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THE EFFECT OF FABRICATON TOLERANCES ON FATIGUE LIFE OF WELDED JOINTS

SHIP STRUCTURE COMMITTEE

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Ship
Structure
Committee

Address Correspondence to:

Executive Director
Ship Structure Committee
U.S. Coast Guard (G-MSE/SSC)
2100 Second Street, SW
Washington, D.C. 20593-0001
Web site: http://www.shipstructure.org

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EFFECT OF FABRICATION TOLERANCES ON FATIGUE LIFE OF WELDED JOINTS

The objective of this project is to conduct a study of the effect of fabrication tolerances on the fatigue performance of welded details in ship construction.

Fatigue life estimation at the design and approval stage is based on assumptions regarding fabrication quality. Most shipbuilding standards include limits on fabrication tolerances such as misalignment, weld profile defects, etc. However, there is limited information available on the extent to which these standards are actually met.

Fatigue life (S-N) curves used in most fatigue prediction methodologies incorporate assumptions related to fabrication tolerances which are often derived from other industries and do not represent shipbuilding practice. The SSC sponsored this project to investigate actual shipbuilding tolerances and to compare these with standard assumptions in fatigue analysis. Shipyard measurements taken in this project indicate that modern automated panel lines achieve fabrication tolerances that are very much better than those assumed in published guidelines for fatigue analysis. This implies that production engineering should aim to allow the maximum number of fatigue-sensitive connections to be made using automated shop processes.

T. H. Gilmour

T. H. GILMOUR
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

A review of available data on fabrication tolerances achieved by shipyards has been undertaken and compared to assumptions and methodologies used in various marine fatigue analysis standards and guidelines. New shipyard data has been gathered to supplement the extremely small amount of prior data available in the public domain.

The project has developed procedures for tolerance data collection and analysis. It has explored the implications of actual tolerances for fatigue life, and has compared the results with those from standard methods using default tolerances and assumptions. A set of recommendations have been developed, covering tolerance measurement techniques that could be used in future extensions of the work, and areas in which the results of this project can be used in analysis and in the development of inspection strategies.

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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			
$inches^2$ $feet^2$	$centimeters^2$ $meters^2$	multiply by	1.9665
$inches^2$ $feet^2$	$centimeters^3$	multiply by	196.6448
$inches^4$	$centimeters^3$	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 tons	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 $pound/inch^2$ $inch^{1/2}$(ksi√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

ABSTRACT

A review of available data on fabrication tolerances achieved by shipyards has been undertaken and compared to assumptions and methodologies used in various marine fatigue analysis standards and guidelines. New shipyard data has been gathered to supplement the extremely small amount of prior data available in the public domain.

The project has developed procedures for tolerance data collection and analysis. It has explored the implications of actual tolerances for fatigue life, and has compared the results with those from standard methods using default tolerances and assumptions. A set of recommendations have been developed, covering tolerance measurement techniques that could be used in future extensions of the work, and areas in which the results of this project can be used in analysis and in the development of inspection strategies.

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LIST OF ABBREVIATIONS AND SYMBOLS

2SD	Two Standard Deviations
ABS	American Bureau of Shipping
AHTS	Anchor Handling Tug Supply Vessel
AWS	American Welding Society
BMT	British Maritime Technology
BS	British Standard
COV	Coefficient of Variation
DNV	Det Norske Veritas
FE	Finite Element
FOSM	First Order Second Moment
HSE	Health & Safety Executive (UK)
IACS	International Association of Classification Societies
ISO	International Standard of Operation
MODU	Mobile Offshore Drilling Unit
PSF	Partial Safety Factors
SCF	Stress Concentration Factor
SSC	Ship Structure Committee
TWI	The Welding Institute
VLCC	Very Large Crude Oil Carrier

$\bar{x}$	sample mean
$t_{\frac{a}{2},n}$	*t*-distribution value at an exceedance area of $a/2$
a	level of significance in the range 0 to 1
m	population mean
s	population standard deviation
K	stress concentration factor
$K_{t\alpha}$	additional stress concentration factor due to angular mismatch (normally used for plate connections only)
K_g	Stress concentration factor due to the gross geometry of the detail considered
K_n	additional stress concentration factor for un-symmetrical stiffeners on laterally loaded panels, applicable when the nominal stress is derived from simple beam
K_{te}	additional stress concentration factor due to eccentricity tolerance (normally used for plate connections only)
K_w	stress concentration factor due to the weld geometry
n	sample size
S	sample standard deviation

1. INTRODUCTION

1.1 General

Fatigue life estimation at the design and approval stage is based on assumptions regarding fabrication quality. Most shipbuilding standards include limits on fabrication tolerances such as misalignment, weld profile defects, etc. However, there is limited information available on the extent to which these standards are actually met. There is also limited understanding amongst most designers, builders and owners regarding the extent to which fabrication tolerances may influence life expectancy and/or through-life maintenance costs.

Fatigue life (S-N) curves used in most fatigue prediction methodologies incorporate assumptions related to fabrication tolerances. However, these are often derived from other industries, and do not necessarily represent shipbuilding practice. With a better understanding of actual shipyard fabrication tolerances, it should be possible to improve the prediction accuracy of fatigue analyses, and potentially to link the selection of construction standards to life expectancy assessment and through-life maintenance cost.

The Ship Structure Committee has, therefore, sponsored this project to investigate actual shipbuilding tolerances, to compare these with ‘standard’ assumptions in fatigue analysis, and to establish their significance.

1.2 Report Outline

Section 2 of this report defines the project objectives and the general approach that has been adopted in order to fulfill these. Section 3 presents a general description of fatigue life analysis, and how fabrication tolerances have typically been incorporated in design methodologies. Sections 4 - 7 then describe the work undertaken in this project in order to meet the original objectives, and to account for some of the challenges encountered in the course of the work. Conclusions and recommendations for further work in this area are provided at Sections 8 and 9.

Detailed data and analyses are provided as a set of Appendices to this report.

2. OBJECTIVES AND APPROACH

2.1 Objectives

As outlined in the Introduction, the general objective of this project has been to conduct a study of the effect of fabrication tolerances on the fatigue performance of welded details in ship construction. The full extent of anticipated benefits of this could include:

- More realistic fatigue life predictions, based on better information;
- Better demonstration of the effects of construction tolerances on long-term vessel performance or maintenance requirements;
- Improved understanding of the costs/benefits associated with tighter fabrication tolerances and resulting life maintenance costs; and
- Improved ability to evaluate a particular yard's quality control or construction tolerance performance.

This initial project was expected to focus on the first two of these potential outcomes.

As work progressed on the project, the detailed objectives were refined to incorporate the development of recommendations in a number of areas that will need attention before the full range of potential benefits can be realized. These include:

a) development of improved data collection protocols and tools;
b) additional analysis of in-service experience; and
c) consideration of erection sequencing to optimize achieved tolerances.

These issues are also addressed in the project report.

2.2 General Approach

The project was planned to encompass three main tasks, as outlined below:

2.2.1 Task 1: Data Collection

This task was to encompass a literature review of applicable data for fabrication or structural tolerance data for welded ship structural details, and limited shipyard surveys to collect new data.

2.2.2 Task 2: Statistical Analysis

This task was to compute statistical distributions describing the variability in welded ship structural details and construction tolerances.

2.2.3 Task 3: Identification of Effect on Fatigue Life

This task was to demonstrate the effects of actual and design tolerances on normal and leak stresses and on design life.

While these principal tasks were accomplished, the more detailed sub-tasks within them were revised as the project progressed in order to take account of early findings regarding the (lack of) data available from prior work and the difficulty in obtaining new data. The project report describes the work actually undertaken and the rationale for certain changes in focus during the project.

3. TECHNICAL BACKGROUND

3.1 Overview

Many materials, including steel, when subjected to repeated strains (of sufficient magnitude) will weaken and eventually initiate cracking. If repeated loading continues, the cracks will grow through the member thickness and increase in length. The development of these cracks through this process is termed fatigue crack initiation and growth. Fatigue damage in large structures – such as ships – normally accumulates most rapidly at joints or discontinuities, where stresses are raised above those in the surrounding structure by local effects.

Ships operate in environments that apply variable amplitude loading cycles, meaning that the structural components of a ship will experience repeated loading or strain events throughout the life of the ship. Fatigue cracking in ship structure can therefore be a serious safety and monetary issue if it occurs. Much effort has gone into the study of fatigue problems with ship structure.

Fatigue is a complex problem primarily related to structural geometry, with secondary links to material properties. Due to the inherent variability of the fatigue damage accumulation process, pure analytic procedures cannot accurately predict the occurrence of fatigue failure in a real structure. All methodologies are based upon empirical results from fatigue testing representative samples. The normal process is to create (or extract from a real structure) a set of test specimens, and then apply constant amplitude cyclic loads until a crack appears. The number of cycles before failure is the fatigue life for that specimen. No two specimens are alike, thus even under the most controlled conditions each specimen will fail after a different number of cycles. By performing many tests however, and then fitting a curve through the data with consideration given to the test result variance, it is possible to predict within given confidence limits when failure will occur for a particular set of specimens. This data is normally presented in the form of an S-N curve such as shown in Figure 3.1.

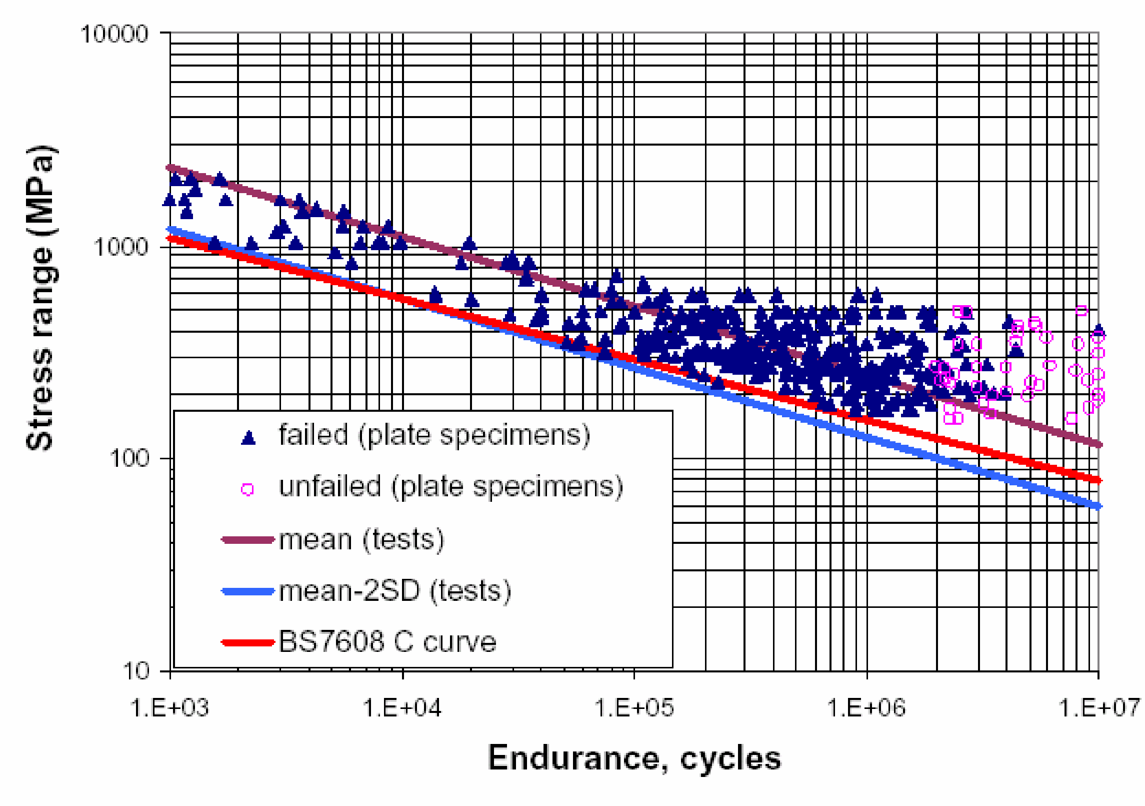

Figure 3.1: Typical S-N Curve
(Reprinted from "Re-evaluation of fatigue curves for flush-ground girth welds", 2003. Prepared by TWI for HSE.)

Many structures, including ships, will not experience constant amplitude cyclic loading as was used on the test specimens. It was established by Miner-Palmgren that the amount of fatigue damage accumulated during each load cycle is proportional to the stress during that cycle. The Miner-Palmgren law (hypothesis) can be stated as:

> *"For a particular stress range, S_1, the constant amplitude endurance, N_1, is a measure of the fatigue damage as a result of S_1, as applied for n_1 cycles, is n_1/N_1 of that needed to cause failure. Failure occurs under a sequence of different stresses when the sum of all ratios n/N equals unity. That is:*
>
> $$\frac{n_1}{N_1}+\frac{n_2}{N_2}+\frac{n_3}{N_3}+\ldots=\sum\frac{n_i}{N_i}=1 \text{ at failure}$$
>
> *Values of N_i are taken from the appropriate design S-N curve for each value of S_i."*[1]

[1] S.J. Maddox, Fatigue Strength of Welded Structures, Second Edition, 1991

The variability in the test data is largely a result of imperfections in the welded test specimens. To use S-N data to predict fatigue life, the designer must assume that the structure will have imperfections similar to the test specimens. The current project was intended to test the validity of this assumption.

3.2 Classification of Imperfections in Welded Joints

Welded joints cannot be perfect. All joints have flaws/imperfections that reduce the structural integrity or fatigue life of the joint. Imperfections lead to higher localized stress, thus fatigue cracks most always start at an imperfection. The localized stress is often called the notch stress.

For fatigue design it is important to know the effect of an acceptable imperfection on the fatigue life of the welded joint, and conversely when an imperfection becomes unacceptable within the analytical framework used as the design basis. To do this the imperfections must be identified or classed, and each type of imperfection must be quantified by its relevant parameters.

There are three main classes of imperfections that will decrease the fatigue life of a welded joint:

a) Planar Flaws (sometimes called Surface Weld Discontinuities)

- i) cracks
- ii) lack of fusion or penetration
- iii) undercut, root undercut, concavity and overlap. (On some occasions, undercut and root undercut in welds are treated as shape imperfections.)

b) Non-Planar Flaws (sometimes called Embedded Weld Discontinuities)

- i) cavities
- ii) solid inclusions, e.g. porosity and slag (On some occasions cavities and solid inclusions are treated as planar flaws.)

c) Geometrical / Shape Imperfections

- i) axial misalignment
- ii) angular misalignment
- iii) imperfect weld profile
- iv) undercut and root undercut (if it gives rise to stress concentration effects)

A comprehensive classification of the various types of weld flaws that may be encountered is given in ISO 6520 (AWS D3.5).

It was agreed at the outset of this project that the scope would be limited to geometrical imperfections, as these are the fabrication tolerances that can be handled explicitly using standard design tools. However, some additional discussion of the fatigue effects of all types of imperfections is provided in the following pages to supply context for the subsequent analyses.

3.2.1 Planar and Non Planar Flaws

Non-planar flaws such as weld porosity and slag inclusion will reduce fatigue life, but are less harmful than planar flaws for the fatigue life of a welded connection when kept below normal workmanship levels. Planar flaws such as weld toe undercuts, cracks, overlaps, porosity, slag inclusions and incomplete penetration can have a significant influence on fatigue life. Figure 3.2 illustrates many of the planar and non-planar flaws that can exist in a welded joint.

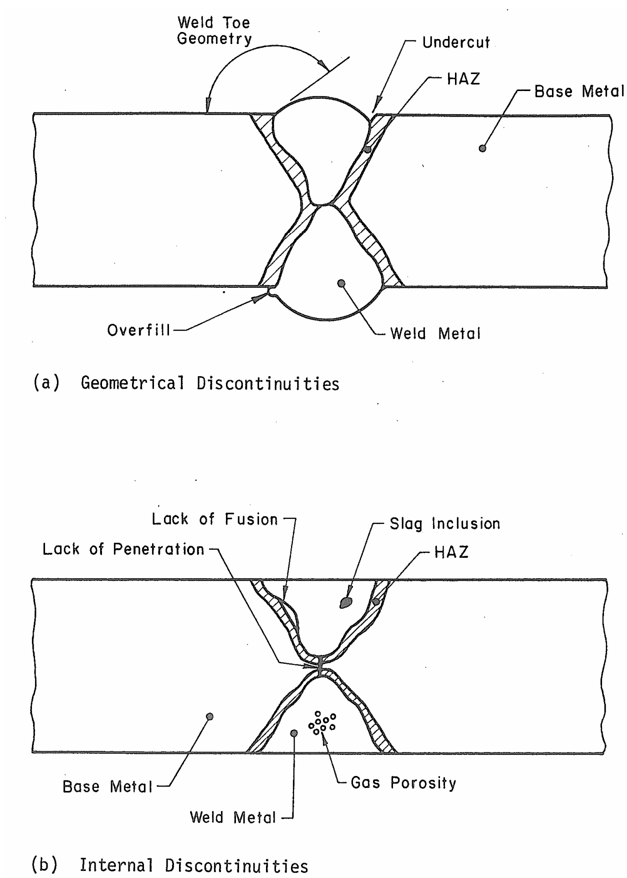

Figure 3.2: Common Geometrical and Internal Weld Discontinuities
(Reproduced from: Bowman D., and Munse W.H.)

Non-destructive testing is required to quantify the dimensions of planar and non-planar imperfections. Obtaining a statistically significant sample of these types of defects requires considerable effort.

Most fatigue assessment methodologies consider the effect of planar and non-planar imperfections by assuming that samples upon which the S-N curves were developed contained representative quantities of planar and non-planar imperfections. Some of the scatter in the experimental S-N curve data is considered to be representative of planar and non-planar imperfections contained in a typical welded joint. However, this is an assumption that may warrant further attention in the future.

More in-depth methodologies have been developed for the assessment of the effect of planar and non-planar imperfections on fatigue life. The British Standard, BS 7910, “Guide on Methods for assessing the Acceptability of Flaws in Structure” (replacing PD 6493, and PD 6539) provides an integrity management procedure based upon a fitness for purpose philosophy.

3.2.2 Geometric Imperfections

Geometric imperfections in welded joints such as misalignment, angular misalignment, angular distortion, excessive weld reinforcement and otherwise poor weld shapes can reduce fatigue life by several orders of magnitude. Geometric imperfections differ from planar and non-planar flaws in that their effect is to enhance existing *regions* of stress concentration in the welded joint, chiefly the weld toe, rather than to provide additional sites for possible fatigue crack initiation.

The effect of the misalignment is to cause an increase or decrease in stress in the joint when it is loaded, due to the introduction of local bending stresses. This applies to both butt and fillet welded joints, but only under loading which results in membrane stresses transverse to the line of misalignment.

For reasons outlined, it was decided at the outset to focus the study on geometric imperfections in butt-welded plates and stiffeners, and fillet welded cruciform joints. These joints compose the majority of welded joints in a ship and are fatigue sensitive to imperfections. An aim of the study was to *quantify* the effects of geometric imperfections in terms of fatigue life. In this regard, formulae already exist for estimating the increase in stress due to geometric imperfections. The development of these formulae and issues concerning their application is discussed in Section 3.3 and in subsequent sections. Finally, most geometric imperfections to some degree can be measured relatively easily without the use of any special non-destructive testing equipment. The figures in Section 3.3 provide a sample of the individual geometric imperfections possible in typical butt and cruciform welded joints.

3.3 Use of S-N Curves in Design

Three different ideologies have developed with regard to the creation of S-N curves and their use in fatigue analysis. The three approaches are commonly referred to as:

1. Nominal stress approach
2. Hot Spot (Structural) stress approach
3. Notch stress approach

To evaluate fatigue strength properly, there should be consistency between the stress with which the S-N curve is defined and the one with which fatigue strength is calculated. A brief overview of each approach is presented in the following subsections.

3.3.1 Nominal Stress Approach

The nominal stress approach uses S-N curves that have been derived using test pieces that contain various attachments giving rise to structural discontinuity effects, and various welds, but usually no macro-geometric effects. Fatigue strengths given in the S-N curves are nominal stresses that exist in the structure just outside of the welded joint.

The testing procedure used to derive Nominal Stress S-N curves does not explicitly account for the effects of imperfections. Most nominal stress procedures (such as BS5400) class each detail according to its quality and configuration. Each individual detail is then associated with an S-N curve that should account for expected quality and configuration in predicting the fatigue life of the detail. The S-N curves are multiples of each other, as shown in Figure 3.3. This approach essentially says that all welded steel has the same fatigue life, thus the same fatigue curve. The difference in fatigue life is due to the stress concentration resulting from the weld quality, material quality, weld geometry and the overall geometry of the detail.

This approach can work well if it can be assumed that the detail under consideration will have the same stress pattern and imperfections as the detail upon which the S-N curve was derived. Some potential disadvantages have been summarized as follows:

> *"Most S-N curves proposed by international institutes such as IIW and BS 5400 are defined with the nominal stress range and the related weld-joint type. The nominal stress excludes the stress concentration due to geometric shape such as structural discontinuities and presence of attachments. At most of the critical points in ship structure where fatigue strengths are concerned, there are stress concentrations that depend not only on structural detail shapes but also on applied loading pattern. Furthermore, it is often hard to define the nominal stress due to the complexity of structure and loading. Accordingly, there is a high possibility is misevaluating the fatigue strength when it is evaluated with the nominal stress basis."*[2]

3.3.2 Hot Spot Stress Approach

The S-N curves for this approach are based upon estimated stress at the toe of the weld. Some of the uncertainty concerning the stress concentration due to the weld shape is removed using this approach. Normally a coarse mesh Finite Element (FE) model, or analytic methods are used to establish the nominal stress just outside of the weld detail. A fine mesh sub-model of the weld detail is then created to determine the stress at the toe of the weld. This stress is then used with the hot spot S-N curves to estimate fatigue life for that joint.

In a hot spot S-N curve testing program the nominal stress would still be measured. The stress at the toe of the weld is determined using a FE model of the test specimen to establish a stress concentration factor that would give stress at the toe. In the FE model the toe of a weld is a singularity, and thus stress is normally determined at a small distance from the root.

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[2] Kang, W., Kim, S, "A Proposed S-N Curve for Welded Ship Structures", supplement to the *Welding Journal*, July 2003.

There are various extrapolation standards, but it is usually taken somewhere between 0.5 to 1.5 plate thicknesses from the root. Some errors are introduced using this methodology.

> *"The resulting value of hot spot stress may differ depending on the FE program or on the element type, although the procedure for the calculation is just the same. It is necessary to establish a more appropriate procedure for the calculation of the hot spot stress that may represent the state of stress in relation to the fatigue behavior of welded joints."*[3]

Error can also be introduced if there is no consistency in the weld profile of the test specimens, or if the FE model does not accurately represent the test specimens. Most of the hot spot S-N curves in use are derived largely from nominal stress S-N curves developed for BS5400. The weld profile data for most of the nominal stress S-N curves has not been accurately recorded (e.g. SSC-369)[4]. Thus in this derivation, reasonable assumptions regarding the weld profiles of the test specimens had to be made in order to determine the stress concentration factor (SCF) for the samples.

Even with possible derivation errors, it is generally accepted that the hot-spot stress approach is more accurate than the nominal stress approach. Provided the hot-spot S-N curve is accurate, the methodology allows for more freedom and accuracy in the types of structural details and weld details that may be analyzed. The hot spot stress approach is becoming more widely accepted as a more accurate and practical approach to fatigue analysis of ship structures. This is largely because advances in computing mean that it is now feasible to use FE models for determination of stress.

The uncertainties concerning the planar and non-planar imperfections still exist with this approach. For fatigue analysis it is still important that the quality of the weld detail match the weld quality of the samples upon which the S-N curve has been derived.

3.3.3 Notch Stress Approach

The notch stress approach is based upon S-N curves derived for smooth specimens that contain no geometric notches. A stress concentration factor is then determined to account for the increase in stress due to each possible type of geometrical imperfection. Using this methodology a fine mesh FE model of the welded detail is not required since the increase in stress at the weld toe is found using an appropriate stress concentration factor. The relationship between nominal, hot spot stress, and notch stress can be expressed as follows:

$$? s_{notch} = K_w \bullet ? s_{hotspot} = K_g \bullet K_w \bullet ? s_{nom}$$

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

[3] Kang, W., Kim, S, "A Proposed S-N Curve for Welded Ship Structures", supplement to the *Welding Journal*, July 2003.
[4] Stambaugh, K., et. al "Reduction of S-N Curves for Ship Structural Details" SSC Report 369.

The development of empirical formulae for these SCF and for stress concentration factors pertaining to axial and angular misalignment is addressed in the following pages. The derivation of the notch stress S-N curves is a possible source of error for this approach. Most notch stress S-N curves in use in the marine industry have been derived largely from the S-N curves developed for BS5400. Again, the level of imperfections in these curves is not precisely known, thus assumptions were made in order to develop a notch stress S-N curve. There is also uncertainty associated with the development and application of stress concentration factors. Most SCF factors have been developed using analytical methods, or FE analysis to predict the stress at the notch due to a particular imperfection. With the FE approach, this is done for many geometric variations and then regression analysis is used to determine an appropriate formula. It is necessary to assume a weld shape for the FE analysis. Real welds will differ from the assumed shape; thus depending on the sensitivity of the detail, significant errors are possible.

The development of the SCF factors for increase in stress due to weld profile has meant that it is possible, within the error limitations, to address the effect of imperfect weld profile on fatigue life.

The uncertainties concerning the planar and non-planar imperfections still exist with this approach. For fatigue analysis it is still important that the quality of the weld detail match the weld quality of the samples upon which the S-N curve has been derived.

Det NorskeVeritas (DNV) is one of the organizations that use a notch stress approach to fatigue life calculations. Their methodology is well suited to assess the influences of construction tolerances on fatigue life, and is thus described in more detail below.

