. They have conducted allot of work at NTNU and more is to come. Moan has also worked allot with DNV and helping them in there work. He has also done some work with Damage Tolerance Analysis.

C.J Roberts & Ass.	John Roberts	10/7/1999	16042417960	John_Roberts@bc.sympatico.ca	John presented a paper at FAST 99 about Damage Tolerance Analysis. The applicability to the current effort is under investigation and it may not help.
ABS	Houston	10/7/1999	(281) 877-6772		Weren't aware of any work that is currently being done to develop aluminum fatigue data but recognize that this part of the industry is moving forward and ABS is making plans to increase involvement in the high speed industry. Fax: 281 877 6031
CTH	Birger Karlsson	10/20/99	+46317721242	bk@em.chalmers.se	Prof. in Material Science with good knowledge in steel, aluminum, fatigue and fracture mechanics. Recommended Rolf Sandstrom at KTH.
NTNU	Jukka Mononen	10/26/99	+358 9 451 3932	Jukka.Mononen@bygg.ntnu.no	Jukka is a Ph.D. Student at the NTNU in Trondheim. He is conducting fatigue tests on aluminium alloys using different weld techniques. His result may be of interest. However he is not done testing yet.
Helsinki University of Technology,Ship Laboratory	Mirka Seppala Sec. At HUT Ship Laboratory.	10/26/99		mirka.seppala@hut.fi	HTU is conducting project in ship design. I ordered a couple of papers about ship hull design loads and fatigue analysis. It is worth looking more into.
NTNU	Oyvind Helland	11/04/99			Prof. at NTNU. Has a lot of knowledge in fatigue tests, but Bards Thesis contain all information that Oyvind knows about at this time.
KTH	Rolf Sandstrom	11/22/99	+4687908321	Rsand@material.kth.se	Suggested Kosteas as contact, so nothing new. He has a profound knowledge in fatigue he was going to see if he could find more data bases.
TU Delft	Jan Zuidema		+31152782208	j.zuidema@tnw.tudelft.nl	They had started some tests on fatigue in aluminum, but nothing else at the moment. These tests might are not completed but may be of interest in the future.
LTU	Erkki Niemi	11/04/99		Erkki.niemi@quicknet.inet.fi	Retired. But has done a lot of research. Got a number of his papers
NTNU	Arne Alborg	11/15/99		arne.aalberg@bygg.ntnu.no	He suggested that I should talk to Haagesen.
KTH	Karl Garme	11/29/99		Garme@fkt.kth.se	Involved in full scale tests about slamming on HSC at KTH and will most likely be helpful in understanding the forces that act on a HSC.
TU Delft	Bakker				Recommended Jan Zuidema.
TU Delft	Spinkster			j.a.pinkster@wbmt.tudelft.nl	Recommended B. Boon.
TU Delft	B.Boon			b.boon@wbmt.tudelft.nl	Suggestions were similar to those made by others interviewed for this report.
AMERAC	Stephen Cook				
AMERAC	Kim Klaka	01/09/00		K.Klaka@cmst.curtin.edu.au	He said that they had allot of co-operation with the University of NSW and to contact Prof. Don Kelly.
UNSW	Don Kelly	01/10/00	+61293854160	d.kelly@UNSW.EDU.AU	Don had been working on the project with AMECRC, but some parts of it might be confidential so it might take a while to get that cleared. He was going to get back to me with the appropriate contact for further discussion. The person who had been on the project were a Mr Ruben Spyka, but he had left the AMERAC.
LUT	Salme Arola	01/10/00		Salme.arola@lut.fi	
IIW		01/10/00			Fax: 33 149 90 3680
ABS (Houston)	Bill Hanzelak				

ABS (New Jersey)	Paul				Said that he did not know anything about stress histogram for HSC.
Lloyds	Sue Rutherford	01/10/00		rdd-asrd@lr.org	Lloyd were not doing anything concerning fatigue in aluminum HSC. Nothing!
SINTEF	O. Orjaseter	01/20/00	+47 73592914		Orjaseter has conducted a number of aluminum fatigue tests that are included in the report. He gave me some guidance in how to interpret the results. He has been writing many articles about aluminum fatigue and should have a profound knowledge about it.

PROJECT TECHNICAL COMMITTEE MEMBERS

The following persons were members of the Project Technical Committee that represented the Ship Structure Committee to the Contractor as the resident subject matter experts. As such they performed technical review of the initial project proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, performed technical review of the work in progress, and edited the final report.

Project Technical Committee Chairperson

Dr. Roger Basu	American Bureau of Shipping

Project Technical Committee Members

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LT Joe Dufresne	United States Coast Guard
LT Lee Boone	United States Coast Guard
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Mr. Chao Lin	Maritime Administration.
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http://www.ntis.gov/fcpc/cpn7833.html

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