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PROBABILITY BASED DESIGN (PHASE 4) SYNTHESIS OF THE RELIABILITY THRUST AREA

SHIP STRUCTURE COMMITTEE
2000

Ship Structure Committee

An Interagency Advisory Committee

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PROBABILITY BASED DESIGN (PHASE 4)
SYNTHESIS OF THE RELIABILITY THRUST AREA

Our mission of the Ship Structure Committee (SSC) is to improve the safety and integrity of marine structures, implemented through a strategy of sponsorship of research projects concerned with structural reliability engineering. This report reviews and critiques nine SSC reports, assesses the objectives of the reliability thrust area, appraises success in realizing these objectives, and develops recommendations to provide guidance to the future direction of SSC efforts.

The quality of the work as reported is good in parts. However, many questions can be asked regarding the assumptions made in the reports and the absence of careful checking of model accuracy. None of the reports could be graded as having successfully achieved their objectives. Consequently, they do not appear to provide an appropriate basis for the SSC to properly achieve a goal to develop a probability-based design approach for ship structures. There does not appear to be any opportunity for careful reflection upon the models adopted and the methodologies pursued. Because the practice in some of the technologies is not well established, there will be a variety of approaches available. Thus, any chosen set of models and methodologies will be consultant dependent. If the goal is to develop a probability-based approach to ship design, then the models and the methodologies adopted must reflect widespread consensus among the industry and be independent of who does the work.

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16. Abstract

One of the goals of the Ship Structure Committee (SSC) is to improve the safety and integrity of marine structures, implemented through a strategy of sponsorship of research projects concerned with structural reliability engineering. This report reviews and critiques nine reports, assesses the objectives of the reliability thrust area, appraises success in realizing these objectives, and develops recommendations to provide guidance to the future direction of SSC efforts.

The quality of the work as reported is good in parts. However, many questions can be asked regarding the assumptions made in the reports and the absence of careful checking of model accuracy. None of the reports could be graded as having successfully achieved their objectives. Consequently, they do not appear to provide an appropriate basis for the SSC to properly achieve a goal to develop a probability-based design approach for ship structures. There does not appear to be any opportunity for careful reflection upon the models adopted and the methodologies pursued. Because the practice in some of the technologies is not well established, there will be a variety of approaches available. Thus, any chosen set of models and methodologies will be consultant dependent. If the goal is to develop a probability-based approach to ship design, then the models and the methodologies adopted must reflect widespread consensus among the industry and be independent of who does the work.

The critical reviews are presented in Appendices A to J. Conclusions are summarized in Chapter 2. A framework for the development of appropriate technologies in this area is discussed in Chapter 3 and the success of the present achievements is assessed in Chapter 4. Chapter 5 presents recommendations aimed at ensuring the goals of the Strategic Plan are realized.

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CONVERSION FACTORS

(Approximate conversions to metric measures)

To convert from	To	Function	Value
LENGTH			
inches	Meters	divide	39.3701
inches	Millimeters	multiply by	25.4000
feet	Meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
inches^2 feet	centimeters^2 meters	multiply by	1.9665
inches^2 feet	centimeters^3	multiply by	196.6448
inches^3	centimeters^3	multiply by	16.3871
MOMENT OF INERTIA			
inches^2 feet^2	centimeters^2 meters^2	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$\sqrt{in}$)	mega Newton MNm$^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	Joules/mm^2	multiply by	0.1753
kilo pound/inch	kilo Joules/m^2	multiply by	175.3
TEMPERATURE			
Degrees Fahrenheit	Degrees Celsius	subtract & divide by	32 1.8

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1. INTRODUCTION

1.1 Background

The purpose of the Ship Structure Committee (SSC) is to promote safety, economy, education, and marine environment protection in the U.S. and Canadian maritime industry through the advancement of marine structures technology. The SSC has achieved this through programs of research which have been in place now for over 50 years.

The aims of the SSC are currently being effected through the SSC Strategic Plan, initially endorsed in 1992 but updated in 1994 to reflect the participation of two Canadian organizations. One of the national goals of the SSC is to improve the safety and integrity of marine structures, implemented through a strategy of sponsorship of research projects concerned with, among other things, structural reliability engineering.

1.2 Objectives

The objective of this present project is to:

> To conduct a peer review of the projects in the reliability thrust area and provide guidance to the future direction of SSC efforts.

1.3 Tasks

The objectives are to be achieved through the four main tasks as follows:

1. To Review and Critique the Documents Generated Under the SSC Sponsored Reliability Thrust Area.
2. To Assess the Objectives of the Thrust Area.
3. Appraise Success in Realizing Objectives.
4. Develop Recommendations.

The relevant documents are:

1. SSC Report # 322, Analysis and Assessment of Major Uncertainties Associated with Ship Hull Ultimate Failure
2. SSC Report # 351, An Introduction to Structural Reliability Theory
3. SSC Report # 363, Uncertainties in Stress Analysis on Marine Structures
4. SSC Report # 368, Probability Based Ship Design Procedures: A Demonstration
5. SSC Report # 371, Establishment of a Uniform Format for Reporting of Structural Material Properties for Reliability Analysis
6. SSC Report # 373, Probability Based Ship Design: Loads and Load Combinations

7. SSC Report # 375, Uncertainty in Strength Models for Marine Structures
8. SSC Report # 392, Probability Based Ship Design: Implementation of Design Guidelines (Phase III)
9. SSC Report # 398, Assessment of Reliability of Existing Ship Structures Phase II

In addition, as a result of discussions at a meeting of the Project Technical Committee, the Contractor agreed to include report SSC-387:

Guideline for Evaluation of Finite Elements and Results

in the documents considered in this work.

1.4 Report Organization

The critical reviews conducted to date are presented in Appendices A to J. The conclusions of these are summarized in Chapter 2. A framework for the development of appropriate technologies in this area is discussed in Chapter 3 and the success of the present achievements to realize this is assessed in Chapter 4. Chapter 5 presents recommendations aimed at ensuring the goals of the Strategic Plan are realized.

2. CONCLUSIONS OF CRITICAL REVIEW

2.1 Basis

The documents listed in Section 1.3 have been subjected to critical review. The reviews are presented in detail in Appendices A to J with summaries in Section 4.3. In executing these reviews, an attempt has been made to recognise the state-of-the-art at the time that the reports were prepared. This has altered in a number of ways since the first of these was undertaken (around 1983-84). Some of these developments have been closely associated with the investigators that have undertaken part of this work, e.g., Mansour (1981) and subsequent publications in the field of load combinations.

2.2 Main Findings

SSC-322 sought to generate sufficient information that reliability indices for ships hulls subjected to most relevant hull girder bending moments could be determined. This was done well in relation to loads but not in relation to strength because of incomplete information of plate effective widths which mislead the authors on ultimate strength assessment capabilities.

SSC-351 aimed to introduce and summarise the state-of-the-art on structural reliability theory specifically addressed to the marine industry. The goal is to a certain extent achieved except that the report is not balanced in a number of ways which, unfortunately, tends to confuse the reader. The simple nature of the limit state equations considered does not permit the normal lessons regarding sensitivities and where to invest effort to be learnt. A relevant ISO standard 2394 that could have been exploited in the conduct of this work seems to have been ignored, as does a vast amount of relevant European literature.

SSC-363 aims to quantify the errors in stress analysis of marine structures and to provide the information necessary to establish safety criteria in design. It is not entirely successful in this respect although it does, fairly unusually among the reports reviewed, attempt to separate aleatory and epistemic uncertainties. This is not a simple task and there does appear to be fundamental differences in interpretation as to which variables fall into one of the two categories. The authors assume that a SRSS (square root of sum of squares) can be used to combine almost all uncertainties irrespective of any possible correlation between the basic variables or not. Mesh refinement is ignored when assessing the accuracy of FEA (finite element analysis) as are a range of full-scale measurement programs that have been exploited in reliability assessments.

SSC-368 primarily seeks to provide a demonstration of a code calibration although it conducts some secondary tasks relating to definitions for reliability analysis and the direction of future SSC activities. The prime work is largely a reworking of some of that presented in SSC-351 but with no explanation as to the reasons why changes have been introduced. The very small sample size used in the exercise avoids the need to fully formalize the approach: this is felt to be misleading in respect of the amount of work that would normally be required to undertake a code calibration. A variety of ship girder strength models are investigated with little comment as to the most realistic. The fatigue assessment is unclear as to the detail considered and ignores the critical sideshell region where overall and local stress patterns combine in a complex way complicated by intermittent immersion. The definitions provided on reliability analysis are very useful but the critique on future SSC activities is subjective.

SSC-375 aims to develop and demonstrate a method for quantifying the bias and uncertainty in structural strength algorithms: a detailed approach is presented. However, much of that reported is confusing and inconsistent with the works of others in the field.

SSC-387 seeks to develop an assessment methodology for evaluating finite element models and their results and, by implication, FEA software. The work is successfully realized although it is only concerned for linear elastic static and frequency determination analyses. Checks at three levels are proposed, Level 1 being the top one and a summary of the more detailed assessments. Level 3 is a set of guidelines for the detailed Level 2 assessment. Five sample ship structure components are investigated ranging from details to large assemblages. Four are concerned with strength and the fifth fatigue. The report is carefully prepared and some interesting recommendations for future work are proposed. An obvious choice is to extend the work to include non-linear and dynamic response solutions. Considering the importance of these in interpreting large- and full-scale results and in providing a contribution to strength databases that can be exploited in the development of limit state design codes, these would seem to be worthy. Another suggestion of value is the creation of a library of validated numerical and experimental results. If this were to relate to fatigue as well as strength, it would have several important uses including an ability to quantify the accuracy of loading and strength limit state models, provide a basis for regulators and independent investigators to assess the inputs to reliability analyses, and even possibly create a basis for the qualification of personnel and organizations that conduct FEA, experiments, and other operations with sophisticated software and hardware in connection with quality assurance schemes and similar.

SSC-392 aims to provide a demonstration of a probability-based design code for ships and, as such, repeats a lot of the material presented in SSC-398. A review of target reliabilities is presented but the question is never raised as to whether floating structures should, in principle, have the same reliability as bottom-founded structures. The differences in reliability between stiffened panel and hull girder failures found for the two vessels considered (tanker and naval cruiser) and in their targets are very significant: some explanation of this found wanting. The partial factor determination does not proceed on the basis of calibration against existing successful designs and thus ignores engineering experience, the basis of the evolution of engineering design. As such, the approach might have legal implications. The commentaries present details of the formulations rather than a justification for their selection and are totally unbalanced in that hull girder strength receives one-sixth of the attention of plate panel buckling. The report does achieve its prime objective of presenting a demonstration of a probability-based design code for ships but does so in a far from convincing manner whilst generating results that seem to raise more questions than they solve.

SSC-398 seeks to provide a methodology for ship reliability and sensitivity assessments, to demonstrate its application, and to recommend minimum acceptable reliability levels on the basis of typical assessments as well as design strategies having the greatest returns with respect to reliability. The work involves a substantial repeat of material presented in SSC-373 although significantly updated in parts, for example, the non-linearity involved in sagging v hogging is recognised, and hull girder strength assessments are denoted primary, secondary and tertiary depending on their relative participation in hull girder collapse. However, none of the formulations account for the effects of pressure. The lack of comparisons with full-scale data makes it difficult to decide whether short- or long-term assessments should be performed because it is not clear how to combine the aleatory and epistemic uncertainties. Only a nominal value of yield stress in used in the reliability analysis and modelling uncertainties are ignored: these normally constitute the parameters having the greatest impact on reliability. This lack of consideration of modelling error renders the sensitivity study of little use particularly as the adopted sensitivity measures do not seem appropriate. This work is judged to not be entirely successful.

2.3 Summary

The current aims of the SSC in the area of structural reliability engineering are listed in Section 4.1. The findings from the critical reviews of the projects executed to date are presented above. They do not suggest that the aims have been fully realized. The main weaknesses appear to be:

- modelling uncertainty parameters (modelling errors) that reflect the accuracy of the adopted load and strength models have received insufficient attention. These are likely to have the greatest impact on determined reliability among all the parameters involved in the process.
- in the hierarchy of development of the various models required to conduct reliability analysis, strength and loading would be the first to be considered, followed by the determination of their distribution parameters, and then the choice of the reliability methodology.
- in the move towards implementation in a LRFD (Load and Resistance Factor Design ≈ Limit State Design) code, considerable additional input is required including the preferred format for the limit state equation, i.e., the safety format, the design standard against which the LRFD code will be calibrated, and a representative sample set of designs judged to be successful in the context of their original design standard.

Some of the reasons for the work conducted to date not achieving the SSC objectives are discussed in Section 3.

3. FRAMEWORK FOR DEVELOPMENT

3.1 Background

A number of reliability-based codes have been developed in recent years and a number are presently underway, such as:

- Probability based load criterion for American National Standard A58
- LRFD alternative to API RP 2A concerned with fixed offshore steel structures
- Limit State Design code for UK steel bridges, BS 5400: Part 3
- ISO LRFD specifications for fixed steel and concrete offshore structures and floating production systems: the latter include monohulls (ships), semi-submersibles and tension leg platforms
- LRFD specification for self-elevating mobile drilling units (SNAME T&R Bulletin 5-5A)
- EC3 European code for steel buildings.

The remarks, comments and conclusions that follow draw on direct experience in some of these and indirect participation in others.

3.2 Development of a Code

The development of a code document is usually effected by a committee or groups of committees, each responsible for preparing specific sections in the form of recommendations generally determined at the time to reflect or represent best practice. The work of a committee is often assisted by additional bodies (e.g., researchers, consultants, academics, etc) in achieving its goals. The results of the committee deliberations are issued for public comment and, where received, such comments have to be formally answered if rejected. Formal implementation of the code normally involves a voting procedure among the participating organizations.

The usual reason why a code is developed is that it has a customer or is perceived to have one. The customer is usually a combination of interested parties, mostly with direct involvement in the outcome, from a number of viewpoints. For example, in the development of a code relating to steel buildings, the following parties are likely to form part of this customer group:

- steel manufacturers as they wish to promote the use of more steel at the expense of other construction materials
- steel fabricators since they do not wish to see more onerous tolerance requirements implemented or other factors introduced that might be perceived to increase their costs (of course, they wish the opposite)
- steel research organizations as they wish to see advances in the technology implemented in the market place
- welding organizations to ensure that new technologies are appropriately reflected in the document and that test requirements are effective and practical

- academics often wishing to promote their research findings
- consultants with desires to stay abreast of the technology and conduct some of the development work.

The work of most code committees is voluntary. This always has the effect of slowing the progress significantly. The alternative of using some form of contract may be exploited for some development work but, in general, there is a strong desire that such efforts should not appear to be driven by financial interests particularly as control over them is very difficult to maintain. This arises because of the lack of time in cost-driven activities to consider alternatives and to reflect upon choices, and because the contractor's preferred solutions will be what appears in the document. An example of this occurred during the preparation of BS 5400: Part 3 (UK steel bridge code). This was initially put out to tender and, upon completion, rejected and the process restarted but with voluntary undertakings.

Recognising this, most successful code development exploits this voluntary route, and it would seem that the more the end customer is involved, i.e., as in directly contributing to the preparation of the draft, etc, the more successful the end product and the shorter the time-scale for its development and implementation. The requirement of successful direct involvement is that the participating organizations (or the personnel thereof) have the knowledge and experience to prepare material to the appropriate standard for that part of the code for which they are responsible.

The process of development of structural standards outlined above is applicable, in particular, to land-based structures and their derivatives (fixed offshore structures including tension leg platforms). Standards in the marine industry have involved through a somewhat different process. All early developments were conducted by Classification Societies relatively independent of each other. To facilitate an efficient design process, the explicit technical content of their rules was kept to a minimum. The provisions provided were determined from a combination of technical expertise and experience. The latter derived from observations in the field fed back to the rules to minimize the consequences of direct loading from the environment and the consequences of exposure to a salt-laden atmosphere.

Over the last few decades, however, the technical input was increased dramatically in order to deal with the introduction of unusual and novel designs such as large tankers, LNG carriers, etc. This resulted in some cases in a direct design route for the determination of scantlings although, in general, the design of traditional vessels has remained fairly firmly via the rules route. During this same time frame, the various classification societies have traded ideas and information through IACS (International Association of Classification Societies) which has provided them with an opportunity to reduce some of the differences between their requirements.

However, this process still seems to have a long way to go in many aspects of ship design. Because of the commercial pressures involved it has, until fairly recently, restrained the societies in a number of ways from implementing more advanced or exacting requirements. In an effort to overcome this hurdle which seems tightly controlled by the need to have an efficient design process, ABS developed and implemented in 1993 a computerised design capability for particular vessel types

(SafeHull) that exploited the use of advanced technology but in a form that is relatively transparent to the end-user, the ship designer. Other societies have made efforts to generate similar capabilities most of which are founded in the working stress design ethos so their development is not directly applicable to the present situation.

3.3 The Code Customer

Of course, an end customer for a code is not always obvious. In the case of steel buildings in Europe (EC3), the end-users are consultants throughout the community. Their ability to really influence EC3 has been minimal but then it has taken some 15 years to produce the document. In complete contrast, the draft of the ISO code for fixed steel offshore structures for the petroleum and natural gas industries has been prepared in less than three years and should be in place within a five year timetable even allowing for the vagaries of the ISO organization. This has been possible because of the intimate involvement of the organizations ultimately directly responsible for its exploitation in the market place, namely, the oil companies.

The absence of a significant participation by oil companies in an attempt within the UK to development a national offshore structures code (remembering the international nature of most oil companies) meant that BS 6235 was never really used despite eight years of effort by the relevant committee. A contributing factor was that, in this time, seemingly little more was achieved than to place the then equivalent API document in BSI covers.

In contrast, for the development of the LRFD alternative to API RP 2A, the oil companies were all closely involved and many of them technically as they had contributed to the development of the working stress design version of its many editions - the Twentieth was issued in 1993. They participated closely in the preparation of the load and strength provisions (mainly improvements to the existing requirements), sometimes assisted by small contracts to consultants, but with the bulk of the reliability assessment and partial factor derivation handled by one consultant. However, the work by this consultant was far from continuous, it lasted for nearly ten years, as each development was closely scrutinised by the customers and the implications of the proposals evaluated by relevant major design contractors.

3.4 The Present Position

The present programme of research being promulgated by the CMS and SSC in the area of reliability is not necessarily aimed at the production of a LRFD-based code. However, it is difficult to believe that the use of research in the area of structural reliability engineering by itself will achieve the desired goals without the preparation of a documented approach that can be readily appreciated by the customers of the research and effectively implemented. It would thus appear that the efforts in this respect, as reflected in the reports currently under review and the framework under which they are being prepared, is consistent with a desire to produce a LRFD-based code.

Some of the acknowledged customers of the SSC are designers, owners, regulators, class societies, and shipbuilding and repair yards. Most of these make direct use of codes and standards to effect or review designs. Some are directly involved in the workings of the CMS but not, it would seem, at the level where they can or do provide direct input to the development of the code except for one possible exception, ABS.

3.5 A Way Ahead

In terms of efficiency, the role model for the development of a code should look no further than ISO TC67/SC7 (TC indicates Technical Committee and SC Sub-Committee) which is responsible for creating ISO 13819, offshore structures for the petroleum and natural gas industries. This is done ostensibly on the basis of voluntary effort, but since it is done with the blessing of the customer, the oil industry, the companies involved allow their personnel to participate in all meetings (involving a considerable amount of international travel), sometimes allow working time to be spent preparing and reviewing provisions, occasionally contribute financially to projects that have spin-offs for the code development, and less usually directly fund pieces of work to small contractors or consultants to resolve particular issues.

An important feature of this arrangement that has contributed to its success is the selection of a suitable chairmen for all of the working groups through which the work is undertaken. The framework for the fixed steel structures part is a working group (WG) that reports directly to ISO TC67/SC7. The WG comprises some ten panels, each of which is responsible for a main chapter or two within the proposed standard. Because of the breadth of responsibility, some of the panels are further divided into sub-panels (designated technical core groups). In the case of the panel concerned with structural strength, these deal with:

- tubular member ultimate strength including damage residual strength and grout filling
- tubular joint ultimate and fatigue strengths
- other joints such as grouted pile to sleeve connections
- structural analysis.

For the present application aimed at a LRFD code for ship structures, the following areas would likely require the formation of panels:

- environmental description and parameters
- response including dynamic effects and fatigue loading
- hull girder strength
- details both strength and fatigue
- safety format and partial load and resistance factor determination.