Under the DNV approach, the S-N curves used in notch stress analysis are based on smooth test samples where the notch stress is equal to the nominal stress. The K-Factors used in this report are thus defined as:

$$K = s_{notch} / s_{nominal}$$

Thus the notch stress range to use with the appropriate S-N curve is:

$$?s_{notch} = K \cdot ?s_{nominal}$$

The overall K factor is a combination of K-factors arising from different geometric imperfections.

$$K = K_g \cdot K_w \cdot K_{te} \cdot K_{ta} \cdot K_n$$

Where:

K_g = *Stress concentration factor due to the gross geometry of the detail considered.*
K_w = *Stress concentration factor due to the weld geometry.*
K_{te} = *Additional stress concentration factor due to eccentricity tolerance (normally used for plate connections only).*
K_{ta} = *Additional Stress concentration Factor due to angular mismatch (normally used for plate connections only).*
Kn = *Additional stress concentration factor for un-symmetrical stiffeners on laterally loaded panels, applicable when the nominal stress is derived from simple beam analyses (not considered in this report).*

Table 3.1 and Table 3.2 give the formulas for the individual stress concentration factors calculated. The formulas are derived from the DNV Classification Note No. 30.7: "Fatigue Assessment of Ship Structures". The derivation, application and accuracy of some of these formulas are discussed in Section 6.

For some geometries, DNV provides default values that have been established for normal design fabrication of welded connections. These values are also presented in Table 3.1 and Table 3.2. For comparison, the corresponding maximum fabrication tolerances adopted by the International Association of Classification Societies are also presented.

The situations and parameters outlined in Tables 3.1 and 3.2 are illustrated in Figures 3.3 to 3.6 and Figures 3.7 to 3.9 respectively.

Table 3.1: Stress Concentration Factors Applicable to Butt-Welded Plates and Stiffeners of Same Thickness

(Published in DNV Classification Note: Fatigue Assessment of Ship Structures)

DNV Stress Concentration Factors Formulae	IACS Standard	DNV Default	Notes
Angular Misalignment – Seam Halfway Between Supports $K_{t\alpha} = 1 + \frac{\lambda}{4}\alpha\frac{s}{t} = 1 + \lambda\frac{e}{t}$ $\lambda = 6$ for pinned ends $\lambda = 3$ for fixed ends	e = 4 to 7 mm depending on location. Limit is e = 6 to 9 mm depending on location.	e = 6 mm For 12mm plate, assuming pinned ends $K_{t\alpha} = 4$	IACS standard is for "Fairness of plating between frames" not necessarily for butt joints. $e = (\alpha \cdot s)/4$ only if the seam is at the middle of the span.
Angular Misalignment $K_{t\alpha} = 1 + \lambda s_1 \frac{\alpha_1}{t} = 1 + \lambda\frac{e}{t}$	Same as above.	Same as above.	
Weld Reinforcement $K_w = 1.0 + 0.5(\tan\theta)^{1/4}$	$\theta < 60°$	$\theta < 45°$ Gives K_w = 1.5	For each butt-welded joint there are four K_ws. One for each weld root angle.
Misalignment $K_{te} = 1 + \frac{3e_0}{t}$	For high strength steel $e_0 < 0.15t$ or $e_0 < 3$ mm. For others steels $e_0 < 0.2t$ or $e_0 < 3$ mm	$e_0 = 0.15t$	
Gross Geometry $K_g = 1.0$			Simple details with a $K_g = 1.0$ were selected for the survey.

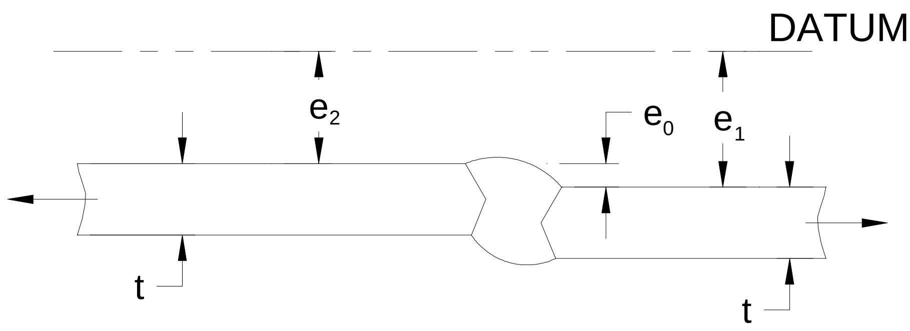

Figure 3.3: Butt-Welded Plate Misalignment - Variables

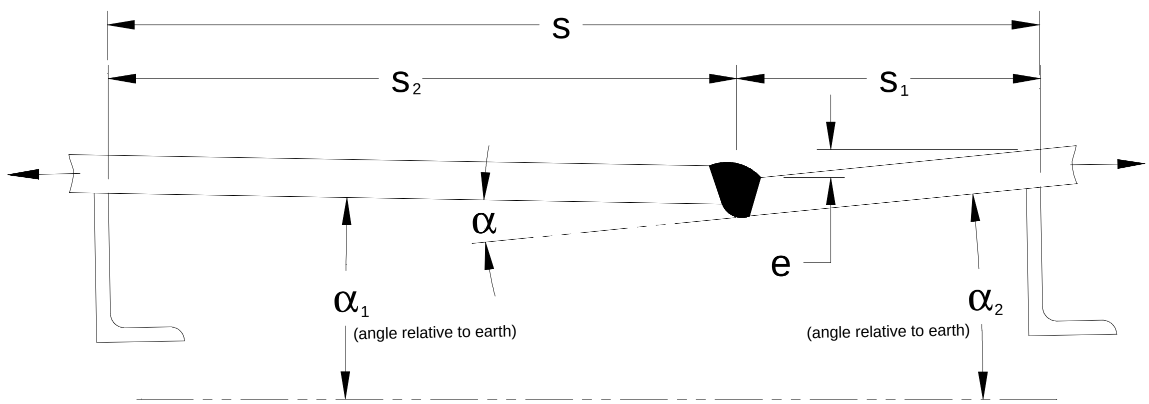

Figure 3.4: Butt-Welded Plate Angular Misalignment - Variables

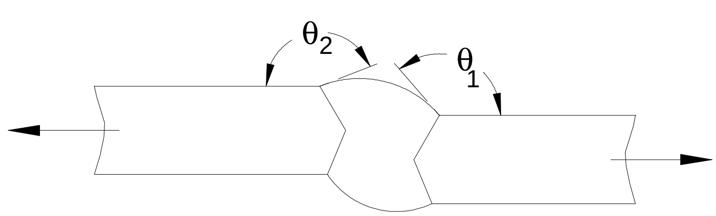

Figure 3.5: Butt-Welded Plate Weld Toe Angle - Variables

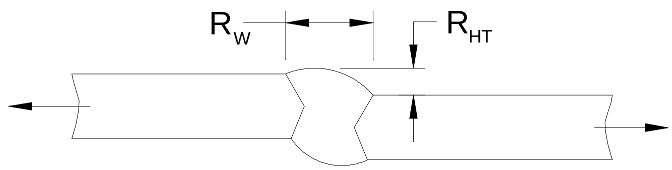

Figure 3.6: Butt-Welded Plate Weld Reinforcement - Variables

Table 3.2: Stress Concentration Factors Applicable to Fillet Welded Cruciform Joints
(Published in DNV Classification Note: Fatigue Assessment of Ship Structures)

DNV Stress Concentration Factors Formulae	IACS Standard	DNV Default	Notes
Misalignment $K_{te} = 1 + \frac{6 \times t^2 \times e}{l_1\left(\frac{t_1^3}{l_1} + \frac{t_2^3}{l_2} + \frac{t_3^3}{l_3} + \frac{t_4^3}{l_4}\right)}$ $e = \frac{t_1}{2} + e_0 - \frac{t_2}{2}$ $t_1 \leq t_2$ $e_0 \leq 0.3t_1$	For high strength steel. $e_0 = (5t_1 - 3t_2)/6$ For other $e_0 = (2t_1 - t_2)/6$ Where t_3 is less than t_1, then t_3 should be substituted for t_1 in the standard.	$E_0 \leq 0.3t_1$	
Weld Geometry *For axial stress in direction of intercostal member* $K_g K_w = 1.2 + 1.3(\tan q)^{1/4}$ *Gives stress at toe of weld.*	θ at weld toe ≤ 90°. States that in areas of stress concentration and fatigue the class society may require a lesser angle.	$K_g K_w = 2.5$ for θ = 45°	
Weld Geometry *For axial stress in direction of continuous member* $K_g K_w = 0.9 + 0.9(\tan q)^{1/4}$ *Gives stress at toe of weld.*		$K_g K_w = 1.8$ for θ = 45°	

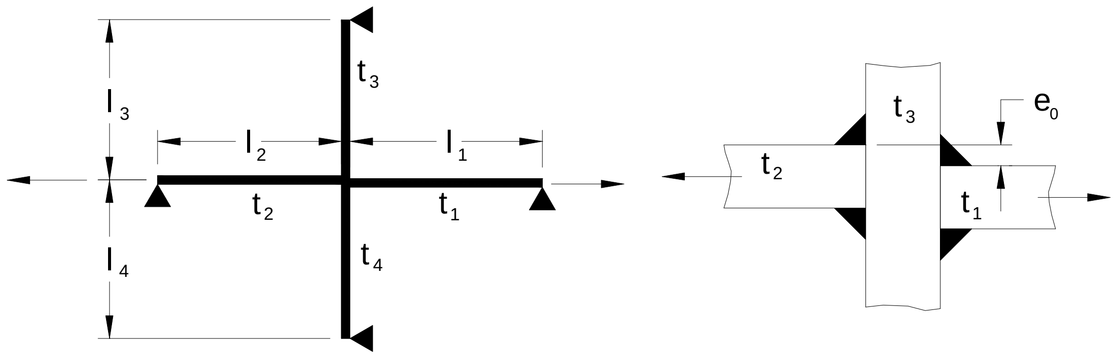

Figure 3.7: Cruciform Joint Misalignment – Variables

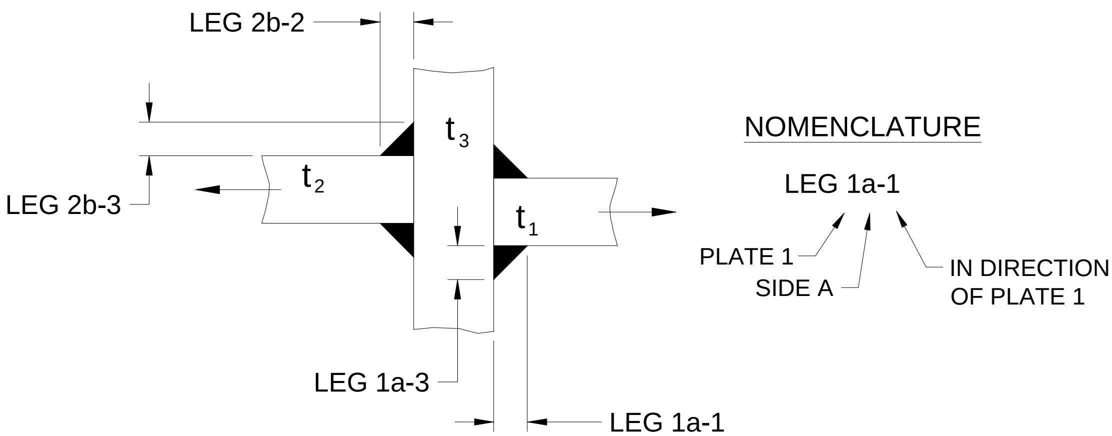

Figure 3.8: Cruciform Joint Weld Geometry – Variables

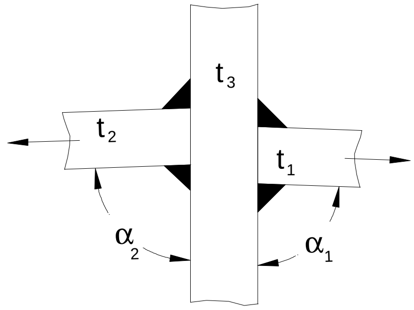

Figure 3.9: Cruciform Joint Angular Misalignment – Variables

3.3.4 Axial and Angular Misalignment Imperfections - Application in S-N Curve Analysis

It is important to note that test specimens are normally considered free of axial and angular misalignment, although there is some uncertainty in this assumption:

> *"It is likely that some of the nominally-aligned test specimens used to generate the data upon which design S-N curves are based were actually misaligned, with the result that some misalignment is always acceptable. For example, in the case of butt welds, there is some evidence [65][5] to indicate that the design S-N curve already embodies the effect of misalignment corresponding to $K_m = 1.3$. However, further work is needed to confirm this, and to consider cruciform joints."*[6]

However, assuming that the increase in local stress in butt and fillet welded joints is not embedded in the S-N curves of either fatigue analysis approach, the stress range used in the fatigue analysis must always be increased by a suitable factor to account for any anticipated misalignment in the detail. Formulae have been developed for estimating this increase in stress for certain types of misalignment, the DNV examples provided at Section 3.3.3 being one example of this.

More generally, as shown in Figure 3.10, angular misalignment in an axially loaded joint will induce a bending moment and a secondary bending stress in the joint.

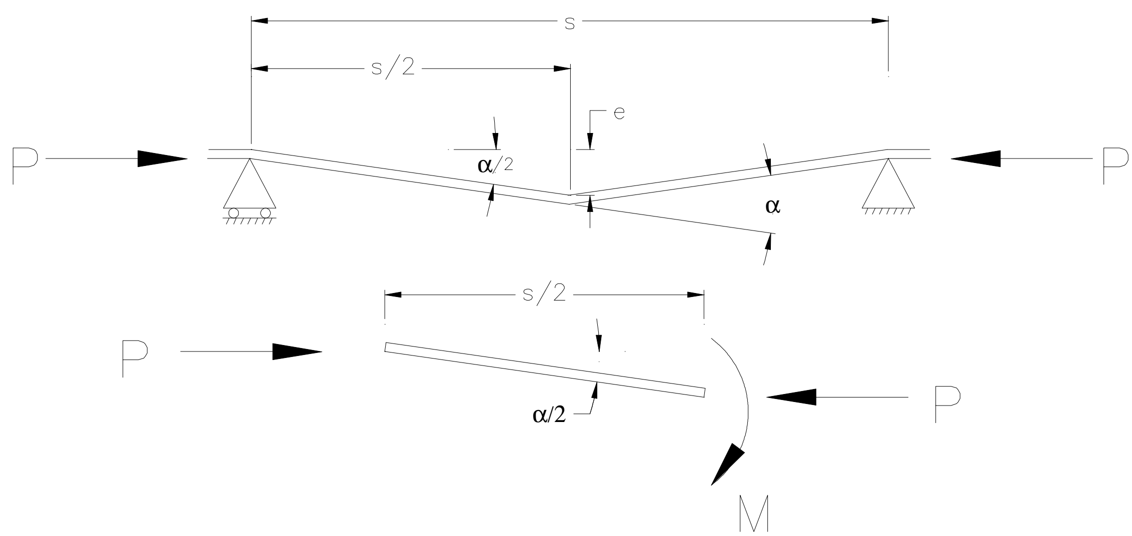

Figure 3.10: Angularly Misaligned Plating - Seam Halfway between Supports

[5] Maddox, S.J., 1985. "Fitness for purpose assessment of misalignment in transverse butt welds subject to fatigue loading", IIW, document XII-1180-85. (unpublished).
[6] BS 7910:1997, "Guide on methods for assessing the acceptability of flaw in fusion welded structures – Draft for public comment".

The stress must be resisted axially, thus the bending stress in terms of developing a SCF formula can be thought of as an apparent increase in axial stress equal to:

$$K_{ta} = 1 + \frac{s_b}{s_a}$$

where the axial stress is equal to:

$$s_a = \frac{P}{A} = \frac{P}{t \times b}.$$

The bending stress is equal to:

$$s_b = \frac{My}{I} = \frac{6M}{bt^2}$$

for a flat plate. The bending moment at the joint:

$$M = P\frac{s}{2}\sin(\frac{a}{2}) = P\frac{s}{2}\frac{a}{2} = P\frac{sa}{4}$$

for small angles. Substituting M in the formula for s_b gives:

$$s_b = \frac{3Psa}{2bt^2}.$$

Substituting s_a and s_b into the formula for K_{ta} gives:

$$K_{ta} = 1 + \frac{3}{2}s\frac{a}{t}.$$

This is the same formula[7] provided by DNV in Classification note 30.7 and can be reduced to:

$$K_{ta} = 1 + 6\frac{e}{t}$$

if e instead of α and s is known. Also, note that for fixed end supports:

$$K_{ta} = 1 + \frac{1}{2}s\frac{a}{t} = 1 + 3\frac{e}{t}.$$

The derivation of this formula illustrates many important points regarding its application to fatigue design of ship structures.

Generally, the plating in ship structure is lofted such that weld seams can be as close as possible to a stiffener or support. This is done specifically to avoid the problem of secondary bending stress due to misalignment. The formula above in terms of α, angle between plates, does not apply directly. Figure 3.11 illustrates misalignment in a more typical ship structure.

[7] The same formula is given by Maddox in “Fatigue Strength of Welded Structures, Second Edition”.

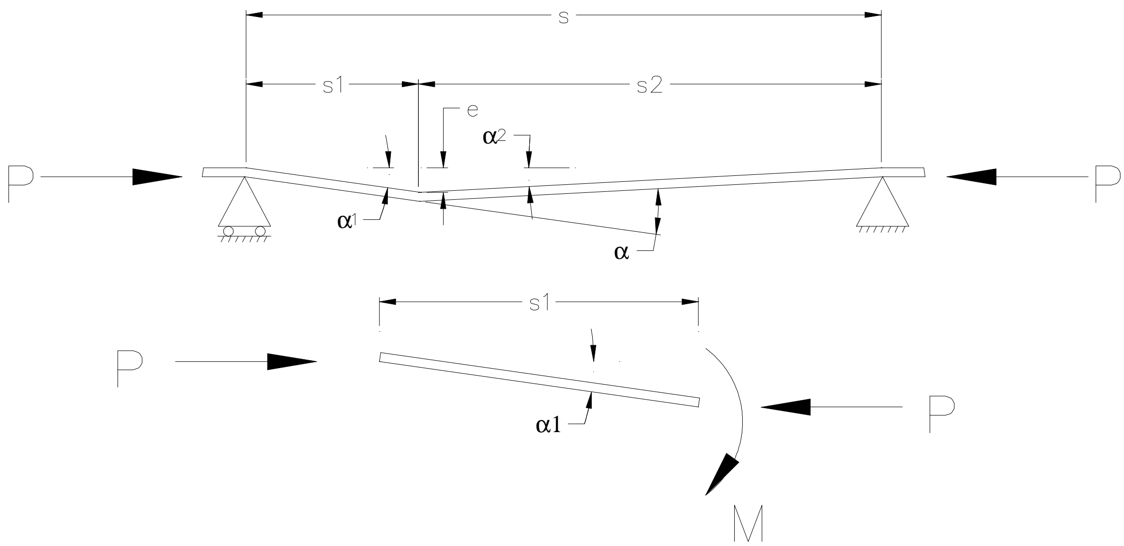

Figure 3.11: Angularly Misaligned Plating - Seam at Location other than Halfway between Supports

The derivation of the $K_{t\alpha}$ formula for this geometry is the same as above except that s/2 is replaced by s1 and α/2 is replaced by α1. Making these substitutions gives $K_{ta} = 1 + 6s_1 \frac{a_1}{t}$

For a given value of e however, the value of $K_{t\alpha}$ will be the same irrespective of the location of the seam. For example for e = 6 mm is $K_{t\alpha} = 4$ for both geometries.

A number of systematic experimental studies of the effects of misalignment have been undertaken (for example by the UK Department of Energy, as reported in Maddox, 1991) from which Figure 3.12 is reproduced. Work of this type has been used more in establishing tolerance limits than in developing more sensitive analytical treatments of the tolerances that actually exist in fabricated structures.

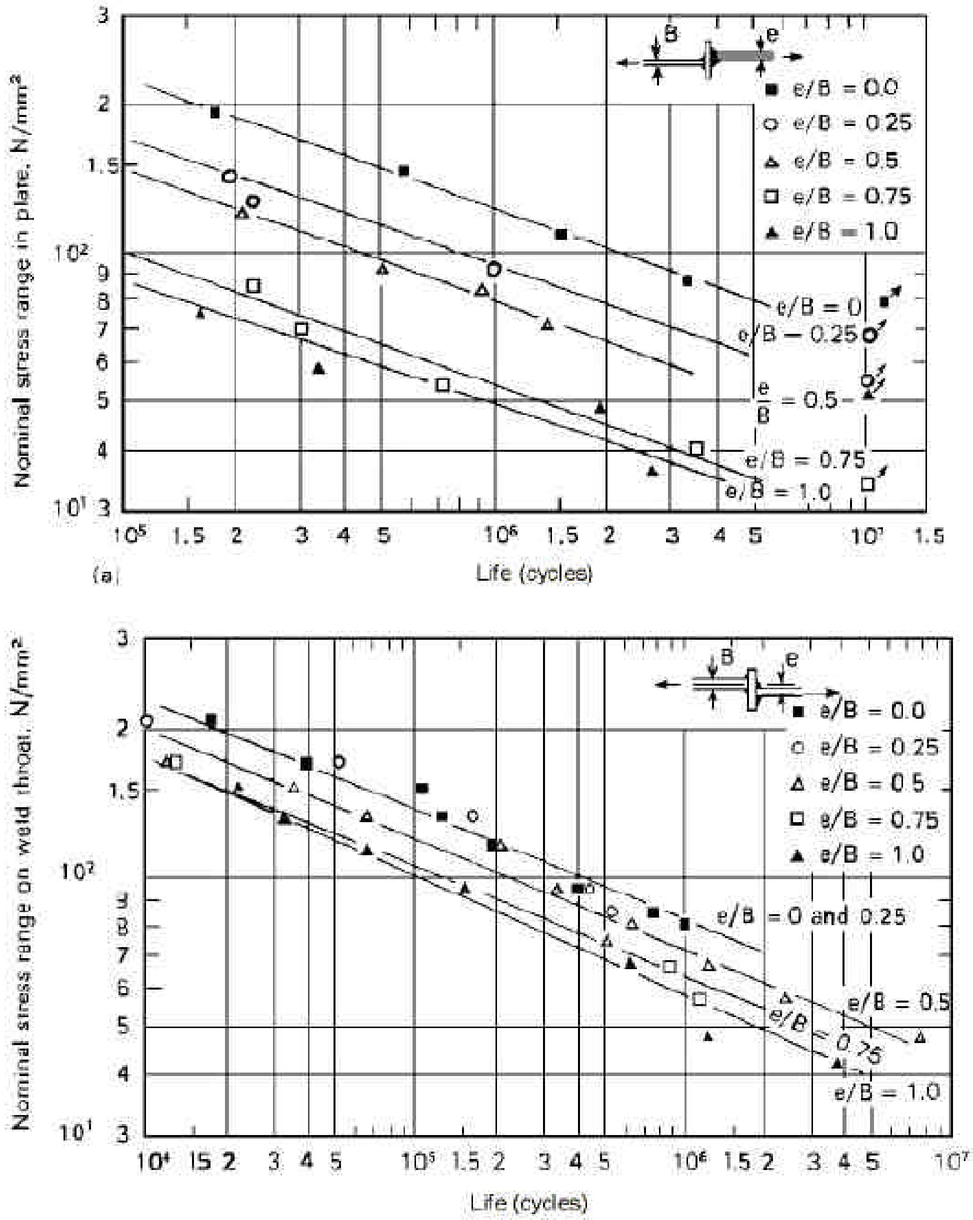

Figure 3.12: Effect of Misalignment on Fatigue Strength (Maddox, 1991)

3.4 Sensitivity in Fatigue Life Calculations

The discussion presented in DNV Classification Notes No. 30.7, Section 2.4 provides a good overview of some of the uncertainties in fatigue life prediction, some relevant aspects of which are presented and discussed below:

"2.4.2
Because of the sensitivity of calculated fatigue life to the accuracy of estimates of stresses, particular care must be taken to ensure that stresses are realistic.

Fatigue damage is proportional to stress raised to the power of the inverse slope of the S-N curve. Small changes in stress result in much greater changes in fatigue life. Special attention should be given to stress raisers like eccentricities and secondary deformations and stresses due to local constraints. Due considerations should, therefore be given to the fabrication tolerances during fatigue design.

2.4.3
There is rather a large uncertainty associated with the determination of S-N curves. The scatter in the test results, which form the basis for the S-N curves, is generally accepted to relate to the normal variation of weld imperfection with normal workmanship…. The ratio between calculated fatigue lives based on the mean S-N curve and the mean minus two standard deviations S-N curve is significant as shown in (Figure 3.13)".

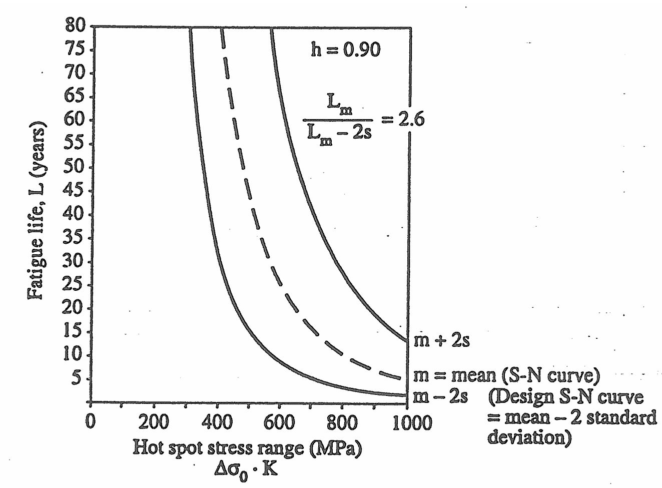

Figure 3.13: Fatigue Life Influence of Stress Level and S-N Data for Welded Connections

Two important aspects of fatigue life can be identified from the text and figure above. First, the exponential nature of the relationships between stress range and fatigue life lead to dramatic changes in expected outcome (life) for modest changes in stress. The second noteworthy aspect is that most S-N design curves are based upon the mean minus two standard deviation curves for the relevant experimental data set. Through this assumption, the S-N curves are associated with a 97.6% probability of 'survival'. This level of conservatism is intended to mitigate some of the unknowns in fatigue life prediction. An implicit assumption is that the level of scatter in the experimental data is representative of that in the 'real world'. As can be seen from the example in Figure 3.13, the scatter is normally considerable,– in this case, a factor of 2.6 on design life.

As stress range is affected by the local stress concentration factor DNV highlights the influence of uncertainties in SCF:

> ***"2.4.4***
> *There is also uncertainty associated with the determination of stress concentration factors. The error introduced in the calculated fatigue life by wrong selection of stress concentration factor is indicated in (Figure 3.14)".*

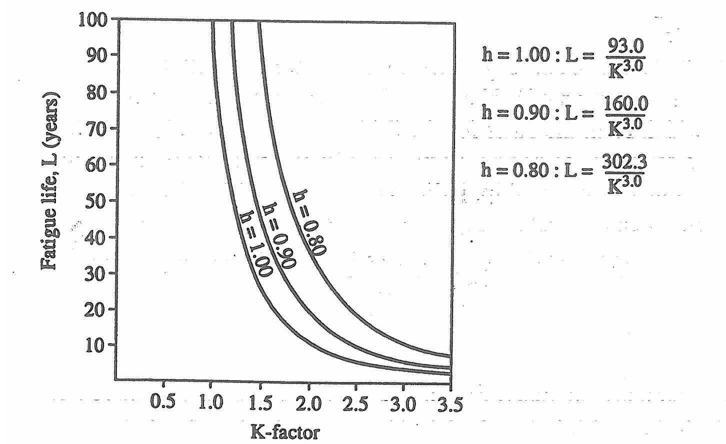

Figure 3.14: Fatigue Life Sensitivity to Stress Concentration Factor K and Weibull Shape Factor H

Figure 3.14 essentially replots Figure 3.13 to emphasize that incorrect assumptions regarding SCF can be as or more important to fatigue life assessment as is the analysis of global stress level (or the lifetime distribution of loads). The Weibull shape parameter h is related to the expected loading and is not addressed in the current research.

3.5 Implications for the Current Project

Based on the foregoing, it is suggested that any fatigue life analysis should be based on:

1. An understanding of the anticipated stress concentration factors, based on the design and the construction tolerances;
2. The availability of a suitable analysis methodology, incorporating a suitable fatigue life (S-N) curve; and
3. An ability to quantify the impacts of any differences in the assumptions or the uncertainties underlying either (1) or (2).

The work on the current project has therefore aimed to address all of these aspects of the problem to the extent possible, within the available level of effort.

4. DATA COLLECTION

Task 1 of the project included two major thrusts – the collection of existing, relevant information and data through literature surveys, and the collection of new shipyard data to supplement and extend the literature.

4.1 Literature Review

This subtask has included two main components:

a) collection of published and other available data on construction tolerances, including:
   - standards (shipyard, industry, class, etc.)
   - data on achieved outcomes
b) collection of references on the effects of construction tolerances on fatigue life, strength, and other characteristics

Sources have included previous SSC projects, published reports and studies, standards and related documents, and other materials available to the contractors.

The three main outcomes of this subtask have been:

i) a bibliography including a summary of each significant reference, noting (inter alia) the purpose, scope, and conclusions of the document (presented at Appendix A).
ii) data for inclusion in the project databases and analyses.
iii) definition of the parameters to be characterized in the exploration of tolerances.

Several of the main findings of the literature survey were essentially negative. Virtually no data on actual achieved shipyard tolerances appears to have been published; an elderly and partial exception to this rule being background material for the1975 Japanese Shipbuilding Quality Standards, presented in SSC Report 273 (1978). Even in this case the level of detail presented is insufficient to allow for its systematic application to further statistical analysis (see also Section 5). Thus, while classification societies, shipbuilding associations, and other bodies have published tolerance standards, there is no body of knowledge in the public domain to relate these standards to actual outcomes.

A second area in which data is lacking is in the definition of the data underlying design S-N curves. As discussed in Section 3, these are assumed to incorporate some levels of misalignment, weld imperfections, material properties etc., that contribute to their scatter. However, as the criteria for specimen (or outcome) acceptance/rejection are not reported in any of the reports accessed by the project team, it is not possible to assess their absolute or relative importance.

4.2 Field Data Collection

Prior to the initiation of the contract, three North American shipyards had indicated that they would be prepared to permit collection of data on their actual fabrication tolerances to support this project. However, when contacted subsequently one was no longer prepared to cooperate (due to management changes) and a second had no significant work under way. The third yard did allow access, and another yard eventually also cooperated. Efforts were made to extend the surveys to other yards, but were unsuccessful due to apparent concerns over confidentiality of the data, possible disruption to the work in the yard, etc. The recommendations at Section 9 discuss how such concerns might be mitigated more successfully in future projects.

The first field data collection effort (Shipyard #1) aimed to generate data for a reasonably wide range of structural elements/details. It was found that (a) many of the planned measurements were difficult to obtain, and (b) the level of scatter were such that large data sets were needed to generate statistically reliable information. As a result, the second survey (Shipyard #2) focused on a reduced set of parameters, and used an improved tool set to take measurements.

Overall, the survey work concentrated on geometric imperfection in two classes of welded details, butt-welded plates and stiffeners, and cruciform joints. Figure 3.3 through Figure 3.6 illustrate the variables that were measured for butt-welded plates and stiffeners. Figure 3.7 through Figure 3.9 illustrate the variables that were measured for cruciform joints.

4.2.1 Summary of Shipyard Survey #1

The first survey was conducted at a medium sized shipyard (Shipyard #1) that builds mostly barges and workboats. The intent of the survey was to establish measurement techniques, to assess which details should be measured, and also to collect as much data as possible.

The visit revealed that Shipyard #1 collect very little geometric information that is useful to the current study. According to the manager of the dimensional control department:

> *"The yard is most interested in 1) minimizing rework, 2) classification society acceptance, and 3) customer acceptance; the measurement and recording of structural detail data important for fatigue (where compliance is not an issue) is not a high priority. We collect data to monitor the early fabrication processes for control, centering and capability, but typically collect data on the final welded vessel only when required to confirm acceptability on a case by case basis."*

The yard builds vessels mainly to American Shipping Bureau (ABS) class. The tolerance standard they use is the ABS "Guide for Shipbuilding and Repair Quality Standard, July 98" (this document is based on the International Association of Classification Societies (IACS) Shipbuilding and Repair Quality Standard, 1996). This standard is implemented by ABS Surveyors on-site. The ABS Surveyors inspect the Yard's fit-up practices (tools, techniques, technician skill, and final as-fitted results) and visually inspect 100% of the final product. Measurements are generally taken of any questionable areas resulting from inspections.

Most of the BMT Fleet Technology Limited (BMT) Surveyor's time at Shipyard #1 was spent out in the yard taking measurements. To ensure enough data for statistical analysis the survey concentrated on measuring misalignment of two types of welded connections; butt welds at erection joints (for both plating and stiffeners), and fillet welded intercostal joints, mainly double bottom girder/floor intercostal joints. In the two-day visit, 39 butt weld misalignment samples and 28 intercostal misalignment samples were taken.

Approximately 12 hours of time was spent taking measurements. Thus on average it took (12hrs)•(60min/hr)/(39+28 measurements) = 10 minutes per sample detail. The surveyor was developing the measurement process during the visit, and as was expected, the time per sample detail was reduced to approximately eight minutes in the next survey. The latter value can be considered a benchmark for the level of effort that will be required in any future surveys of this type.

Choices regarding what were measured were largely dependant on what could be measured, what was worthwhile measuring, and what was there to measure. At the time of the visit Shipyard #1 had an 80000 BBL Oil and Asphalt Barge on the way ready to launch, and many of the Grand Assemblies for a 120,000 BBL Oil and Asphalt Barge completed and ready for final assembly. Even though these double-hulled vessels are quite simple in construction, they do have many welded connections of interest, especially considering that they are large barges. For instance the 120,000 BBL barge has a length over all of 129.6 m, breadth of 22.12 m and depth of 12.5 m.

Initially for the butt-welded plate connections the intention was to take random measurements without much discrimination for the type of joint. It was discovered quickly that there is very little misalignment at any welds done on the panel line (making up 95% of the longitudinal butt welds in the final product) and that taking such measurements with the available tools would introduce more error than is actually present in the fabrication process. Therefore, these measurements were not pursued. Thus the focus of the survey became field welded erection joints of major assemblies. The statistics involved in such an approach are considered in subsequent sections.

Butt weld misalignment was measured by using a magnet/ruler combination as a datum that would straddle the seam. Digital vernier callipers were used to measure the distance from the datum to the plate on each side of the seam. This method did not prove to be fully adequate thus a better and faster technique was developed for the next survey.

There were few measurable intercostal details on the vessels. Additionally, for a fully assembled vessel such as the 80,000 BBL Barge, it was quite difficult to measure intercostal misalignment. Major misalignment can occur at erection joints, however there is no suitable methodology that would allow this misalignment to be accurately measured. Focus was therefore on double bottom structure grand assemblies of the other barge. Typically, the double bottom structure consisted of 4 longitudinal continuous girders with floors running intercostal between them. Many of the parameters related to the weld detail, such as angle at the toe or fillet size, are quite variable along the length of any particular weld seam or fillet.

At the time, it was the opinion of the BMT surveyor that meaningful measurements could not be taken. Toe angle measurements for the butt welds were taken, but none of the fillet welds at intercostals were measured.

Drawings of the vessels under construction were provided in addition to portions of the build strategy and accuracy control plan. These documents are confidential to Shipyard #1 and are not available for inclusion in the report.

The data collected has been summarised in Section 5. The histograms show that sample sizes for most tolerance measurements will have to be much larger before statistically significant fabrication tolerance distributions can be assigned. Also a statistical prediction is predicated on the process being under control. This is sometimes difficult to achieve where the fit-up process is largely a function of manual efforts.

4.2.2 Summary of Shipyard Survey #2

BMT conducted the second survey at a medium sized shipyard (Shipyard #2) that builds mainly commercial workboats and small military vessels.

At the time of the survey, the shipyard was building an 80m Anchor Handling Tug Supply Vessel (AHTS). The steelwork for the vessel was in the final stages and most of the machinery was in place. All of the major units, except for the bridge, had been fitted. Some of the bow and stern assemblies were fitted but not fully welded.

The shipyard was also building assemblies for a refit on a Mobile Offshore Drilling Unit (MODU). The assemblies inspected were to form a new pipe deck on the MODU.

Both the AHTS and the MODU were surveyed for geometric imperfections in the welded connection details. The survey concentrated mainly on the AHTS since the focus of the study is fatigue life of welded joints in ships, rather than offshore platforms. However, the measurements taken from the MODU assemblies are also valid since they represent general fabrication quality at the yard. Ease of construction, thickness of material, and many other variables will all contribute to how much the structure at welded joints deviate from the ideal.

The focus of the survey was to measure imperfections in the joints between major assemblies. It is more difficult to achieve close tolerances at assembly joints. The tolerances are close on joints done on panel lines meaning the defects are difficult to measure. Focusing on assembly joints identifies major problematic defects and provides confidence in the accuracy of the measurements. Measurements were taken at butt welds between plating, butt welds between stiffeners and welds at cruciform joints.

For the vessels under construction it was difficult to find suitable cruciform joints that could be measured, thus many samples are not at joints between major assemblies.

The items welded together and the locations within the structure are noted in the survey summaries. In the two and half day visit, 59 samples for butt-welded plates, 29 samples for butt-welded stiffeners and 13 samples for intercostal joints were taken.

A wider range of measurements was taken during the survey at Shipyard #2 than at Shipyard #1. The survey at Shipyard #1 illustrated the need for better tools, techniques and also that more extensive measurements were needed to quantify the effect on fatigue that geometric imperfections may have. The techniques employed at Shipyard #2 allowed more measurements to be taken in the same amount of time. The accuracy was also somewhat better. A full discussion of measurement techniques, tools and accuracy is included in Section 4.3.

Obtaining reasonable access to joints of interest was an issue during the survey. The surveyors did not have enclosed spaces training and the shipyard would not allow entrance to any double bottom or side tanks. Many of the joints of interest are in these locations. The shipyard would have offered the training, but time and resources would not allow for it. Many of the joints of interests such as butt-welded stiffeners, or cruciform joints between girders and beams would have required the use of ladders and/or staging to take measurements. A choice was taken not to attempt such measurements. There was much construction activity at the time of survey and the use of a ladder would have interfered considerably with the shipyard activity. Further, the time required per measurement increases considerably with the added complication.

Access to assemblies before they are joined to the ship will allow for more joints of interest, in particular cruciform joints, to be easily measured since the assembly normally is upside down before final assembly. The interest of the study however is joints between major assemblies, which necessarily mean final ship construction.

Shipyard #2 has developed production standards that are mostly based on those of various classification societies. The actual tolerances are proprietary to the shipyard thus BMT could not copy their standard for publication.

Erection joint welds at the shipyard are full penetration and, in general, butt-welded plates and stiffeners that have a thickness less than 20 mm are prepped with a single sided bevel. Most samples had plating less than 20mm thick. The yard employed a ceramic backing technique for many of these welds. Where ceramic backing was not used, the joint was welded from one side, back-gouged and capped on the other side.

The visit revealed that Shipyard #2, as with Shipyard #1, collects very little imperfection information that is useful to the current study.

The staff from the Dimensional Control department at the shipyard was BMT’s liaison during the survey. They provided valuable orientation and assistance during the visit. The BMT surveyors for the most part worked independently in taking measurements.

Fabrication defects are mainly a quality control concern in any yard. Yards such as Shipyard #1 combine Dimensional Control with Quality Control. Shipyard #2 has separate departments that do this work. Larger yards will also have separate departments for this work. Future surveys should concentrate on liaison with persons from the Quality Control Department.

Many of the parameters related to the weld detail, such as angle at the root or fillet size, are quite variable along the length of any particular weld seam or fillet. Nonetheless, a full range of measurements were taken at each location for the purpose of demonstrating that stress concentration factors could be calculated at any one particular location. For consistency, at the start of a set of measurements, a line was drawn at the random point of interest. This was to ensure for example that angle at the weld toe and misalignment was measured at the same place.

Drawings of the vessels under construction were provided by Shipyard #2. These documents are confidential to Shipyard #2 and not available for inclusion in the final report.

The survey data collected is summarised in Section 5.

Monitoring fabrication quality of welded joints and maintaining tolerances is important to receiving a Fatigue Class Notation from a Classification Society. The survey work conducted thus far illustrates the need to ascertain the quality control procedures in shipyards that build ships for Fatigue Class Notation. Any further survey work should be conducted at shipyards that are building such vessels for Fatigue Class Notation.

4.3 Survey Techniques

An important outcome of the project was the development of a methodology for measuring geometrical imperfection variables in welded joints. As will be discussed in Section 6, relatively large sample sizes are required to draw meaningful statistical conclusions regarding weld fabrication quality in a particular ship, or shipyard. Collecting sufficient data, while minimizing effort, requires that quick but accurate methods be employed. The development of a survey plan covering choice of details to measure, and at what stage in the construction the detail is to be measured will also determine the effectiveness of a survey program.

The imperfections in a joint vary along the length of the weld. The approach for the surveys was to, as randomly as possible, pick a particular section and then take measurements that would characterize the bulk properties of the cross section. This section is then considered representative of imperfections anywhere along the length of the weld. The location along the length of the weld, other than stop-start locations may or may not influence the extent of imperfections. To ascertain this influence, the percentage distance from the end along the length was recorded.

Gaining a statistical picture of all the welding imperfections in a particular ship requires, at the very least, a methodological approach for choosing sections to sample. For example, random sections around the entire perimeter of a major erection joint are required to describe statistically what is happening in that joint.

Obtaining access to the many areas of the vessels and limited available survey time were major issues for the BMT surveyors. For this reason, the approach was to concentrate the measurements in areas that were reasonably accessible.

In this regard, the surveyors concentrated mainly on erection joints in the deck and bottom of the vessels and cruciform joints in the double bottom. Many measurements from other areas were also taken simply because the area was accessible.

Most geometric imperfections in welded joints can be measured relatively easily and to adequate accuracy with low cost tools. The methods and tools employed for this project are discussed in the following sections.

4.3.1 Misalignment in Butt Welds

A dial gauge attached to a base, as shown in Figure 4.1, was used to measure misalignment of butt-welded plates. The misalignment was determined by reading the dial on each side of the weld and subtracting the values to obtain the misalignment. The same could be accomplished using the weld gauge shown in Figure 4.2. Accuracy using this tool is less however. As well, the tool may not work for welds that have excessive reinforcement or width.

Both methods are susceptible to errors resulting from angular misalignment and plate distortion since the base of the tool must rest flush with the plate.

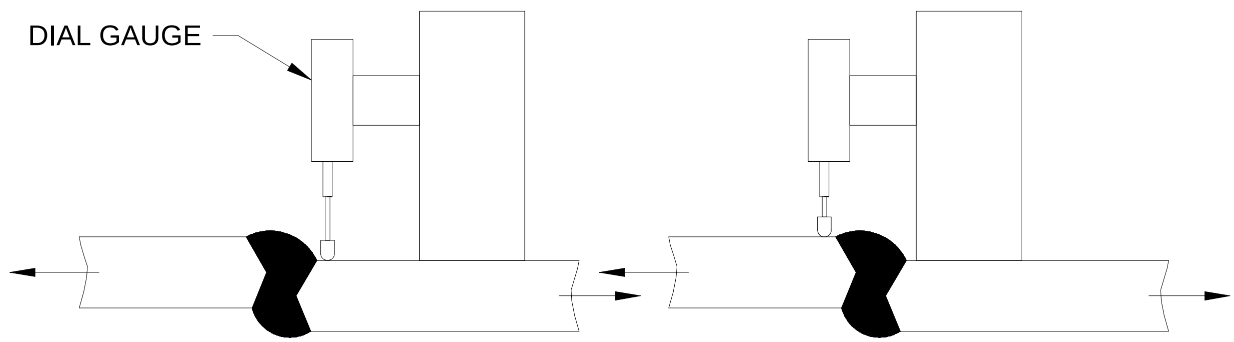

Figure 4.1: Measuring Alignment and/or Weld Reinforcement Height

4.3.2 Weld Reinforcement in Butt Welds

The multi-purpose weld gauge shown in Figure 4.2 was used to measure weld reinforcement height. The dial gauge could also be used. If there is misalignment in the plates, the reading will be different from each side. A protocol must therefore be established for taking measurements relative to the misalignment measurements. Both measurements can then be used to describe the general profile of the joint.

Reinforcement height was only measured from one side of the weld. A true picture of the section would require measurements from both sides.

Locating the exact underside of a weld is problematic as access is often extremely difficult. In a true statistical analysis, this error is mitigated since the profile on one side of the plate is supposed to be representative of the profile on the other side.

The surveys focused on erection joints between major assemblies. The gap between erection joint plates is often quite large meaning that multi passes (done by hand) and large amounts of weld filler are required in places. The result is that butt welds at erection joints rarely resemble the ideal geometry upon which the stress concentration formulas have been determined.

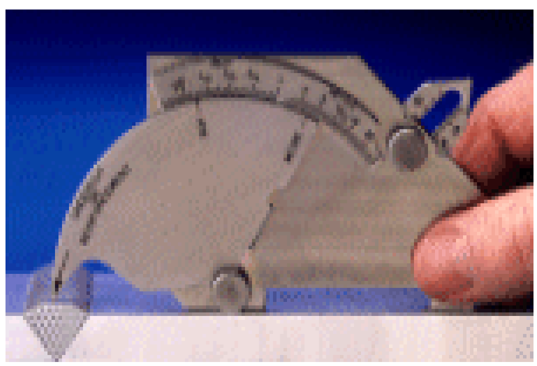

Figure 4.2: Tool for Measuring Weld Reinforcement Height and/or Plate Alignment and Fillet Weld Leg Size

4.3.3 Weld Toe Angle in Butt Welds

The weld toe angle was measured using a tool similar to that shown in Figure 4.3. Weld toe angle is measured by placing the tool flat on the plate and pushing it into the toe of the weld until the rotating piece becomes tangent.

The accuracy of this method is somewhat crude as the weld reinforcement will not often have a circular shape. Based upon the surveyor's experience it is likely that the error in measuring the angle could be up to 5° or 10° using this methodology.

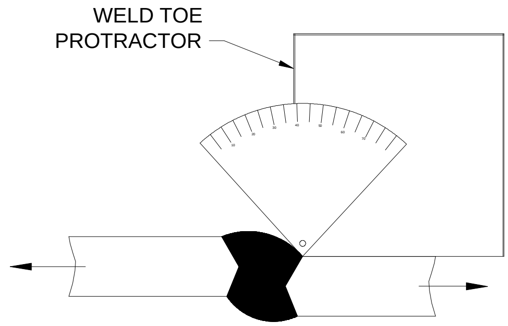

Figure 4.3: Measuring Weld Toe Angle

4.3.4 Angular Misalignment in Butt Welds

The angular misalignment of horizontal plates is quite easily measured using an inclinometer as shown in Figure 4.4. Although this method is straightforward, errors are derived from the accuracy of the inclinometer and also from local distortions that prevent the inclinometer from resting flat on the plate. Local distortion in the plate is in itself an error in that most fatigue analysis methods idealize the plate as being straight.

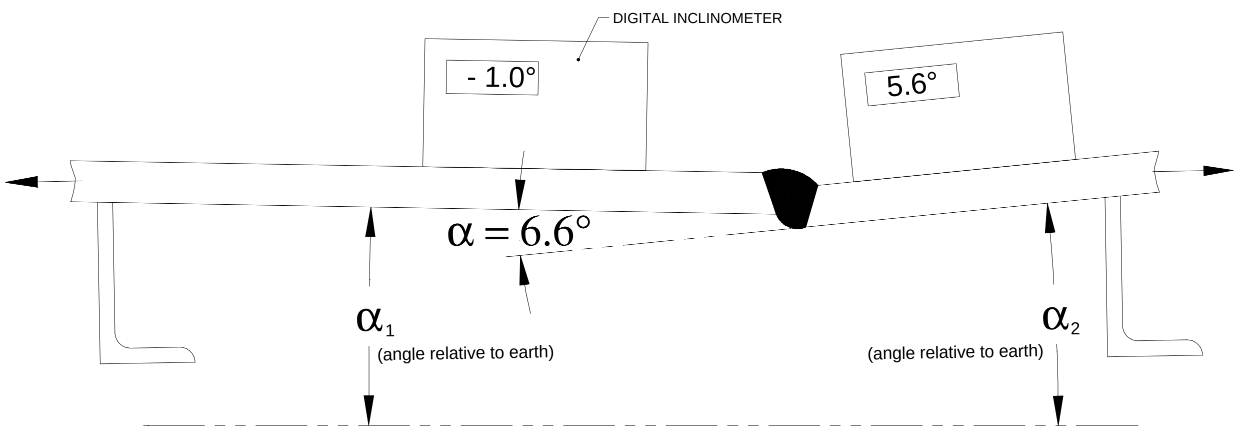

Figure 4.4: Measuring Angular Misalignment

Measuring alignment in vertical joints is more difficult because the inclinometer cannot be used. Although this method was not used in the survey, it is possible to modify the tool shown in Figure 4.5 to measure angular misalignment. Adding parallel extensions to the protractor, as shown in Figure 4.5 allows it to straddle the weld reinforcement, thus enabling an angular misalignment measurement to be taken. Most butt welds will also have plate misalignment. To overcome this, one of the extensions can be made adjustable as shown in the figure.

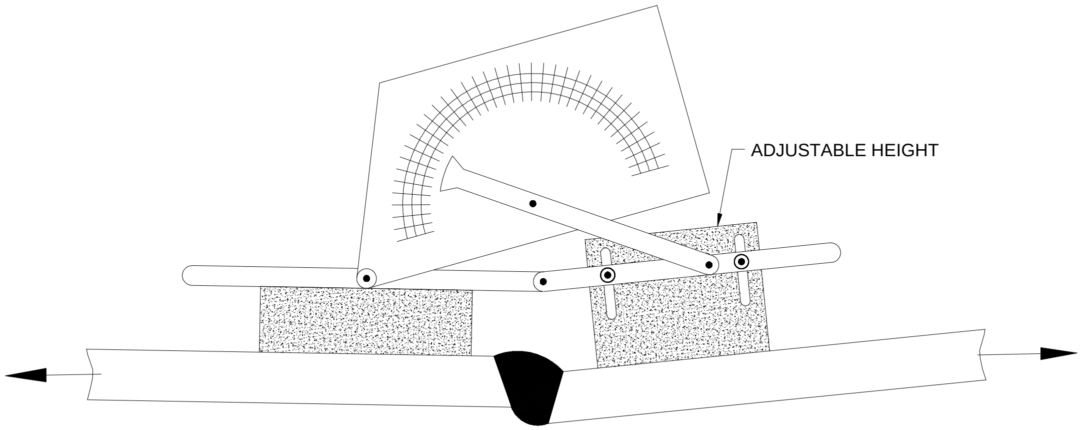

Figure 4.5: Modified Protractor for Measuring Angular Misalignment

4.3.5 Cruciform Joint Misalignment

Cruciform joints are susceptible to misalignment due to their nature, especially if it is not possible for the shipwright to ensure visually that plates on each side of the joint are aligned. Measuring misalignment to the precision of millimeters is equally as difficult for the same reason.

The methodology used in the surveys was to find cruciform joints that had a natural datum and then using a measuring tape, measure the distance that each plate is from that datum. Finding a datum in the completed ship is generally difficult, however, they do exist for some assemblies. The double bottom and deck assemblies shown in Figure 4.6 illustrate how misalignment in cruciform joints can be measured.

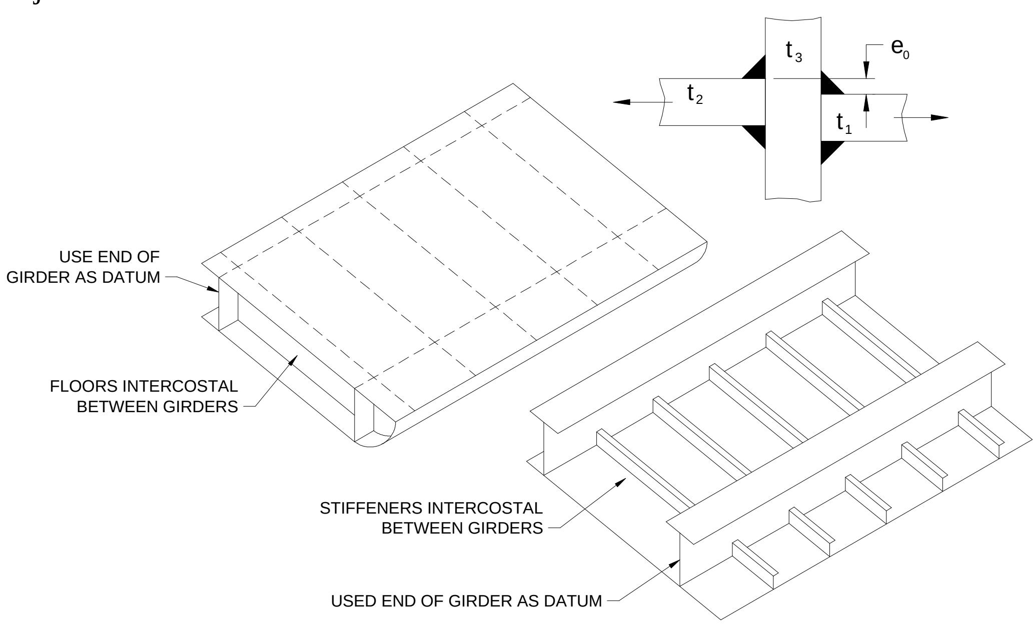

Figure 4.6: Measuring Misalignment in Cruciform Joints

A better methodology is required if all cruciform joints in a vessel are to be surveyed. An artificial datum could possibly be used to determine the alignment of intercostal stiffeners. The datum would consist of a device that will clamp square over a girder. Measurements would then be taken in reference to this device.