Although this does not cover all the aspects that would normally be included in such as exercise such as materials, superstructure and other secondary elements, inspections and surveys, condition monitoring, compliance with international requirements, etc, it provides an appropriate set to realize the immediate objectives of the present activity.

4. ACHIEVEMENTS

4.1 Basis for Assessment

The basis for the assessment of the achievements of the research programs executed to date in the area of structural reliability is an interpretation of the aims of this work as being:

1. to demonstrate the successful application of such methods in connection with ship structural design
2. to document the approach in a LRFD-based code.

In identifying the achievements, account needs to be taken of the framework in which it has occurred as well as the achievements themselves as reflected through the products of the programs, namely, the reports cited in Section 1.3.

4.2 Framework

The organizations that are undertaking the reported work fall mainly into the category of a single contractor even though several individuals contribute to the product and consultants are involved presumably in their traditional role. The resulting document, therefore, is not one built on consensus and deliberation but, to a large extent, reflects the preferences of the contractor involved as usually confirmed by the number of citations by any contractor to his own works.

4.3 Assessment

4.3.1 Report SSC-322

This report collates information with the main objective to provide sufficient data on means and coefficients of variation (COV) to enable ship hull safety indices under extreme wave loads combined with stillwater, thermal, springing, and slamming loads to be evaluated. This is realized although incomplete information on plate effective widths clearly misleads the authors with respect to the scope of structural assessment capability. The probabilistic procedures and techniques used reflect a slightly limited view of reliability analysis capability available at the time. Notwithstanding, the study addresses the major loading needs in relation to this problem.

4.3.2 Report SSC-351

The objective of this report is to provide an introduction and summary of the state-of-the-art in structural reliability theory directed specifically towards the marine industry.

This goal is realized reasonably well although the emphasis in relation to several aspects seems unbalanced. For example, the safety index approach equivalent to the mean-value first-order second-moment (MVFOSM) reliability method is used frequently throughout the text yet the author believes (and the document reflects it) that Level 3 methods should be exploited more fully. The improved version of the Level 2 Hasofer/Lind approach is less frequently exploited yet this is the basis of probably the most widely used of all reliability methods, namely, First-Order Reliability Methods (FORM) or Advanced First-Order Second-Moment (AFOSM) methods as they are often (earlier) described as. Further, all the analysis and information concerning strength pertains to ship structures yet, when it comes to fatigue, this concentrates almost entirely on offshore structures.

The information relating to strength only provides statistical information on material properties and a limited amount on plate dimensions. As illustrated in Chapter 10, in the relative magnitudes in the partial safety factors derived therein, strength issues can predominate yet, the parameter having the greatest influence on strength uncertainties, the modelling uncertainty parameter which reflects the accuracy of the strength model, is not even considered. The reported literature searches when discussing strength issues seem to ignore a vast amount of European documents on many of the cited subjects.

The discussion concerning partial safety factors concentrates on those found directly from the reliability analysis. These do not necessarily have anything to do with the partial load and resistance factors used in codified limit state design. This, however, is not made clear.

The limit state equations considered throughout in relation to strength are generally in an extremely simple format, expressing strength and loading in univariate form, e.g., M_w for wave bending moment and R for primary bending strength, or possibly the product of yield stress and section modulus. Strength will be a function of stiffened panel strength at least involving variables specifying deck stiffened panel geometry and structural entities. Wave bending moment will be a function of significant seastate, spectrum, RAO, and duration yet none of these parameters, nor those pertaining to strength, appear in the limit state equation. Consequently, the lessons that can be learnt from including these variables in the reliability analysis such as, in the words of the author, explicit consideration and evaluation of uncertainties associated with design variables, a framework of sensitivity measures, and providing means to weigh variables in terms of their significance, are lost. In contrast, when reporting on fatigue reliability analysis of offshore structures, the limit state equation is a function of, for example, the accumulated damage, the S-N curve parameters, the stress parameter (itself a function of the largest stress range, the total numbers of stress cycles, and the Weibull shape and location parameters), and the modelling uncertainty parameter. With this level of detail, the sensitivity to a partial factor for each variable can be evaluated providing guidance on whether the variable can be treated as deterministic or not, whether it should be part of safety format, or whether further studies on it are needed in relation to additional data or other investigations.

Considerable international effort has been put into creating ISO codes of which 2394 (General principles on reliability for structures 1986) is extremely relevant dealing with safety format, partial load and resistance factors, characteristic values, combinations of loads, properties of materials, and geometric parameters. In addition, it considers quality control covering procedure, criteria, acceptance, process and control. However, it is not included in the review of relevant codes reported in Chapter 6 (see Appendix B Section 3.6).

4.3.3 Report SSC-363

In seeking to quantify errors in the load prediction process, extensive use is made of SRSS. This assumes an independence of parameters that does not always exist and effectively tries to pre-judge the results that will be obtained from a formal reliability analysis when the relative influence of the uncertainties will be correctly addressed and ranked. This combination of contributions from various entities camouflages the true source of the influential variables so that identification of the important parameters becomes difficult if not strictly impossible. For example, an uncertainty in wave-induced bending moment does not provide the means of assessing the contributions from wave height, period, heading, speed, etc. Further, the distribution parameters determined for, say, wave bending moment may be a function of wave height if the modelling is not reasonable. In these circumstances, SRSS is not a valid means of accumulating errors.

Allocating modelling uncertainties as aleatory or epistemic is not always obvious. Wave heights are measured for only part of a exposure period so 'modelling' is necessary when assuming this is representative of the compete period. Yield stress is measured by a tensile test that introduces a measuring (modelling) bias. Yet both are treated as random variables.

In trying to determine the important environmental parameters, use is made of wave-induced bending moment data. Unless the vessel response to each of the input parameters is exact, the influence inferred from the response will not necessarily be a realistic measure of the contribution of that parameter. Ideally, such response data should be part of the input to a reliability assessment.

Possibly the most important requirement in FEA modelling is mesh refinement: this is ignored in this report. Full-scale measurement results from offshore platforms and in the public domain are not considered despite the important roles they play in subsequent reliability assessments of offshore structures.

These, plus several other findings by these authors (Appendix C), suggest that the full appreciation of the needs of a reliability assessment were lacking at the time that this report was prepared. The consequent ranking of variables is thus not necessarily valid from the point of view of their impact on reliability so the proposed order of their strategies for reducing the effects of the uncertainties needs to be adopted with care.

4.3.4 Report SSC-368

This report is in two parts, the first concerned with a demonstration of a (preliminary) code calibration, and the second with definition and techniques relevant to probability and reliability-based analysis and design. Within the latter, recommendations are made concerning the direction of future SSC activities.

Part 2 can be viewed largely as an expansion of an example analysis presented in SSC-351 but with some important differences. No assessment is made of the impact of these changes which include a reduction in wave-induced bending moment COV from 100 to 9% albeit also with a change in probability distribution. The calibration procedure involves a very small a sample and, because of that, it does not need to be fully formalized. As a result, it possibly gives a misleading impression of the amount of work involved.

Part 2 begins by identifying ultimate strength limit states for hull girder primary bending. By their definition, it is quite clear whether these will over-or under-estimate the true value of strength and thus reliability. Plate buckling continues to be promoted, inappropriately, as an ultimate strength limit state. The use of effective sections as the basis for determining section moduli is to be strongly encouraged. Serviceability and fatigue limit states are addressed although the latter still do not seem to address the sideshell waterline problem of independent inplane and out-of-plane cycles coupled with intermittent immersion, nor is the detail analysed actually identified.

The determined failure probabilities are high. The lack of calibration of the wave load used against the vessel in question could have contributed to this.

A considerable proportion of the remainder of the document is a repeat with some embellishments of the contents of SSC-351.

The recommendations for future SSC activity provide an opportunity to pass comment on these. Although some have clearly been overtaken by events, a possibly more objective assessment of many of them could be made.

4.3.5 Report SSC-371

Review incomplete.

4.3.6 Report SSC-373

This work seeks to define the characteristics of ship design loads relevant for use in reliability assessment and appropriate ship load models and load combination procedures.

This report describes a useful load combination approach that, whilst being a departure from that traditionally followed when developing a LRFD-based code, has minimal human interference.

The report also finds weaknesses in the work reported in SSC-363. It is successful in identifying a suitable load combination approach that seems to offer advantages over the approach frequently adopted in the development of LRFD-based codes. It gives careful consideration to the operational factors that may effect the extreme loads experienced by ships at sea. In relation to fatigue, an approach is reported that has found favour with at least two major classification societies. It uses an assumption that the long-term distribution is known in advance. The procedure is promising but probably needs substantiation through comparisons with more rigorous techniques (unless these are the means by which some of the ship structure location dependent parameters used in the procedure are derived).

4.3.7 Report SSC-375

The aim of this work is to develop and demonstrate a method for quantifying the bias and uncertainty in structural strength algorithms. A detailed method of approach is presented.

Use of identical notation for different parameters confuses the definitions of importance measures. It appears to pre-suppose that the Ship Structural Design strength algorithms are the best available and exhibit longevity.

The interpretation of the apparent success of large research efforts in industries other than the shipping industry seems misplaced. Maybe a lack of international collaboration could be a contributing factor to this possible inability to make the most of the monies available.

On three significant fronts, identifying relevant strength algorithms, LRFD codes, and test data, this report seems very much out-of-date. The report on the uncertainty assessment is not clearly presented. The use of measured data that are well below their nominal values in the interpretation of the results, the discarding of data relating to flat-bar stiffeners without justification, the unexpected introduction of both lateral pressure and transverse stress in what appeared to be an assessment of axially compressed models, all contribute to the feeling that this is a less than satisfactory document. This is compounded in the interpretation of the term modelling uncertainty where the authors use a definition that is not consistent with that used by other reliability analysts.

4.3.8 Report SSC-387

This study aims to develop an assessment methodology for evaluating finite element models and their results, and by implication finite element analysis (FEA) software, with particular application to ship structures.

The methodology is developed on three levels, Levels 1 and 2 being addressed through a set of forms that the analyst and checker are required to complete before accepting (or rejecting) the results of a FEA. Level 3 is a set of guidelines for interpreting the questions posed at particularly Level 2. Level 1 is, in effect, a summary of the Level 2 assessment.

The checks appear to be comprehensive and the guidelines entirely appropriate.

The example analyses presented concentrate on ship structure elements and/or components and include a reinforced deck opening, a stiffened panel, a vibration isolation system, a mast, and a bracket connection detail. All except the last are concerned with strength issues, the last relates to fatigue. The results are reported in detail (in an appendix) and criteria for acceptance promoted. The selected examples are judged to be entirely appropriate covering details and overall structure, static and frequency analyses, application of different element types, and mesh refinement.

The recommendations for future work are not entirely unexpected and, in the context of reliability-based applications, some would appear important to undertake. In addition, implementation of some would provide opportunities to interface with the growing human factors awareness and need.

For example, limit state code development and application requires data on ultimate and fatigue strengths, some of which can be generated through the considered exploitation of FEA solutions. These require the application of non-linear FEA and, most critically, their benchmarking. Strain-rate effects are important in dynamic conditions (slamming) calling for the benchmarking of dynamic analyses. The creation of a library of well documented numerical and experimental results, as proposed by the authors, could be an important facility in the quantification of strength and fatigue modelling uncertainty (accuracy) parameters. This would enable regulators and others to readily check the input for reliability assessments and code calibrations without the disagreements that presently arise through the use of different databases. The library could also be used as a basis for qualification of personnel and organizations to undertake FEA, experiments and operations involving sophisticated software and hardware, as well as facilitate implementation of quantity assurance schemes.

4.3.9 Report SSC-392

The objective of this project is to provide a demonstration of a probability-based design code for ships. It repeats a considerable amount of the material presented in report SSC-398.

In reviewing the target reliabilities adopted for different industries in several countries, no consideration is given to whether floating units should have the same inherent safety level as structures fixed to ground. A difference is expected because of the additional failure modes such as flooding and instability likely to be suffered by the former that do not affect the former. The determined target reliabilities for a tanker and a cruiser raise a number of questions such as why should cruisers be safer than tankers, why is panel buckling classified as an ultimate limit state, why is the difference in reliability between stiffened panel failure and hull girder failure so different for a cruiser and for a tanker (2 orders of magnitude for the cruiser, 0.8 for the tanker), and is not the target for a cruiser too high.

The partial factor determination does not proceed on the basis of calibration against existing successful designs. This seems to ignore engineering experience which is the basis of the evolution of engineering design. It might also have some legal implications.

The commentaries seem to present details of the adopted formulations rather than a justification as to their selection. These are also totally unbalanced as the section devoted to hull girder strength is less than one sixth of that devoted to plate panel buckling.

The report does achieve its objective in that it presents a demonstration of a probability-based design code for ships but does so in a far from convincing manner whilst generating results that seem to raise more questions than they solve.

4.3.10 Report SSC-398

This work has several objectives among which are to provide a methodology for ship reliability and sensitivity assessments, to demonstrate its application, and to recommend minimum acceptable reliability levels on the basis of typical assessments. It should also recommend design strategies having the greatest returns with respect to reliability.

Although there is substantial repetition of material presented in SSC-373, new results are presented in the form of charts to account for the non-linearity in sagging and hogging moments (albeit via a dimensional normalizing approach). Hull girder, stiffened panel and plate failure modes are classified as primary, secondary, and tertiary. In many reliability assessments, the assessments are effected both at a component and then at a system level. Stiffened plate failure and hull girder failure seem to fit these roles appropriately. It is not clear that plate failure necessarily falls into the same category as discussed in Section 4.4. Effective width and strength formulations are adopted that do not seem to account for the effects of lateral pressure.

For reliability assessment, it is not clear whether a short- or long-term assessment should be performed. The choice to some extent depends how the aleatory and epistemic uncertainties are summed. Ideally, the analysis would aim to generate a once in n-years return period response. However, because of modelling errors and uncertainties, the combination of environmental (wave height, spreading, etc) and operational parameters (heading, speed, avoidance measures, etc) to be combined accounting for joint probabilities to approximately realize this is difficult to make in the absence of appropriate full-scale measurement data. Then the question arises as to whether the analysis applies to new designs or is it to be used for reassessment.

The initial deformation used in the generation of the database on the structural strength of four ships is not uniquely defined. If applicable to plate panels it should very with some relationship to plate slenderness as well as to thickness.

For the reliability analysis, a nominal value of yield stress is used rather than mean value. The analysis proceeds ignoring modelling error and on the basis of moments relating to the hull girder section and not in terms of basic variables. Thus, the results of the sensitivity study are of little use since they do not identify the important basic variables. The adopted sensitivity measures raise questions as two give the same result whilst the third seems to be factored by the wrong variable. Thus, on neither the reliability front nor the sensitivity front has the report objectives been realized.

4.4 Comment on Relevant Failure Modes

The reason why classification of plate failure as an ultimate limit state is questioned is because it rarely controls failure of the hull girder. Whenever longitudinally stiffened panels are present in deck structures, plate panel behaviour is dealt with in the design or assessment of the stiffened panel. This is usually accomplished by initially determining the effective width of the plate to account for its tendency to buckle, such effective width accounting for the untoward effects of plate initial shape imperfections and welding residual stresses. The effective plate and the stiffener are then treated as a beam-column spanning between transverse frames with a first yield criterion marking the limit of load carrying capacity for the beam-column buckling in either direction, i.e., towards the plating or towards the stiffener. For plating in the sideshell and longitudinal bulkheads, these have to be evaluated for, usually, a combination of axial compression or tension, bending and inplane shear. The contribution of such plating to the ultimate capacity of the section will be as a contribution to the bending strength and to the shear strength of the entire cross-section.

Only in the case of transversely framed deck structures might it be argued that plate panel strength controls. It certainly will be more influential than in the case of longitudinally stiffened hulls but, from an assessment point of view, the girder would be checked against an ultimate bending capacity determined using an effective width of plating (based on transverse compression behaviour) acting in conjunction with the 'hard corners' of the structure, i.e., the deck and bottom intersections with the sideshells and longitudinal bulkheads.

The role of lateral pressure in stiffened plate behaviour has received scant attention because of the relatively low influence on stiffened plate strength that it has for the range of pressures normally encountered by ships' hulls. However, there are occasions when lateral pressure can dominate the design of ship girder stiffened plating elements such as watertight bulkheads, bottom plating in the bow regions where slamming occurs, ice-encounter zones to the hull, and decks including hatch-covers subjected to greenwater. The report by Skjeggestad and Bakke on laterally loaded bulkheads (1966) is one reference in which lateral pressure is the dominant load. Another possible source of relevant data is described by Fitzpatrick but no details are given. A number of other documents exist that include lateral pressure effects but they are secondary to the primary inplane loading.

A numerical analysis study by Davidson et al (1991) into the effect of lateral pressure on the strength of plates subjected to longitudinal compression and to transverse compression enabled them to develop a design criterion for such plates. This was extended by Frieze (1996) to deal with the design of stiffened plate subjected to longitudinal and transverse compression as well as inplane shear. It became clear during the preparation of this report that further investigations into the effects of lateral pressure were required although the extent of these can only really be clarified once the results described by Fitzpatrick and other related work is assessed.

Failure modes considered in the present framework of development concentrate on those precipitated by bending resulting from wave loads. Other sources of failure are collision and groundings and impacts with icebergs and similar, depending on the ship's mission. Depending on the vessel type, some of these events have to be considered by other means such as one-compartment and two-compartment flooding. Although this might reduce the size of compartments, it does not necessarily increase structural strength because scantlings can be reduced along with the size of the compartments, at least in the case of a first principles design. The increase in scantlings to cater for ice impacts is likely to increase strength with respect to wave loadings. This creates a degree of robustness which is absent when ice does not have to be catered for. Similarly double skin structures benefit from having additional structure to what is actually needed to resist wave loads.

4.5 Comment on Relevant Probabilities of Failure

In discussing the grading of reliability analysis methodologies into Levels 1 to 3, care is required because there appear to be at least two different gradings in use. The uncertainty centres on whether to classify FORM and similar techniques as Level 2 or Level 3. In European practice, FORM is a Level 2 procedure which, although in some cases may be asymptotically exact, it is generally not despite the fact that it or its more accurate derivative SORM may give very similar answers to Level 3 methods. The significant advantage of FORM is that sensitivity measures can readily be found, not necessarily a straightforward process when Monte Carlo and similar simulations are used to determine reliability. Further, when conducting partial factor derivations, these require reliability determinations across the full sample space for each variation of any of the load or resistance factors. Curve or surface fitting to the results from the reliability analysis enables these to be efficiently conducted without recourse to complete reliability analysis for each iteration.

Level 3 methods may be preferred if the limit state equation is linear simple and the components of the equation are not themselves functions of any other variables. Many of the studies conducted to date have considered relatively simple forms of the limit state equations or the uncertainties have been combined with simple forms of the equations very much in mind even if driven mainly by the expectation of exploiting a safety index solution. Because of the uncertainties surrounding the tails of distributions mainly as a consequence of the lack of adequate data, their likely improvement in accuracy possible with a Level 3 solution is not in fact achievable. This, coupled with the ease with which sensitivity measures can be determined from Level 2 methods, suggests that these provide the more appropriate methods to be adopted in future work in this area.

5. RECOMMENDATIONS

5.1 Strategic

1. The quality of the work as reported is good in parts. However, on many of the important issues, it seems to be lacking. Many questions can be asked regarding the assumptions made in the reports, the absence of careful (any) checking of model accuracy, and thus in the presented results and findings. As it stands, although some of the preliminary reports of the most heavily involved researcher seem to be adequate, none of his later contributions nor any of those of the other contributors could be graded as having successfully achieved their objectives. Consequently, they do not appear to provide an appropriate basis for the SSC to properly achieve a goal to develop a probability-based design approach for ship structures.

2. There appears to be several contributing causes to this situation. At the level at which the work is performed, there does not appear to be any opportunity for thorough peer review and careful reflection upon the models adopted and the methodologies pursued. On the other hand, a more fundamental question revolves around whether the independent contractor system forms an appropriate basis by which to progress this activity. Because there is a research aspect to some features of the work, there will be several ways in which it can be tackled. Because the practice in some of the technologies is not well established, again there will be a variety of approaches available to solve these. Thus, any chosen set of models and methodologies will be consultant dependent. If the goal is to develop a probability-based approach to ship design, then the models and the methodologies adopted must reflect reasonably widespread consensus among the industry and be independent of who does the work.