There are frequently no straightforward methods for measuring misalignment between, for example, longitudinal bulkheads separated by a transverse bulkhead. Where holes are required for system transits then these can be used to establish datum planes. In their absence, holes can be drilled, used and repaired. For most commercial construction this is unlikely to be acceptable on cost or schedule grounds.

4.3.6 Angular Misalignment in Cruciform Joints

This type of misalignment can easily be measured using a protractor such as shown in Figure 4.7. A simple protractor such as shown is accurate within ±0.3°. Local distortion in the plates can be a cause of error.

Figure 4.7: Protractor for Measuring Angular Misalignment in Cruciform Joints

4.3.7 Weld Size in Cruciform Joints

A set of ordinary weld gauges or the weld gauge shown in Figure 4.2 is adequate for measuring the leg size of fillet welds in cruciform joints. It is important to use an appropriate measurement protocol to ensure that the entire cross-section can be fully described subsequent to the measurements being taken.

In typical shipyard construction, the leg size of a filet weld along a cruciform joint will vary considerably. The basic philosophy of the survey is that of looking at random sections and considering them representative of other sections throughout the vessel. Increase in local stress due to the fillet weld is however a result of 3D geometry. In fact, each component of a joint – angles, thickness misalignment, etc., – varies along the length of the joint.

The overall fatigue resistant quality of different joints differs, depending on location, internal support, assembly procedure, and welding types and sequences. Although beyond the scope of this report, it is necessary to consider many parameters before reaching any conclusions on how bulk properties should be interpreted in fatigue analysis.

5. STATISTICAL ANALYSIS OF SURVEY DATA

5.1 Background

As noted in Section 3, fatigue life prediction is inherently probabilistic (statistical) in nature. Fatigue life prediction depends on both the S-N curves underlying the analyses, which include assumed levels of scatter, and also (in the notch stress approach) on the stress concentration factors, *K*s, (or their underlying geometrical properties).

One element that is essential to perform reliability-based design for fatigue of ship structures is the quantification of the basic fatigue damage accumulation process random variables. The definition of these random variables requires the investigation of their variability. In reliability assessment of any structural system, these uncertainties must be quantified. Furthermore, the evaluation of strength and load partial safety factors (PSF) in any design format equation also requires the characterization of these variables. For example, the First-Order Second Moment (FOSM) method for reliability assessment and reliability-based design requires the quantification of the mean values, standard deviations (or the coefficient of variation (*COV*)), and the distribution types of all relevant random variables. They are needed to compute the safety index *b* or the PSFs. Therefore, complete information on the probability distributions of the basic random variables under consideration must be developed.

Quantification of the basic random variables for the stress concentration factor *K* in terms of their means, standard deviations or *COV*s, and probability distributions must be achieved in two steps -- data collection and data analysis. The first step is the task of collecting as many sets of data deemed to be appropriate for representing the random variables under study, while the second is concerned with statistically analyzing the collected data to determine the probabilistic characteristics of such variables.

The objective herein is to quantify the probabilistic characteristics of the stress concentration factors *K*s for use in reliability analysis and reliability-based fatigue design for ship structures. The available statistical information and data on basic random variables for *K* consisted of the data sets from two medium sized shipyards in North America, as described in Section 4. These data were statistically analyzed and studied to quantify the probabilistic characteristics of the various types of the stress concentration factors. These characteristics have been established and summarized for stress concentration factors in terms of the mean values, standard deviations, and the probability distributions.

5.2 Methodology

5.2.1 Descriptive Statistics and Histograms

The raw geometric data collected during each survey is presented in Appendix B. The figures in Section 3 provide definitions for the parameters. The formulas used to calculate stress concentration (*K)* values are those given in Table 3.1 and Table 3.2.

The approach used to quantify the stress concentration factors *K* is based on the statistical first and second moments, i.e., the mean and standard deviation of the basic variables that are used to determine *K*. The data used in these analyses are those collected and measured at the Shipyard #1 and Shipyard #2. These data represents the basic random variables that define the different stress concentration factors as established by DNV. The steps that have been followed to assess the different stress concentration factors are as follows:

1. For each equation that represents the stress concentration factor *K*, select the basic random variables that define *K*.
2. Use the equation to compute *K* for each set of the basic variables that were collected and measured.
3. After the *K* values have been computed from Step 2, perform statistical analysis to quantify its statistical moments (i.e., mean, standard deviation, etc.) and the upper and lower bounds on *K*.
4. Based on the statistical analysis of Step 3, generate a frequency histogram for each *K*.
5. Fit known theoretical/continuous statistical distributions for *K* that closely agrees with the histogram generated in Step 4.
6. Use a commercial statistical software package or a spreadsheet to identify the two theoretical distributions that best fit the data.
7. Document the mean value, standard deviation, upper and lower bounds, and the best two distribution types for *K*.

The Chi-Squared method was used in these analyses to quantify and assess the goodness of fit of the statistical distributions to the estimated stress concentration factor (*K)* data.

5.2.2 Total Stress Concentration Factor

The total (or overall) stress concentration factor K_t , as described in Section 3, is a combination of all different factors due to various geometric imperfections. The total stress concentration factor can be calculated as:

$$K = K_g \cdot K_w \cdot K_{ta} \cdot K_{te} \cdot K_n \qquad (5\text{-}1)$$

Where:

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

K_w = Stress concentration factor due to the weld geometry.

K_{te} = Additional stress concentration factor due to eccentricity tolerance (normally used for plate connections only).

K_{ta} = Additional stress concentration factor due to angular mismatch (normally used for plate connections only).

K_n = Additional stress concentration factor for un-symmetrical stiffeners on laterally loaded panels, applicable when the nominal stress is derived from simple beam analyses (not considered in this report).

The steps that have been followed to assess the total stress concentration factors *K* are similar to those for the individual *K*-factors and they are given as follows:

1. For each case weld type, calculate the total concentration factor *K* using Eq. 1.
2. For each *K* computed in Step 1, perform statistical analysis to quantify its statistical moments (i.e., mean, standard deviation, etc.) and the upper and lower bounds.
3. Based on the statistical analysis of Step 2, generate a frequency histogram for each *K*.
4. Fit known theoretical/continuous statistical distributions for K that closely agree with the histograms generated in Step 3.
5. Use a commercial statistical software package such as @Risk and BestFit or a spreadsheet to identify the two theoretical distributions that best fit the data.
6. Document the mean value, standard deviation, upper and lower bounds, and the best two distribution types for *K*.

5.2.3 Confidence Interval on the Mean Values

The mean and standard deviation for the samples of the individual stress concentration factors (e.g., K_{te}, K_w, etc.) represent a best estimate of the population value. However, they are only estimates of random variables, and they do not necessarily correspond to the true values. The accuracy of these estimates can be assessed using confidence intervals. Confidence interval provides a range of values in which the true value of a *K*-factor can be expected to lie. Many two-sided (1- α)% confidence intervals have one of the following two forms depending whether the population standard deviation (s) is known or not (Ayyub and McCuen 2003):

$$\bar{x} - Z_{\frac{a}{2}}\left(\frac{s}{\sqrt{n}}\right) \le m \le \bar{x} + Z_{\frac{a}{2}}\left(\frac{s}{\sqrt{n}}\right) \qquad \text{(5-2a)}$$

$$\bar{x} - t_{\frac{a}{2},n}\frac{S}{\sqrt{n}} \le m \le \bar{x} + t_{\frac{a}{2},n}\frac{S}{\sqrt{n}} \qquad \text{(5-2b)}$$

where:

$\bar{x}$ = sample mean
$t_{\frac{a}{2},n}$ = *t*-distribution value at an exceedence area of $a/2$.
a = level of significance in the range 0 to 1.
S = sample standard deviation
n = sample size
m = population mean.
s = population standard deviation

The steps that have been followed to compute confidence interval are as follows:

1. Select a two-sided confidence interval for each *K*-factor.
2. Specify desired level of confidence as 99, 95, and 90%.

3. Perform statistical calculations (e.g., mean, standard deviation, and $\bar{x}$, *n*, and *S* of Eq. 2) for each individual *K* value.
4. Determine the value of the distribution factor $t_{a/2}$ based on the confidence level and *K* sample size. For a sample size greater than 32, use *z*-statistics, otherwise use *t*-statistics.
5. Compute the confidence interval for each individual *K* value.

5.2.4 Sample Size Determination

The selection of a sample size is the first step in performing statistical analysis. In this report sample size calculations were performed for illustrative purposes and for assessing the suitability of the sample sizes used in this study. Sample sizes for SCF were determined herein for the purpose of future sampling projects that might take place in other shipyards.

The sample size (*n*) can be computed based on two-sided confidence interval on the sample mean as follows:

$$n = \left(\frac{Z_{a/2}}{\frac{H}{s}} \right)^2 \qquad (5\text{-}2c)$$

where *H* = half the width of a confidence interval as defined in Eq. 5-2a. A similar equation for n can be written to correspond for Eq. 5-2b as follows:

$$n = \left(\frac{t_{a/2,n}}{\frac{H}{S}} \right)^2 \qquad (5\text{-}2d)$$

The solution of these equations needs to be completed using an iterative solution approach. The following table shows samples sizes as a function of the ratio H/σ for $\alpha = 0.1$ (with $Z_{\alpha/2} = 1.96$) based on Eq. 5-2c:

H/σ	Sample size *n*
0.1	384
0.2	96
0.3	43
0.4	24
0.5	15

Typical values for the ratio H/σ based on the data collected in the range 0.2 to 0.5 leading to the conclusion that the sample size should have been 15 to 96.

5.3 Butt-Welded Plates

The stress concentration factors applicable to butt welds are those listed at Table 3.1, which for convenience are repeated as equations 5.3 – 5.5 below.

$$K_{ta} = 1 + \frac{l}{4} a \frac{s}{t} \tag{5.3}$$

$$K_w = 1.0 + 0.5(\tan q)^{1/4} \tag{5.4}$$

$$K_{te} = 1 + \frac{3e}{t} \tag{5.5}$$

5.3.1 Shipyard #1 Data

5.3.1.1 Stress Concentration Factor K_{ta}

The data required to calculate K_{ta} were not measured during this initial survey.

5.3.1.2 Stress Concentration Factor K_w

The stress concentration factor K_w was computed using equation (5.4). Table 5.1 shows the result of the statistical analysis of K_w based on the Shipyard #1 data. Figure 5.1 provides a histogram of K_w with normal and extreme-value distribution fits. According to the Chi-Squared goodness-of-fit test, the normal distribution is better than the extreme-vale distribution. The Chi-Squared test value is 30 for the normal distribution and 117 for the extreme-value distribution.

Table 5.1: Statistics on Stress Concentration Factor K_w based on Shipyard #1 Data

N	38
Minimum	1.270
Mean	1.370
Maximum	1.440
Standard Deviation	0.040
Coefficient of Variation (%)	3.22
99% Confidence Interval on the Mean	1.353 to 1.387
95% Confidence Interval on the Mean	1.357 to 1.383
90% Confidence Interval on the Mean	1.359 to 1.381

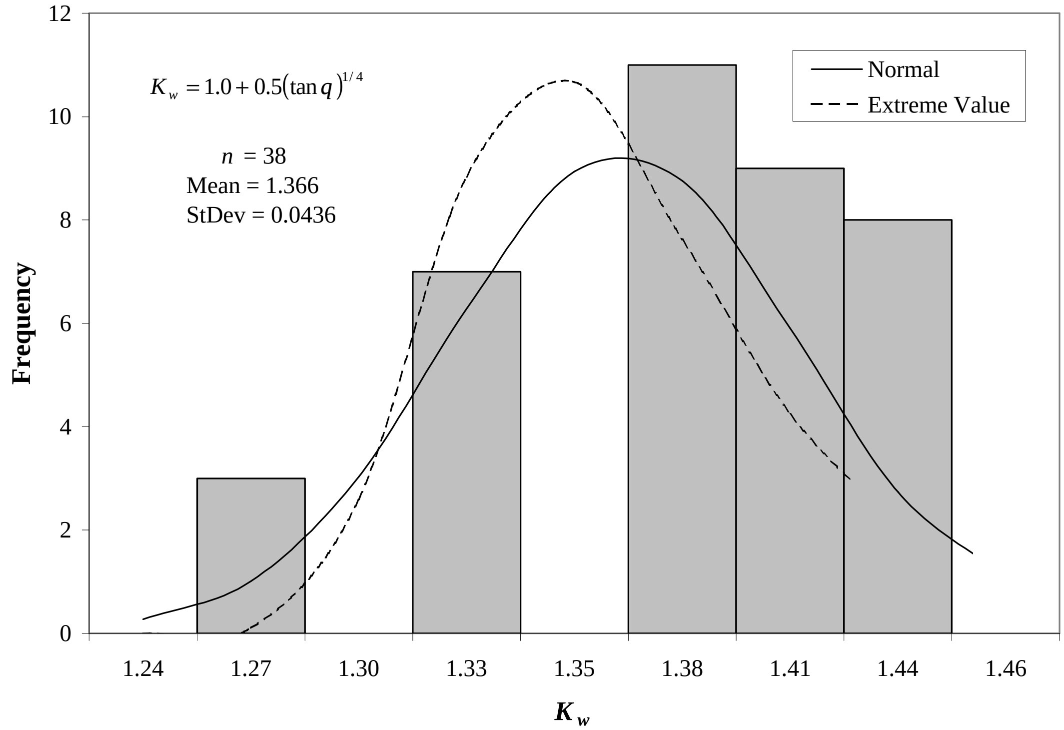

Figure 5.1: Histogram for K_w with Extreme-Value and Normal Distribution Fits

5.3.1.3 Stress Concentration Factor K_{te}

The stress concentration factor K_{te} was computed using equation (5.5). Table 5.2 provides the result of the statistical analysis of K_{te} based on Shipyard #1 data. Figure 5.2 provides a histogram of K_{te} with normal and lognormal distribution fits. According to the Chi-Squared goodness-of-fit test, the normal distribution is superior to the lognormal distribution. The Chi-Squared test value is 8 for normal distribution and 9 for the lognormal distribution.

Table 5.2: Statistics on Stress Concentration Factor K_{te} based on Shipyard #1 Data

N	19
Minimum	1.02
Mean	1.26
Maximum	1.47
Standard Deviation	0.13
Coefficient of Variation (%)	10.0
99% Confidence Interval on the Mean	1.18 to 1.34
95% Confidence Interval on the Mean	1.20 to 1.32
90% Confidence Interval on the Mean	1.21 to 1.31

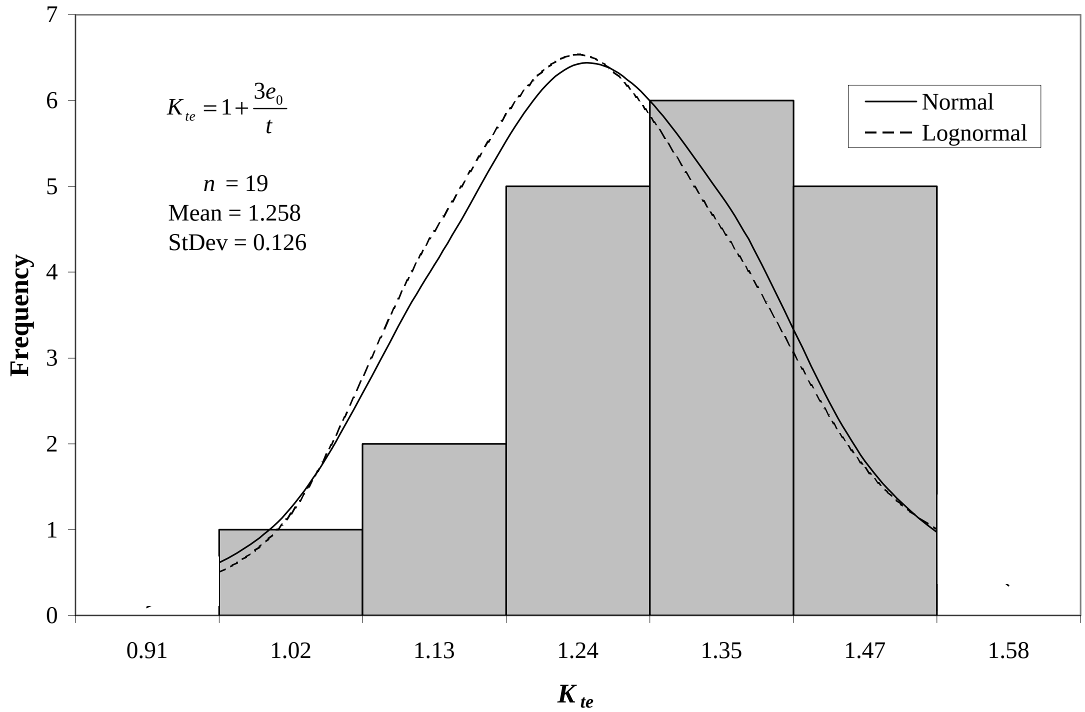

Figure 5.2: Histogram for K_{te} with Normal and Lognormal Distribution Fits

5.3.2 Shipyard #2 Data

5.3.2.1 Stress Concentration Factor K_{ta}

The stress concentration factor K_{ta} was computed using equation (5.3), and assuming free rather than fixed end conditions. Table 5.3 provides the result of the statistical analysis of K_{ta} based on Shipyard #2 data. Figure 5.3 shows a histogram of K_{ta} with lognormal and exponential distribution fits. According to the Chi-Squared goodness-of-fit test, the lognormal distribution is better than the exponential distribution. The Chi-Squared test value is 29 for the lognormal distribution and 34 for the exponential distribution.

Table 5.3: Statistics on Stress Concentration Factor K_{ta} based on Shipyard #2 Data

N	37
Minimum	1.001642
Mean	5.000042
Maximum	17.54774
Standard Deviation	4.445186
Coefficient of Variation (%)	88.9
99% Confidence Interval on the Mean	3.12 to 6.88
95% Confidence Interval on the Mean	3.57 to 6.43
90% Confidence Interval on the Mean	3.80 to 6.20

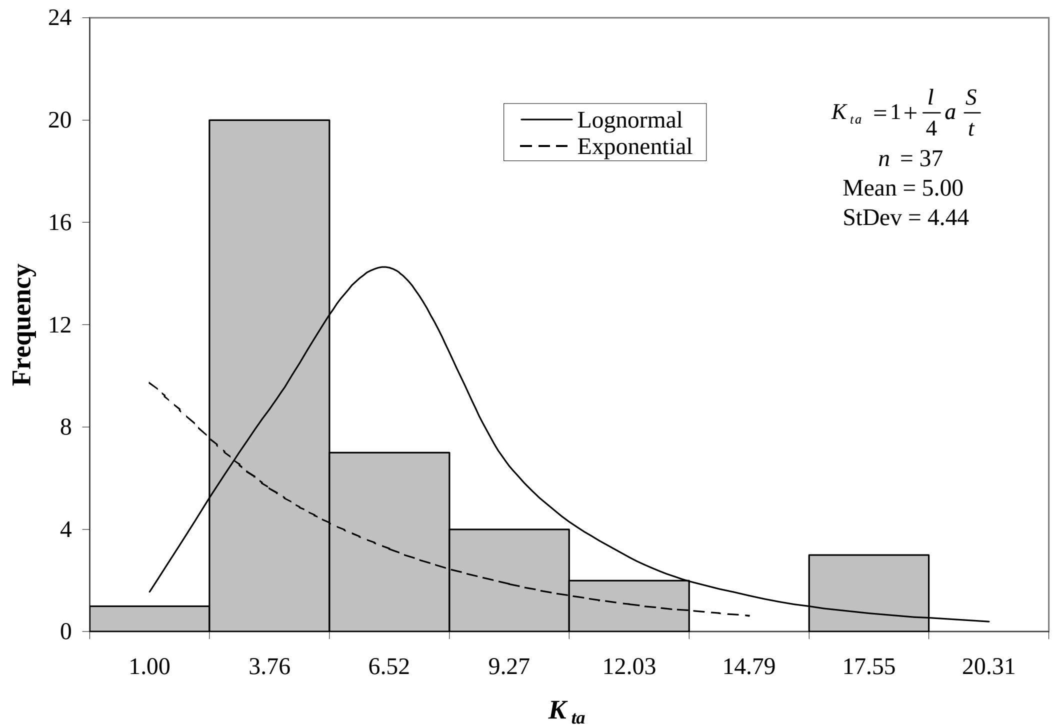

Figure 5.3: Histogram of K_{ta} with Lognormal and Exponential Distribution Fits

5.3.2.2 Stress Concentration Factor K_w

The stress concentration factor K_w was computed using equation (5.4). Table 5.4 provides the result of the statistical analysis of K_w based on Shipyard #2 data. Figure 5.4 provides a histogram of K_w with normal and extreme-value distribution fits. According to the Chi-Squared goodness-of-fit test, the normal distribution is superior to the extreme-value distribution. The Chi-Squared test value is 19 for the normal distribution and 43 for the extreme-value distribution.

Table 5.4: Statistics on Stress Concentration Factor K_w based on Shipyard #2 Data

N	118
Minimum	1.27
Mean	1.43
Maximum	1.57
Standard Deviation	0.05
Coefficient of Variation (%)	3.77
99% Confidence Interval on the Mean	1.418 to 1.442
95% Confidence Interval on the Mean	1.421 to 1.439
90% Confidence Interval on the Mean	1.422 to 1.438

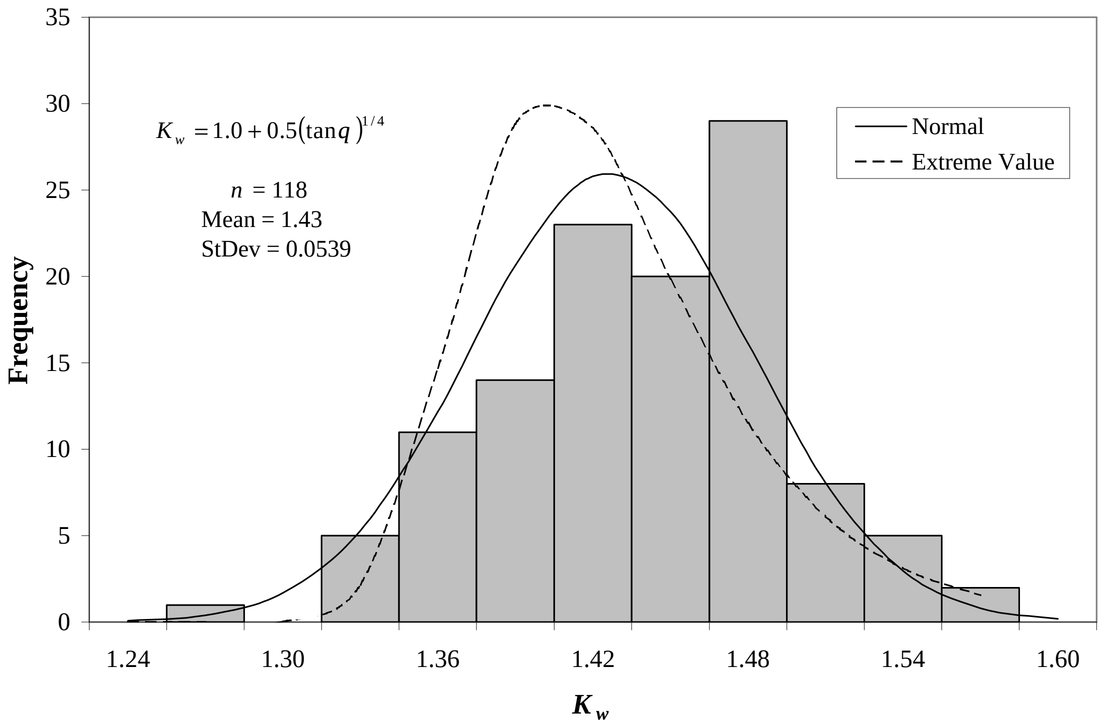

Figure 5.4: Histogram of K_w with Normal and Extreme-Value Distribution Fits

5.3.2.3 Stress Concentration Factor K_{te}

The stress concentration factor K_{te} was computed using equation (5.5). Table 5.5 provides the result of the statistical analysis of K_{te} based on Shipyard #2 data. Figure 5.5 provides a histogram of K_{te} with lognormal and Weibull (smallest) distribution fits. According to the Chi-Squared goodness-of-fit test, the lognormal distribution is superior to the Weibull (smallest) distribution. The Chi-Squared test value is 14 for the lognormal distribution and 16 for the Weibull (smallest) distribution.

Table 5.5: Statistics on Stress Concentration Factor K_{te} based on Shipyard #2 Data

N	59
Minimum	1.00
Mean	1.23
Maximum	1.72
Standard Deviation	0.17
Coefficient of Variation (%)	13.5
99% Confidence Interval on the Mean	1.173 to 1.287
95% Confidence Interval on the Mean	1.187 to 1.273
90% Confidence Interval on the Mean	1.194 to 1.266

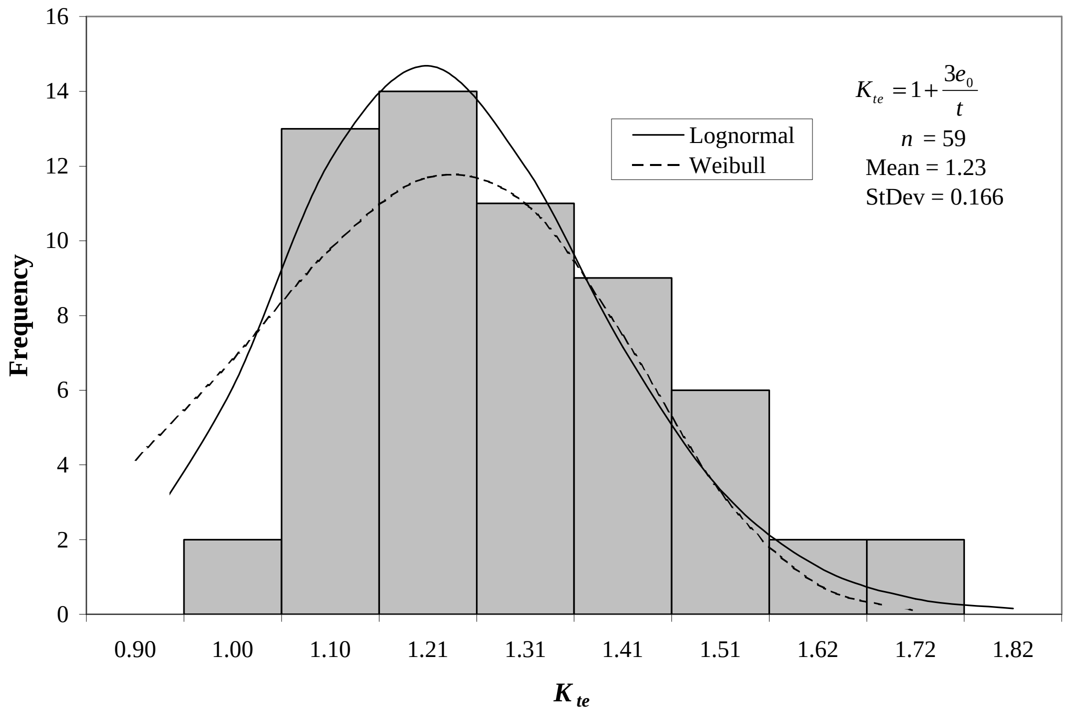

Figure 5.5: Histogram of K_{te} with Lognormal and Weibull Distribution Fits

5.4 Butt-Welded Stiffeners – Shipyard #2 Data

5.4.1 Stress Concentration Factor $K_{t\alpha}$

The stress concentration factor K_{ta} was computed using the formula in Table 3.1. Table 5.6 provides the result of the statistical analysis of K_{ta} based on Shipyard #2 data. Figure 5.6 shows a histogram of K_{ta} with exponential and extreme value (Type I Gumbel largest) distribution fits. According to the Chi-Squared goodness-of-fit test, the exponential distribution is better than the extreme-value distribution. The Chi-Squared test value is 0.5 for the exponential distribution and 0.5 for the extreme-value distribution.

Table 5.6: Statistics on Stress Concentration Factor K_{ta} based on Shipyard #2 Data

N	8
Minimum	1.00
Mean	2.38
Maximum	7.65
Standard Deviation	2.28
Coefficient of Variation (%)	95.96
99% Confidence Interval on the Mean	0.30 to 4.46
95% Confidence Interval on the Mean	0.80 to 3.96
90% Confidence Interval on the Mean	1.05 to 3.71

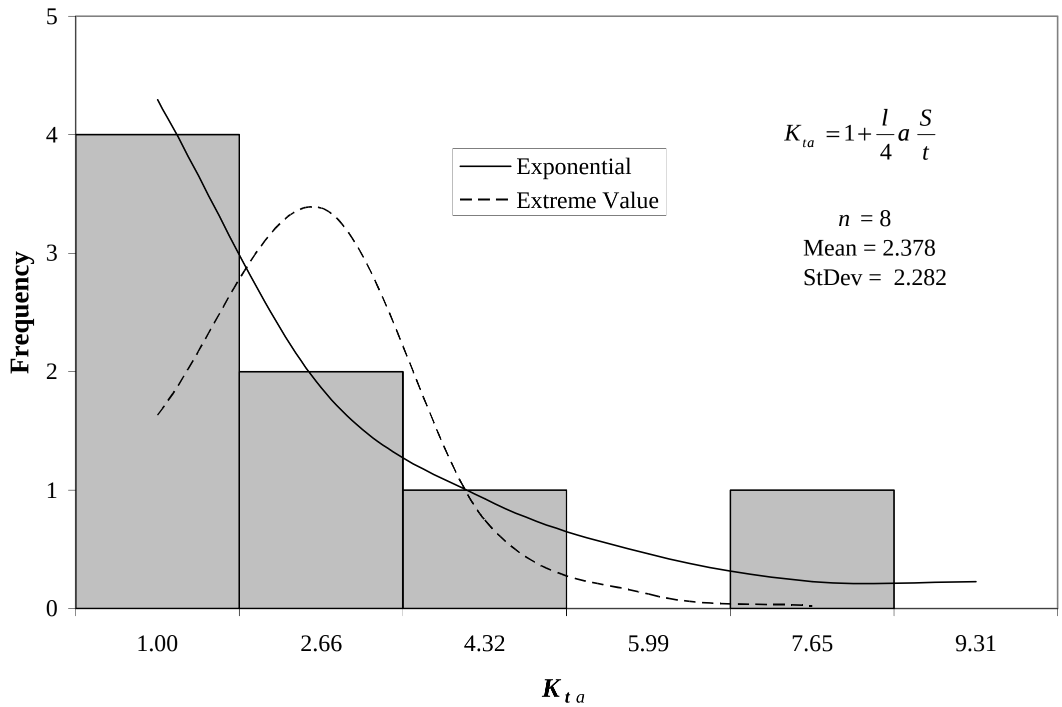

Figure 5.6: Histogram of K_{ta} with Exponential and Extreme Value (Type I Gumbel largest) Distribution Fits

5.4.2 Stress Concentration Factor K_w

The stress concentration factor K_w was computed using the formula in Table 3.1. Table 5.7 shows the result of the statistical analysis of K_w based on Shipyard #2 data. Figure 5.7 provides a histogram of K_w with normal and extreme-value distribution fits. According to the Chi-Squared goodness-of-fit test, the normal distribution is superior to the extreme-value distribution.
The Chi-Squared test value is 45 for the normal distribution and 58 for the extreme-value distribution.

Table 5.7: Statistics on Stress Concentration Factor K_w based on Shipyard #2 Data

N	44
Minimum	1.00
Mean	1.43
Maximum	1.77
Standard Deviation	0.10
Coefficient of Variation (%)	6.97
99% Confidence Interval on the Mean	1.39 to 1.47
95% Confidence Interval on the Mean	1.40 to 1.46
90% Confidence Interval on the Mean	1.41 to 1.45

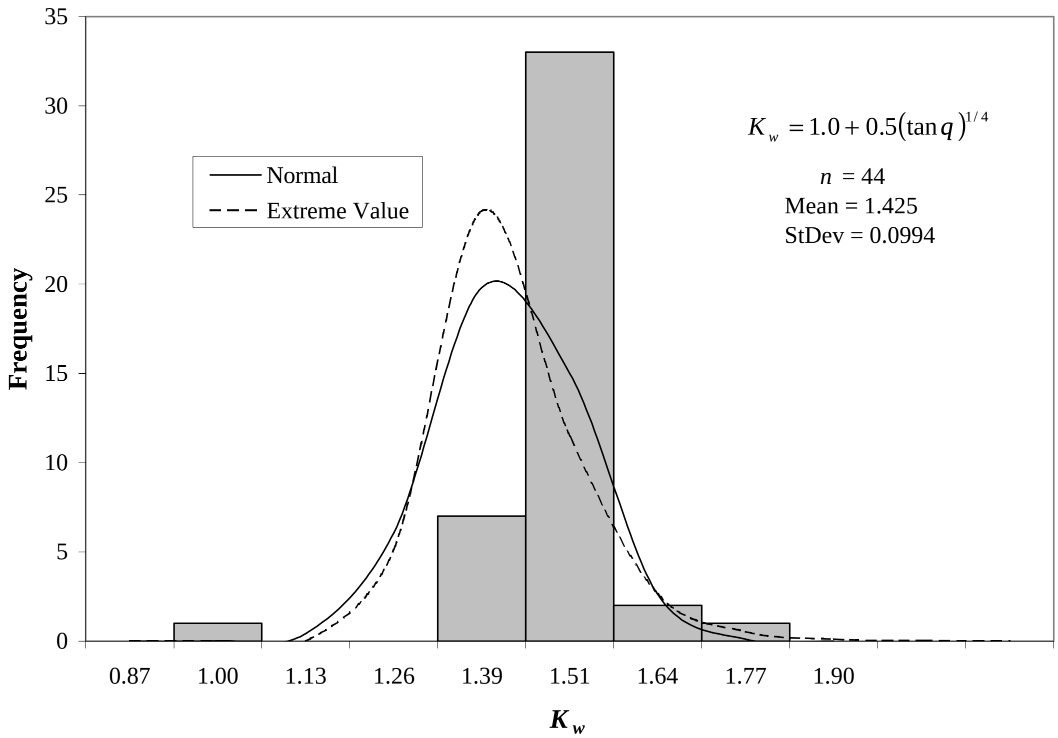

Figure 5.7: Histogram of K_w with Normal and Extreme Value (Type I Gumbel Largest) Distribution Fits

5.4.3 Stress Concentration Factor Kte

The stress concentration factor K_{te} was computed using the formula in Table 3.1. Table 5.8 provides the result of the statistical analysis of K_{te} based on Shipyard #2 data. Figure 5.8 shows a histogram of K_{te} with exponential and extreme-value distribution fits. According to the Chi-Squared goodness-of-fit test, the exponential distribution is superior to the extreme-value distribution. The Chi-Squared test value is 6 for the exponential distribution and 106 for the extreme-value distribution.

Table 5.8: Statistics on Stress Concentration Factor K_{te} based on Shipyard #2 Data

N	22
Minimum	1.00
Mean	1.20
Maximum	1.61
Standard Deviation	0.17
Coefficient of Variation (%)	14.2
99% Confidence Interval on the Mean	1.11 to 1.29
95% Confidence Interval on the Mean	1.13 to 1.27
90% Confidence Interval on the Mean	1.14 to 1.26

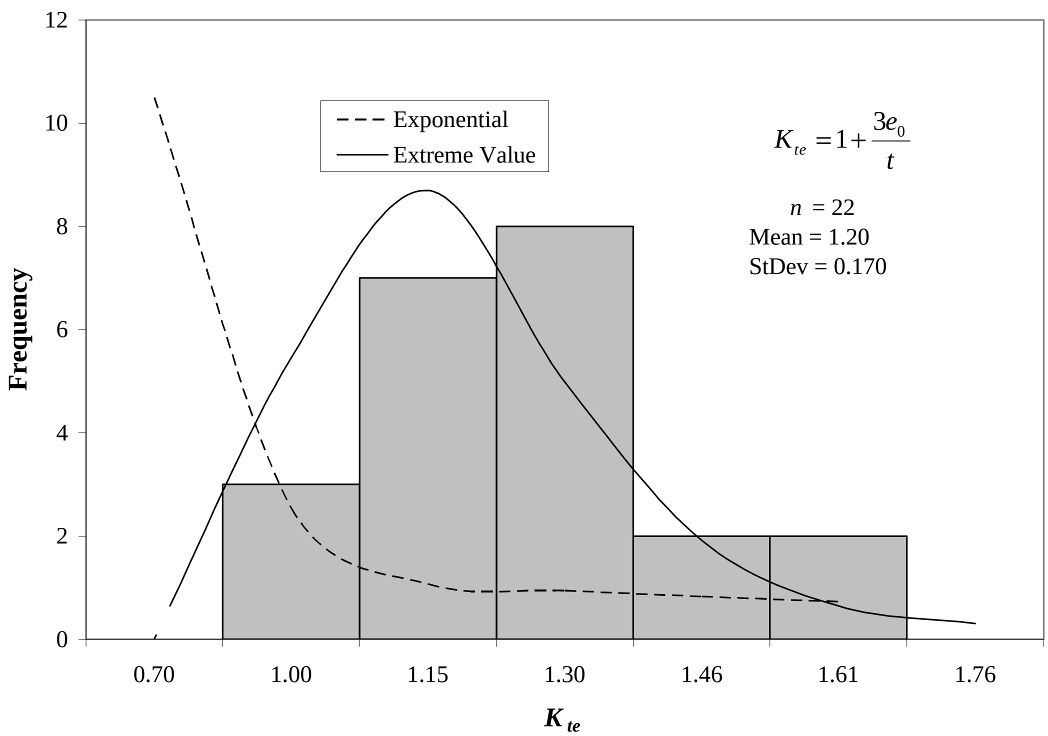

Figure 5.8: Histogram of K_{te} with Exponential and Extreme Value (Type I Gumbel largest) Distribution Fits

5.5 Cruciform Joints – Shipyard #2 Data

The notch stress concentration factors and formulae applicable to cruciform joints were listed at Table 3.2 and are listed again below for convenience.

$$K_{te} = 1 + \frac{6 \times t^2 \times e}{l_1 \left(\frac{t_1^3}{l_1} + \frac{t_2^3}{l_2} + \frac{t_3^3}{l_3} + \frac{t_4^3}{l_4} \right)} \tag{5.6}$$

$$K_g K_w = 1.2 + 1.3 (\tan q)^{1/4} \tag{5.7}$$

$$K_g K_w = 0.9 + 0.9 (\tan q)^{1/4} \tag{5.8}$$

5.5.1 Stress Concentration Factor K_{te}

The stress concentration factor K_{te} was computed using the formula Table 3.2.

Table 5.9 provides the result of the statistical analysis of K_{te} based on Shipyard #2 data. Figure 5.9 shows a histogram of K_{te} with extreme-value and exponential distribution fits. According to the Chi-Squared goodness-of-fit test, the extreme-value distribution is better than the exponential distribution. The Chi-Squared test value is 12 for the extreme-value distribution and 185 for the exponential distribution.

Table 5.9: Statistics on Stress Concentration Factor K_{te} based on Shipyard #2 Data

N	26
Minimum	1.00
Mean	1.08
Maximum	1.33
Standard Deviation	0.09
Coefficient of Variation (%)	8.81
99% Confidence Interval on the Mean	1.035 to 1.125
95% Confidence Interval on the Mean	1.045 to 1.115
90% Confidence Interval on the Mean	1.051 to 1.109

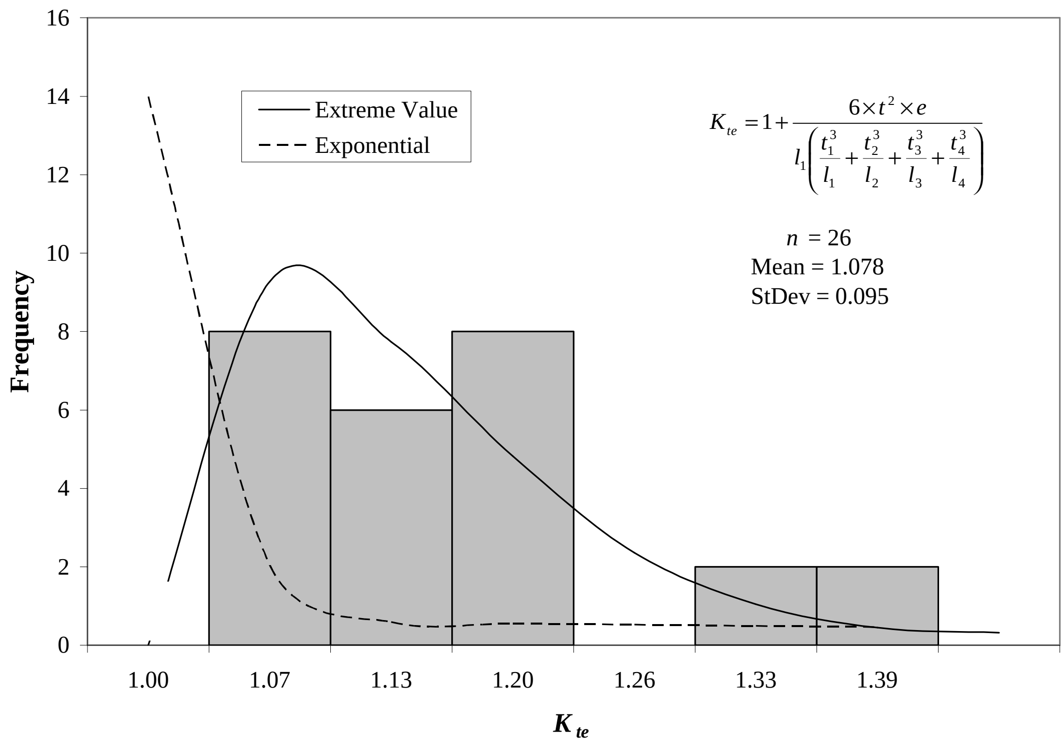

Figure 5.9: Histogram of K_{te} with Extreme-Value and Exponential Distribution Fits

5.5.2 Cruciform – Fillet Weld

The stress concentration factor as the product K_g K_w was computed using the formula in Table 3.2.

Table 5.10 provides the result of the statistical analysis of K_g K_w based on Shipyard #2 data. Figure 5.10 shows a histogram of K_g K_w with normal and Weibull (smallest) distribution fits. According to the Chi-Squared goodness-of-fit test, both have equal level of fit. The Chi-Squared test value is 5 for both distributions.

According to the Chi-Squared goodness-of-fit test, the lognormal distribution is better than the Weibull (smallest) distribution. The Chi-Squared test value is 12 for the lognormal distribution and 28 for the Weibull (smallest) distribution.

Table 5.10: Statistics on Stress Concentration Factor K_g K_w based on Shipyard #2 Data (for Fillet Weld)

N	26
Minimum	2.410
Mean	2.565
Maximum	2.746
Standard Deviation	0.081
Coefficient of Variation (%)	3.150
99% Confidence Interval on the Mean	2.52 to 2.61
95% Confidence Interval on the Mean	2.53 to 2.60
90% Confidence Interval on the Mean	2.54 to 2.59

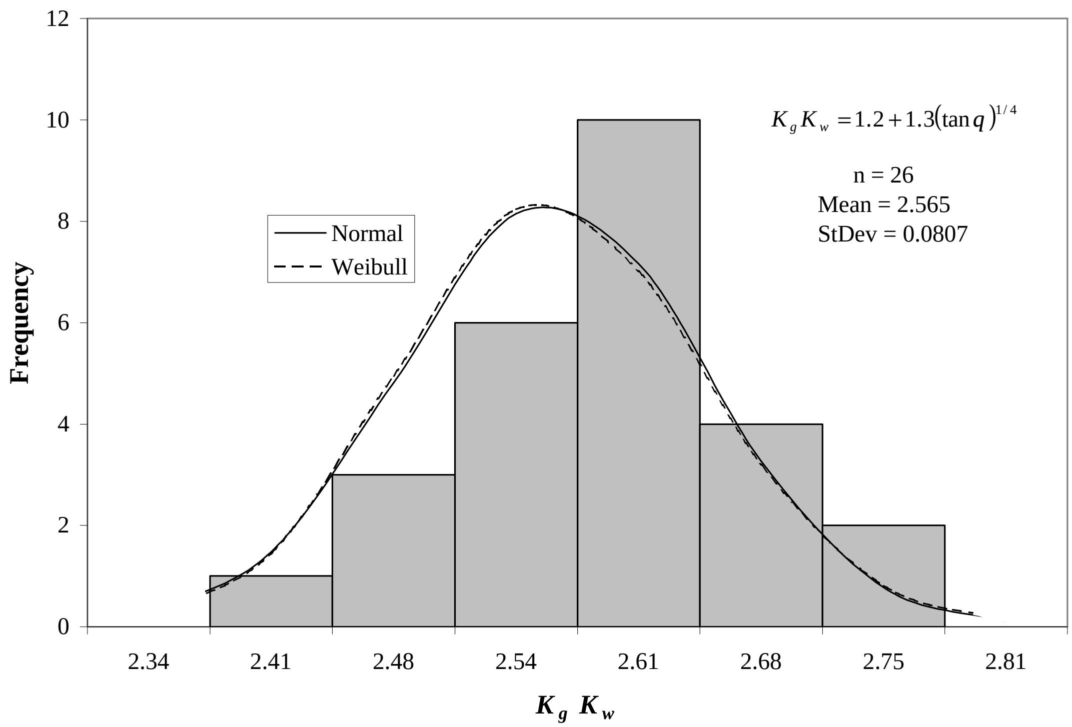

Figure 5.10: Histogram of K_g K_w with Normal and Weibull (smallest) Distribution Fits for Fillet Weld

5.5.3 Cruciform – Full Penetration Weld

The stress concentration factor K_g K_w was computed using Eq. 5-8. Table 5.11 provides the result of the statistical analysis of K_g K_w based on Shipyard #2 data. Figure 5.11 shows a histogram of K_g K_w with lognormal and Weibull (smallest) distribution fits.

Table 5.11: Statistics on Stress Concentration Factor K_g K_g based on Shipyard #2 Data (for Full Penetration Weld)

N	26
Minimum	2.42
Mean	2.55
Maximum	2.70
Standard Deviation	0.07
Coefficient of Variation (%)	2.56
99% Confidence Interval on the Mean	2.51 to 2.59
95% Confidence Interval on the Mean	2.52 to 2.58
90% Confidence Interval on the Mean	2.53 to 2.57

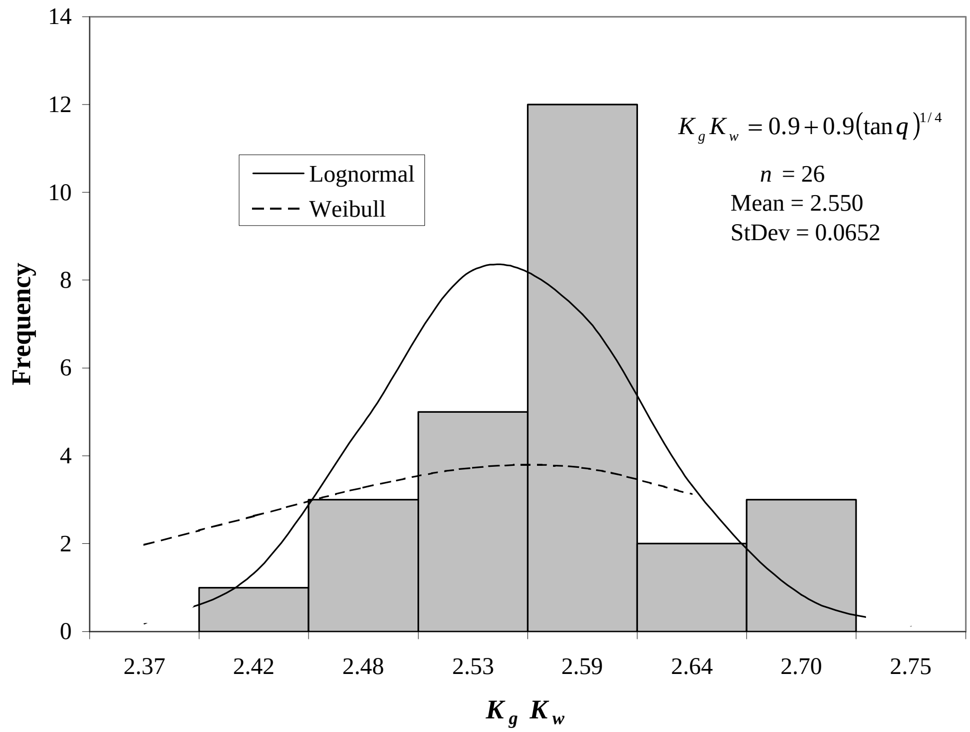

Figure 5.11: Histogram of K_g K_w with Lognormal and Weibull Distribution Fits for Full Penetration Weld

5.6 Total Stress Concentration Factor

The total stress concentration factor *K* was calculated based on Eq. 5-1 and on the individual concentration factor values obtained from the statistical analyses of the previous sections. Statistical analyses were performed as well as histograms with best-known theoretical distributions and generated for each weld type such as butt-welded plates, butt-welded stiffeners, and intercostals joints.

5.6.1 Butt-Welded Plates

5.6.1.1 Shipyard #1

The total concentration factor K was computed using equation (5-1). The values for K_n and K_g in equation (5-1) were taken as 1. Table 5.12 shows the result of the statistical analysis of K based on the Shipyard #1 data. Figure 5.12 provides a histogram of K with normal and lognormal distribution fits. According to the Chi-Squared goodness-of-fit test, the normal distribution is better than the lognormal distribution. The Chi-Squared test value is 5.4 for the normal distribution and 6.2 for the normal distribution.