3. On a larger scale, is the SSC's customer base fully and appropriately involved in the activities? On the grounds that most of the work has been performed by academics or academically oriented consultants, it would appear not. Designers at the end of the day will have to use whatever reliability-based code is developed. As end users who will need to understand the code requirements and to implement them into computer codes, they should have a say in any developments. Ship owners and operators have to pay for any additional costs that might arise from the introduction of this revised technology. They should be ensuring that in fact their costs decrease as a result of the introduction of this more rational approach. They can only do this through some intimate involvement probably at all stages of the development even to the extent of hands-on. Class societies have to classify vessels designed in accordance with the new code. They need to be convinced that all stages of the process can be defended and this can be done most effectively by active participation in its preparation. The discussion presented in Section 3.5 outlines one way by which the remainder of the work required to fulfil the SSC objectives could be realized that would avoid some of the pitfalls identified in the current approach.

4. Taking one step further back, because the development of reliability-based codes is a goal for probably a number of countries, and because the amount of work involved is significant, perhaps it should be tackled on a much wider front. One perceived obvious route is via IACS although the progress they have seemingly made to date in other areas would not encourage one to think this would be an effective option. A similar arrangement involving IMO would probably suffer the

same fate. Possibly it could done under the umbrella of NATO or through some partnership between the recently-formed North American trading block and the European Union (EU). This route would ensure the widest possible input and peer review. It would provide an opportunity, through the resources that should become available, to bring on board other practices that would augment those presently available to the U.S. and Canada alone.

5.2 Technically Specific

In reliability assessments of ship structures:

1. Geometry parameters can be treated as deterministic although this may need to be confirmed in the case of deck and bottom plating thickness.

2. Elastic modulus can be taken as deterministic but yield stress needs to be treated as a random variable with a mean value based on tensile coupon test results when wave-induced bending moments dominate and similarly derived static values of yield for dominant stillwater load conditions.

3. Hull girder and stiffened panel ultimate strength models require comparison against test data (and realistic numerical models) so the distribution parameters for their associated modelling errors can be evaluated.

4. Models for wave-induced bending moments require characterisation (determination of distribution parameters) against full-scale data.

5. Consensus is required about the preferred methodology for determining an appropriate return period of response for ship design and how this might be achieved given the current status of metocean, i.e., environmental parameter, data records.

6. The load factor methodology promoted in some reports is extremely promising particularly because its form is compatible with LRFD-based design code formats. Consensus is required concerning its generality and any further development. Class society and naval experience should be helpful in identifying load combinations to be addressed. However, in identifying a safety format, account should be taken of relevant ISO codes in this area such as ISO 2394.

7. The long-term simplified fatigue design approach based on the use of the Weibull distribution and developed in some of the reports needs substantiation against a dynamic spectral fatigue design approach to ensure appropriate values of the shape parameter are available for different ship details and various locations around the ship structure.

8. Target reliabilities initially require a calibration approach to determine appropriate values followed by adjustments based on judgements concerning successful designs, target reliabilities in other industries but recognising that floating structures probably need one order in probability of failure terms more reliability than comparable bottom-founded structures, and an expectation that

component and system reliabilities should differ by about one order in probability of failure terms. Plate bucking should be treated as a serviceability and not an ultimate limit state.

9. Partial factor determination will require some form of simplified modelling of strength, loading or the reliability process in order that such determination can proceed efficiently. Curve- or surface fitting can be applied in all cases.

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APPENDIX A

REVIEW OF REPORT SSC-322

ANALYSIS AND ASSESSMENT OF MAJOR UNCERTAINTIES ASSOCIATED WITH SHIP HULL ULTIMATE FAILURE

by P Kaplan, M Benatar, J Bentson and T A Achtarides

A.1 OBJECTIVE

To identify the uncertainties associated with loads (demand) and strength (capability) in connection with the practical design of ships and to evaluate them as fully as possible from available published data.

A.2 AIMS

1. To identify and evaluate the load and strength uncertainties necessary for input to a safety index reliability analysis (i.e., mean and COV).
2. To identify probability distributions in relation to these uncertainties, where this information exists, with the view to enabling fully probabilistic approaches to be exploited.
3. To consider partial safety factors in connection with these uncertainties.

A.3 REVIEW

A.3.1 Chapter 2. Probabilistic Analysis of Structures

The concept of safety being a non-deterministic concept is introduced. The generalized equation for evaluating probability of failure (P_f) is given in its various alternatives in terms of the load and resistance probability density functions (pdf) and cumulative distribution functions (cdf). The need for relevant information to determine these pdfs is noted. In the absence of complete information but sufficient to determine the means and standard deviations of the pdfs, the availability of the safety index (β) equation is reported from which P_f can be determined.

A.3.2 Chapter 3. Nature of Uncertainties in Ship Longitudinal Strength: Demand and Capability

Here general consideration is given to loading (demand) and resistance (capability).

The principle loads acting on the ship hull are noted as stillwater bending moments (SWBM), low and high frequency wave bending moments (WBM), and thermal loads. The attention, at the time, given to assessing wave loads is noted involving variability in directional spectra, combined sea and swell (or two seas), variability of spectral shape given significant wave height, and ‘freak’ waves.

In short-term response calculations, uncertainties exist in the determination of responses to regular waves (RAOs) arising from assuming a linear response, inaccuracies in strip theory, and the omission of inertia loads. Ignoring broad-bandedness is noted as leading to over-estimates of response. Operational aspects that affect these uncertainties are cargo distribution, ship heading, and speed.

The absence of statistical data on SWBM is recorded, as are the difficulties in combining the different WBM processes and thermal loading effects. The possible advantage of resorting to the use of full-scale measurements, a practical solution to obtaining overall statistics, is advanced.

In relation to resistance, the availability of statistical data on some aspects of this is noted in relation to geometry, material properties, fabrication imperfections and welding residual stresses, and corrosion and wear. Some structural features that have been noted by others to be important in the evaluation of resistance are listed. The authors conclude most are of little consequence, even the presence of large hatch openings. The potential ability for ships' hulls to redistribute forces in the event of local panel (meaning stiffened panel) failure is noted but the need for a systematic evaluation of relevant data to confirm this is also indicated.

The failure modes for which the information on uncertainties will be used are tension yield, stiffened panel failure (including tripping) and overall grillage buckling.

A.3.3 Chapter 4. Data on Uncertainties of Various Ship Hull Loads

This section reviews the uncertainties associated with the various sources of loading processes, namely, stillwater loads, thermal effects, wave loads, springing vibratory loads, and slamming and whipping.

In relation to stillwater loads, distributions corresponding to loaded and to ballast conditions are identified. Where attempts have been made to exploit logbook records, poor record keeping has shown these to be of little use. Reference is made to a SSC project at the time (SR-1282) aimed to provide such data, and to the results of a major Japanese study involving ten container ships and eight tankers. Container ship cargo loading is noted to demonstrate little variability COV = 30% (as apparently do, according to the authors, general cargo ships) whereas tankers (and ostensibly ore carriers) demonstrate variable conditions, both loading (COV = 52%) and ballast (COV = 99%). The statistics are presented in the form of stresses, the tanker ballast condition stresses being maximum in hogging and significantly larger than the maximum fully loaded condition stresses in sagging. It is noted that representative values of the extremes of these loadings will be required for design or reliability assessment. As an alternative, an appropriate probability distribution could be determined for use with the presented values.

Thermal effects are considered exploiting both calculated and measured results. They result from temperature gradients that arise from air-water temperature differences, the effect in air being a further function of degree of cloud cover, colour of the deck, and time of day. Calculated values appear to demonstrate smaller means but larger COVs than measured values. The results from measurements are noted to be preferred because thermal stresses are generally low compared to those arising from environmental effects and because of their greater reliability. The calculation of thermal stresses is apparently not normally required in ship design except in those cases where low or high temperature cargoes are transported (LNG and asphalt carriers). Their normally relatively long cycles of variation (diurnal) compared with that of wave loads implies they can be taken as constant for design or analysis although still subject to variability.

Wave loads are examined through consideration of seastates, theoretical response operators, methods of extrapolation to lifetime maxima, and combining variabilities.

The effects of seastate are examined from consideration of the spectra determined from wave records from the North Atlantic Station ‘India’, calculated responses of the WOLVERINE STATE, the number of parameters used to describe a spectrum, and application of the ‘India’ spectra to three ship types, a tanker, a bulk carrier, and a container ship. Some of the more important findings are:

- the uncertainty in response is reduced from 0.2 when using a 2-parameter spectrum (Bretschneider) to 0.10 when using a 6-parameter spectrum (Ochi and Hubble),
- the degree of uncertainty associated with vertical bending moment response decreases with increasing seastate level but increases as heading approaches bow seas,
- the range of uncertainty associated with bending moment response due to seastate variability is 0.10 to 0.20 with 0.15 being an appropriate representative value.

Theoretical response operators are usually calculated using strip theory which yield differences when compared with measured values. However, because of the influence of spectral effects, the authors recommended eliminating this by recalculating theoretical and experimental mean square responses using a unit amplitude rectangular spectrum in place of that originally considered. The ratio of the rms (root mean square) values of theoretical and experimental response operators is used as a measure of the uncertainty.

The measured data related to Series 60 ships, a container ship, the SL-7, and the WOLVERINE STATE. SCORES was one of the programs used for the theoretical calculations in its original form and as modified to include speed-dependent terms. The ratios ranged from 0.65 to 1.31 with a mean and standard deviation of 0.959 and 0.061 respectively. They are referred to by the authors as relating to ratios of theoretical to measured values: for reliability analysis application, it should be ratios of measured to theoretical values.

Taking account of full-scale effects as reflected in public domain literature suggests that predictions do generally exceed measurements, which is complicated by lack of complete seastate spectrum details and the absence of complete theory for such cases as fast ships in quartering seas. This is judged to increase the COV to 0.10.

Non-linearity is only briefly considered in acknowledging the differences between sagging and hogging arising from variation in buoyancy and hydrodynamic effects (added mass and damping) particularly for vessels with flare and non-vertical sections at their waterlines - container ships and naval combatants (destroyers, frigates). Based on full-scale data and comparisons between measured and predicted values, the ratio of sagging to hogging vertical bending moments averages 1.2. No corresponding uncertainty (COV) is quoted.

Two methods are available for obtaining lifetime maxima, long-term distribution and extreme value. Both ostensibly give similar results but the latter requires less effort. Both depend on short-term variability determined from 20 minute records under statistically stationary conditions. Bending moment response is confirmed to follow a Rayleigh distribution provided broad-bandedness is recognised. The spectral bandwidth factor ε (see Cartwright and Lonquet-Higgins) is found to range from 0.16 to 0.53 with the majority between 0.30 and 0.36.

Using the long-term distribution approach, the COV of the lifetime maximum wave load from one frigate is found as 0.075. From the extreme value method, the variation of COV with number of cycles for a Rayleigh distribution is presented. Based on 10,000 cycles as appropriate for an operation in a large seastate, a COV of 0.065 is found.

To combine these uncertainties, since they are uncorrelated, the authors use SRSS. Thus,

$$\text{wave load COV} = (0.15^2 + 0.10^2 + 0.05^2)^{0.5} = 0.192$$

close to the value of 20% reportedly often quoted in the literature.

Springing vibratory loads result from encounters with short waves especially those around the first vertical mode (usually only important for long flexible ships). Their prediction has been confirmed by measurements on Great Lakes ore carriers, fast container ships and large tankers. The major problems associated with predictions are knowledge of the form of the high frequency spectral tail, the calculation of wave excitation forces for short waves and high Froude number, damping, and non-linear effects. The uncertainty associated with the tail of spectrum is judged to be 0.20 based on the value obtained for low frequency waves. Again compared with conventional waves, the uncertainty associated with theoretical response operators is judged to be 0.20. Because these loads relate to high frequency waves, the associated COV corresponds to a greater number of cycles than normal wave loads so that, on the basis of extreme value theory, it will approximate 0.05 when considering maxima. Using SRSS, the combined COV is 0.287, noted to be relatively large but, because it is associated with loads that are not generally that significant, except for certain types of vessels, it is not likely to have a significant impact on vessel reliability.

Slamming and whipping loads are transient responses, the former the initial reaction to an impulsive force and the latter the subsequent behaviour in two-node or higher modes. The most difficult feature of theoretical predictions is the determination of the magnitude of the impact and satisfactory estimates of responses are still best found from the interpretation of full-scale data (container ships, frigates, and cargo ships). The slam loads occur within a narrow range of phase angles with respect to wave loads but these differ between ship types. In some cases, the midship moment is significantly enhanced due to coincidence of both maxima. From measured results on four different ship types, whipping bending moments at 10^{-5} and 10^{-8} probabilities of exceedence are tabulated. These were exploited to determine an average COV of 0.21 across the range of considered vessel types. This can be expected to be smaller if only one vessel type is considered. The associated pdf is judged to be exponential based on three sets of measured results and the inference that whipping loads result from the transient response to a impulsive non-linear force with quadratic behaviour. Without detailed consideration of extreme value theory, the COV associated with an estimate of the extreme whipping load is estimated as between 0.05 and 0.10 depending on the number of relevant cycles.

A.3.4 Chapter 5. Combination of Loads

The combinations considered are:

- stillwater, thermal and wave loads
- combined vertical and lateral wave loads
- combined wave and springing loads
- combined wave and whipping loads.

For stillwater, thermal, and wave loads, consideration of joint occurrences of thermal and wave load maxima suggests these are generally non-coincident. Considering the slow variation of thermal loads and their generally small magnitude, thermal loads are ‘added’ to stillwater loads and their uncertainty absorbed within those found for stillwater and wave loads. For stillwater loads, these are argued as not being strictly uncorrelated with wave loads because stillwater loads are a function of the cargo distribution that becomes the inertial load distribution for wave load analyses. The authors conclude this leads to a method for combining the two involving a large representative but constant stillwater load to which wave load is added. A simplified interpretation of linear error theory is then used to find the means and COVs of the combined load. It involves sums of the means and SRSS of standard deviations respectively. This makes two major assumptions, firstly, the pdfs for the loads are Gaussian and, secondly, and more critically, the stillwater and wave load values are linear functions with respect to all its random basic variables. This is acceptable when exploiting a safety index methodology but not for fully probabilistic methodologies such as FORM.

Lateral wave loads are considered for the first time in this report under combined vertical and lateral wave loads. Lateral bending moment is largely a dynamic phenomenon and the approach adopted, consistent with many of those at the time which assume linear responses throughout, is to treat it as an ‘addition’ to the vertical wave bending moment as a function of the section moduli ratio and the correlation coefficient between the two moments. The correlation coefficient is found from several studies to be small and can thus probably be ignored. Compared with the uncertainties associated with vertical bending moment, only the uncertainty associated with theoretical response operators has to be increased from 0.10 to 0.15 leading to a combined COV through SRSS of 0.222.

With respect to combined wave and springing loads, the results of a major study are reported that enables the rms value for the combined vertical bending moment to be simply determined on the basis that springing is a narrow-banded process. The correlation coefficient is required and is found to be close to zero in many cases. For estimates of extremes, two studies are reported, one based on a zero-crossing period approach and the other on a more exact method that accounts for the spectral width parameter. The uncertainty associated with the combining of extremes is small relative to that associated with predicting the rms value. On the basis of extreme value theory, because of the larger number of cycles of combined loading involved, the COV associated with the prediction of extremes is judged to fall into the range 0.05 to 0.10.

To determine the COV for combined wave and springing loads, the same simplified approach as adopted for combining stillwater and wave loads is exploited [although a ‘+’ sign is missing from the relevant equation (24)]. The combined value falls in the range 0.222 to 0.287.

For combined wave and whipping loads, their statistical independence is exploited to realize a combined value equal to the sum of the amplitudes, and a distribution function found by integration of the joint density function over the domain of interest. Because both pdfs are known (Rayleigh and exponential), an explicit expression results. The combination of extremes is also then found from SRSS of individual extremes. The combined COV is found from the same simplified approach of SRSS of standard deviations.

A.3.5 Chapter 6. Ship Hull Strength Analysis

Ship hull strength analysis covers yielding, plastic collapse and buckling of main grillages or their components. Strength is expressed in terms of vertical bending moment capacity.

Yield failure is based on purely elastic response and the attainment of extreme fibre yield. Mention should be made that the relevant section modulus should be the smaller of the values applying to the deck or the bottom.

Plastic collapse assumes full yield can be achieved across all plate and stiffened panel elements, i.e., the plastic hinge condition. A simplified expression is provided based on the total cross-sectional areas of the deck, the bottom and one side.

Buckling modes considered include plating between stiffeners, stiffened plating between transverses, stiffener tripping, and overall grillage. Some appropriate expressions for moment capacity are given in terms of elastic section modulus using a knockdown factor to account for the reduction in strength due to buckling. A similar factor is introduced into the expression for plastic moment capacity to account for buckling of the deck and sides. The same reduction factor is used despite the original accounting for differences in the buckling strength of these different components.

The presented expressions are then used to determine the governing modes of failure and moment capacities of three vessels, a tanker, bulk carrier, and container ship, all considered earlier in connection with wave loading. The weakest mode in all cases was found to be overall grillage buckling. The dominance of this mode is surprising since transverse frames usually provide adequate restraint against it. However, all vessels have stocky plate and stiffener sections - the corresponding buckling strengths are all within 6% of yield - which will have contributed to this predominance.

A.3.6 Chapter 7. Analysis of Uncertainty of Ship Strength

Linear error theory is introduced as the technique by which the distribution parameters for strength will be determined: this theory assumes the variables involved are normally distributed. Relevant expressions for the COVs are derived for the parametric strength equations of Chapter 6 for flexural strength controlled by initial yield and by buckling. The complexities of calculating these expressions in basic variable format are highlighted in respect of the expression for elastic modulus. In relation to the buckling term, considerable discussion is presented concerning its lack of influence, since for the vessels examined, all their buckling strengths were close to yield strength, of their derivation, and of the problems associated with plate non-dimensional slenderness β around 0.5. This last point apparently caused considerable problems and arises from the fact the equation presented for effective width, equation (39) in the report, is incomplete. The presented equation is only valid for $\beta \geq 1.0$. For $\beta < 1.0$, the effective width ratio is constant, its value being unity. However, as a consequence, the authors conclude that the identified expressions may not be applicable to a wide range of ship structures and propose an alternative approach.

The alternative approach is based upon the use of flexural strength calculations found from incremental solutions to discretized ship hull cross-sections, the discretization relating to plates and stiffened panels for which compressive average stress-strain curves have been previously determined via non-linear FEA and similar. These non-linear solutions include the effects of initial geometric distortions and welding residual stresses. The authors believe that such an approach is relatively quick to execute and could enable the validity ranges of the simplified expressions to be established.

Sources of data for determining objective uncertainties for strength variables are discussed covering material properties (yield strength and elastic modules) and geometry (dimensions and material thickness).

Corrosion effects are also considered in some detail. A COV of 0.8 is determined from the literature.

A.3.7 Chapter 8. Subjective Uncertainties in Ship Strength

The source of subjective uncertainties are those which, according to the authors, relate to lack of perfect knowledge. In this category they identify uncertain boundary and loading conditions, shape imperfections, and weld-induced residual stresses. The effects of shape imperfections and welding residual stresses are considered in some detail. There appears to be a lack of recognition that some of the buckling knockdown factors already include allowances for the presence of representative levels of both of these. Tolerances are considered as part of the plate initial deformation assessment and the absence of a consistent shipyard policy on this noted, despite the existence of the JSQS (Japanese Shipbuilding Quality Standard). The use of numerical solutions particularly simplified approaches are promoted as one way of providing insight to subjective uncertainties. The lack of emphasis of using experimental data to help quantify some of the so-called subjective uncertainties needs to be questioned.

A.3.8 Chapter 9. Special Cases - Loads and Strength

This chapter addresses strength issues that fall outside the normal range of design requirements. These are collisions and groundings, survey frequency and maintenance scheduling, time-dependent loads, yield stress variation, and gross errors or blunders.

In relation to collision, needs are reviewed as well as alternative requirements for the structural arrangements, i.e., absorbing versus resisting. Grounding needs are complicated by the desire to control outflow of hazardous cargoes as much as concern for loads/strength. Lack of statistical data is noted as a reason why such loads are usually taken to be deterministic.

Surveys are noted for their ability to feed information and data back so that Class Rules can be upgraded accordingly. However, this is not in a form that is amenable to quantification in probabilistic terms.

The time-dependent effects of corrosion were considered in the report. Other effects such as increase in yield stress during slams and similar events are noted as being ignored.

Gross errors or blunders can occur at any stage in the design cycle. Many are the result of human errors, particularly in operation. Such events should not be considered as part of the tail of a distribution but a discrete event that radically alters the failure probability of the model under consideration. As such, the authors claim they cannot be treated in a formal manner within the context of probabilistic analysis. The work reported in the paper by Baker and Wyatt (1979) would suggest otherwise.