Table 5.12: Statistics on Total Stress Concentration Factor *K* for Butt-Welded Plates based on Shipyard #1 Data

N	19
Minimum	1.352 K_g K_n
Mean	1.712 K_g K_n
Maximum	2.004 K_g K_n
Standard Deviation	0.168 K_g K_n
Coefficient of Variation (%)	9.784
99% Confidence Interval on the Mean	(1.613 to 1.811) K_g K_n
95% Confidence Interval on the Mean	(1.637 to 1.787) K_g K_n
90% Confidence Interval on the Mean	(1.649 to 1.775) K_g K_n

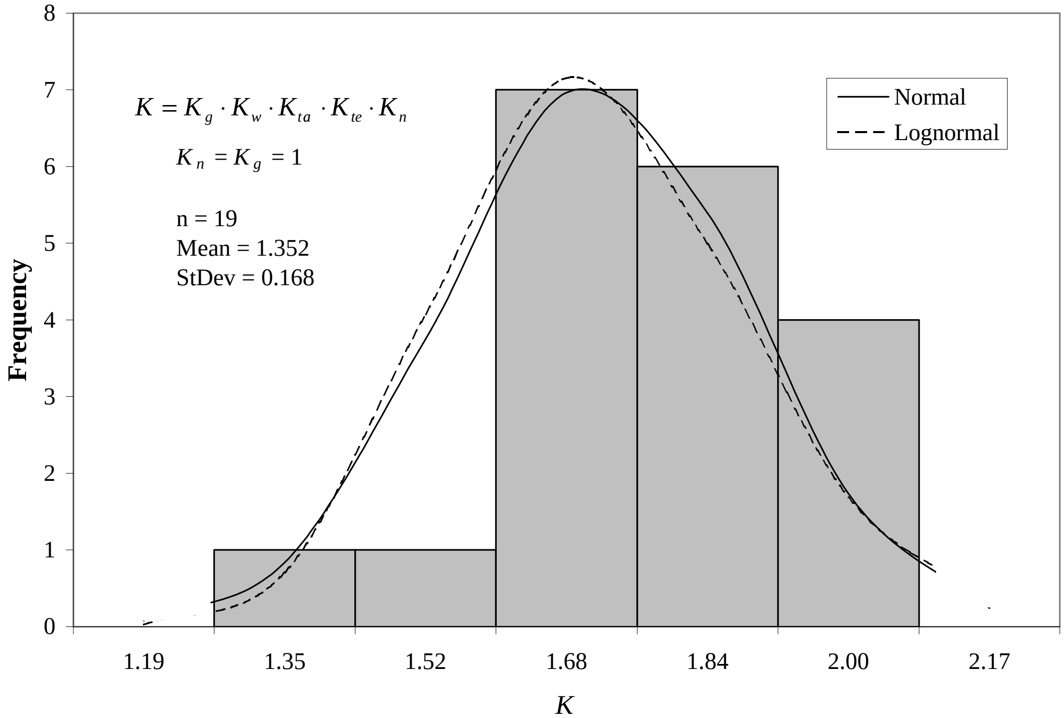

Figure 5.12: Histogram of total Stress Concentration Factor *K* with Normal and Lognormal Distribution Fits for Butt-Welded Plates (Shipyard #1)

5.6.1.2 Shipyard #2

The total concentration factor *K* was computed using equation (5-1). The values for K_n and K_g in equation (5-1) were taken as 1. Table 5.13 shows the result of the statistical analysis of *K* based on the Shipyard #2 data. Figure 5.13 provides a histogram of *K* with lognormal and exponential distribution fits. According to the Chi-Squared goodness-of-fit test, the lognormal distribution is better than the exponential distribution. The Chi-Squared test value is 22.3 for the lognormal distribution and 29.9 for the exponential distribution.

Table 5.13: Statistics on Total Stress Concentration Factor *K* for Butt-Welded Plates based on Shipyard #2 Data

N	37
Minimum	1.552 K_g K_n
Mean	9.221 K_g K_n
Maximum	19.360 K_g K_n
Standard Deviation	8.574 K_g K_n
Coefficient of Variation (%)	92.982
99% Confidence Interval on the Mean	(5.590 to 12.852) K_g K_n
95% Confidence Interval on the Mean	(6.458 to 11.984) K_g K_n
90% Confidence Interval on the Mean	(6.903 to 11.540) K_g K_n

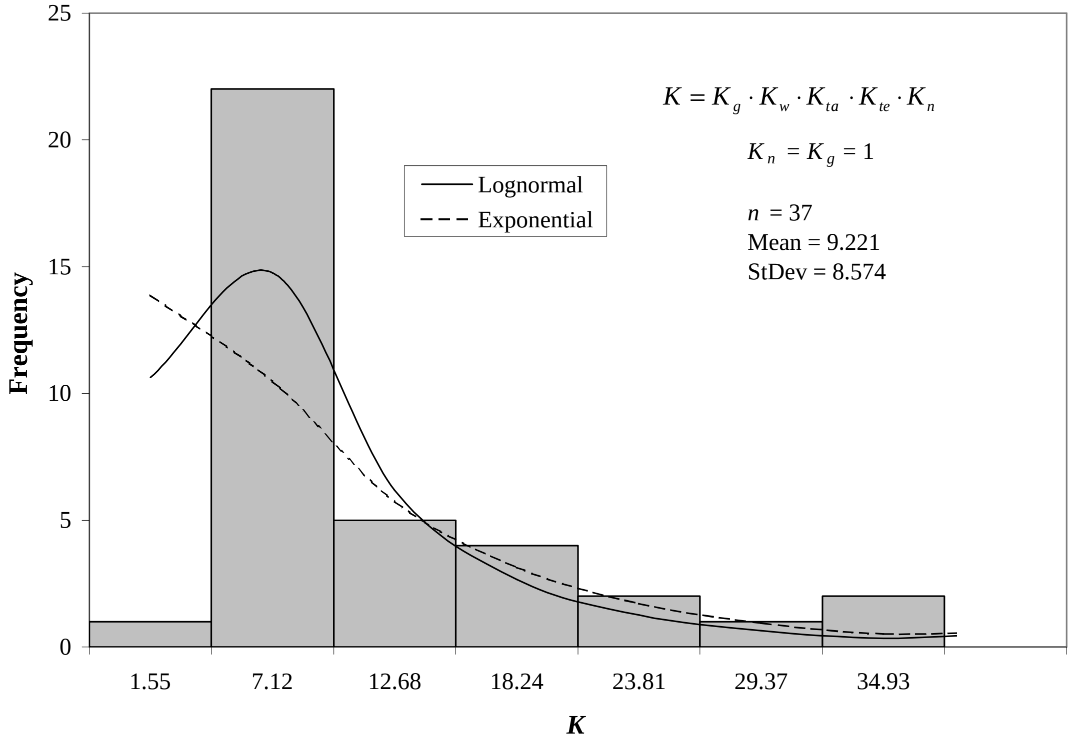

Figure 5.13: Histogram of Total Stress Concentration Factor *K* with Normal and Lognormal Distribution Fits for Butt-Welded Plates (Shipyard #2)

5.6.2 Butt-Welded Stiffeners

The total concentration factor K was computed for butt-welded stiffeners using equation (5-1). The values for K_n and K_g in equation (5-1) were taken as 1. Table 5.14 shows the result of the statistical analysis of K based on the Shipyard #2 data. Figure 5.14 provides a histogram of K with lognormal and normal distribution fits. According to the Chi-Squared goodness-of-fit test, the lognormal distribution is better than the normal distribution. The Chi-Squared test value is 0.4 for the lognormal distribution and 1.3 for the normal distribution.

Table 5.14: Statistics on Total Stress Concentration Factor *K* for Butt-Welded Stiffeners based on Shipyard #2 Data

N	8
Minimum	1.000 K_g K_n
Mean	4.326 K_g K_n
Maximum	14.758 K_g K_n
Standard Deviation	4.523 K_g K_n
Coefficient of Variation (%)	104.558
99% Confidence Interval on the Mean	(0.207 to 8.446) K_g K_n
95% Confidence Interval on the Mean	(1.192 to7.461) K_g K_n
90% Confidence Interval on the Mean	(1.696 to 6.957) K_g K_n

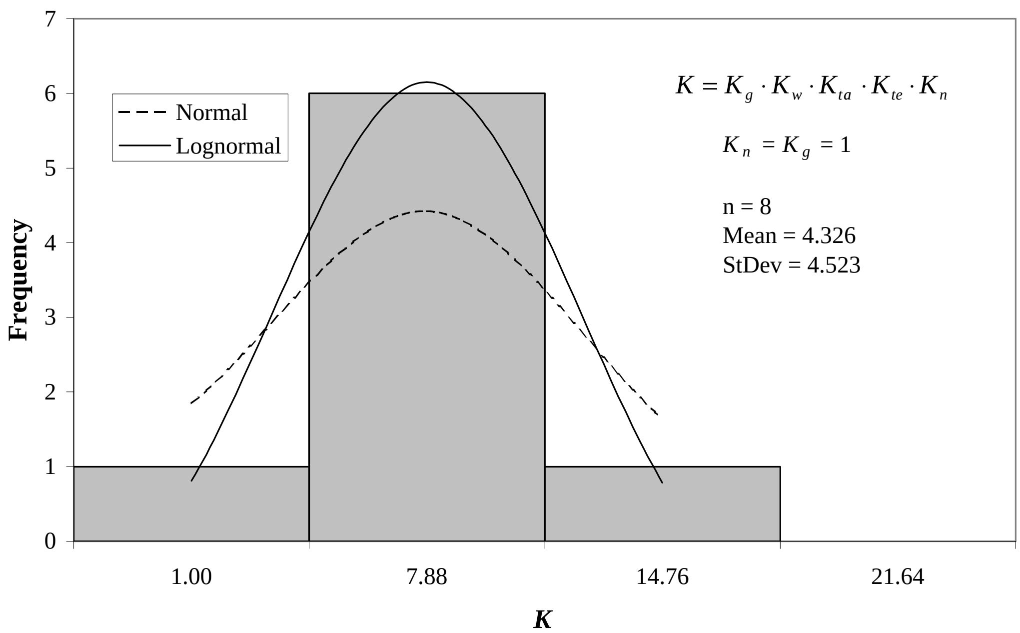

Figure 5.14: Histogram of Total Stress concentration factor *K* with Lognormal and Normal Distribution Fits for Butt-Welded Stiffeners (Shipyard #2)

5.6.3 Cruciform Joints

5.6.3.1 Fillet Weld

The total concentration factor *K* was computed for cruciform joints (fillet weld) using equation (5-1). The values for K_n and K_{ta} in equation (5-1) were taken as 1. Table 5.15 shows the result of the statistical analysis of *K* based on the Shipyard #2 data. Figure 5.15 provides a histogram of *K* with lognormal and normal distribution fits. According to the Chi-Squared goodness-of-fit test, the lognormal distribution is better than the normal distribution. The Chi-Squared test value is 16.5 for the lognormal distribution and 24.7 for the normal distribution.

Table 5.15: Statistics on Total Stress Concentration Factor *K* for Cruciform Joints (Fillet Weld) based on Shipyard #2 Data

N	26
Minimum	2.442 $K_n K_{ta}$
Mean	2.764 $K_n K_{ta}$
Maximum	3.392 $K_n K_{ta}$
Standard Deviation	0.259 $K_n K_{ta}$
Coefficient of Variation (%)	9.354
99% Confidence Interval on the Mean	(2.633 to 2.895) $K_n K_{ta}$
95% Confidence Interval on the Mean	(2.665 to 2.863) $K_n K_{ta}$
90% Confidence Interval on the Mean	(2.681 to2.847) $K_n K_{ta}$

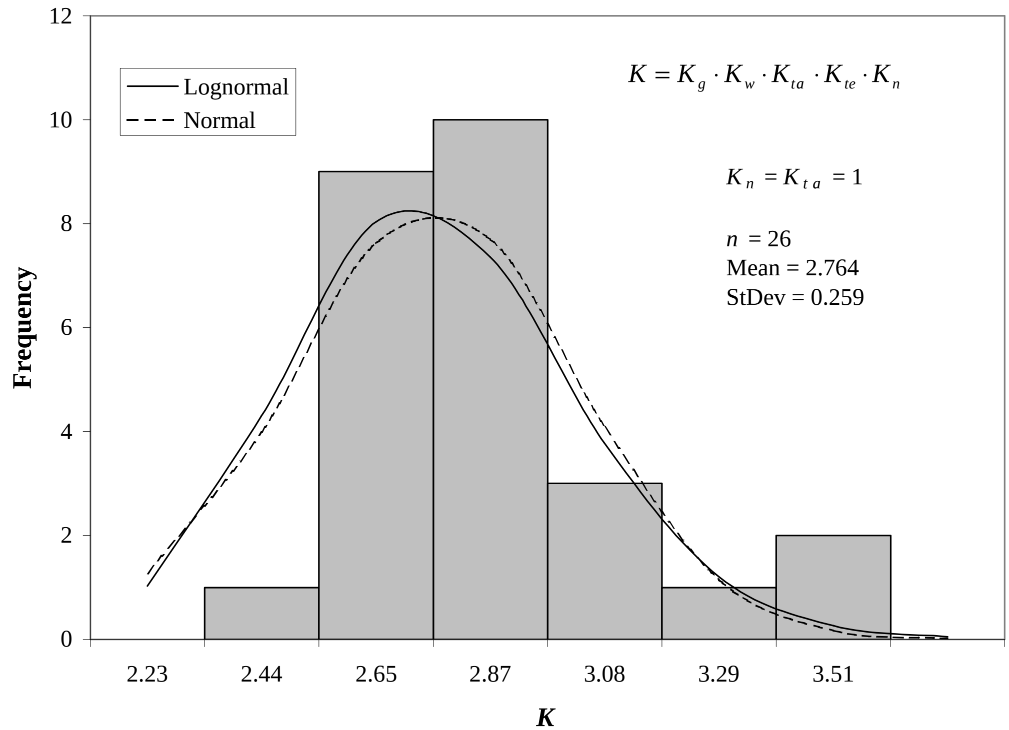

Figure 5.15: Histogram of Total Stress concentration factor *K* with Lognormal and Normal Distribution Fits for Cruciform Joints, Fillet Weld (Shipyard #2)

5.6.3.2 Full Penetration Weld

The total concentration factor *K* was computed for cruciform joints (full penetration weld) using equation (5-1). The values for K_n and K_{ta} in equation (5-1) were taken as 1. Table 5.16 shows the result of the statistical analysis of *K* based on the Shipyard #2 data. Figure 5.16 provides a histogram of *K* with lognormal and normal distribution fits. According to the Chi-Squared goodness-of-fit test, the lognormal distribution is better than the normal distribution. The Chi-Squared test gave a value of 25.4 for the lognormal distribution and a value of 36.7 for the normal distribution.

Table 5.16: Statistics on Total Stress Concentration Factor *K* for Cruciform Joints (Full Penetration Weld) based on Shipyard #2 Data

N	26
Minimum	2.479 K_n K_{ta}
Mean	2.750 K_n K_{ta}
Maximum	3.576 K_n K_{ta}
Standard Deviation	0.285 K_n K_{ta}
Coefficient of Variation (%)	10.355
99% Confidence Interval on the Mean	(2.607 to2.894) K_n K_{ta}
95% Confidence Interval on the Mean	(2.641 to 2.860) K_n K_{ta}
90% Confidence Interval on the Mean	(K_n K_{ta}2.659 to2.842) K_n K_{ta}

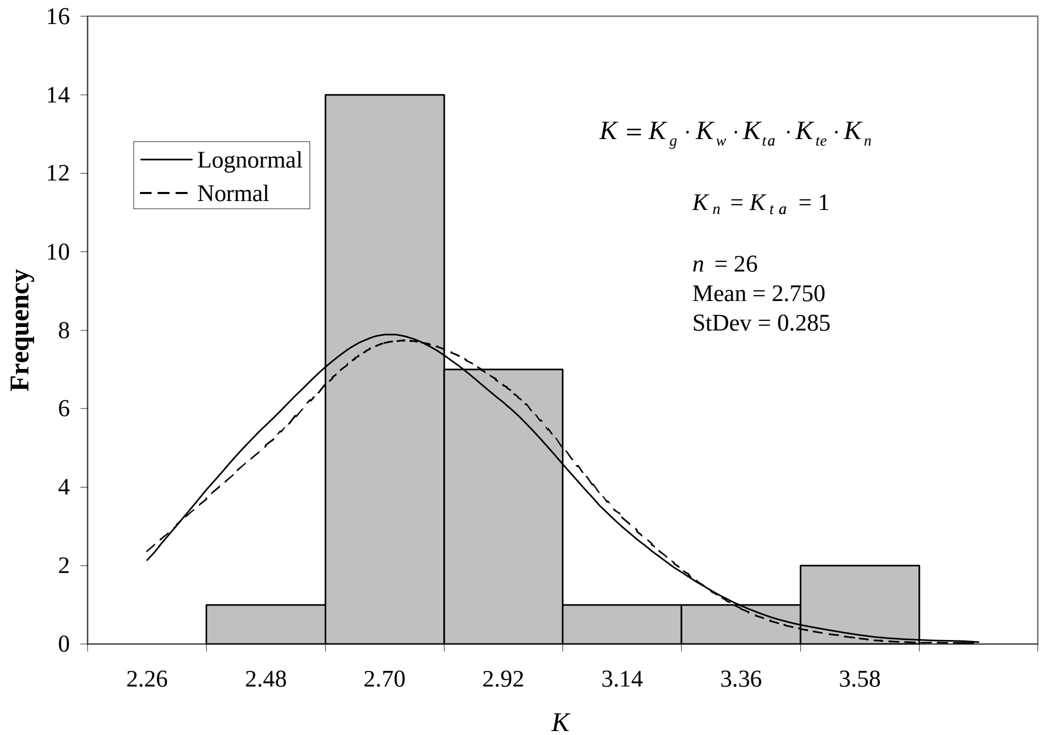

Figure 5.16: Histogram of Total Stress concentration factor *K* with Lognormal and Normal Distribution Fits for Cruciform Joints, Full Penetration Weld (Shipyard #2)

5.7 Summary and Discussion of the Results

In this section, the statistical characteristics of stress concentration factors *K*s for fatigue design of ship structures are summarized and tabulated based on the data collected at the Shipyard #1 and Shipyard #2. These characteristics include the mean *m*, the coefficient of variation (*COV*), and the underlying probability distribution for each stress concentration factor component *K*.

However, since these results should be revised as new data (e.g., more shipyard data) and researches on the subject emerge, and caution must be taken when using these results in reliability assessment and reliability-based fatigue design of ship structures. They represent only the ranges and the weighted averages of the statistical values collected from two limited sources, Shipyard #1 and Shipyard #2; the number of samples in the data sets is not sufficient to provide a high level of confidence in the results. Although the distributions derived above represent the best fits to the available data, it is probable that a single set of distributions will be appropriate to the types of phenomena involved in misalignment, rather that having different distributions for each yard, as indicated (in some cases) by the current data sets.

The summary of the statistical characteristics of the individual stress concentration factors as well as the total stress concentration factors *K*s are provided in Tables 5.17 and 5.18. The different stress concentration factors, as shown in Table 5.17, include factors that are standardized and defined by the various classification societies as employed in Eqs 5-3, 5-4, 5-5, 5-6, 5-7, and 5-8, and in Figures 5.1, 5.2, 5.3, 5.12, 5.13, and 5.14.

These factors include K_{ta}, K_w, K_{te}, and $K_g K_w$ that correspond to various weld types such as butt-welded plates, butt-welded stiffeners, and intercostals joints.

Table 5.17 provides statistical summary for the total concentration factor.

One reason for having statistically treated the data as separate data sets, i.e., Shipyard #1 as one set and Shipyard #2 as another, is that the number of samples due to Shipyard #1 data set is not statistically significant and the samples only cover one type of weld. In order to combine the two shipyard data sets it is necessary that both should have comparable and significant samples covering all types of welds, and better yet to have more than two shipyard data sets each with sufficient number of data points.

Table 5.17: Summary of the Statistical Analyses for the Individual Stress Concentration Factors *K*s based on Shipyard 1 & 2 Data

Weld Type	Descriptive Statistics	Shipyard #1			Shipyard #2		
		K_{ta}	K_w	K_{te}	K_{ta}	K_w	K_{te}
Butt-Welded Plates	Sample Mean	n/a	1.37	1.26	5.00	1.43	1.23
	Coefficient of Variation (%)	n/a	3.22	10.0	88.90	3.77	13.5
	99, 95, and 90 % Confidence Interval on m	n/a n/a n/a	mean ± 0.0167 mean ± 0.0127 mean ± 0.0107	mean ± 0.0768 mean ± 0.0585 mean ± 0.0491	mean ± 1.882 mean ±1.432 mean ± 1.202	mean ± 0.0119 mean ± 0.0090 mean ± 0.0076	mean ± 0.0570 mean ± 0.0434 mean ± 0.0364
	Distribution Type	n/a	Normal (30)* Extreme Value (Type I Gumbel largest) (117)**	Normal (8)* Lognormal (9)**	Lognormal (29)* Exponential (34)**	Normal (19)* Extreme Value (Type I Gumbel largest) (43)**	Lognormal (14)* Weibull (smallest) (16)**
Butt-Welded Stiffeners	Sample Mean	n/a	n/a	n/a	2.38	1.43	1.20
	Coefficient of Variation (%)	n/a	n/a	n/a	95.96	6.97	14.2
	99, 95, and 90 % Confidence Interval on m	n/a n/a n/a	n/a	n/a	mean ± 2.076 mean ± 1.580 mean ± 1.326	mean ± 0.0388 mean ± 0.0295 mean ± 0.0248	mean ± 0.0934 mean ± 0.0710 mean ± 0.0596
	Distribution Type	n/a n/a n/a	n/a	n/a	Exponential (3)* Extreme Value (Type I Gumbel largest) (11)**	Normal (45)* Extreme Value (Type I Gumbel largest) (58)**	Exponential (6)* Extreme Value (Type I Gumbel largest) (106)**
		Fillet Weld K_q K_w	Full Penetration Weld K_q K_w	K_{te}	Fillet Weld K_q K_w	Full Penetration Weld K_q K_w	K_{te}
Cruciform Joints	Sample Mean	n/a	n/a	n/a	2.57	2.55	1.08
	Coefficient of Variation (%)	n/a	n/a	n/a	3.15	2.56	8.81
	99, 95, and 90 % Confidence Interval on m	n/a	n/a	n/a	mean ± 0.0455 mean ± 0.0346 mean ± 0.0290	mean ± 0.0409 mean ± 0.0311 mean ± 0.0261	mean ± 0.0354 mean ± 0.0269 mean ± 0.0226
	Distribution Type	n/a	n/a	n/a	Extreme Value (Type I Gumbel largest) (12)* Exponential (199)**	Normal (5)* Weibull (smallest) (5)**	Lognormal (12)* Weibull (smallest) (28)**

(-) = Chi-Squared Test Value
* = First best fit distribution according to the Chi-Squared goodness of fit
** = Second best fit distribution according to the Chi-Squared goodness of fit
n/a = not available

Table 5.18: Summary of the Statistical Analyses for the Total Stress Concentration Factors *K*s based on Shipyard 1 & 2 Data

Weld Type	Descriptive Statistics	Shipyard #1		Shipyard #2	
		K		K	
Butt-Welded Plates	Sample Mean	1.712		9.221	
	Coefficient of Variation (%)	9.78		92.98	
	99, 95, and 90 % Confidence Interval on m	mean ± 0.0990 mean ± 0.0753 mean ± 0.0632		mean ± 3.631 mean ± 2.763 mean ± 2.318	
	Distribution Type	Normal (5.4)* Lognormal (6.2)**		Lognormal (22.3)* Exponential (29.9)**	
Butt-Welded Stiffeners	Sample Mean	n/a		4.326	
	Coefficient of Variation (%)	n/a		104	
	99, 95, and 90 % Confidence Interval on m	n/a		mean ± 4.119 mean ± 3.134 mean ± 2.630	
	Distribution Type	n/a		Lognormal (0.4)* Normal (1.3)**	
		Fillet Weld	Full Penetration Weld	Fillet Weld	Full Penetration Weld
		K	K	K	K
Cruciform Joints	Sample Mean	n/a	n/a	2.764	2.750
	Coefficient of Variation (%)	n/a	n/a	9.354	10.355
	99, 95, and 90 % Confidence Interval on m	n/a	n/a	mean ± 0.1306 mean ± 0.0994 mean ± 0.0834	mean ± 0.1439 mean ± 0.1095 mean ± 0.0919
	Distribution Type	n/a	n/a	Lognormal (16.5)* Normal (24.7)**	Lognormal (25.4)* Normal (36.7)**

(-) = Chi-Squared Test Value
* = First best fit distribution according to the Chi-Squared goodness of fit
** = Second best fit distribution according to the Chi-Squared goodness of fit
n/a = not available

6. DISCUSSION OF DATA

6.1 Overall Stress Concentration Factors

As noted in Section 4.2, the shipyard data analyzed in Section 5 has been taken from large block assemblies and from completed sections of ships. The fabrication quality at the panel line level in both yards was sufficiently good that measurements were effectively within the accuracy limits of the data collection tools. This indicates that (subject to adequate weld properties) fatigue problems are much more likely to manifest themselves at block/unit/assembly joints than within panels.

Table 6.1 compares the stress concentration factors derived in Section 5 for Shipyard #2 to the Det Norske Veritas (DNV) design default values presented in Section 3. It can be seen that for plate connections, the overall mean values derived from the observed data are close to the defaults. For stiffener connections, the shipyard values are close to the defaults for the cruciform connections, but those for the butt-welded stiffeners indicate that the yard can better the default assumptions. The situation with regard to the scatter in the results will be discussed further in Section 6.2.

Table 6.1: Comparison of Survey K Values to DNV Defaults

Weld Type	Descriptive Statistics	Shipyard #2 Data			
		Ktα	Kw	Kte	**Ktotal**
Butt Welded Plates (Assumed free ends, λ = 6)	Mean	5	1.43	1.23	9.22
	Std. Dev.	4.44	0.05	0.17	8.57
	Mean + 1 Std. Dev.	9.44	1.48	1.4	17.79
	Mean + 2 Std. Dev.	13.88	1.53	1.57	26.36
	DNV Default Value	4.03[1]	1.5[2]	1.45[3]	8.9
	Std. Dev. of DNV default value	1.03	n/a	n/a	
		Ktα	Kw	Kte	**Ktotal**
Butt Welded Stiffeners (Assumed free ends, λ = 6)	Mean	2.38	1.43	1.2	4.33
	Std. Dev.	2.28	0.1	0.17	4.52
	Mean + 1 Std. Dev.	4.66	1.53	1.37	8.85
	Mean + 2 Std. Dev.	6.94	1.63	1.54	13.37
	DNV Default Value	4.6[1]	1.5[2]	1.45[3]	10.18
	Std. Dev. of DNV default value	0.4	n/a	n/a	
		Kg Kw	Kte		**Ktotal**
Cruciform Joints	Mean	2.57	1.08		2.76
	Std. Dev.	0.08	0.09		0.26
	Mean + 1 Std. Dev.	2.65	1.17		3.02
	Mean + 2 Std. Dev.	2.73	1.26		3.28
	DNV Default Value	2.5[4]	1.18[5]		3.01

1. DNV default for Ktα based upon e = 6 mm. Assumed that the seam is at the middle of supports, such that Ktα = 1+l(e/t). Used the plate thicknesses in the survey to calculate Ktα. the default value given is the mean of the sample.

2. DNV default for Kw based upon q = 45°

3. DNV default for Kte (butt joint) based upon misalignment = e_0 = 0.15t

4. DNV default for KgKw based upon θ = 45°

5. DNV default for Kte (cruciform joint) based on e = 0.3t. The Kte values are dependent on the distance the joint is from supports. The values from the survey were used to determine the default K value.

It should be noted that most aspects of the comparisons above are relevant to fatigue analysis using any classification society methodology, not only that of DNV. All the SCF numbers calculated for axial and angular misalignment have meaning in all fatigue analysis standards. As previously discussed, it is assumed that the test samples used to develop S-N curves had no discernible misalignment. Therefore, in principle it does not matter if the nominal stress, hot spot stress, or notch stress approach is being used - stress ranges used in the S-N curve calculation should be increased to account for any misalignment. Most standards thus provide formulae to determine the secondary bending stress caused by the axial loading of the misaligned joints, though in practice the nominal stress approach is normally used without any correction.

Conversely, it is important to consider that the SCF values determined for imperfect weld profile relate only to the notch stress analysis (DNV) approach. Thus, while the overall mean SCFs presented on the previous page are of interest, so too are the individual SCFs. This is discussed further in Section 7.

6.1.1 Stress Concentration Factor $K_{t\alpha}$

It can be seen from the results presented in Table 6.1 that the largest individual stress concentration factor (applicable to butt connections) in terms of both mean value and standard deviation tends to be $K_{t\alpha}$. The calculation of $K_{t\alpha}$ requires assumptions in addition to measurements; a key assumption in the analyses above is that the plate ends are free rather than fixed at the end supports. In both shipyards surveyed, the typical configuration was as shown in Figure 6.1, where unit butt welds were located between transverse stiffeners. In a buckling analysis, the plate would normally be considered as simply supported, especially for the relatively thin plate being used in the vessels under construction. However, the assumption is certainly conservative, especially for fatigue analysis.

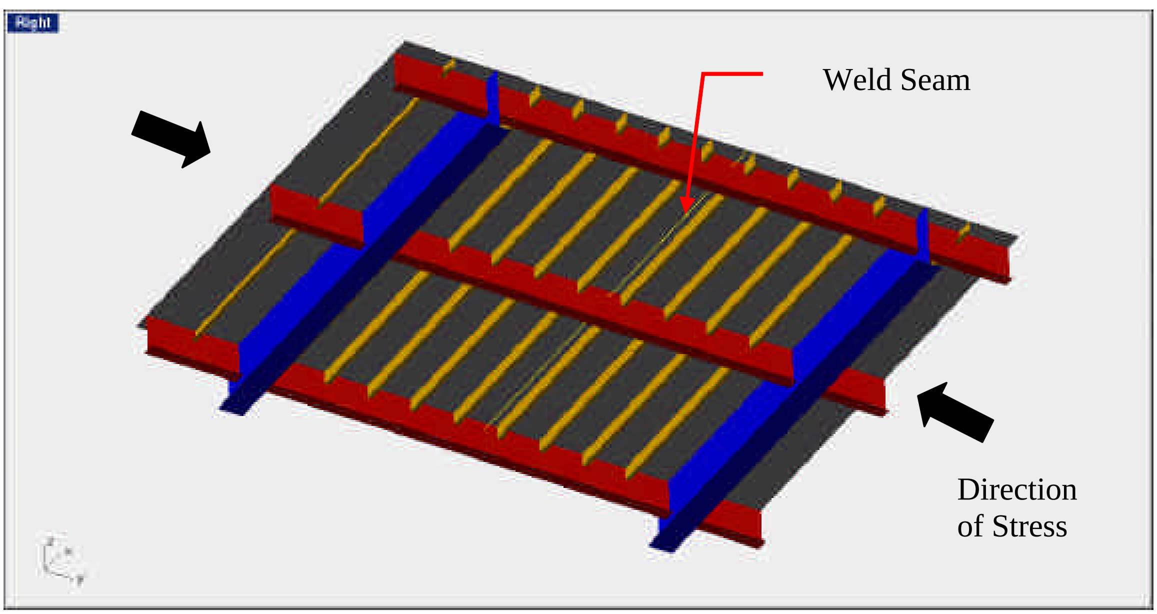

Figure 6.1: Typical Butt Weld

As noted in Section 3, the formula for $K_{t\alpha}$ is:

$$K_{t\alpha} = 1 + \frac{\lambda}{4}\alpha\frac{s}{t} = 1 + \lambda\frac{e}{t}$$

where λ = 6 for pinned (simply supported) ends
λ = 3 for fixed ends

Thus, changing the assumed fixity effectively reduces the SCF by up to 50 %. The effect on the survey data is shown in Table 6.2 (for butt-welded plate only). It can be seen that the fixity assumption has a major effect on fatigue life prediction, and this appears to be an area in which more work needs to be undertaken to provide designers with useful guidance.

Table 6.2: Effect of Fixed vs. Free and Assumption on SCFs

Weld Type	Descriptive Statistics	Shipyard #2 Data			
		$K_{t\alpha}$	Kw	Kte	**Ktotal**
Butt Welded Plates (Assumed free ends, λ = 6)	Mean	5.00	1.43	1.23	9.22
	Std. Dev.	4.44	0.05	0.17	8.57
	Mean + 1 Std. Dev.	9.44	1.48	1.4	17.79
	Mean + 2 Std. Dev.	13.88	1.53	1.57	26.36
	DNV Default Value	4.03	1.5	1.45	8.9
	Std. Dev. of DNV default value	1.03	n/a	n/a	
		$K_{t\alpha}$	Kw	Kte	**Ktotal**
Butt Welded Plates (Assumed fixed ends, λ = 3)	Mean	3.00	1.43	1.2	5.51
	Std. Dev.	2.23	0.05	0.17	4.324
	Mean + 1 Std. Dev.	5.23	1.48	1.37	8.85
	Mean + 2 Std. Dev.	7.46	1.53	1.54	13.37
	DNV Default Value	2.52	1.5	1.45	5.48
	Std. Dev. of DNV default value	0.52	n/a	n/a	

6.2 Variability

The scatter in the results for SCFs obtained from the shipyard data is considerable, and for plate butt welds is more than is implied in standard S-N based fatigue analysis procedures. To illustrate this, it is necessary to refer back to the discussion presented at Section 3.4.

In this DNV analysis approach (and that of other classification societies), stress ranges are based on mean stress concentration factors, taking into account expected (default) values for misalignment, etc. The potential variability in the actual outcomes is accounted for by displacing the design S-N curve by two standard deviations (2SD) from the underlying curve (Figure 3.13). The 2SD value in the DNV curves approximates to an additional stress concentration multiplier of approximately 2.5, whereas as shown in Table 6.1 the 2SD shipyard values from this project ranged from a low of less than 1.2 for the cruciform joints to as high as 2.9 for the butt-welded plates (ratio of 2SD to mean total SCF).

These results imply that it may be inappropriate to use the same 2SD 'safety factor' for all types of joint. In fact, the DNV approach is unusual in this regard, as most design S-N curves for specific joint types have individual 2SD values, as shown in Figure 6.2 and Table 6.3. Butt-welded plates are normally analyzed using a 'D', 'E' 'F' or 'F2' curve (depending on location and quality), and cruciforms by 'F2'. It can be seen that the variability in the shipyard plate sample is somewhat greater than the 2SD assumption underlying any of the S-N curves.

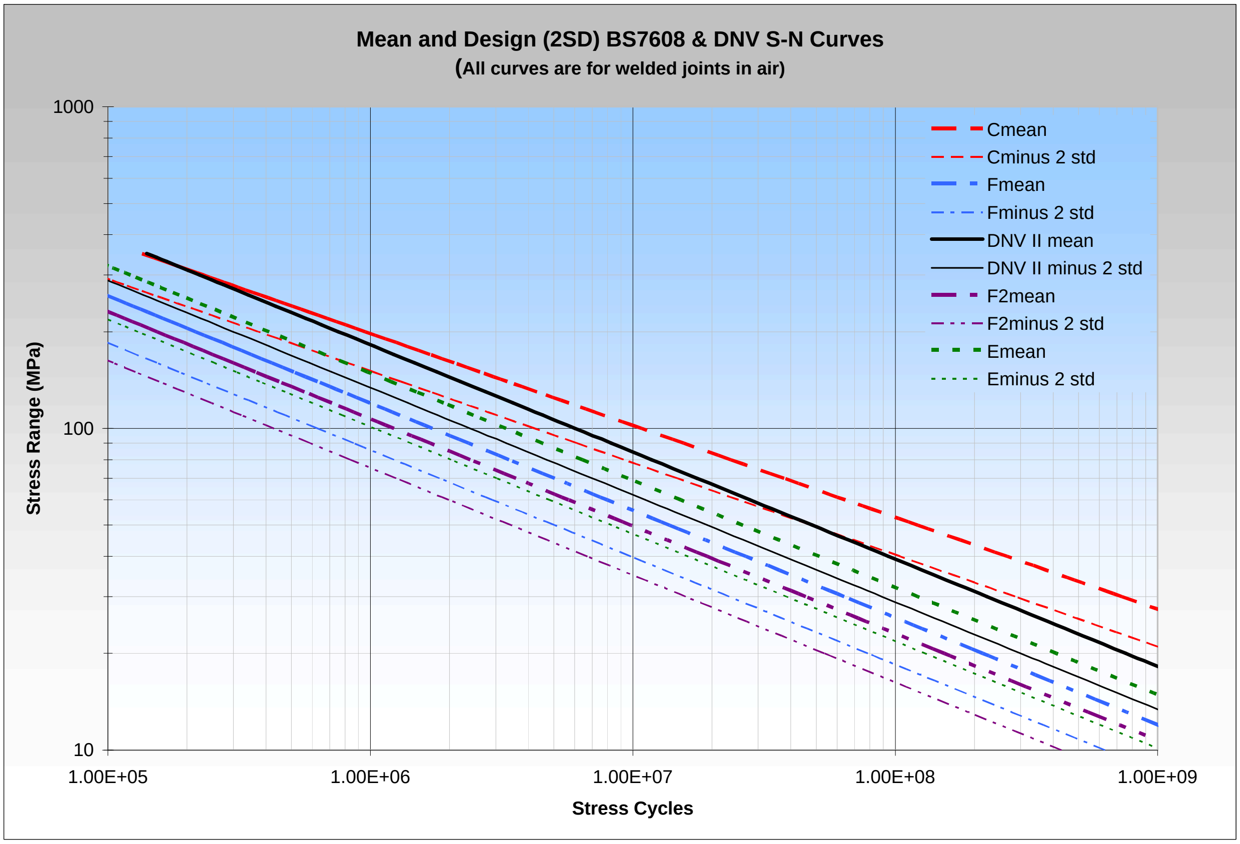

Figure 6.2: S-N Design Curves Showing 2SD Offsets

Table 6.3: 2SD Equivalent SCFs

Curve	2SD Eq SCF
C	2.56
D	2.62
E	3.16
F	2.74
F2	2.86
DNV	2.51

It should also be recognized that the S-N curve 2SD offsets are intended to account for scatter from all sources, including the internal imperfections listed in Section 3.2. Therefore, the fatigue life of the shipyard samples would be expected to display more variability than that due to the geometric imperfections alone. Therefore, while the results for the butt-welded plates certainly imply more scatter in fatigue life outcome than implied in the design methodology, those for the cruciforms do not necessarily guarantee less scatter in the final outcome.

A further point is that the plate data represents final unit assemblies, whereas equivalent cruciform connections could not be accessed during either shipyard survey. If the final assembly stage is most likely to show poor outcomes, the collected data set may not reflect worse case results for cruciform connections.

7. FATIGUE LIFE CASE STUDY

7.1 Basis for Analysis

In order to illustrate the potential significance of the data collected in this project, it has been used to revisit analyses undertaken in SSC Project 427 “Life Expectancy Assessment of Ship Structures”[8]. For a typical very large crude oil carrier (VLCC) (Figure 7.1) operational profile and scantlings a lifetime stress history was developed (Figure 7.2). Fatigue life has been estimated using various assumptions regarding stress concentration factors for deck butt welds. Such welds are not normally considered as the most probable locations for fatigue cracking problems, but can still provide a useful illustration of the significance of the tolerances measured during the project.

Figure 7.1: Example VLCC (from SSC 427)

[8] Dinovitzer, A. “Life Expectancy Assessment of Ship Structures” SSC Report 427, 2003.

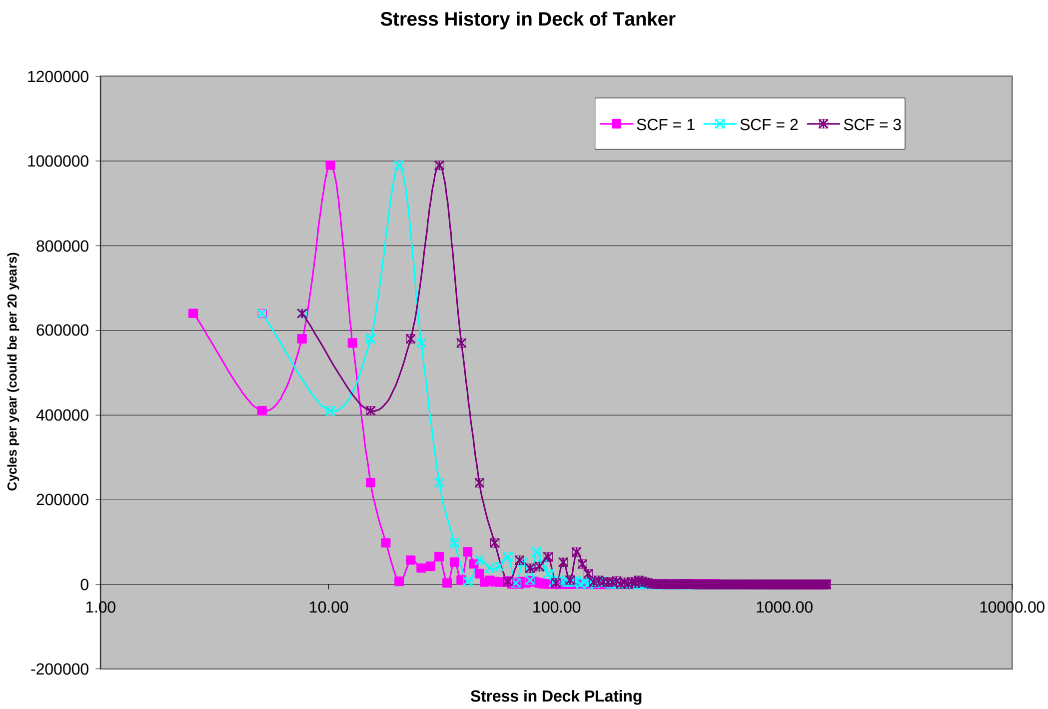

Figure 7.2: VLCC Notional Stress History

The data for butt weld connections from Shipyard #2 have been utilized in order to develop a picture of the expected variability in fatigue life resulting from the geometric stress concentration factors measured in the shipyard. The outcomes have been based on two S-N curves - the standard curve utilized with the DNV notch stress approach, and the standard curve for class F2 structural details from BS 5400 (nominal stress approach), as shown in Figure 6.2. These outcomes have then been compared with notional design outcomes using these two methodologies.

In a large tanker, plate thicknesses will be considerably greater than those used in most of the assemblies surveyed in Shipyards #1 and #2. Also, such a ship would be built under fatigue class notation, with (presumably) tighter tolerances and/or more extensive inspection. It is therefore probable that most of the individual tolerance parameters for the tanker would differ from those measured in the project. Therefore, the potential outcomes for the notch stress analyses are shown for various hypothetical values of K_{total} as follows:

- Case 1: $K_{total} = K_{ta}.K_{te}.K_{w}$
- Case 2: $K_{total} = K_{te}.K_{w}$
- Case 3: $K_{total} = K_{w}$

The first of these assumes that no significant differences would exist between the notional tanker fabrication tolerances and the actual measured values. The second assumes that angular misalignment becomes negligible for the heavier plate used in large tanker construction.

The third is used to examine the effect of weld geometry in isolation, and to illustrate comparisons between the notch and nominal stress approach.

The angular misalignment stress concentration factor $K_{t\alpha}$ has been taken from analysis using fixed end restraint, as it has been assumed that the heavier structure is more likely to behave in this way. $K_{t\alpha}$ has also been adjusted to account for thickness effects, noting again that:

$$K_{ta} = 1 + \frac{l}{4} a \frac{s}{t} = 1 + l \frac{e}{t}$$

The notional tanker hull plate is approximately twice the thickness values for the measured data, and so $K_{t\alpha}$ values have been recalculated on this basis. These changes to the calculation of $K_{t\alpha}$ result in a distribution of outcomes as shown in Figure 7.3, which can be compared with the values shown at Figure 5.3 for the effect of the same absolute tolerances on the structures actually surveyed.

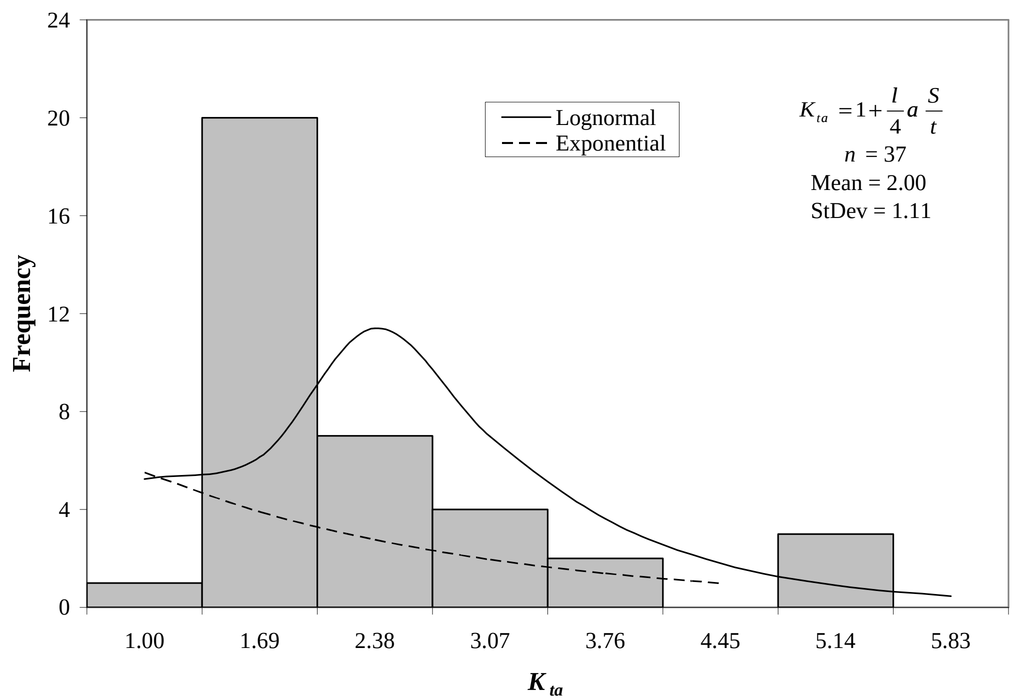

Figure 7.3: K_{ta} Adjusted for Thickness, Fixity

The misalignment factor K_{te} also includes plate thickness in its formula. Most classification societies express permissible misalignment as a function of plate thickness. In the absence of better information, it has been assumed that the same proportional misalignment would be experienced for the notional tanker as for the actual structures surveyed. This assumption may warrant further investigation in future.

7.2 Case Outcomes

Figures 7.4 to 7.6 illustrate the outcomes of the analyses using various combinations of the stress concentration factors and the DNV notch stress approach. Table 7.1 then compares the outcomes with the predictions that would be generated by 'standard' notch and nominal stress analyses; the former using the DNV default tolerance (and hence SCF) values for a vessel of this configuration, and the latter only applying the F2 S-N curve to the nominal (SCF = 1) stress history. 'Fatigue life' is used as convenient shorthand for crack initiation and growth to the point where some form of intervention might be anticipated.

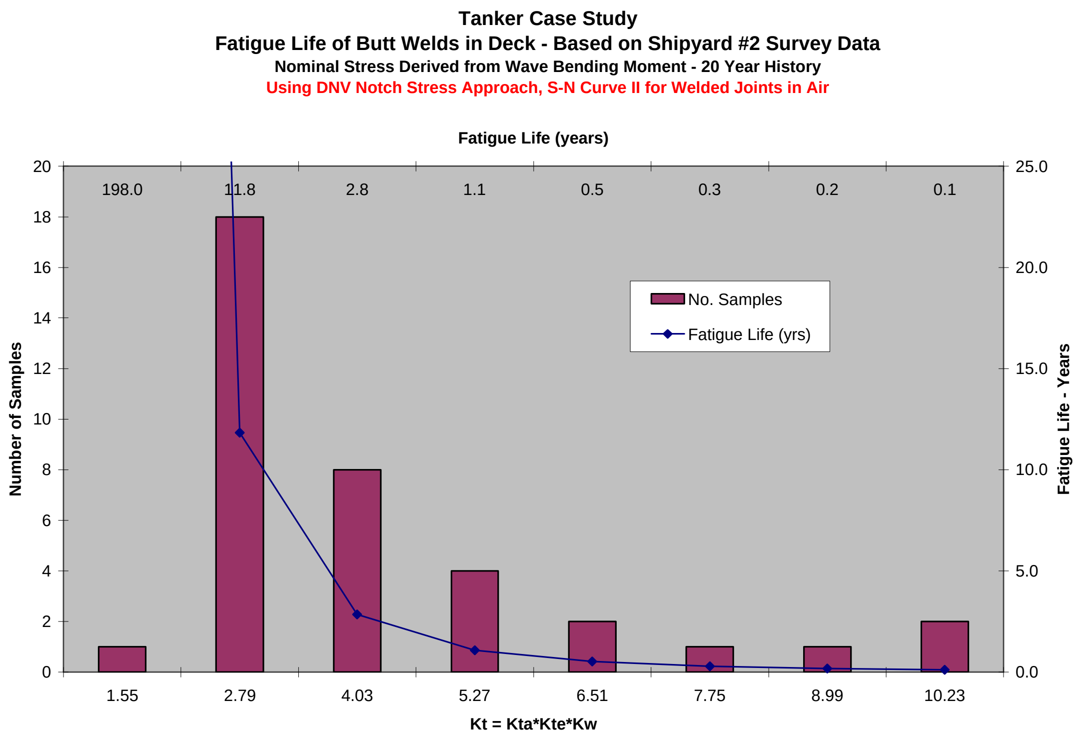

Figure 7.4: Case 1 Fatigue Life Analysis with $K_{total} = K_{ta}.K_{te}.K_{w}$

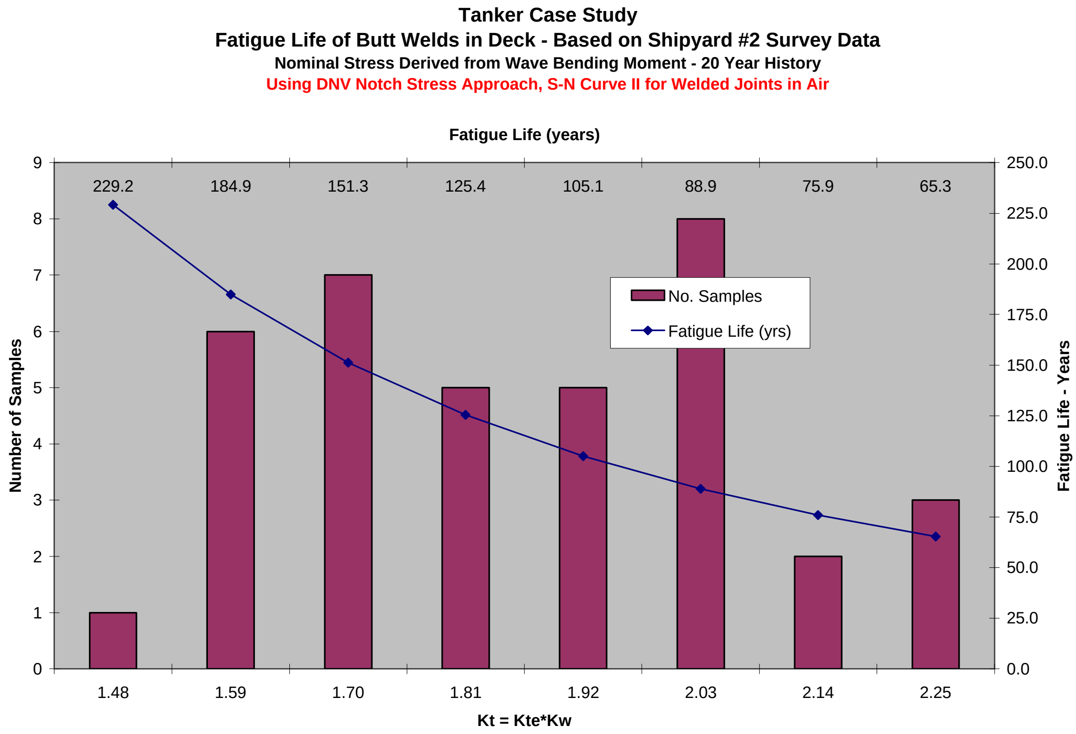

Figure 7.5: Case 2 Fatigue Life Analysis with $K_{total} = K_{te}.K_{w}$

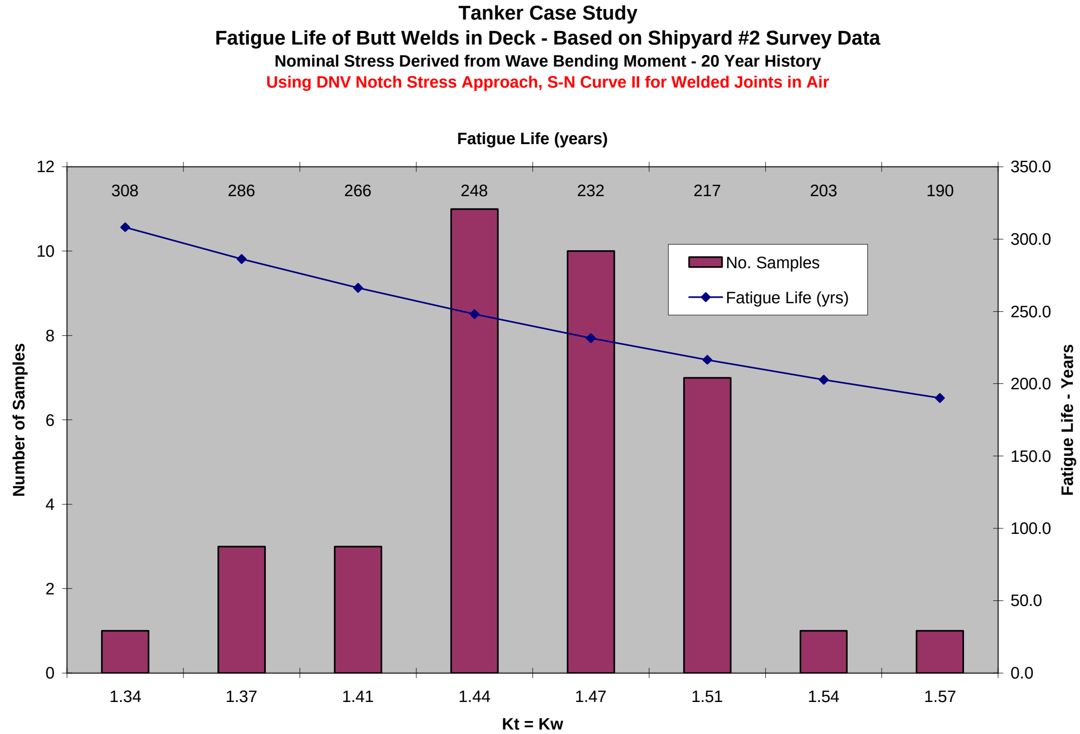

Figure 7.6: Case 3 Fatigue Life Analysis with $K_{total} = K_{w}$

Table 7.1: Fatigue Life Prediction Comparisons

Case	Mean K (mod. survey data)	Mean Fatigue Life (yrs)	DNV Default K	DNV Default Fatigue Life (yrs)	Nominal (F2) Stress Fat. Life (yrs)
Notch 1: K = Kta*Kte*Kw	3.66	15.1	3.82	13.3	132.7
Notch 2: K = Kte*Kw	1.80	126.4	2.18	71.5	132.7
Notch 3: K = Kw	1.44	247	1.5	219.5	132.7

The variability in outcome illustrated in these Figures and in Table 7.1 illustrates the importance of assigning appropriate values to anticipated fabrication tolerances at the design stage, and also of applying effective inspection and acceptance strategies during construction. While the mean fatigue life in Case 1 might be considered marginally acceptable, approximately 20% of the sample have predicted life expectancies of less than 1 year, which would almost certainly not be acceptable. All of these samples in the unadjusted data set had one or more measurements outside the nominal tolerance limits being applied by the shipyard and by the classification societies for the structures. However, as noted the work being undertaken was not to fatigue class notation, and the actual angular misalignment of thicker plate would be expected to be much lower than that found in the thinner plate of the surveys. Therefore, Case 1 can be regarded as the extreme 'worse case' outcome, although an analysis based on the survey data could easily be used to generate and justify the results.