A.3.9 Chapter 10. Application to Reliability Evaluation

The authors indicate that the information available is not sufficient to permit a fully probabilistic approach to be demonstrated in relation to a ship in operation. However, they recognise that a safety index solution could be found with what is currently available and that, similarly, application of the fully probabilistic approach can be demonstrated. They proceed to do this based on assuming that both resistance and stillwater bending moment are deterministic and that the loading results from combined conventional wave and slam effects. The probability of survival in a seastate is found as the sum of probabilities of survival under wave load alone and under combined wave and slam. The probability of survival during a voyage is then the product of surviving in all seastates. The availability of relevant expressions for both distribution functions enables the calculation to proceed although no sample results are given.

A.3.10 Chapter 11. Design Load Estimation

Based on the information presented in the report, this chapter guides the designer in broad step-by-step terms to obtaining an estimate of the combined stillwater and wave (including springing or slam effects) loads. The stillwater value adopted is the maximum of the ballast or load condition augmented by (constant) thermal loads as required. The wave load combined with either springing or slam effects is the mean extreme value. The total uncertainty is found by generalization of the simplified approach described earlier, namely, SRSS of standard deviations although expressed entirely in terms of means and COVs.

The authors then suggest that a reference value used in probabilistic analysis is the characteristic value, for which the standard equation is given. This is not strictly correct, the characteristic value is one of the products of a reliability analysis that is used in design in combination with partial load and resistance factors. The authors are seemingly not fully aware of this limit state design approach although they summarise a simplified approach for obtaining what is, effectively, a characteristic value for design load based on a known value of safety index.

A.3.11 Chapter 12. Conclusions and Recommendations

The conclusions are drawn heavily from the results presented in each of the chapters. As noted above, one or two of these are not entirely appropriate as they are based on incomplete information (although known at the time).

The recommendations are entirely expected and consistent with the findings of the report. Perhaps more emphasis should have been placed on the need for full-scale measurements in relation to improving the knowledge and understanding of loading and response. The state of knowledge in relation to strength would be improved through the use of more large-scale model tests and numerical simulations, not just the latter as suggested by the authors.

APPENDIX B

REVIEW OF REPORT SSC-351

AN INTRODUCTION TO STRUCTURAL RELIABILITY THEORY

by A E Mansour

B.1 OBJECTIVE

To provide an introduction and summary of the state-of-the-art in structural reliability theory directed specifically towards the marine industry.

B.2 AIMS

1. to consider the kind and nature of existing data on the design variables of a marine structure,
2. to consider the numerical nature of the analysis of complex structures that typically exist in the marine environment.

B.3 REVIEW

B.3.1 Chapter 1. Introduction and Summary

Following presentation of the objective and aims of the proposed study, the role of reliability analysis in a general probabilistic design procedure is described together with some basic concepts of reliability, such as, the limit state function, the limit state surface, the computation of probability of failure P_f from a joint probability density function over the range where the limit state function is less than or equal to zero, the simplification of this to a convolution integral when load and resistance are statistically independent, and the further simplification if load and resistance are also normally distributed in which case:

$$P_f = \Phi(-\beta)$$

where Φ is the standard normal cumulative distribution function and
β is the safety index given by

$$b = \frac{m_R - m_Q}{\sqrt{s_R^2 + s_Q^2}}$$

in which μ, σ are mean and standard deviations respectively and R, Q denote resistance and load respectively. [Note that R and Q are not used to designate resistance and load in this document.]

The information necessary to perform a reliability analysis of a marine structure is described in broad terms, covering load and resistance.

B.3.2 Chapter 2. Load Information in Reliability Analysis of Marine Structures

The concept of a random process is introduced in relation to describing the surface of the sea. The definitions necessary to exploit this information in statistical form are then given in detail. These are then extended to include those pertaining to stationary and ergodic processes, to the spectral density of a stationary random process, and to narrow- and wide-band random processes: their application to typical wave data is then discussed. Typical wave spectra are reviewed and the peak distribution of a general stationary Gaussian random process examined.

The dynamic loads and response of a floating vessel considered as a rigid body are then defined in terms of the Response Amplitude Operator (RAO). On the basis of linearity, input and output characteristics are identical except that narrow-bandedness is not necessarily retained. The form of the response spectrum and its relationship with the wave spectrum are reviewed and the existence of a Fourier pair through consideration of the time domain equivalent to the frequency domain description demonstrated. Non-dimensional forms of RAOs are introduced and their determination exploiting both solutions to ship equations of motions and towing tank experiments described.

Forward speed effects on the response spectrum are considered using frequency mapping as are the effects of short-crested seas.

For the long-term prediction of wave loads, the Weibull distribution is claimed to fit well data on ship wave bending moments. Extreme wave loads can also be predicted using a variety of theoretical techniques. Four are considered involving order statistics, the asymptotic Type-I extreme distribution, upcrossing analysis, and a two stage random process. Comparison between the results of the first, third and fourth give identical results, only the asymptotic Type-I distribution differs, and significantly because it is essentially an upper bound. According to Mansour (1987), the upcrossing analysis is the easiest to handle.

A useful comparison is made between non-encounter of events and their return period.

The stochastic combination of loads on marine structures are considered from two points of view, decomposition of measured records into their basic components and the combining of analytically determined response components. The former is clearly illustrated with examples of rigid body, springing and slamming responses. The latter is considered in greater detail, firstly, by combining wave-induced responses at different frequencies (in both the frequency and time domain) and, secondly, by adding the mean response due to stillwater and thermal loads. Two examples are presented on the combining of wave-induced responses, one covering vertical and horizontal bending, the other vertical and springing behaviour.

B.3.3 Chapter 3. Strength Information Required for Reliability Analysis of Marine Structures

Sources and types of uncertainties in relation to strength variables are described. Basic distribution types are reviewed and linear random error analysis introduced. Some statistics relating to yield strength, ultimate tensile strength and elastic modulus are presented. Inconsistencies and uncertainties associated with yield strength are noted. The availability (or lack of) of data on plate dimensions including thickness, corrosion, residual stresses, and fabrication tolerances and imperfections is discussed. The conclusions suggest the literature search did not extend to include European information sources.

B.3.4 Chapter 4. Basic Reliability Concepts Based on Fully Probabilistic Methods - Level 3

A procedure for implementing a fully probabilistic methodology is described together with an example application. The initial introduction repeats much of that presented in SSC-332 (see Appendix A) and then formulates a fully probabilistic methodology for a ship hull girder subjected to stillwater and wave-induced bending moments. The strength is simply treated as a univariate problem normally distributed: this clearly facilitates the realization of a solution at least in presentation terms.

B.3.5 Chapter 5. Level 2 Reliability Analysis

The mean-value first-order second-moment (MVFOSM) method is summarised and its relationship with the safety index (β) approach demonstrated. The 2-parameter version is presented graphically in reduced variable space. The weaknesses of this method are identified and a stepwise improvement via the Hasofer/Lind formulation described together with the final step via the Rackwitz/Fiessler algorithm. Correlation is introduced via a simple transformation process for normal variables with only passing reference to the widely used Rosenblatt transformation technique.

A superficial representation (linear limit state equation) on the reliability index analysis of 128 vessels is made. The variation of β with ship length, static bending moment, and traditional factor of safety is illustrated: the safety implications are highlighted. A Hasofer/Lind solution to a non-linear version of the equation is considered in more detail.

B.3.6 Chapter 6. Level 1 Reliability Analysis

The need for a Level 1 analysis is discussed. It is introduced as if these were required for all the basic variables participating in a design problem. However, code safety formats generally only apply partial factors to resistance in its entirety and to loads according to their categorisation (dead, live, wave, etc.). The procedure presented for partial factor derivation is not consistent with code safety format requirements.

The safety formats adopted by a number of codes is reviewed, American Petroleum Institute (API) RP 2A, European Committee for Concrete (CEB) Model Code, National Bureau of Standards (NBS) A58, National Building Code of Canada, and Det Norske Veritas. Similarities and differences are noted, in particular, the resistance factors ϕ (North America) and γ (Europe), and the use of load combination factors. The concept of calibration as a process by which code partial factors can be derived is introduced.

B.3.7 Chapter 7. Simulation and the Monte Carlo Method

Monte Carlo simulation is discussed and its interpretation as simply a ratio of trials or via a fitted distribution. The generation of random numbers, both of uniform and prescribed distributions, is described. Sample sizes are considered to realize specific levels of accuracy together with procedures for reducing the number of simulations actually required. An example evaluation of a random function is determined analytically and by simulation followed by the presentation of an independently executed P_f calculation using linear and non-linear limit state equations for a ship in waves and simulation versus a first-order reliability method.

B.3.8 Chapter 8. Systems Reliability

The concepts of 'series' and 'parallel' failure systems are introduced and methods for determining bounds on the P_f in each case described. The general system (combination of series and parallel sub-systems) is considered and methods for solving it briefly considered, these are probabilistic network evaluation technique, fault tree and event tree. An example is presented to determine the bounds on the P_f of a ship hull in primary bending.

B.3.9 Chapter 9. Fatigue Reliability

The general requirements for fatigue design in the wider perspective are given emphasising good design, construction practice and fabrication practices.

A closed-form fatigue design procedure is presented in some detail. It relates, entirely unexpectedly, to the joints of fixed offshore steel jacket structures. Alternative methods for determining fatigue damage are tabulated. The sources of uncertainty in the process are identified and relevant data on means and COV listed.

Reference is made to Munse's fatigue reliability analysis for ships based on the two-parameter Weibull distribution. Different approximations are made for the Weibull shape and scale parameters. The need to correct for broad-bandedness when using Rayleigh-based procedures is noted.

Detailed descriptions are then given on how to apply the (Wirsching) method (as demonstrated for tubular joints) and Munse method based on lognormal and Weibull distributions of cycles respectively. In neither case, however, is the procedure for determining the loading history carefully spelt out. For ship sideshells this is a complex combination of overall direct stress and local bending stress. The latter varies more directly with wave height than does the overall stress and can be dramatically altered by immersion.

The concept of a target safety index, which is a function of design life given a service life, is introduced and presented graphically. From this, the benefits of inspections and repairs can be demonstrated.

Fatigue failure in a ‘fail-safe’ structure is used as the basis for introducing system fatigue reliability. Uncorrelated and correlated failures in a series system are used to demonstrate that correlation in such circumstances reduces probability of failure. Typical results are presented graphically.

B.3.10 Chapter 10. Applications to Ships and Marine Structures

Methodologies for performing long-term and short-term analyses leading to probabilities of failure that include relevant failure modes are outlined. An example of a short-term analysis is performed at Level 3. Different seastates are considered as well as procedures for calculating P_f. The results of a parametric study using one of the procedures is presented in non-dimensional graphical form covering a wide range of seastates, for first yield failure.

The results of short-term analyses at Level 3 using the four extreme distributions considered in Chapter 2 (see Section B.3.2) are plotted and tabulated against a number of hourly wave encounters for the vessel considered in the previous example.

A long-term analysis of the same vessel is presented in two parts, firstly, a comparison between the results at Levels 2 and 3 and, secondly, the effect of correlation between stillwater and waved bending moments. The process of establishing the weighted exposure to each seastate over the 20 year lifetime is demonstrated. Not surprisingly, the Level 2 and 3 probability estimates differ: this is explained through examination of a failure surface demonstrating the difference between the true failure surface (curved) and the linear approximation by which the probability of failure is determined. Perhaps the effect of using a parabolic representation of the failure surface could have been used to demonstrate the improvement possible with a higher order solution because, in many practical cases, the differences demonstrated between Level 3 and 2 solutions are not significant, as noted by the author.

The effect of correlation between the stillwater and wave bending moments is examined using a correlation matrix. The effect of the particular coefficient varying from 0.0 to 0.9 is presented. As expected, failure probability increases with increasing correlation but the effect is small and can, justifiably, be generally ignored.

The reliability of the eighteen vessels considered in Chapter 5 (see Section B.3.5) is compared when determined at Level 3, using the MVFOSM method, and using an improved first-order method. The last appears to be identical to the Rackwitz/Fiessler methodology but it is described as the Hasofer/Lind method with transformation to normal variables. When compared with the Level 3 method, the Level 2 methods provide non-conservative estimates of failure probabilities.

Partial safety factors on resistance and total bending moment are determined per the procedure presented in Chapter 6 (see Section B.3.6). The range of the factors is not consistent with those that might normally be used in design. It needs to be emphasised that these factors are a result of an assessment and are not to be construed as reflecting values appropriate for design.

The reliability and partial safety factors implied in the 1982 ABS rules for ship longitudinal strength are determined from an examination of ten vessels. A first yield strength criterion was used - a relatively low value of yield strength was adopted for this, 214 MPa - together with COVs of 10 and 12%, again relatively low since the COV of yield strength alone is around 6 to 8%. The ABS rules stillwater bending moment was assumed to represent, reasonably, the 95% exceedence level. The COVs adopted were 9.1 and 38.1%, covering the range of information in the literature.

It is unlikely that the upper value would apply to loadings around the rule limits. The ABS rule wave bending moment was assumed to fit an exponential distribution (COV = 100%) and to correspond to the 0.01 exceedence level based on a conservative assessment of critical wave loads. Safety indices were determined (MVFOSM) and presented as a function of ship length. Safety indices and partial safety factors were also determined by transforming the exponential distribution at the most likely failure point into an equivalent normal distribution. A significant reduction in safety indices is realized as a result.

B.3.11 Chapter 11. Concluding Remarks and Recommendations

Some shortcomings are noted regarding the wider use of probabilities and reliability methods in the design process, these are:

1. More information is needed than for normal design.
2. Education in the basics of probability theory, reliability analysis and statistics is lacking.
3. The inertia of industry is inhibiting implementation.
4. True reliabilities have not been delivered, only notional values.

The advantages of exploiting reliability analysis are briefly reviewed and, since they are judged to outweigh the shortcomings, a number of recommendations are made, as follows:

1. The present effort should continue since at least some of the developed technologies will be exploited in the fullness of time.
2. ‘Standard’ procedures are needed for estimating and combining loads in order to avoid ambiguity in their determination.
3. Target reliability should be determined for ship primary strength exploiting standard loading procedures.
4. Further study of reliability methods for stiffened panels and plates is required.
5. Level 3 methods and simulation should be promoted more strongly.
6. Simplified system reliability analysis procedures are required.

B.3.12 Appendices A and B

Appendix A presents Useful Information in the form of probability distributions, estimation of Weibull distribution parameters, use of Weibull probability paper, and safety index v P_f for normal and other distributions. Appendix B provides a brief description of CALREL and its input needs and output interpretation.

APPENDIX C

REVIEW OF REPORT SSC-363

UNCERTAINTIES IN STRESS ANALYSIS ON MARINE STRUCTURES

by E Nikolaidis and P Kaplan

C.1 OBJECTIVE

To quantify the error in stress analysis of marine structures, to provide necessary information to establish safety criteria in design.

C.2 AIMS

1. To locate the sources of error in all steps of load effect prediction process.
2. To provide quantitative information on all types of error.
3. To rank errors in terms of their influence in design.
4. To recommend strategies for reducing (the effect of) the most important uncertainties.

C.3 REVIEW

C.3.1 Chapter 2. Types of Uncertainties

Chapter 2 considers Uncertainties and their classification. These are divided into those demonstrating inherent natural randomness - Type I or aleatory - and those reflecting a lack of knowledge through attempts to model phenomena - Type II or epistemic. The former can be reduced through data gathering and the latter by improved modelling.

In Section 2.2, two mathematical representations of modelling uncertainties are described - Ang and Cornell and Ditlevsen - equations (2.1) and (2.3) respectively. In equation (2.1), the descriptions of B_I and B_{II} seem to have been interchanged, the former appears to reflect modelling uncertainty whilst the latter seems to be a measure of natural randomness.

Based on FOSM (linear) reliability theory and assuming independence, the uncertainties in B_I and B_{II} are determined as the SRSS (square root of sum of squares). The limitation of this is noted but the authors' use of it is defended on the grounds of frequent use by others and that the information necessary for more accurate approaches such as FORM ≡ Advanced FOSM is not usually available.

The Ang and Cornell and Ditlevsen models are compared in Table 2.1. The greater difficulty in using the latter is demonstrated involving as it does the treatment of variables in 'reduced variable' space. The relationship between the statistics of actual and predicted values within the Ang and Cornell model is demonstrated. This is shown to involve a SRSS approach.

This SRSS approach to the combination of uncertainties seems to be widely supported by the authors, not only directly as illustrated particularly in this section but also in the strong support of the uncertainties determined by Bea and his colleagues in relation to offshore structures which have been derived in precisely the same manner. The Ang and Cornell basic model is widely used to relate actual and predicted values. However, for application in FORM, there is no need to combine the uncertainties prior to an analysis of this sort. Indeed, it is misleading to do so for the very same reasons that FOSM should not be used in a reliability evaluation, namely,

- the result is not invariant for the same structural problem expressed in different mechanical terms, for example, stresses instead of forces,
- parameters determined at the mean of the surface of the basic reliability Z-function which correspond to a FOSM evaluation differ from those determined at the 'failure point' on this same surface as is performed in a FORM,
- SRSS is identical to combining uncertainties in FOSM methods,
- sensitivity factors determined via FOSM methods differ from those found from FORM,
- as presented, it appears that the predicted value X_P is a single entity whereas it usually consists of a mathematical combination (i.e., summations and multiplications) of basic variables, some of which will be raised to powers other than unity and have probability distributions different from the log-normal type implicit in the form as presented,
- as noted later in the report, the measure of modelling error B may not be independent of some of the basic variables that appear in X_P in which case the SRSS approach to assessing uncertainty is not valid,
- similarly, in detailed assessments, not only may the bias in X_P be a function of the basic variables but also may be the standard deviation of X_P.

Section 2.3 considers the effects of uncertainties on lifetime extreme loads. They rightly suggest that Type II uncertainties should not be treated as random because of the different way in which Type I and Type II uncertainties combine with time. Type I uncertainties relate to events that are independent, so extreme value theory can be used to combine these with time. This results in increasing bias and decreasing COV (coefficient of variation) with increasing numbers of events. Modelling uncertainties are (Type II) fully correlated from one event to the next so the uncertainty is unchanged no matter how many events are considered.

While this is correct, it is not always easy to distinguish between random and modelling uncertainties. For example, wave heights are usually the results of measurements. However, because sampling is limited (e.g., 20 minutes in 3 hours), we construct statistical models of wave heights which are then used in the assessment of a structures response to the, now, 'modelled' wave height. Strictly, therefore, such wave heights are of Type II modelling form. Yield stress is measured via a tensile test which is conducted at such a speed that the value of yield stress is affected: increases between 5 and 12% are typical. When assessing the value of stress, we use an area based on the original specimen dimensions and not those that exist at the time. Although the first of issues is the more important, both contribute to the fact that are widely accepted random values of yield stress are in fact modelling dependent.

A solution to the problem of combining these two types of uncertainties over a life-time or service life of a structure is to avoid the need to do so by calculating any required reliability for a time-scale consistent with a period corresponding to the duration of the independent natural hazard. For example, for offshore structures, the length of independence of the extreme weather hazard is one year. By treating hazards on an annual basis, the problem of how to deal with the Type I and II uncertainties can be eliminated. This does of course require that the acceptable level of reliability for the hazard in question is expressed in annual terms: this is not usually a problem. On the other hand, for ships, each voyage is probably the extent of the independence between hazardous events.

C.3.2 Chapter 3. Loading Environment

Chapter 3 considers Loading Environment, fairly extensively from the ship viewpoint, Section 3.1, and less so for offshore structures, Section 3.2. For ships, the assessment of uncertainties was derived from two studies. One in particular concentrates on several issues ostensibly pertaining to the environment such as wave spectra, short crestedness, directionality of weather systems, visual observation of wave heights, correlation between subsequent peaks, broad-bandedness, and heavy weather countermeasures. The interpretation of the results of this study seems to be based on the effects that each of the phenomena has on the wave bending moment. Although there may be little alternative to using bending moment as a measure of such effects, the Section aims at uncertainties in the modelling of the environment whereas it is using a response based approach to assessing this.

Modelling of the environment is a task independent of response as practised by oceanographers concerned with offshore structures. In such studies, hindcast techniques have been in long use supplementing the direct measurements of wind, wave and currents - Cardone et al (95). The accuracy of the hindcast models is determined against the measurements, directly and not through any structure response mechanism. The same approach should have been adopted in this work.