Notch stress fatigue life analysis requires the designer to consider the influences of various fabrication tolerances, although the data required to address them may not normally be available (hence the use of defaults). Where nominal stress analysis is undertaken, designers often lack useful guidance on which underlying S-N curves are most appropriate, and on what (if any) situation specific factors should also be taken into account. It is normally assumed that weld geometry effects (K_w) are incorporated in the nominal S-N curves. It is much less clear whether any misalignment effects are included, although they are typically excluded from analysis. From Table 7.1, a nominal stress analysis would give similar outcomes to the mean of notch stress analyses based on actual linear misalignment and actual weld profiles.

8. CONCLUSIONS

1. There is very little information in the public domain on actual fabrication tolerances achieved by the shipbuilding industry. Neither of the two yards visited during this project collect data of the type required to analyze fatigue performance. Classification societies do not publish the basis for their standards or for their design guidance.

2. Measurement of many tolerance/imperfection parameters is difficult and time-consuming. There are no simple means of measuring many intercostals' tolerances to an adequate degree of accuracy. For many 'bulk' parameters (for long connections) there are no generally accepted procedures to define appropriate values for use in fatigue analysis.

3. Documentation of the derivation of standard S-N fatigue analysis curves does not include sufficient information on the quality of experimental samples to allow the influence of imperfections of various types to be isolated. In turn, this increases the difficulty of identifying the significance of actual fabrication tolerances and imperfections.

4. Shipyard measurements taken in this project indicate that modern automated panel lines achieve fabrication tolerances that are very much better than those assumed in published guidelines for fatigue analysis. This implies that production engineering should aim to allow the maximum number of fatigue-sensitive connections to be made using automated shop processes. Similarly, in-service inspection for fatigue cracking should concentrate on joints made late in the erection sequence, rather than those made under shop conditions.

5. Measurements of block and large assembly connections indicate that the mean fabrication tolerances are similar to default values assumed in published fatigue design guidance notes. However, the level of scatter is higher than that implied by standard fatigue analysis practice. This implies that more fatigue cracking may occur earlier in life than expected, unless fabrication and inspection procedures catch and reject most samples outside nominal tolerance limits.

6. The level of scatter appears to be highly dependent on the type of joint. This is broadly in line with much fatigue design practice, but the variability observed between joint types was greater than expected. This implies that lower safety factors may be acceptable for some types of joints, though more understanding of the contribution of internal defects to the overall variability of fatigue outcomes would be needed to confirm this. It also implies (more strongly) that in-service inspection should focus on joint types expected to show high variability.

7. The measurements taken in this project covered a relatively small range of joints, material properties, thicknesses, and joining (welding) techniques. It is highly probable that more extensive data collection would allow more trends to be identified, and thus assist designers in selecting appropriate assumptions on expected tolerances for the type of project under development.

8. Fatigue design guidance provided by most classification societies requires designers to make assumptions that can have a considerable influence on predicted outcomes. For example, in nominal stress analysis it is unclear what (if any) fabrication tolerances should be treated explicitly. In notch stress analysis, assumptions regarding effective end fixity of plates and stiffeners can be crucial to the acceptability of predicted results. Predictions from fatigue analyses using both the nominal and notch stress approaches can vary dramatically depending on the analyst's approach and the relevance of the tolerance data available.

9. RECOMMENDATIONS

1. A number of the conclusions reported in Section 8 are based on relatively small samples of data from projects that were not subject to fatigue notation quality analysis or inspection procedures (commercial or military). Therefore, it would be highly desirable to collect similar data for these types of project. Based on experience in this project, this will require the support and cooperation of the owner and/or classification/inspection authority to gain access to the shipyards and vessels.

2. Conclusion (4) that fatigue damage is most likely at the final block or unit assemblies is important to the development of through-life inspection strategies, and should be tested by examination of fatigue damage records against production drawings.

3. Future refinement of fatigue analysis, methodologies should consider the actual material grades, thicknesses, and fabrication processes that are to be used in a project when making assumptions regarding expected fabrication tolerances. Guidance in existing fatigue analysis methodologies tends to be too general in nature.

4. For 'design and build' projects, owners and certifying authorities may wish to ensure that design and analysis assumptions are matched to actual shipyard practices and to the standards of fabrication achieved on previous and similar projects. This may require many shipyards to revise their current data collection and reporting procedures.

5. Due the difficulty in collecting many tolerance parameters and to the potential variability in the approaches that could be taken in characterizing certain values, it would be desirable to develop a practical guide to tools and measuring methods that could be used by inspectors (shipyard, class, and owner representatives). Material developed in this project and reported herein could provide some elements of such a guide.

6. Further work by the SSC is recommended to address the end fixity issue for the determination of stress concentration factors. This would be most effectively accomplished by a combination of experimentation and numerical analysis.

APPENDIX A
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APPENDIX B: SHIPYARD DATA

SHIPYARD 1: BUTT-WELDED STIFFENERS (RAW DATA)
SHIPYARD 1: BUTT-WELDED PLATES (RAW DATA)
SHIPYARD 2: BUTT-WELDED STIFFENERS
SHIPYARD 2: INTERCOSTAL JOINTS (RAW DATA)
SHIPYARD 2: BUTT-WELDED PLATES (RAW DATA)

SHIPYARD 1: BUTT-WELDED STIFFENERS (RAW DATA)

Butt Welded Stiffeners - Webs of Same Thickness

Raw Data

Note: There was no data taken for the angular misalignment of these butt welds. In addition, the welds were perpendicular to the stiffeners, thus the Kta SCF does not directly apply.

n =	20														
						Mean	12.00			1.55	11.43	21.43			
						Std. Dev	0.00			1.22	4.76	4.76			
No.	One or Two sided Welding? (O or T)	Dist. along Length	Ship No.	Stage in construction / GA No.	Items Butt Welded together	Type of Seam	t (mm)	e_1 (mm)	e_2 (mm)	e_0 (mm)	q_1	q_2	a_1	a_2	Notes
1	O		6094	Ship, GA16 to GA17	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	103.5	103.4	0.09	5°	30°			
2			6094	Ship, GA16 to GA17	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	100.7	101.2	0.53	10°	15°			1,2,3 are on same seam
3			6094	Ship, GA16 to GA17	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	100.1	101.4	1.32	10°	20°			
4			6094	Ship, GA16 to GA17	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	97.41	100.8	3.42	10°	20°			
5			6094	Ship, GA16 to GA17	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	100.7	101.4	0.7	20°	25°			4,5,6 are on same seam
6			6094	Ship, GA16 to GA17	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	42.23	42.78	0.55	15°	20°			
7			6094	Ship, GA16 to GA17	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	40.15	42.7	2.55	10°	20°			
8			6094	Ship, GA14 to GA15	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	41.9	42.59	0.69					7,8,9 are on same seam
9			6094	Ship, GA14 to GA15	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	41.44	42.54	1.1					
10			6094	Ship, GA14 to GA15	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	42.31	42.55	0.24					
11			6094	Ship, GA14 to GA15	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	45.94	42.46	3.48					10, 11, 12 are on same seam
12			6094	Ship, GA14 to GA15	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	43.38	42.4	0.98					
13			6094	Ship, GA14 to GA15	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	43.66	42.43	1.23					13, 14 are on same seam
14			6094	Ship, GA13 to GA14	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	41.8	42.46	0.66					
15			6094	Ship, GA13 to GA14	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	40.26	42.27	2.01					
16			6094	Ship, GA13 to GA14	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	37.62	42.15	4.53					
17			6094	Ship, GA13 to GA14	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	41.42	42.34	0.92					
18			6094	Ship, GA13 to GA14	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	41.17	42.25	1.08					
19			6094	Ship, GA13 to GA14	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	40.17	42.48	2.31					
20			6094	Ship, GA13 to GA14	Long. Bottom Stiff. (Bulb PL)	Transverse Erection Joint	12	39.95	42.46	2.51					

SHIPYARD 1: BUTT-WELDED PLATES (RAW DATA)

Butt Welded Plates - Plates of Same Thickness

Raw Data

No.	One or Two sided Welding? (O or T)	Dist. along Length	Ship No.	Stage in construction / GA No.	Items Butt Welded together	Type of Seam	t (mm)	e_1 (1/1000) inch	e_1 (mm)	e_2 (1/1000) inch	e_2 (mm)	e_0 (1/1000) inch	e_0 (mm)	s (mm)	s (mm)	r ht (mm)	r w (mm)	α_1 (deg)	α_2 (deg)	β_1 (deg)	β_1 (deg)	Notes
n =	59					Mean	13.41	64.05	0.52	188.14	4.78	-167.51	-4.25	612.88	374.24	2.29	17.81	0.46	-0.05	29.49	29.62	
						Std. Dev	6.13	13.44	0.79	39.76	1.01	44.31	1.13	541.79	405.71	0.95	4.57	1.41	1.72	11.55	11.57	
1		5%	1	Ship	Deck plate of SS. A-deck	Panel line	8	72.87	1.850898	230	5.842	-157.13	-3.991102	360	360	3.5	16	0	-0.8	28°	28°	1, 2 are on the same seam. ~2.35 m
2		85%	1	Ship	Deck plate of SS. A-deck	Panel line	8	70.63	1.794002	210	5.334	-139.37	-3.539998	360	360	3	15	0.9	-0.5	36°	43°	
3		10%	1	Ship	Deck plate of SS. A-deck	Panel line	8	70.27	1.784858	208	5.2832	-137.73	-3.498342	360	360	4	17.2	1.4	-1.3	45°	45°	~ 0.73 m
4		5%	1	Ship	Deck plate of A-deck	Unit erection joint	8	70.09	1.780286	140	3.556	-69.91	-1.775714	560	140	1	20.4	0	-2.2	18°	36°	4, 5, 6 are on the same seam. ~5m
5		50%	1	Ship	Deck plate of A-deck	Unit erection joint	8	71.79	1.823466	230	5.842	-158.21	-4.018534	560	140	2.5	21.4	-0.4	-2	33°	31°	
6		95%	1	Ship	Deck plate of A-deck	Unit erection joint	8	69.62	1.768348	187	4.7498	-117.38	-2.981452	560	140	2.5	19	0.4	-3	30°	30°	
7		95%	1	Ship	Deck plate of main deck	Unit erection joint	11	73.23	1.860042	235	5.969	-161.77	-4.108958	150	550	1.5	15.5	1.1	0.8	39°	23°	7, 8 are on the same seam. Port side. ~2 m
8		75%	1	Ship	Deck plate of main deck	Unit erection joint	11	72.31	1.836674	220	5.588	-147.69	-3.751326	150	550	3	16.5	-0.6	0.3	46°	41°	
9		10%	1	Ship	Deck plate of main deck	Unit erection joint	11	72.19	1.833626	260	6.604	-187.81	-4.770374	150	550	3	16.5	0.4	-1.1	34°	20°	Same longitudinal location as 7,8. Stbd. Side. ~3 m
10		25%	1	Ship	Deck plate of main deck	Unit erection joint	13	70.63	1.794002	260	6.604	-189.37	-4.809998	150	550	1	18.5	0.7	2	15°	5°	Inboard from 9 and seperated by a longitudinal blk'hd. ~2 m
11		5%	1	Ship	Deck plate of main deck	Unit erection joint	12	74.01	1.879854	145	3.683	-70.99	-1.803146	550	150	0.5	14.8	0.3	0	15°	25°	11, 12, 13 14 are on the same seam. Weld extends the width of beam at ~ midships.
12		24%	1	Ship	Deck plate of main deck	Unit erection joint	12	72.34	1.837436	210	5.334	-137.66	-3.496564	550	150	2	12.4	0.4	-0.8	25°	21°	
13		75%	1	Ship	Deck plate of main deck	Unit erection joint	12	72.57	1.843278	230	5.842	-157.43	-3.998722	550	150	3	15.6	0.7	0.2	24°	25°	
14		95%	1	Ship	Deck plate of main deck	Unit erection joint	12	73.1	1.85674	190	4.826	-116.9	-2.96926	550	150	1	13	-0.4	0.1	35°	35°	
15		5%	1	Ship	Deck plate of main deck	Unit erection joint	12	40.2	1.02108	100	2.54	-59.8	-1.51892	550	150	1.5	20	0.2	-0.2	15°	10°	15, 16, 17, 18 are on the same seam. 16 runs longitudinally.
16		25%	1	Ship	Deck plate of main deck	Unit erection joint	12	41.34	1.050036	125	3.175	-83.66	-2.124964	550	150	2.5	18.4	1	-1.2	25°	20°	
17		50%	1	Ship	Deck plate of main deck	Unit erection joint	12	43.37	1.101598	125	3.175	-81.63	-2.073402	550	150	1.5	19.8	-1	-2.5	12°	34°	
18		95%	1	Ship	Deck plate of main deck	Unit erection joint	12	43.28	1.099312	240	6.096	-196.72	-4.996688	550	150	3	19.8	0.3	-1.6	35°	30°	
19		75%	1	Ship	Outer shell	Unit erection joint	11	43.14	1.095756	200	5.08	-156.86	-3.984244	550	150	2.5	17	n/a	n/a	n/a	n/a	19, 20, 21, 22 are on the same seam. 19, 20 are vertical welds on the outer shell. 21(S), 22(P) are on the USK.
20		90%	1	Ship	Outer shell	Unit erection joint	12		0	155	3.937	-155	-3.937	550	150	2.5	18.6	n/a	n/a	n/a	n/a	
21		67%	1	Ship	Outer shell	Unit erection joint	12		0	180	4.572	-180	-4.572	550	150	3	19.5	-2.7	4.4	35°	30°	
22		33%	1	Ship	Outer shell	Unit erection joint	12		0	210	5.334	-210	-5.334	550	150	2	13.5	-1.9	1.2	20°	25°	
23		45%	1	Ship	Outer shell	Unit erection joint	12		0	230	5.842	-230	-5.842	150	550	2.5	17.5	n/a	n/a	n/a	n/a	23, 24 are on the same seam. Vertical weld on outer shell.
24		55%	1	Ship	Outer shell	Unit erection joint	12		0	150	3.81	-150	-3.81	150	550	3.5	15.6	n/a	n/a	n/a	n/a	
25		75%	1	Ship	Tank top plating	Unit erection joint	11-25		0	190	4.826	-190	-4.826	550	150	2	20.8	-0.4	3	40°	30°	Unit 11 - 31 of tank top.
26		75%	1	Ship	Tween deck plating	Unit erection joint	11		0	170	4.318	-170	-4.318	550	150	1.5	14.6	1.8	2.1	22°	22°	Unit 33 - 10 of t'ween deck
27		67%	1	Ship	Tank top above prop shaft	Unit erection joint	25		0	180	4.572	-180	-4.572	150	550	2.5	16.5	n/a	n/a	35°	50°	27, 28, 29 are on the same seam. Location where USK is sloping to transom
28		75%	1	Ship	Tank top above prop shaft	Unit erection joint	25		0	225	5.715	-225	-5.715	150	550	2	16.8	n/a	n/a	35°	40°	
29		90%	1	Ship	tank top above prop shaft	Unit erection joint	25		0	160	4.064	-160	-4.064	150	550	3	23	n/a	n/a	60°	60°	
30		5%	1	Ship	Tank top plating	Panel line	9		0	210	5.334	-210	-5.334	150	550	3	18.8	1.7	0.5	30°	40°	Aft of 27, 28, 29
31		33%	1	Ship	Tween deck plating	Panel line	11		0	150	3.81	-150	-3.81	550	150	0.5	17.4	0.8	2.5	30°	20°	31, 32, 33, 34 are on the same seam. Aft of 30. 33, 34 are vertical welds. Within unit 4
32		25%	1	Ship	Tween deck plating	Panel line	11		0	235	5.969	-235	-5.969	550	150	2.5	16.5	0.6	-0.6	45°	40°	
33		67%	1	Ship	Wing tank blk'hd	Panel line	11		0	210	5.334	-210	-5.334	550	150	3.5	16.7	n/a	n/a	30°	40°	
34		50%	1	Ship	Wing tank blk'hd	Panel line	11		0	105	2.667	-105	-2.667	550	150	2.5	21	n/a	n/a	40°	40°	
35		20%	1	Ship	Tank top	Unit erection joint	11		0	150	3.81	-150	-3.81	550	150	3.5	19.3	-1.9	-1.6	45°	25°	35, 36, 37 are on the same seam. 35 is horizontal. 36, 37 are verticle
36		33%	1	Ship	Wing tank long. Blk'hd	Unit erection joint	11		0	150	3.81	-150	-3.81	550	150	3.5	21	n/a	n/a	40°	35°	
37		75%	1	Ship	Wing tank long. Blk'hd	Unit erection joint	11		0	170	4.318	-170	-4.318	550	150	3.5	20.2	n/a	n/a	50°	40°	
38		75%	1	Ship	Wing tank long. Blk'hd	Unit erection joint	25		0	250	6.35	-250	-6.35	550	150	3.5	16.5	n/a	n/a	20°	50°	38, 39 are on the same seam. Unit 32 to unit 9
39		33%	1	Ship	Wing tank long. Blk'hd	Unit erection joint	25		0	210	5.334	-210	-5.334	550	150	1.5	10.6	n/a	n/a	35°	50°	
40		50%	1	Ship	Tank top plating	Unit erection joint	25		0	210	5.334	-210	-5.334	550	150	1.5	10.6	n/a	n/a	15°	15°	40, 41, 42, 43 are on the same seam. Unit 12 to unit 32
41		25%	1	Ship	Tank top plating	Unit erection joint	25		0	200	5.08	-200	-5.08	550	150	1	13.3	n/a	n/a	10°	15°	
42		80%	1	Ship	Tank top plating	Unit erection joint	25		0	190	4.826	-190	-4.826	550	150	2.5	18.5	0.8	-0.9	40°	25°	
43		67%	1	Ship	Tank top plating	Unit erection joint	25		0	145	3.683	-145	-3.683	550	150	1	18.5	1.5	1.2	25°	30°	
44		75%	1	Ship	Wing tank long. Blk'hd	Unit erection joint	8		0	185	4.699	-185	-4.699	550	150	2.5	11.8	n/a	n/a	20°	20°	44, 45, 46 are on the same seam. Noted presence of extensive grinding
45		50%	1	Ship	Wing tank long. Blk'hd	Unit erection joint	8		0	240	6.096	-240	-6.096	550	150	2.5	10.9	n/a	n/a	10°	15°	
46		25%	1	Ship	Tank top plating	Unit erection joint	8		0	170	4.318	-170	-4.318	550	150	1	11.8	2.1	1.7	15°	15°	
47		67%	1	Ship	Long. inboard blk'hd. Stbd	Unit erection joint	9		0	130	3.302	-130	-3.302	550	150	3	15	n/a	n/a	25°	25°	47, 48 are on the same seam. Verticle welds
48		75%	1	Ship	Long. inboard blk'hd. Stbd	Unit erection joint	9		0	115	2.921	-115	[redacted]	550	150	3	15.6	n/a	n/a	30°	35°	
49		50%	1	Ship	Long. outboard blk'hd. Stbd	Unit erection joint	9		0	200	5.08	-200	-5.08	550	150	3.5	19.1	n/a	n/a	50°	45°	Same longitudinal location as 47,48
50		33%	1	Ship	Tank top plating	Hand weld	35		0	220	5.588	-220	-5.588	550	150	2.5	28.5	6.1	3.6	25°	35°	Plating on an angle to horizontal
51		5%	2	Assembly	Top side deck plating for a pipe deck	Unit erection joint across stiffeners	13		0	175	4.445	-175	-4.445	1060	1500	1	19.3	-0.9	2	20°	20°	4 m long weld.
52		25%	2	Assembly	Top side deck plating for a pipe deck	Unit erection joint across stiffeners	13		0	235	5.969	-235	-5.969	1060	1500	3	21.3	0	-1.4	45°	25°	
53		90%	2	Assembly	Top side deck plating for a pipe deck	Unit erection joint across stiffeners	13		0	130	3.302	-130	-3.302	1060	1500	0.5	19	0.3	-1.2	10°	30°	
54		10%	2	Assembly	Top side deck plating for a pipe deck	Unit erection joint	10		0	170	4.318	-170	-4.318	3230	270	2	17.2	-0.6	-0.6	30°	30°	
55		90%	2	Assembly	Top side deck plating for a pipe deck	Unit erection joint	10		0	170	4.318	-170	-4.318	3170	620	2	15	-0.3	-0.3	30°	40°	
56		5%	2	Assembly	Top side deck plat for a pipe deck	Unit erection join across stiffeners	13		0	205	5.207	-205	-5.207	1040	1450	1	41.3	1	-0.9	20°	15°	s measured to web (frame). ~4 m long.
57		25%	2	Assembly	Top side deck plat for a pipe deck	Unit erection join across stiffeners	13		0	200	5.08	-200	-5.08	1040	1450	1	19.8	1.7	-1.4	20°	10°	
58		95%	2	Assembly	Top side deck plat for a pipe deck	Unit erection join	13		0	180	4.572	-180	-4.572	1040	1450	2	21.2	1.5	-1.8	25°	25°	
59		50%	2	Assembly	Top side deck plate for a pipe deck	Unit erection join across stiffeners	11		0	195	4.953	-195	-4.953	500	240	4	21.6	1.3	0.4	35°	20°	2.3 m long weld

SHIPYARD 2: BUTT-WELDED STIFFENERS

		θ_1		θ_2		θ			α	
BIN theta2 15 - 37.5	BIN theta 0 - 26.25	*Bin*	*Frequency*	*Bin*	*Frequency*	*Bin*	*Frequency*		*Bin*	*Frequency*
15	0	0	1	15	3	0	5		0	4
20	5	20	4	20	1	8.75	4		0.225	2
25	10	40	14	25	6	17.5	7		0.45	1
30	15	60	2	30	8	26.25	3		0.675	0
35	20	More	1	35	2	More	3		More	1
40	25			40	1					
	30			More	1					

SHIPYARD 2: INTERCOSTAL JOINTS (RAW DATA)

Intercostal Joints

Raw Data

No.	Full Penetration? (y/n)	Dist. Along Length	Ship No.	Stage in construct'n / GA No.	Costal 1	Cont. Mem.	Costal 2	t_1 (mm)	t_2 (mm)	t_3 (mm)	Costal 1 to Datum (cm)	Costal 2 to Datum (cm)	e_0 (mm)	$0.3t_1$ (mm)	e_0=<$0.3t_1$ (mm)	$_1$ (deg)	$_2$ (deg)	l_1 (mm)
							Mean	9.85	9.85	19.23			1.73	2.95		90.50	90.22	
N =	13						Std. Dev	0.55	0.55	3.96			1.67	0.17		0.35	0.32	
1	n	10%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	149.8	149.6	2	3	y	91°	90°	2495
2	n	16%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	224.7	224.45	2.5	3	y	91°	90°	2495
3	n	22%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	299.55	299.8	2.5	3	y	91°	90°	2495
4	n	27%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	374.45	374.45	0	3	y	91°	90°	2495
5	n	32%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	449.45	449.45	0	3	y	91°	90°	2495
6	n	38%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	524.4	524.55	1.5	3	y	91°	91°	2495
7	n	43%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	600.25	600.8	5.5	3	n	91°	91°	2495
8	n	48%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	22	675.05	675.4	3.5	3	n	91°	91°	2495
9	n	33%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	16	102.3	102.2	1	3	y	91°	90°	2500
10	n	67%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	16	98.1	98	1	3	y	90°	91°	2500
11	n	33%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	16	97.6	97.9	3	3	y	91°	90°	2500
12	n	67%	2	Assembly	L6x4 stiffener	Girder	L6x4 Stiffener	10	10	16	102.3	102.3	0	3	y	90°	90°	2500
13	n	50%	2	Assembly	Web	Girder	Web	8	8	10	58.1	58.1	0	2.4	y	90°	90°	2050

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