Equation (3.1) is noted to recognise that the mean square of the bending moment is under-estimated for long ships (>250 m) and small wave heights (H_s < 5 m) as a result of spectral shape variability. The fact that the loads induced in such circumstances will be small should also have been mentioned.

Equation (3.4) presents the only measure of the uncertainties associated with the loading environment in that it gives a procedure for correcting visually observed wave heights.

In connection with offshore platforms (Section 3.2), an example is given of the comparison by Bea between measured and predicted wave heights and the inference on the distribution parameters for the modelling uncertainty (hindcast) given (presumably by the author) that the distribution is log-normal: the COV is reported as 0.13. From the same source, the random uncertainty is found as 0.30 which the present authors combine with the modelling uncertainty (SRSS) to find the total uncertainty as 0.33. The authors then report that Bea then corrects the extreme wave height distribution and recommends the COV to be 0.08 from which the uncertainty in the mean square bending moment is reported as 0.16 (=2 * 0.08).

This does seem misleading. It is not clear whether the final conclusion regarding COV is 0.33 or 0.08. Further, bending moments on offshore structures are expressed in simple bending moment terms, not mean square bending moments. Because the bending moment on an offshore structure varies approximately with maximum wave height H raised to the power 2, then the COV of the calculated moment is 2 * COV, that is either 0.66 or 0.16. This needs clarification.

Work by Wirsching is also discussed here, again the emphasis being on wave loads and not on the metocean parameters that are ostensibly the subject matter of this section. Work by Guedes Soares and Moan is discussed and the uncertainties associated with wave height considered together with the uncertainties associated with wave period. A correlation coefficient of 0.50 is reported as having been determined in this study.

Once a reasonable hindcast model is developed, it is possible to generate joint probabilities between many of the components describing a sea condition as a combination of wind, wave and current in-line and normal components. For example, Peters et al (93) derived fourteen pairs of parameters in one such case. The problem of determining relevant metocean parameters for an immature offshore area is discussed by Driver et al (94). Detailed wind, wave and current measurements were made over an 18 month period and included six relatively distant typhoons. Thirty nine typhoons were then hindcast using three models concerning with wind field modelling, wave field computations and surface mixed-layer current modelling leading initially to omni-directional metocean parameter descriptions and then detailed directional estimations. The project lasted five years but clearly demonstrated what could be achieved on the basis of limited hurricane/typhoon records and 18 months of detailed site measurements.

C.3.3 Chapter 4. Loads

In the Chapter on Loads, the authors move immediately, in the case of ship (Section 4.1), to the use of SRSS but now applied to standard deviation (incorrectly termed variance in several locations) rather than COV as in Chapter 3. This indicates that the uncertainties are now assumed to relate to normally distributed variables instead of the lognormally distributed ones examined earlier.

The effect of increasing the scope of the description of subject, here applied to in relation to ship stillwater bending moments and shear forces, namely, per voyage, then per class and then all classes of ships, is noted to automatically increase the variance overall. The implications of this are hinted at but not spelt out. While this may be true for the average values considered here, from a reliability viewpoint, it is only of concern if the variance is increased in relation to maximum moments. This is illustrated in Tables 4.1 and 4.2 where standard deviations are quoted for all ships within a class for a range of classes but with a maximum load effect of only 0.8 times the corresponding classification society value. The authors do then consider this using extreme value theory, the results of which are presented in Table 4.3. It is not clear from this table, considering that the same number of voyages is examined across all ship classes, why Cargo vessels have a larger most probable extreme stillwater bending moment than OBO vessels considering that they exhibit smaller within class and individual ship variabilities and a smaller average stillwater bending moment.

The influence of errors in response amplitude operator determination is examined in some detail, firstly from a simplified overall viewpoint and secondly from a more detailed perspective separating the linear and non-linear components: significantly different measures of uncertainty are reported in each case. In the second of these, the linear bias is derived independently as a function of relative heading angle, Froude number and block coefficient and then significant wave height. Both lead to similar levels of uncertainty. It raises the question whether there may have been some advantage in including wave height with the other parameters. The authors postulate a reason for the major difference in overall uncertainty in that the detailed approach examined errors at an individual frequency level rather than a comparison of bending moments. This argument is supported since reliability will be dominated by extreme moment conditions so it is the uncertainty in this that is important not necessarily what happens under conditions considerably less than extreme.

The finding that the error (bias) due to ignoring non-linearities is as significant as it is - up to 1.28 - is of concern. This will have a significant effect on reliability.

The authors consider one study on the accuracy of hydrostatic pressure assessment. The conclusions of the study indicate that pressures are accurately predicted yet the authors upper and lower bound values for bias are totally inconsistent with this. It is difficult to believe that the differences derive entirely from the errors in prediction at sterns and bows. If the authors' estimates are valid, questions will arise about the accuracy of side shell fatigue load assessments which are dominated by pressure loading on ship side shells.

In the section devoted to Offshore Structures (Section 4.2), considerable attention is paid to the combining of random and modelling errors over numbers of years, based on the minimum length of time for independence of the random event under consideration. The authors clearly demonstrate the outcome of doing this pointing out, quite rightly, that the total level of uncertainty is under-estimated if the modelling error is not treated correctly. One alternative to this was mentioned earlier, that is, to base reliability assessments on an annual basis and set targets accordingly. Another alternative is to approach the problem as one of defining the extreme combination of metocean parameters including allowance for joint occurrences for the duration of interest, say 20 or 100 years, and conducting the load assessment for this combination. In this way, the modelling error does not need to be accumulated over the period in question, it is accounted for once only, and only the accumulation of the uncertainties in the metocean parameters, which reduce in this process, need to be considered.

A detailed listing is presented of the inputs to the Guedes Soares and Moan analysis of a vertical pile subjected to extreme storm conditions. With this much detail, it would have proved far more effective if the sensitivities derived in the analysis were also reported, presuming of course that a FORM solution was used although this is not made clear by the authors.

C.3.4 Chapter 5. Loads Combinations

The relatively small section devoted to Load Combinations (Section 5.0) is a reflection of the dearth of information in this area - see ISSC Proceedings. That the SRSS approach comes out so well in the authors' Monte Carlo simulation is of interest for its simplicity. It does not do so well in later studies (ISSC '94).

C.3.5 Chapter 6. Structural Analysis

Chapter 6 is devoted to the uncertainties associated with structural analysis. Four aspects are considered in connection with ship structures, FEA, beam theory, shear lag and connection rigidity, and a number of issues in relation to offshore structures primarily concerned with their dynamic response.

The FEA studies on ships relate to two comparisons of FEA results with those from models and full-scale data. The FEA-model test comparisons are discussed at some length pointing out the not insignificant discrepancies that arise in certain loading modes. Some of this is due to the fact that FEA over-estimates stiffness although the modelling bias demonstrated under loading case 1 (pure bending) is not consistent with this. Some is due to experimental error, as acknowledged by the authors, and as demonstrated by the lack of symmetry in the model test results even in bending.

The comparison with full-scale results does not provide any direct measure of the accuracy of FEA since they include the effects of uncertainties in load analysis. These in principle are the most valuable set of results from a reliability viewpoint since they incorporate all the uncertainties from (apparently) all sources. Assuming the uncertainty in the load analysis is as reported, the final COV for FEA is given as 0.125 although the bias is not simultaneously quantified.

This degree of accuracy seems only to apply to pure bending loading as the other comparisons are less favourable - Table 6.2. FEA of aircraft structures and car bodies are referenced and found to be not dissimilar to those found for ship structures although the information cited is very limited and the conclusion in relation to the analysis of car bodies that 'it is more difficult to predict the response to longitudinal bending than that due to torsional loading' is contradictory to that determined from the assessment of the ship studies.

An issue that is of paramount importance in relation to the accuracy of FEA solutions that is not discussed is that of mesh refinement. This is particularly relevant in connection with the accuracies discussed in the report in connection with the model test subjected to loading case 2 - pure torsion. Mesh refinement has a substantial impact on FEA accuracy and is normally checked through the execution of convergence studies. Such studies should be expected in any reasonable FEA work and would necessarily be included in any user instructions for the execution of such studies. That it is the user who has a significant impact on final accuracy was proven again during a 'blind' benchmarking exercise by Nichols et al (1994) involving pushover analyses of plane frame tubular structures typical of offshore jacket platforms. This study found that users of the same program often demonstrated larger differences in results than between users of different programs even though all analysed the same structure.

The section concerned with shear lag (Section 6.1.3) seems overly concerned with detail particularly when two of the four approaches considered lead to constant values of shear lag effective breadth. The one approach that demonstrates excellent agreement with the test results (BuShips), incorporates some influence of ultimate strength. (Whether this relates to the stiffened panel or to the plate is not clear). This is not expected since shear lag is normally considered as an elastic problem. Indeed, the two major studies undertaken by Moffat and Dowling (1975) and Lamas et al (1983) in relation to shear lag in steel box girders found that, for frequent combinations of the important parameters, the ultimate strength of a stiffened flanges was unaffected by the presence of shear lag despite the fact that the shear lag would precipitate an earlier onset of plate buckling and a very different sequence of stiffener failures than was the case when shear lag was not present.

The influence of joint flexibility and rigid beam lengths considered in Section 6.1.4 would seem more at home in the section devoted to FEA.

The section on offshore platforms (Section 6.2) is rather limited. It appears to assume that only a dynamic analysis is relevant for such structures. This is far from the case as a majority of fixed platforms are in relatively shallow water. Of course, deepwater fixed platforms require a dynamic analysis as do the remainder of offshore structures only briefly considered by the authors, namely, tension leg platforms (TLP) semi-submersibles and floating production systems (FPS).

Joint flexibility does influence deepwater jacket response as noted by the authors and as had been studied earlier by Barltrop et al () with similar conclusions.

Although available at the time of their report, the authors have not reported on the two sets of full-scale comparisons by Ohmart (1983) and Haring et al (1979) available on measured versus predicted fixed offshore structure responses. These give similar findings for bias, approximately 0.9, and COV, 0.25, and both suggested that the ratios were lognormally distributed. Since these account for all uncertainties in the loading and response of jacket structures except those associated with wave height, they provide a more complete picture and measure of the uncertainties involved in the process and are directly amenable to inclusion in reliability analysis.

The reported work of Moses in connection with the dynamic analysis of jackets has been overtaken by later investigations that result in significantly smaller levels of uncertainties in such circumstances.

C.3.6 Chapter 7. Fatigue

The Chapter devoted to Fatigue concerns itself primarily with the uncertainties associated with stress concentration factors and cumulative fatigue damage, as other aspects, modelling of the environment, load modelling and load effect evaluation, have been considered in early sections of the report. The remainder of the section is concerned with demonstrating that random uncertainties can be neglected in fatigue reliability assessment and identifying the relative contributions of the different sources on uncertainty on fatigue damage. The outcome of the former confirms the long-held view that random uncertainties are relatively unimportant in fatigue assessment modelling. The findings of the latter are limited in that a FOSM approach is used in the assessment and only offshore structures are considered. As demonstrated very clearly in the fatigue problems associated with the TAPS tankers, as discussed by Hughes and Franklin (1993), Rolfe et al (1993) and Sucharski and Cheung (1993), the most critical requirement for any fatigue assessment is that an appropriate one should be performed. Clearly the more rational this is, the lower will be the associated uncertainties. A dynamic spectral fatigue assessment is now widely accepted as a preferred approach although the levels of detail to which this is taken is still open to debate.

APPENDIX D

REVIEW OF REPORT SSC-368

PROBABILITY-BASED SHIP DESIGN PROCEDURES: A DEMONSTRATION

by A E Mansour, M Lin, L Hoven and A Thayamballi

D.1 OBJECTIVE

To provide a demonstration on the use of probability-based ship design methods and to compare the results with traditional design methods.

D.2 AIMS

To identify:

1. the benefits and drawbacks of the use of probability-based design methods compared to the traditional methods;
2. the additional information necessary to conduct probability-based designs;

and to provide

1. a summary of the proposed probability-based method showing how it can be applied to generate new designs of uniform safety and how it can be used to assess the safety of an existing design;
2. a discussion of the current and future SSC projects in reliability and loads.

D.3 REVIEW

D.3.1 Part 1 Demonstration of Probability-Based Rule Calibration

D.3.1.1 Chapter 2. Preliminary Assessment of Reliability Levels Implied in ABS Rules

This assessment is an expanded version of that presented in Section 10.2.5 of SSC-351 but with some notable differences. These are:

- the use of lognormal distributions for the resistance variables of section modulus and yield stress despite being apparently based on SSC-351 where normal distributions were used.
- COVs on section modulus and yield stress of 4 and 7% respectively, again ostensibly based on SSC-351 where no uncertainty is adopted for section modulus and the COV on yield stress is recorded as 8.9% based on a literature survey of relevant data (Section 3.5 of SSC-351).
- the mean value of yield stress is increased from 214 MPa to 235 MPa
- a wave bending moment distribution for which COV = 9% instead of 100%
- use of FORM and SORM instead of β and an advanced Level 2 procedure.

The results seem to suggest that the reliability is dictated by the ratio of wave to stillwater bending moments which suggests that the uncertainties associated with resistance have no influence on the results. This is not surprising since no strength modelling uncertainty has been considered.

D.3.1.2 Chapter 3. Calibration Procedure

A calibration procedure is demonstrated by which the determined partial load and resistance factors lead to designs that on average match the target and, simultaneously, demonstrate a small spread of reliabilities compared with the values assessed in Chapter 2 (see D.3.1.1). This demonstration is, however, a little misleading because too few example designs have been included in the assessment. This is clearly illustrated in the decision that 'in Eq. 3.2 ϕ_y is arbitrary'. In a formal calibration exercise, no such restraint would be introduced at this stage. The problem would be set up as one of constrained optimisation with the same objectives as stated here, namely, average reliabilities to coincide with the target, and the spread to be minimized, but this would be formally expressed in mathematical terms and the all partial factors would be free variables. The result may well indeed be similar in the present case but, in a larger sample base, the need for a formalization of the derivation would become apparent.

D.3.2 Part 2 Demonstration of Probability-Based Hull Girder Safety Analysis

D.3.2.1 Chapter 4. Development of Limit States for an Example Ship

The aim of this study is to identify relevant limit states for ship hull girder collapse. A tanker designed to ABS rules was selected for this purpose. Limit states at ultimate, serviceability and fatigue are to be considered under sagging conditions only because the corresponding wave bending requirement is significantly higher than that in hogging. The ultimate limit states considered were:

- deck initial yield - section modulus based on an effective cross-section with yield taken as the appropriate limiting stress,
- fully plastic collapse,
- buckling instability allowing for plate buckling, stiffened plating column buckling (based on plate effective width), and stiffener flexural/torsional buckling,
- orthogonal stiffened panel buckling (denoted cross-stiffened panel buckling in the report).

The deck initial yield definition will over-estimate strength since stiffened panel buckling is ignored. However, use of plate effective widths in the determination of the section modulus is the best method for doing this. Plate buckling is not an ultimate limit state as such but rather a serviceability limit state and should be considered as such.

Hull girder primary bending strength is determined via an equation reported at ISSC '91 which is a function of the plate slenderness and stiffened panel column slenderness of the girder cross-section critical stiffened panel.

The serviceability limit state considered is limited to plate buckling but as determined by elastic critical buckling rather than the buckling at ultimate strength. Because post-buckling strength is present among more slender plates, it is questionable whether the elastic critical buckling stress is the most appropriate criterion. A more relevant one might be a limit on out-of-plane deflection of plate panels.

The fatigue limit state adopted is identical to that presented in Chapter 9 of SSC-351. As such, it does not account for the combined variation of overall and local responses that the sideshell, for example, will be subjected to, complicated by the issue of immersion.

The stillwater moment is determined from ABS rules maximum allowable, in sagging.

The rms value of the wave-induced bending moment is determined from published data as a function of Froude number, significant wave height, beam/draft ratio, length/beam ratio, block coefficient, and ship speed. The extreme value assumes a 3-hour seastate (approximately 1000 peaks) and follows the procedure given in SSC-351.

For fatigue, the ISSC '91 sea scatter diagram is applied to determine rms value for each seastate.

D.3.2.2 Chapter 6. Reliability and Safety Indices for the Example Ship

For reliability, modelling uncertainty parameters are introduced into the limit state equations.

The fatigue detail is a welded deck longitudinal but it does not indicate the location of the detail.

The determined probabilities of failure are relatively high. The loads do not appear to have been specifically calibrated for the vessel in question so some unexpected results are not altogether surprising.

D.3.3 Part 3 Structural Reliability Process Definition

D.3.3.1 Chapter 7. Terminology Associated with Structural Reliability

An extreme set of definitions is presented on loads, strength and structural reliability. These are most useful.

D.3.3.2 Chapter 8. Extrapolation Techniques for Design Loads

Techniques for estimating extreme lifetime wave loads based on short-term and long-term procedures are presented.

Derivation of design loads exploiting both short- and long-term approaches are discussed, the latter usefully including a parameter to account for the particular risk level sought, e.g., 1 in 100.

D.3.3.3 Chapter 9. Serviceability Limit States

Plate buckling is identified to be a relevant serviceability limit state. Corresponding expressions are given for both elastic and inelastic buckling in compression and shear.

For fatigue, one of the procedures summarised in Chapter 9 of SSC-351 is presented in more detail.

D.3.3.4 Chapter 10. Limit States Associated with Lifetime Extreme Loads

This appears to be a re-presentation of Chapter 4 of this report only with some further, albeit little, detail and a different classification of some of the failure modes.

D.3.4 Chapter 11. Conclusions and Discussion

A summary of the study results is presented.

The benefits and drawbacks of using probability-based design promulgated in SSC-351 are regurgitated, although augmented by further benefits reported in the literature relating to comparison of competing designs, inspection/maintenance strategies, minimum life-cycle costs, and a tool for managing uncertainty in engineering problems.

Recommendations for future research are presented based on the work reported to SSC to date by the author and a review of the CMS research recommendations. These are commented upon in turn.

1. Torsional/flexural buckling - a number of formulations are already in existence. An alternative philosophy exists for bridge structures in which torsional buckling of stiffeners is eliminated through restrictions on slenderness. This has the added bonus of eliminating the need for tripping brackets, an expensive and time-consuming constructional feature although it may suffer a weight penalty.
2. Ship hull girder ultimate strength - simplified procedures already exist for this supplemented by a number of analytical techniques that can be relatively easily exploited.
3. Hull girder experiments - a number of very suitable test results exist but more are needed to cover geometries not represented by these. However, the most important use of experiments these days is to substantiate numerical analysis and this does not necessarily need tests that are fully representative of ship structures although there are considerable benefits in ensuring appropriate compatibility exists.
4. Wave data for design wave loads - considerable data already exist and is constantly being updated via satellite records.
5. Sag to hog wave bending ratios and biases on linear wave load motions - non-linear analysis techniques exist for quantifying sag to hog ratios and biases on linear wave load motions but may need supplementing by results from full-scale measurements.

6. Combined wave and slamming - exploitation of existing information seems to be required but after 7 has been conducted.
7. Slamming effects with consideration of shear as well as bending - possibly the exploitation of advanced analysis techniques supplemented by full-scale data.
8. Hull girder target reliabilities based on existing ships - ensure all the tools are in place first.
9. Local structure target reliabilities - introduce philosophy of component v system reliability differentiation, perhaps one order in probability of failure terms.
10. Life cycle costs - application of existing techniques.
11. Inspection intervals and maintenance - benefits are not necessarily as high as originally envisaged.
12. System considerations in fatigue and multiple failure modes - fatigue is designed out by using appropriate safety factors on serviced life (times two perhaps) whilst multiple failure modes may be unusual and probably need consideration on a case-by-case basis.
13. Transverse structures and lateral pressure effects - lateral pressure effects do need more consideration with an emphasis on numerical solutions substantiated by carefully selected tests.

APPENDIX E

REVIEW OF REPORT SSC-371

ESTABLISHMENT OF A UNIFORM FORMAT FOR DATA REPORTING OF STRUCTURAL MATERIAL PROPERTIES FOR RELIABILITY ANALYSIS

by L N Pussegoda, A S Dinovitzer and L Malik

E.1 OBJECTIVE

1. To review the existing database (created by SSC-352) to ensure that it incorporates all the data required in current and potential design practice.
2. To ensure the format is suitable for use in reliability-based design.

E.2 AIMS

1. To develop a material property database format that efficiently and effectively stores individual test information and results on ship structural steel and their weldments tensile and toughness properties.
2. To specify the requirements of a program which will act as a user interface in the retrieval, manipulation and quality assurance of the collected data.

E.3 REVIEW

Review incomplete.

APPENDIX F

REVIEW OF REPORT SSC-373

PROBABILITY BASED SHIP DESIGN; LOADS AND LOAD COMBINATIONS

by A Mansour and A Thayamballi

F.1 OBJECTIVE

The Objective of this work is to define characteristics of ship design loads suitable for use in reliability analysis, and to recommend load models and load combination procedures for use in as subsequent SSC phase on 'Implementations of Design Guidelines for Ships'.

F.2 METHOD OF APPROACH

This is not specifically spelt out but is covered in passing in an analysis of the problem.

F.3 REVIEW

F.3.1 Chapter 1. Introduction and Literature Survey

Several methods for load combination are reviewed: they are all reliability-based techniques. While specific combinations are considered later in the report, it does not approach the problem of load combination in the more traditional sense of existing Load and Resistance Factor Design (LRFD) or Limit State Design (LSD) codes such as API RP 2A-LRFD (1993) or BS 5400: Part 3 (198X) where load combinations have been determined on a historical basis or identified by a committee or group specifically set up by the code-writing organization with the responsibility of selecting appropriate load combinations to be considered by the code.

F.3.2 Chapter 2. Loads for Probability-Based Design

In Chapter 2, Loads for Probability-Based Design, relevant loads are covered under categories concerned with global, local pressure, fatigue and special loads. The need to account for the temporal and spatial variations of some of these is noted, as are the problems of load correlations for which simple expressions are given to determine conditional expected and variance values given the correlation coefficient between two load components.

F.3.3 Chapter 3. Extreme Loads and Load Combinations

Chapter 3 is concerned with extreme loads and combinations. It is divided into three sub-sections that examine hull girder loads, local load and combined girder and local loads.

Two and three correlated load effects are considered in some detail in Section 3.1.2 based on earlier work by the senior author and ABS. (In this, stresses are denoted by 'f' in Section 3.1.2 A and by 'σ' in Section 3.1.2 B which is confusing particularly since σ is also used in Section 3.1.2 A to denote standard deviation.) These combinations are aimed at maximum vertical and horizontal moments and torsion under low frequency wave excitation. They involve the use of correlation coefficients between the components under consideration. They result in a probabilistic load factor by which the secondary load component is added to the primary load component to generate the combined load. The available information on such correlations seems mainly to be based on full-scale data whereas the increasing use of 3D motions analysis computer programs may eventually supersede the need for such simple but useful techniques.

For combined low frequency wave-induced and springing loads (Section 3.1.3), the two correlated load effects methodology is exploited. Again full-scale data are used to indicate possible levels of correlation between the two components and relative stress levels.

The combination of low frequency wave-induced and slamming loads is considered in some detail in Section 3.1.4, even to the extent of using a FORM solution to complete the approach. The two correlated load effects methodology is discussed in relation to this but, unexpectedly, not exploited in this section. Instead, it is covered in Section 3.1.6, seemingly successfully, since previous work, including that of Nikolaidis and Kaplan (SSC-363), suggests the correlation between these two sources of loading is minimal (widely separated source frequencies).

Section 3.1.5 considers the addition of stillwater loads through determination of the short term, the long term and then the extreme long term distributions. Could not the two correlated load effects methodology also be exploited in this case?

Local Loads are considered in Section 3.2 concentrating on wave low frequency and slamming pressures and cargo inertial loads. Load combinations are considered through the two correlated load effects methodology and phase differences discussed.

Combined hull girder and local loads are discussed in Section 3.3 using the two and three correlated load effects methodologies. These are demonstrated using results from full-scale measurements. Critical load combinations are identified concentrating on the mid-body and forward quarter body regions.

F.3.4 Chapter 4. Fatigue Loads, Load Models and Load Combinations

Fatigue is dealt with in Chapter 4, firstly via a design approach and secondly via an analysis methodology. The design approach, based on the S-N technique, assumes the long term stress distribution is fully defined through the use of a pre-defined distribution (Weibull) and an extreme nominal stress range that accounts for the combined effect of all loads at the detail under consideration. Both the 'linear' and 'bilinear' S-N curve solutions are given. The Weibull shape parameter is used to differentiate between details and their locations around the hull as demonstrated in the report based on the ABS Double Skin Tanker Guide and its predecessor. A comparison is presented here in Figure F.1 between values of the shape parameters to be adopted for different locations on a vessel as given by the ABS Guide and by Cramer et al (1995) as reportedly adopted by DNV. (The latter paper provides an example fatigue analysis with and without appropriate simplifications.)

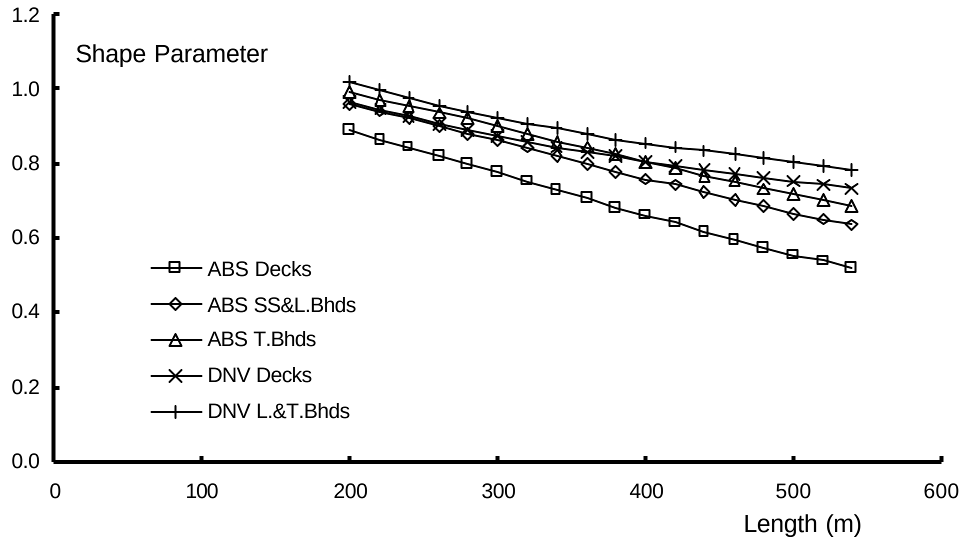

Figure F.1. Comparison of ABS and DNV Weibull shape parameters

Some details of the spectral fatigue methodology are presented in Section 4.4 including an extension to account for variation of the wave profile along the sideshell together with consideration of forward speed and direction of heading relative to the waves.

F.3.5 Chapter 5. Modelling Errors

Modelling errors are dealt with in Chapter 5 and begin with a summary of the findings reported in SSC-363. Weaknesses and inaccuracies contained within these results are reviewed. Important factors are:

- spectral shape variability
- visual wave data uncertainty
- heavy weather countermeasures especially for smaller vessels
- stillwater load control (Table 5.2 suggests bulk carriers in ballast are more critical than tankers when loaded - why was this fact not specifically cited in the report)
- omission of non-linearities in sagging-hogging moment assessment
- local pressures particularly external
- the possible success of SRSS (square root of sum of squares) for load combinations
- FE modelling errors
- fatigue damage prediction.

Two load combination procedures are reviewed, the in-phase out-of-phase method and the K-factor method: the latter was used extensively earlier in the report. They are noted to be essentially identical provided the bandwidth parameter is less than 0.65. The advantage of the latter is that it is in a form not dissimilar to some limit state design code approaches to combining primary loads with secondary loads.

F.3.6 Chapter 6. Impact of Operational Factors on Design Loads

Chapter 6 discusses the impact on design of, firstly, storm avoidance and ship routing and, secondly, heavy weather countermeasures. Operational aspects of these are discussed together with some statistics concerning the latter. As for all 'mobile' structures, human factors significantly influence their perceived and actuarial levels of safety.

APPENDIX G

REVIEW OF REPORT SSC-375

UNCERTAINTY IN STRENGTH MODELS FOR MARINE STRUCTURES

by O Hughes, E Nikolaidis, B Ayyub, G White and P Hess

G.1 OBJECTIVE

The Objective of this project is to develop and demonstrate a method for quantifying the bias and uncertainty in structural strength algorithms (or computational models) in order to further the overall goal (i.e., the long-term effort to develop a reliability-based method for the structural design of ship structures).

G.2 METHOD OF APPROACH

1. Develop a methodology for the modelling and analysis of uncertainties in strength parameters. The methodology should be suitable for the development of a reliability-based design method for ship structures. Strength parameters include both basis strength variables and strength predictors. The uncertainties include bias and randomness for the basic strength variables (e.g., yield stress, dimensions, sizes, etc), and model uncertainties in strength predictors (e.g., buckling strength, plastic capacity, etc.).
2. Identify the failure modes of the principal structural members of ships.
3. For the failure modes that involve modelling uncertainty, review the availability of sufficient data to demonstrate the method,
4. On the basis of this review, determine which failure mode is most suitable for this demonstration
5. For the selected failure mode (panel compressive failure) collect data about strength parameters and apply the method to assess the uncertainties in the strength parameters.
6. Determine further research needs for uncertainty modelling and analysis of strength parameters.

G.3 REVIEW

G.3.1 Chapter 3. Methodology to Assess Uncertainty in Strength Parameters

This section begins with a summary of definitions of uncertainties including those appropriate to Bayesian statistics. Some relative importance measures are introduced but the derivations are confusing because the same notation is used to describe different events. For example, in equation (3.50a), ΔX_{Pi} is defined as:

> the change in the mean value of the predicted strength due to the change in the *mean value* of the ith basic variable

whereas in equation (3.52a), ΔX_{Pi} is defined as:

> the change in the mean value of the predicted strength due to the change in the *coefficient of variation* of the ith basic variable.

The consequence is that the resulting simplified equations, namely, (3.50b) and (3.52b), appear identical yet are not. Similarly, equations (3.50a) and (3.54a) are defined identically but because the different processes of involved in the derivation, namely, perturbations of the *means* versus *standard deviations*, the resulting equations, (3.50b) and (3.54b), are different.

G.3.2 Chapter 4. Methodology to Assess Uncertainty in Strength Parameters

Chapter 4 deals with Failure Modes and Strength Assessment Models. It indicates that the problem identified in 1987 of the lack of accurate and efficient algorithms for limit state evaluations and the absence of corresponding computer implementations had been resolved through the publication of Hughes' book on Ship Structural Design (SSD) and development of the MAESTRO computer program. While accepting these developments have helped reduce the problem, strength formulations are never sacrosanct, particularly with ISO code developments for offshore structures in full swing, and the need of most designers/analysts for strength formulation computer coding that they can implement into their own programs or independent software other than MAESTRO.

Mention is made in the section concerned with the Necessity of Experimental Data (4.2.1) about the ability of some industries to mount large test programmes that enable comprehensive ranges of tests to be conducted to identify most/all the relevant failure modes. Seemingly implicit in this is that the shipbuilding industry is unable to mount similar programmes and thus generate the data necessary for the substantiation of appropriate strength models. This does not seem to be born out by at least some evidence that such large-scale tests have been performed such as:

- GKSS one-twelfth and one-seventh scale bow and sideshell impact test of the late 1960s and early 1970s (Woisin 1976)
- Eurotom one-fifteenth scale bow and sideshell impact tests (CETENA 1971)
- large number of impact tests in Japan
- joint Japanese-Netherlands grounding tests
- Norwegian reliability studies for marine structures
- EU-funded programmes on reliability of ship structures
- USA work on double-bottom hulls.

The opportunities to undertake relevant tests do seem to have been there. The inadequacy of the resulting databases both in terms of test numbers and ranges of tests must rest with the organizations involved, particularly at a local level. The inadequacies in the databases have long been known, as pointed out in the ISSC Proceedings over many years.

The criteria adopted for selection of the failure mode for further treatment are not unreasonable. However, the example chosen could be considered too simple in that sufficient data are available from which to determine modelling accuracy. A more challenging problem would have been to select a mechanism for which only limited data were available and demonstrated how one might proceed in such a case. This constitutes a frequently encountered problem in the lives of reliability analysts.

G.3.3 Chapter 5. Algorithms and Data for Compressive Collapse of Stiffened Panels

Chapter 5 deals with the algorithms and available data for the chosen failure mode of compressive collapse of stiffened panels. It initially identifies what is termed the 'standard algorithm' as adopted in SSD, claiming that it was originally developed under the guidance and sponsorship of the Merrison Committee. The formulation developed under the auspices of the Merrison Committee basically treated axial compression and did not account for lateral loading effects. The formulation developed in SSD is thus a derivative of the original algorithm.

In the survey of available algorithms, it is disappointing to record that the latest date of the cited publications as 1980. The works of Davidson et al (1991) and Bonello et al (1993) [based on the PhD thesis by Bonello (1992)] on stiffened plates subjected to compression and lateral pressure seem to have made important contributions to the development of this technology and their omission is of concern.

The survey of current code-based design practices (5.2) seems limited. While it might be expected to concentrate on ship-oriented rules, it also contains reference to USA onshore codes that are, or were expected in the near future to be, in a LRFD (Load and Resistance Factor Design) format. There does seem to be some important omissions bearing in mind that the shipping industry is international and that considerable effort has been undertaken to develop LRFD codes (or Limit State codes as they tend to be known as in Europe). Some useful additions might be:

- API RP 2T, Recommended Practice for Planning, Designing and Constructing Tension Leg Platforms (and associated Bulletins 2U, Stability Design of Stiffened Shells, and 2V, Design of Flat Plate Structures)
- API RP 2A-LRFD, Recommended LRFD Practice for Planning, Designing and Constructing Fixed Offshore Platforms, June 1988 (Draft).
- Eurocode No 3, Design of Steel Structures, Draft 5, 1990.
- Canadian Standards, Preliminary Standard S473-M1989, Steel Structures Part 3 of the Code for the Design, Construction, and Installation of Fixed Offshore Structures, February 1989.
- ISO 2394, General Principles for the Verification of the Safety of Structures, First Edition - 1973-02-15.
- ISO 2394, General Principles on Reliability for Structures, Second Edition - 1986-10-15.

The sources of data noted to be available (5.3) on axially compressed stiffened panels is limited to three. Appendix K of this report lists the references recently collated by the author in support of a review project on stiffened panels subjected to axial compression and lateral pressure. It amounts to 49 citations of which only three are post-1990. The major concern with the test series identified by the authors as being appropriate is that they relate only to single bay models. Such models are notoriously difficult to test with confidence because:

- without strain gauges distributed along the length of the panels it is extremely difficult to, for example, apply pure axial compression without the introduction of bending arising from initial plate out-of-flatness and initial stiffener out-of-straightness,
- if pure axial conditions are realized at low load levels, then plate-induced failure (Mode II) is the only likely failure mode,
- if stiffener-induced failure is required, then the axial load has to be applied eccentrically and this cannot be effected again without the extensive use of strain gauges.

Continuity effects in stiffened panel behaviour are particularly important as noted by Carlsen (1980). These clearly are not reflected in single span tests.

G.3.4 Chapter 6. Demonstration of Uncertainty Assessment for Collapse of Stiffened Panels

Chapter 6 presents the main section of the report, namely, Demonstration of Uncertainty Assessment for Collapse of Stiffened Panels. It describes the test data selected in Chapter 5 in some detail, starting with what is described as ‘Faulkner’s nominally identical series’. The geometry of this set is apparently used in the uncertainty analysis but this, confusingly, is never clearly spelt out.

In the section devoted this particular test series (6.1.1), the randomness of the geometry and material variables to be used in the analysis is determined. Where information is available from the test measurements, this is used. Otherwise, previous experience or values deduced from other experimental results are adopted. The values proposed for the uncertainty analysis (Table 6-1) are generally reasonable but it seems difficult to believe that it is worth retaining COV values (on geometry variables) of less than 1% except in relation to plating thickness. A COV of 1.5% on elastic modulus means it can be treated as deterministic. The large COV on eccentricity is representative of stiffened plate initial imperfections although it could be argued that since stiffened plates are generally constructed to particular tolerances, it is only the variation around the maximum that is strictly of relevance. (This seems analogous to the problem of the uncertainty associated with wave-induced forces, it is only the distribution of the maximum values that is of importance in an ultimate strength reliability evaluation.)

In Table 6-1, the mean value of plate yield stress is reported to be smaller than the nominal value. This would not be acceptable in practice and its use in the uncertainty analysis can be expected to affect the interpretation of the results.

The selection of the second and third data sets (6.1.2 and 6.1.3) involving 'Faulkner's parametric series' and Panels A6 and H: Michelutti is difficult to follow. Having focused in on Faulkner's nominally identical series to form the basis of the uncertainty analysis, there seems no need for further data series especially when the selection raises questions as to:

- why are flat bar stiffeners ignored and only T-stiffeners considered
- why was a panel pre-disposed to fail in Mode I ignored when the extent of eccentricity of the loading was known.

The results of the uncertainty analysis are presented in two sections, 6.2.1 which is concerned with the strength results and 6.2.2 which addresses sensitivities to the basic variables.

The opening section on strength, 6.2.1, somewhat unexpectedly, indicates that the analysis will consider transverse inplane loads and lateral pressure in addition to axial loads. Most of the preceding discussion and description has concentrated on axially loaded stiffened plates with little indication that these additional load patterns were to be considered. According to the information presented in Appendix B on the standard algorithm, only one comparison has been conducted using this algorithm against test data involving the presence of lateral pressure and none when transverse load was present. The algorithm does not explicitly account for the effect of pressure on plate response, dealing only with the effect from a stiffened plate viewpoint. The work of Davidson et al (1991) clearly demonstrates that plate behaviour and strength are influenced by the presence of pressure and that this needs to be recognised in the assessment of stiffened panel strength. The accuracy of the standard algorithm does not seem to have been established in connection with lateral pressure or transverse loads.

To include the effect of the uncertainty associated with the effect of welding residual stresses, additional simulations are performed, one involving Faulkner's algorithm because it explicitly accounts for residual stress levels. It would have been instructive if the uncertainty as expressed by COV that was derived from this process had been reported directly rather than indirectly later in Table 6.4.

The observations made of the findings of the analysis based on inferences from the graphically presented results could have been considered further. For example, observations 1. and 2. (Page 42 of the report), comment on the variation of standard deviation without seemingly putting it into context that such variations are not unexpected since the means are changing substantially. What is of more interest is whether the coefficient of variation is also changing. In Figure 6.3, it does, reducing form 14% for the lower levels of axial strength to 8% at the higher levels. Further, differences are noted to exist between the calculated and nominal strengths because of differences, or lack of, between the mean and nominal values of some of the basic variables. The latter point, whilst very clearly a correct interpretation of the results, reflects a possible poor choice of nominal and mean values for the study. An examination of the figures without a careful reading of the text might encourage a reader to believe that stiffener-induced failure was far more reliable than plate-induced failure because the former coincides with the mean minus two standard deviation whilst the latter coincides with the mean.

The generally different hierarchies of rankings obtained from the sensitivity coefficients makes difficult one of the perceived advantages of this form of analysis, that is, in the words of the authors ‘They can be used to allocate resources in design and in collecting data for the statistical properties of the random variables’.

The notation used in Tables 6.5 to 6.10 without definition is unhelpful. The relatively high ranking of stiffener elastic modulus in Mode I failures is surprising.

The section on Results for modelling uncertainty (6.3) is not easy to follow. To begin with, modelling uncertainty is defined in terms of equation (3-3), i.e.,

$$B_1 = X_A / X_E$$

where X_A is actual strength and X_E is experimental strength. This is completely contrary to the interpretation of the same equation made by Nikolaidis and Kaplan (SSC-363) where modelling uncertainty is given by X / X_P where X is defined as the actual value and X_P is the theoretical prediction thereof. The actual value is taken by Nikolaidis and Kaplan to be coincident with the experimental value where appropriate. In some cases, it may relate to field measurements such as wave heights and similar.

The interpretation by Nikolaidis and Kaplan is the one almost universally adopted by structural reliability analysts.

Equation (3.3) is one term of the Ang and Tang definition of total bias B. The complete expression is

$$B = B_1 B_2 B_3$$

where $B_2 = X_E / X_P$, $B_3 = X_P / X_D$ and X_D is the design value. The authors claim to determine modelling bias by calculating the total bias, presumably defined by X_A / X_D, and using the definition of B_3 together with the random bias evaluated in section 6.2 but what term corresponds to the random bias? The authors then indicate that the modelling bias cannot be calculated from equation (3.3), i.e., B_1, because this would require calculation of the predicted strength. Since in B_1, X_E is the experimental strength, the authors now seem to be equating their predicted strength with X_A, i.e., their predicted strength is the actual strength. This is further confused in the section dealing with Parametric series on page 51 where the total bias is given in Table 6-13 as the ratio of the experimental strength to the nominal strength, i.e., X_E / X_D which seems to contradict their earlier definition.

The several paragraphs within section 6.3 devoted to ‘uncertainty in panel end rotational restraint’ seems entirely out of place. In the light of the comments made above about the selection of relevant test data, some justification is required for using only single panel length models: the presented arguments are not felt to be adequate. The apparent lack of test data seems to be more a problem of collation than fact. The torsional rigidity inherent in open section cross frames is agreed not to be significant. The fact that multi-bay panels are approximately identical so they will all approach collapse at the same time is difficult to justify. As demonstrated in the Figures in Appendix B, stiffened panel failure even in the presence of low levels of lateral load, fail with alternate directions of buckles in adjacent stiffened panels, and the strengths of panels failing in Mode I can be significantly different from the strengths of panels failing in Mode II as evidenced by the authors in Figures 6-2 to 6-9. Here, Mode I strengths are presented in Figures 6-2 to 6-5 with the corresponding Mode II strengths in Figures 6-6 to 6-9. There are substantial differences between the two for each corresponding pair both without and with pressure present. Carlsen (1980) has probably provided the most appropriate interpretation of the behaviour of stiffened panels subjected to compression only. This is, in the words of the present author, as follows:

> With the general predilection for stiffened panels under the action of welding residual stresses to initially deform towards the stiffener, low levels of load are likely to simply amplify these. As the load level increases, the panels with the larger levels of initial deformation will begin to dominate and the alternating pattern of deflections in adjacent panels will emerge. Because the panel with the plate in secondary compression, i.e., the panel with the larger initial deformation, is less flexurally less stiff than the (adjacent) panel with the stiffener subjected to secondary compression (because the plating is not generally fully effective), the growth in deflection is driven by this panel. However, because the lever arm to the stiffener outstand (tip) is always significantly greater than that of the plating, yielding always occurs first in the outstand of the stiffener of the panel deflecting towards the plating. This yielding does generally signify that collapse of the stiffened panel is imminent.

In design work performed by the author involving stiffened panels subjected to pressure and axial compression, where the pressure has been sufficient to effectively clamp the stiffened plating at the cross frames, first yield is found to occur in the stiffener outstand at the cross frame location. Thus, failure is not triggered by a response typical of a single span model.

G.3.5 Chapter 7. Conclusions and Recommendations for Future Research

In the section devoted to Recommendations to future research (7.2.1), including the need to introduce the additional work reported in Appendix A: Review of stiffener tripping, the concern over stiffener buckling/tripping seems a little misplaced. This problem was addressed in detail by Chatterjee (1978) as part of the development work that led to the local cross-sectional requirements for flat, angle- and T-bar stiffeners in BS 5400: Part 3 (1982). The criteria account for local buckling, tripping (≈flexural-torsional buckling for a stiffened plate) and included interaction with the plating. The criteria were calibrated against the ten one-quarter scale box girders tested at Imperial College in the early 1970's involving flat and angle-bar stiffeners (Dowling et al 1973).

Similarly, it might appear that the advances made in general in the late 1970s and early 1980s leading to revisions of the bridge and building codes in UK and Europe were possibly adequate to deal with the problem of flexural-torsional buckling of beams. In an effort to implement procedures for the reliability assessment of ship structures, large and full-scale results are needed, such as those of Dowling et al 1973, Lamas et al (1983) that dealt with the problem of shear lag, Mansour et al (1990) tests on closed and open deck vessels, and Dow (1991) involving a one-third scale frigate test.

APPENDIX H

REVIEW OF REPORT SSC-387

GUIDELINE FOR EVALUATION OF FINITE ELEMENTS AND RESULTS

by R I Basu, K J Kirkhope and J Srinivasan

H.1 OBJECTIVE

To provide a method for evaluating finite element models and results (for ship structural assemblages), and also FEA (finite element analysis) Software.

H.2 AIMS

To develop an assessment methodology on three levels pertinent to linear elastic static FEA, and linear dynamic FEA involving natural frequency and mode calculations only.

H.3 REVIEW

The report is divided into five main Parts of which the first and last, Introduction and Conclusions and Recommendations, consist of one section and the remaining three of up to five sections.

H.3.1 Part 1 Project Overview - Introduction

The need for the methodology is discussed and introduced. It is on three levels, namely,

- Level 1 - a check list of attributes of the FEA that need to be evaluated
- Level 2 - a detailed version of Level 1 for which Level 1 acts as a summary
- Level 3 - guidelines on acceptable FE modelling practice cross-references with the Level 2 checklists.

H.3.2 Part 2 Assessment Methodology for Finite Element Analysis

The Level 1 check is divided into five main categories, each of which is sub-divided into between four and six sub-categories. For every sub-category, a list of detailed checks is provided to be assessed at Level 2 each with a cross-reference number to the guidelines themselves. The complete set of forms at both Levels 1 and 2 are presented.

H.3.3 Part 3 Guidelines for Assessing Finite Element Models and Results

The guidelines are prepared following the sequence of Level 1 and Level 2 checks.

H.3.3.1 Chapter 1. Preliminary Checks

These cover documentation, job specification and FE software requirements, reasons for using a particular FEA software package and personnel competence.

Complete documentation is clearly essential including software manuals. A job specification is required to ensure the FEA is performed to that specification. This includes a justification for using FEA in preference to alternative approaches, including experiments.

Requirements for finite element software include an assessment of the vendor's quality system. Three methods for validating such software are independent analysis, experimental results, and service experience. It is correctly noted that a comprehensive set of verification examples, whilst convincing, do not constitute a proof. The results from other FEA solutions do, of course, provide appropriate validation exercises assuming they are well established and documented or are consistent with other benchmarks. The maintaining of a register of validation exercises is an extremely worthwhile undertaking.

The importance of personnel competence cannot be over-emphasised. The authors note that two groups of personnel are involved, the analyst and the checker. Their requirements in respect of experience differ. The authors offer the experience requirements prepared by NAFEMS as an appropriate set of minimum requirements.

H.3.3.2 Chapter 2. Engineering Model Checks

These are to check the idealization of the structure and cover analysis type and assumptions (static, dynamic, linear, 2D v 3D), geometry assumptions (how much is required, do parts of the structure offer effectively stiff supports, exploiting St Venant's principle), material properties (account for temperature and strain-rate dependencies), stiffness and mass properties (warping effects usually neglected in beam elements but which are important for open cross-sections, shear stiffness in short beams is of importance and may be overlooked, lumped v consistent masses for dynamic analyses, more refined mass distribution for higher dynamic modes, added mass from fluid interaction), dynamic degrees-of-freedom (the lumping of masses, specific guidance on dynamic degrees-of-freedom), and loads and boundary conditions (for ships, extract from Gianotti & Associates 1984 lists typical loads).

H.3.3.3 Chapter 3. Finite Element Model Checks.

This is a relatively comprehensive section covering element types, mesh design, substructures and submodelling, loads and boundary conditions, and solution options and procedures.

For element types, guidance includes:

- avoid large numbers of simple elements and small numbers of very complex ones
- linear elements to a relatively fine mesh are usually good in areas of special interest, e.g., discontinuities, thermal gradients, etc.

- at gradients, the orders of the element stress functions must be compatible
- higher order elements may be limited in type so mixing may be a problem.

An appreciation of the structural action to be modelled is important. For example, use truss elements for braces of triangulated structures but beam elements for the chords, and membrane elements for decks involving inplane load only, but plate bending elements in the case of out-of-plane loading. Remember, a number of elements do not account for shear at all or only as an approximation. Solid elements are clearly appropriate where through-thickness behaviour is important.

Mesh design can be critical. Generally, the steeper the gradient, the more refined the mesh. The balance is between accuracy and cost (usually time-wise). If deflections are only of interest, fewer elements are required. For non-linear or vibration analysis, the reverse is true. Higher frequencies need more refinement than lower frequencies. Localized loads require more refinement than distributed loads. For plane elements, aspect ratios must be limited, three for stresses and five for displacements. Square shapes are preferred to quadrilateral and triangular elements should be equilateral. Skewing and warping of elements degrades performance. Mesh transitions should always be gradual and mesh generations may need assistance to realize an appropriate gradation. Transitions should not be attempted in regions of high stress or deflection gradients. A rule-of-thumb is provided: ideally, the strain energy in each element should be constant.

Stiffness ratios in adjacent structure should not exceed 10^4 to avoid ill conditioning. Rigid sections of structure on flexible supporting structure are usually better treated by converting them to rigid bodies with appropriate links. Care is required in linking elements of different type because of incompatibilities with regard to degrees-of-freedom. Solid elements only have translational degrees-of-freedom whereas beams and plate/shell elements also have rotational ones. When linking such combinations, constraints may be required or the beam (or plate) extended through the solid element. Most plate/shell elements do not have a shape function for rotation normal to the plane of the element, i.e., inplane rotational stiffness is not modelled.

Substructuring is used to reduce computational effort and where core capacity is limited, but can be software dependent. Basic steps in substructuring are presented together with appropriate guidelines. The technique of static condensation, exploited in substructuring, is demonstrated. An alternative to substructuring, the two-stage analysis, uses a coarse mesh to obtain displacement boundary conditions to be applied to a more refined representation of a local part of the structure. The displacements to be applied to new boundary nodes in the refined mesh are found by linear interpolation. The refined mesh is usually more flexible than its coarse mesh equivalent. The stress resultants can be factored up by the ratio of stresses found from the global model to stresses found from the refined model. This is best done using vector norms of the forces involved as described in the report.

Ships, being supported by a pressure distribution around the hull, are prone to support problems. Models in 2D must have two translations and a rotation constrained to avoid inappropriate rigid body motion. Guidance is given on the introduction of such supports. Conditions where symmetry can be exploited are discussed. Care is required to ensure wanted modes are not unnecessarily suppressed.

Constraints, i.e., the coupling of degrees-of-freedom between several nodes, can be used to enforce symmetry on equal displacements between different element types. Releases can be introduced through coupling. Some FEAs offer constraint equations, a linear equation relating translations or rotations at nodes.

Loading can simply be applied as forces or displacements at nodes, remembering that some elements may not have all the degrees-of-freedom relevant for the desired loading. Face pressure may be applied to the faces of some elements: it acts perpendicular to that face. Some FEA software allows pressure to be applied at nodes so that pressure gradients can be easily introduced. Edge loads can be applied to membrane and plate bending elements, and to beams. Thermal loads can be applied directly or, in some cases, by specified nodal temperatures with temperature-dependent material properties. Inertia loading covers translational and angular accelerations and angular velocity. Weight is treated differently among FEA and usually needs to be handled with care.

On solution options and procedures, three types are considered: static, dynamic and buckling. Only the second is considered at any length, referring to the Design Response Spectrum Method, direct integration, modal superposition, and transient response analysis.

H.3.3.4 Chapter 4. Finite Element Results Checks

The importance of this is emphasised. Some checks specifically identified include:

- errors and warnings - dependent upon the FEA software
- verify mass and centre of gravity - apply a 1g loading if necessary
- self-consistency
- static balance, i.e., reactions equal loads
- ensure FEA software defaults are correct
- a checklist is provided - it should be followed.

When examining displacement output, remember displacements are determined more accurately by FEA than stresses, beam and plate bending elements may be plotted using straight lines but are calculated using a cubic polynomial, higher order modes will be less accurate than lower order ones, and in 2D and 3D problems, the accuracy may differ with direction.

Because stress results are less accurate, many FEA outputs average nodal stresses. Plotting stress contours indicates qualitative rates of change which can be investigated in more detail if not smooth or too close. Stress discontinuities can occur between lower order 2D and 3D elements because of their limited displacement functions. When checking for possible buckling (via a linear analysis), use the orthogonal stress fields not equivalent stresses like von Mises.

H.3.3.5 Chapter 5. Conclusions Checks

When quantifying the accuracy of FEA results, remember many closed-form solutions are limited in their application. The accuracy of the load description needs to be assessed. Design equations for strength implicitly account for buckling, initial imperfection and residual stress effects, and inaccuracies in loading and boundary conditions. The results from linear FEA contain none of these so care is required when trying to compare the two. Other simplifications in the FEA need to be remembered, joints are not modelled in detail, and inplane results may have been determined when out-of-plane are also important.

H.3.4 Part 4 Benchmark Problems for Assessing FEA Software

H.3.4.1 Chapter 1. Introduction

The aim is to provide suitable benchmark problems for ship structure analysis.

The use of benchmarks by FEA developers is emphasised as usually aiming to verify one specific aspect of the code. The example selected may have little in common with practical solutions. Thus the benchmarks presented seek to redress this imbalance. They are intended to be rigorous but not over-demanding on resources. Because of the absence of a relevant closed-form solutions for the problems selected, the results of three separate FEA solutions are used to provide a basis for the benchmarking.

H.3.4.2 Chapter 2. The Benchmark Problems

The problems selected were:

- a reinforced deck opening, including deck stiffening and two deck plate thicknesses,
- stiffened plate under pressure loading using four different FE models, in particular, beams and plates for the stiffeners,
- vibration isolation system involving a point mass including rotational inertia terms, spring elements with stiffnesses in three directions, and rigid beam elements,
- mast structure incorporating inertial loading in three directions, two materials and modal analysis,
- bracket connection detail is a fatigue-prone detail incorporating 3D geometry, shell elements of varying thickness, coarse to fine mesh transitions, and prescribed displacement boundary conditions. A singularity (infinite stress) exists in the solution and, practically, the stress must be determined a finite distance from this location.

Full details of the benchmarking exercises are presented in Appendix D of the report.

H.3.4.3 Chapter 3. The Benchmark Test FEA Programs

The FEA software selected is ANSYS, MSC/NASTRAN and ALGOR. This represents an appropriate selection.

H.3.4.4 Chapter 4. Application of Benchmarks for Assessing FEA Software

Very usefully, the input data for the benchmarking exercises are available to those who wish to conduct their own benchmarks. As expected, differences between the results were expected and obtained. The authors provide criteria for acceptance, as follows:

- Category 1 - displacements, reaction forces and lower mode natural frequencies - within 2%,
- Category 2 - beam and plate element stresses and higher mode natural frequencies - between 2 and 5% provided there is a reasonable explanation for differences greater than 2%,
- Category 3 - greater than 5% is generally unacceptable.

H.3.5 Part 5 Conclusions and Recommendations

The conclusions briefly summarise the contents of the report. The recommendations include:

- obtaining feedback of exploiters of the assessment methodology to refine it as necessary
- expanding the scope to include dynamic response, non-linear behaviour, and composite materials
- the starting of a library of well documented numerical and experimental results, beginning with the present solutions
- the development of design criteria which take account of the differences arising from FEA solutions compared with traditional assessments and designs.

In connection with reliability-based developments, some of these recommendations are highly pertinent. For example, limit state design equations require data and information pertaining to the strength of components. This is obtained through experiments or carefully performed numerical solutions. The latter require more than just the introduction of material and geometrical non-linearities. Because real structural elements contain unavoidable shape imperfections and residual stresses, both constructional and welding, these must be incorporated within any FEA to enable realistic results to be generated. Selecting appropriate levels for such shape imperfections and residual stresses is an exacting task.

Dynamic loading and response can have a significant impact on the behaviour of vessels and their components. At a local level, strain-rate effects lead to increased strength. This extends to global analyses as well to which inertia loading must be added and the complication of, for example, bow immersion, greenwater on decks, etc.

A well-documented library could be an asset but does require well experienced staff to perform any updating and upgrading. Just as criteria have been developed to linear elastic FEA, relevant criteria could be developed for non-linear FEA, dynamic FEA, and ultimate strength and fatigue tests. With a view to avoiding disagreements concerning the accuracy of proposed limit state equations because different databases have been used in the process, such a library would prove invaluable.

Another possible use for such a library might be to provide a basis for the assessment of competence of personnel, organizations, FEA software, test facilities, etc. With the growing sophistication of hardware and software, and operations that individuals are expected to perform, and the implementation of quality assurance at all levels, the availability of such a library would facilitate personnel and organizations achieving required standards.

H.3.6 Appendices

Four appendices are presented, namely,

A. Evaluation Forms for Assessment of Finite Element Models and Results - these are blank forms for the Level 1 and Level 2 assessments, reviewed in Section H.3.2, in a form ready for immediate use.

B. Example Application of Assessment Methodology - a sample application of the methodology applied to an arctic tanker web frame and undertaken by an independent organization.

C. Examples of Variations in FEA Modelling Practices and Results - presents the results of the analyses of three structures (stiffened panel, multiple deck openings, and mast) each of which is examined with different modelling approaches, namely, the use of different elements, and mesh refinement.

D. Ship Structure Benchmarks for Assessing FEA Software - details of the analyses described in Part 4 of the report and reviewed in Section H.3.4 are presented.

APPENDIX I

REVIEW OF REPORT SSC-392

PROBABILITY-BASED SHIP DESIGN IMPLEMENTATION OF DESIGN GUIDELINES FOR SHIPS: A DEMONSTRATION

by A E Mansour, B Ayyub, P W Wirsching and G J White.

I.1 OBJECTIVES

To provide a demonstration of a probability-based design code for ships. This report might more universally be expressed as ‘a model probability-based design code for ships’.

A not inconsiderable amount of this report seems to be a repeat of information and text presented in previous reports in this series.

I.2 REVIEW

I.2.1 Appendix B Target Reliabilities

Target reliabilities are summarised covering those used in a range of different countries and industries. In considering these, very careful attention should be paid to the differences in consequences of failure for ships (and other floating structures) compared with those applicable to bottom-founded structures which includes land-based structures. In the event of near collapse of bottom-founded structures, the unit often remains standing even if in a precarious situation. A similar degree of damage to a floating structure is likely to lead to its sinking through associated causes that do not necessarily have the same effect on a bottom-founded unit. These associated causes include flooding and instability, neither of which is of concern to bottom-founded structures.

As a consequence, it is strongly recommended, when interpreting target reliabilities for land-based and bottom founded structures, that any determined value be increased by about one order of magnitude in probability of failure terms to account for the fundamental differences in outcome of serious incidents to floating structures versus bottom-founded structures.

The recommended target values listed in Table B.5 raise a number of questions, some of which have been raised in the earlier reviews:

- Why are cruiser targets at a higher level of safety than those of tankers? Cruisers presumably should be capable of maximising payload at the expense of unnecessary self-weight or is the extra weight a reflection of the need to survive a missile attack or similar. Do not tankers have to be safe enough to protect not only the environment but also their crew? Is a tanker crew less important than that of a cruiser?
- If girder initial yield is not relevant to failure in anyway, does it need a target?

- Unstiffened panel buckling has no particular impact on stiffened panel or girder strength so why place it in the category of a strength limit state? It would seem possible to categorise unstiffened panel buckling on similar lines to that of a Category 1 or 2 fatigue crack.
- The difference between first component failure, i.e., stiffened panel failure, and system collapse, i.e., hull girder collapse should be consistent and probably about one order of magnitude in probability of failure terms. The differences shown in the table between the targets for these two modes for the tanker and the cruiser depart being about 0.8 of one order of magnitude for the tanker and nearly two orders of magnitude for the cruiser.
- Given the targets relate to lifetime reliabilities, if this corresponds to 20 years, then the targets appear to be too high particularly for cruisers.

I.2.2 Appendix C Partial Safety Factors (PSF) and Safety Check Expressions

The procedure reported for the evaluation of partial factors is apparently not based on a calibration approach, the process by which nearly all LRFD partial factor determinations have been effected. The critical reason for strongly recommending the calibration approach is that it exploits relevant engineering experience, and by appropriate selection of calibrator structures, can also reflect successful designs. It may also be important to follow this process in order not to introduce step changes in design requirements because, in countries with legal systems based on precedence, step changes in design requirements and, also most likely, commensurate changes in safety standards, blur the basis of engineering judgement.

I.2.3 Appendices D to G

The Commentaries presented in Appendices D to G seem more a presentation of the details of the selected procedure rather than a justification of it; at least of the reasons that commentaries are prepared.

The attention devoted in the commentaries to the primary failure mode, hull girder collapse Appendix D, amounts to five pages whilst that devoted to the tertiary failure mode (and one that should probably be classified as a serviceability limit state), i.e., buckling of plate between stiffeners, amounts to 32 pages. The balance needs redressing.

APPENDIX J

REVIEW OF REPORT SSC-398

ASSESSMENT OF RELIABILITY OF SHIP STRUCTURES PHASE II

by A E Mansour, P W Wirsching, M D Luckett, A M Plumpton, Y-H Lin, D B Preston, G J White, A K Thayamballi and S M Chang.

J.1 OBJECTIVES

1. Provide a methodology for assessing the reliability level of the structure of existing ships. The computerised methodology will estimate failure probabilities associated with each identified failure mode. [Presumably this should begin 'Provide a computerised methodology....].
2. Select four ships and perform reliability analysis relative to each identified failure mode for each select ship.
3. Recommend minimum acceptable reliability levels for each ship type and failure mode to be used as guidelines for ship designers for future ships.
4. Provide a methodology for performing sensitivity analysis of reliability levels to variations in design parameters, i.e., loads and stresses, materials and strength, and geometry of the structure.
5. On the basis of the sensitivity analysis performed, recommend design strategies that are likely to have the highest payoffs in terms of reliability.

J.2 REVIEW

The version of this report that is available for review has not been completed. A lot of editorial work is required.

J.2.1 Chapter 2. Methodology for Assessing Structural Reliability of Ships

Chapter 2.1 covers a Methodology for Constructing Probabilistic Models of Wave Loads and Load Combinations.

The methodology for determining slightly non-linear wave loads and their combinations appears very useful and complete.

The results shown in the design charts for estimating non-linear sagging and hogging moments seem helpful but presumably require calibrating against full- or large-scale data and extending to cover a suitable range of ship types and classes. However, the use of dimensional quantities a/H_s and $(b-3)/H_s^2$ to assist in this is of concern. Appropriate normalising functions are usually non-dimensional.

The section on slamming (2.1.4) provides access to a further method (SLAM) compared with that treated in SSC-373 although there is substantial repetition of material form SSC-373 in the current report on this matter.

The procedure for combining loads appears in a LRFD-type format that was introduced and expanded upon in SSC-373 appears well founded. Has it received independent critical review and substantiation?

Section 2.2 is concerned with a Methodology for Constructing Statistical Models for Non-Linear Hull Strength.

The failure modes are cited as:

- Primary - involving overall hull response and failure
- Secondary - stiffened panels between transverse bulkheads and web frames
- Tertiary - plate between stiffeners.

Plate buckling has a role to play in stiffened panel failure and also in primary hull failure where it is transversely framed. In the context of longitudinally framed vessels, plate buckling is probably more realistically considered to be a serviceability limit. The plate geometries of some ships hulls are such that panting of the plating is inevitable but this can occur with considerable reserve of strength left in the stiffened panels and the overall girder. The greater concern if this occurs is the onset and progress of fatigue damage, again usually considered to be a serviceability limit rather than an ultimate limit state.

Stiffened panel failure can be treated as secondary although it would normally be taken to indicate the onset of primary failure. However, they can be separated, and it some vessels where significant redistribution of stresses can occur, they are clearly not synonymous. However, since stiffened panel failure usually marks the onset of collapse, the load at which it occurs can be compared with the girder overall collapse load as a means of quantifying, in strength terms, the degree of redundancy available. In reliability analysis, these two events would play the same roles, stiffened panel failure corresponding to component failure and overall collapse to system failure.

The basis of the ALPS/ISUM computerised procedure for determining hull collapse loads is presented (2.2.2) followed by details of a simple formulation for achieving the same goal (2.2.3). The latter is judged to be a more appropriate starting point for reliability assessment of vessels in the context of design. However, the former is useful if sufficient numbers of solutions can be executed in order to improve our understanding of the simplified models as well as in the reliability analysis of individual ships.

The new equation of Paik and Lee presented as (2.2.19) looks remarkably like the one used by Committee V.I of ISSC ’91 and for which the background was given in Frieze and Lin (1991).

The section on stiffened panel strength (2.2.4) rightly points out the need to design transverse frames to be adequate not to collapse in the event of longitudinal stiffened panel failure. Suitable criteria for this can be found in BS 5400: Part 3 (1982). Effective widths are discussed but formulae only given for the case of longitudinal compression. In the Review of SSC-375, mention was made of the work of Davidson et al (1991) in connection with lateral pressure effects. This study covered pressure interaction in relation to both transverse compression as well as longitudinal compression. It is not clear why the Paik and Lee equation (2.2.19), which provides a closed form expression for stiffened panel compressive strength as a function of both plate panel parameters and stiffened panel, is not used in this section devoted to stiffened panel strength. For consistency, if nothing else, (2.2.19) would seem the appropriate equation to use.

The interaction equation between vertical and horizontal bending introduced in Section 2.2.6 will be useful in the context of reliability assessment if it can be demonstrated to have universal application even if the 'k' parameter has to be evaluated for each ship type and class.

Section 2.3 presents a Methodology for Estimating Ship Failure Probabilities.

Some basic reliability concepts are first introduced (2.3.1) but are also repeated in (2.3.4.1). Short and long-term procedures for determining wave encounters are discussed at some length. Not surprisingly, there seems considerable uncertainty as to what constitutes an appropriate climate to define for a vessel and whether this should be done on a short- or long-term basis. As discussed above in the review of SSC-363, difficulties exist from an offshore structures reliability standpoint in deciding the best (better) basis on which to execute reliability analysis. When considered on an annual basis, the problem of accounting for the differences between aleatory and epistemic uncertainties can be eliminated but then the derived reliability has to be put into context of what constitutes an appropriate return period for the considered storm (100 years is used in the Gulf of Mexico in conjunction with an associated current and wind speed whilst in the UK a combination of 50-year return period waves, current and wind is used based, it has to be admitted, primarily on the need to satisfy a statutory regulatory requirement than a sound scientific rational). The same approach can be used over the likely lifetime of a unit which requires the, say, 20-year life-time loading to be determined so that, again, the problem of combining the Type I and II uncertainties does not arise. The objection to this is that unless the lifetimes of all the structures under consideration are the same, then some common basis has to be determined that will enable the conversion from one time scale to another.

Another issue that can complicate the choice of the loading pattern to be considered is whether the reliability analysis is being performed as part of a process for the determination of a LRFD -based design approach of whether it is for a re-assessment of an existing vessel or class of vessels. If the former, a decision is required concerning the basis on which the analysis will proceed. For world-wide service, it is probably prudent to use the North Atlantic route as the basis. However, another class or two could be classified for less onerous routing leading to lighter weight vessels but with the same level of reliability as those plying the North Atlantic. If the latter, previous and future routing can be specifically addressed to identify the relevant wave climate and the lifetime that might be appropriate to input to the analysis.

The section on Estimation of Ship Failure Probabilities (2.3.4) briefly reviews available reliability analysis techniques and then some computerised software for executing such analysis. Two simple formulations are presented for estimating failure probabilities (2.3.4.3). As well as lacking in the definition of the some of the variables used, they are also short on summaries of the bases. The first, which exploits closed-form equations, appears to possibly be a probability of exceedence approach.

J.2.2 Chapter 3. Database on Loads for Four Ships

Chapter 3 is devoted to the creation of a Database on Loads for Four Ships, based on the approaches summarised in Chapter 2.

J.2.3 Chapter 4. Database on Structural Strength for Four Ships

The effect of residual stresses and initial deformations on girder ultimate strength are examined. It is not clear as to what these effects are meant to reflect. Presumably residual stresses refer to the level of longitudinal compressive welding residual stress assumed to exist in the plating. The use of a 10% level of welding residual stress in plating is consistent with that found to account for the effect of stresses on compressive stiffened panel response in box girders (Frieze and Dowling 1977). In relation to initial deformations, these could either be plate or stiffener initial deformations although since the magnitude is normalized with respect to the plate thickness it is likely to be the former. If this is the case, the use of an initial bow in the plate of 0.5 times the plate thickness is excessive. Several studies have been conducted to quantify plate initial distortions where upper limits are in the range plate width divided by 150 to 250. For a plate of width 600 mm and of width to thickness ratio of 30, 0.5 times the plate thickness is 10 mm. Plate width over 200 is 3 mm.

J.2.4 Chapter 5. Reliability Analysis and Failure Probabilities

In Section 5.2, the inappropriateness of the first yield moment is discussed in some detail. Perhaps if the cross-sectional modulus was based on effective plate widths in the deck and (double) bottom, and the onset of yield was checked in both tension and compression, then closer correspondence with primary and secondary failure strength might be realized although it would still not provide a measure of secondary strength unless the column slenderness of the stiffened panels was 0.15 or smaller.

The input for yield stress appears to be the nominal value. It should be the mean for which a usually reliable measure where wave-induced loading and response feature is the tensile test coupon result.

The fairly serious problem with the reliability analysis as presented is that it has not been conducted using the basic variables but only the cumulative measures of these and has not accounted for strength modelling uncertainties. Thus for girder ultimate strength, the analysis has been performed on the numerical values derived for M_u whereas it should have been performed on a formulation that involved the deck, bottom and sideshell geometries, the material properties particularly yield stress, and should have accounted for the differences between the measured values of girder strength and predictions (the modelling errors) for which information had already been reported in Table 2.2.2.

As a direct consequence, it is not possible to conduct a sensitivity study with the expectation that the influence of the basic variables (including modelling uncertainties) will be considered. In this detailed basic variable form, the sensitivity studies would probably indicate that elastic modulus and geometry variables (except possibly plate thickness) can be treated as deterministic, that modelling error is the dominant 'strength' variable, and that yield stress is of secondary influence. Further, if simulations were conducted using strength basic variables that included residual stresses and initial imperfections they would probably indicate that neither needed to be treated as random variables. This is because when the full range of their variabilities is considered as in a Monte Carlo simulation, then their influence is very much reduced compared with just dealing with their maximum values as tends to happen when treating stiffened panels in isolation as in a strength determination. Alternatively, the effect of yield stress alone, for example, might simply account for the combined effects of yield stress, residual stresses and initial deformations.

Similar findings would occur in connection with loading basic variables if these were considered directly instead of indirectly as in the reported study. Wave height is most likely to be the most critical basic variable but whether it would surpass the influence of modelling errors is uncertain. As pointed out in the report, even second-order strip theory does not fully account for bow emergence under extreme conditions so differences between true and predicted levels of wave-induced bending moments can be significant.

J.2.5 Chapter 6. Sensitivity Analysis

This aspect has already been considered above from the viewpoint of what can be learned from the present analysis. Notwithstanding, the basis for the sensitivity measures adopted is not clear. If α and γ always give the same result, why consider both? The third and fourth measures, δ and η, look remarkably similar to the measures generally described as parametric sensitivities except that δ should be multiplied by μ not σ in order that the expression is suitably normalized.

J.2.6 Chapter 7. Fatigue Reliability Assessment

Review incomplete.

APPENDIX K

REFERENCE LIST FOR STIFFENED PANELS SUBJECTED TO AXIAL COMPRESSION AND AXIAL COMPRESSION COMBINED WITH LATERAL PRESSURE

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ANNEX

FINAL REVIEW OF DR. P.A. FRIEZE'S REPORT ON SSC PROJECT SR-1362

BY PROFESSOR D. FAULKNER

Table of Contents

1. MATERIAL REVIEWED

1.1 Dr. P.A. Frieze's Draft Final Report dated May 1997 and subsequent correspondence. Hereafter, the phrase "the Reviewer" refers to Professor D. Faulkner.

1.2 Ship Structure Committee Reports and Projects:

SSC-322 by Kaplan et al 1984, *Analysis and Assessment of Major Uncertainties Associated with Ship Hull Ultimate Failure*

SSC-351 by Mansour 1990, *An Introduction to Structural Reliability Theory*

SSC-363 by Nikolaidis and Kaplan 1991, *Uncertainties in Stress Analysis on Marine Structures*

SSC-368 by Mansour et al 1993, *Probability-Based Ship Design Procedures: A Demonstration*

SSC-371 by Pussegoda et al 1993, *Establishment of a Uniform Format for Data Reporting of Structural Material Properties for Reliability Analysis*

SSC-373 1994 (see para 1.3)

SSC-375 by Hughes et al 1994, *Uncertainty in Strength Models for Marine Structures*

SSC-392 by Mansour et al 1996, *Probability-Based Ship Design: Implementation of Design Guidelines for Ships: A Demonstration.*

SSC-398 by Mansour et al 1997, *Assessment of Reliability of Ship Structures Phase II*

1.3 Also included in the list received from the US Coast Guard was: (6) SSC-373, by Mansour and Thayamballi, 1994 *Probability Based Ship Design: Loads and Load Combinations*. However, this was never received by the Reviewer. Nevertheless, the ABS and open literature publications of Mansour and Thayamballi (sometimes with others) are familiar to the Reviewer.

2. APPROACH ADOPTED

2.1 To avoid being overly influenced by Dr. Frieze's report, especially as it was clearly quite critical in places, the Reviewer gave priority first to an eyeball review of all the SSC reports provided. The notes taken during this stage were then subsequently compared with the detailed comments in Dr. Frieze's report.

2.2 This preliminary review suggested that there was appreciable overlap and two reports in particular appear to synthesise the most important work of the reliability thrust program:

(7) SSC-375 by O. Hughes et al 1994

(10) SSC-392 by A. Mansour et al 1996

That being so, the Reviewer has provided a separate section of this report to each of these two reports with comments (in no particular order).

2.3 The question of inadequate modelling of both loading but especially ultimate strength was raised by Dr. Frieze and as these are agreed as being important weaknesses of the work they too are singled out as separate sections and an associated Appendix.

2.4 The final four sections then offer further comments in relation to Dr. Frieze's report, some final Food for Thought, Conclusions and Recommendations.

3. BRIEF NOTES ON SSC REPORT 375, 1994

3.1 There are no references to numerical models, either to be used as a "model" for testing with experiments, or as being more reliable than experiments and therefore an acceptable basis for testing analytical models which are more useful for design.

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3.2 Judgement of modelling excellence is based only on bias and coefficient of variation – no mention of skewness, sensitivity of X_m to changes in basic variables, robustness, etc. Moreover, the authors' modelling uncertainty (parameter) is the inverse of that widely adopted. The multiplicative total bias model appears to have led to confusion.

3.3 The tendency to use polynomial type curve fit to lower bounds of experimental data is certainly not approved. Moreover, it appears that the ratio (mean)/(characteristic value) is not sensible as used.

3.4 Interesting but often unconvincing classification of uncertainty types. Likewise, the section on Bayesian Techniques is interesting, but is nevertheless unconvincing in its later use.

3.5 Failure modes and strength models:

- Preference for "standard" algorithms from O. Hughes' Ship Structural Design (1988) shows an unjustified bias. European comparisons of stiffened panel formulations are better

- Reference to API cylinder tests does not appear to be justified, as most in early 80s were sponsored by Conoco and ABS and included some UK tests

- Status regarding available data in Table 4.1 for the various member failure modes is generally agreed.

3.6 Modelling of compression collapse of longitudinally stiffened panels:

- Preference for Perry-Robertson based modelling is not agreed. Shanley's tangent modulus modelling for columns reduce scatter when compared with test data

- Reliance mainly on single bay tests is stated as being justified on the basis of low torsional stiffness of transverse stiffeners (agreed) and because the individual bays being approximately equal is not agreed. Bays nearing collapse tend to bend inward and outward in adjoining bays and this generally leads to significantly different plate effectiveness and neutral axis positions in adjacent bays. This in turn gives rise to differing end moments and collapse loads in each bay. Relevant test data should have been consulted

- The treatment of tripping is not well reviewed, but it is agreed there is a need for good test data. In particular, compression induced plate element buckling can interact with tripping in a de-stabilising manner. This problem has now been adequately solved by Morandi and Faulkner.

3.7 The review is disappointing in concentrating only on compression of stiffened panels. Even at that it ignores:

- Transversely stiffened plate panels
- Orthogonally stiffened panels

Both of which exist in practical structures.

3.8 Moreover, the demonstration of the sensitivity of the design to the modelling parameters in a reliability-based code is not even described.

3.9 There is no discussion of the effects of tests with small sample size. The limited choice of test data is also of concern. As stated above, much has been achieved in Europe in particular in terms of tests and improved modelling.

3.10 No reference is made to API Bulletin 2U 1987 for stiffened shells and 2V for flat stiffened plate structures.

4. BRIEF NOTES ON SSC REPORT 392, 1996

4.1 The approximate treatment of moderately non-linear load combinations is good, but it is generally the highly non-linear waves that sink ships. These are largely ignored, although the use of second order strip theory is a step in the right direction. See Section 6 below.

4.2 There is much repetition of earlier reports (inevitable to an extent).

4.3 Tertiary (plate) "failure" by itself is not agreed as an ultimate limit state. This does appear to be a repetitive USA practice. If considered at all, it should be as a serviceability limit state.

4.4 Paik and Lee have plagiarised ISSC'91 work, but the choice of strength limit states is acceptable in this case. The expression (2.5.1) for sizing transverses is potentially very useful, but no reference appears to be given. The "Commentary" (Appendix E) is misnamed!

4.5 Elsewhere the choice of the old Frankland type compression strength of plate elements seems strange and appears not to be justified. There is an almost total neglect of European modelling. On plate effectiveness in particular, Guedes Soares has been totally neglected, although he more than any one has adopted excellent modelling techniques (more on this in the next Section 5).

4.6 The use of nominal values of yield stress is not agreed for reliability work, unless care is taken to find experimental mean values also. This appears not to be the case.

4.7 Fatigue, as expected, has been treated excellently (apart perhaps from the multiplicative biases). It is not of course an ultimate limit state. The default values for the Weibull shape parameter are wide apart and are surprising to the Reviewer in the absence of an explanation.

4.8 Target reliabilities appear to pay no attention to differing seriousness of consequence. In particular, there are very good reasons for expecting a tanker, for example, to have a higher notional reliability index than for a naval cruiser. And yet the authors have the reverse! Warships are generally more weight critical, have much higher standards of material control, workmanship, and watertight integrity, and these, plus good operational experience, justify lower notional safety levels.

4.9 The selection of partial safety factors appears to ignore calibration with previous successful designs.

4.10 It is relatively easy to focus on adverse factors in almost any report. There is, however, much that is good and useful here, for merchant ships in particular. An application to a specific design, with comparisons and a commentary, would be more convincing.

5. STRENGTH MODELLING

The elements for good strength modelling were initiated during the Conoco-ABS development of a Rule Case Code for structural design of Tension Leg Platforms(1). They were expanded upon later(2,3) and fall into two sets of requirements: Statistical and Engineering.

5.1 Statistical Requirements

Lederman(4) defines four desirable characteristics required for good estimators from a statistician's viewpoint:

1. **Consistency:** The procedure should produce an estimate which is accurate. That is, if a sample replicates the population the estimated parameters (e.g. strength) should be close to the population parameters (e.g. experimental strength). Furthermore, the estimates should improve as the sample size n increases:

$$\left.\begin{array}{l} E\left[\hat{X}_m\right] \rightarrow X_m \\ \mathrm{var}\left[\hat{X}_m\right] \rightarrow 0 \end{array}\right\} as\ n \rightarrow \infty$$

   Where X_m is the best (maximum likelihood) estimate of the model parameter having a high probability of being close to the population parameters.

2. **Sufficiency**: Some procedures enable more information to be extracted from the sample than others do. A sufficient estimator is one which can extract all the information from the sample which is relevant to the parameter.

3. **Low Bias:** The best estimate may differ from the population parameter due to a bias:

$$B_n(X_m) - E\left[\hat{X}_m\right] - X_m$$

   An unbiased estimate is not necessarily the most important property of an estimation procedure, because an unbiased estimate for X_m will not in general result in an unbiased estimate for some quantile X_{mk} owing to the statistical uncertainty of the population.

   For example, section 4.1 of Ref. [3] showed that using best mean value estimates for stiffened cylinder strength under axial compression gave supposed 5% 'lower bound' characteristic value which varied from 0% to 56%. It is for such reasons that the Reviewer has consistently advocated the use of unbiased mean value estimators, as the sample population at lower bounds is sparse, poorly defined, and inevitably it shifts as more test data becomes available [6].

4. **Low Sampling Variance:** With a finite sample size each estimator will have some statistical uncertainty, usually characterised by its variance. Furthermore, models with more than one parameter will have multivariate-distributed parameters. A good estimator will have minimum sampling variance, thereby reducing the uncertainty in its estimates. It is important to apply goodness of fit tests and to quote confidence limits, using classical statistics.

5.2 Engineering Requirements

Faulkner et al[2] and Prince-Wright[5] defined four engineering requirements which have been used and illustrated[3]:

1. **Robustness:** Methods must be robust, that is, it would be possible to obtain solutions to the model parameter(s) for nearly all samples of data without prior knowledge of the model parameter. Further test data within the range should not upset (depart from) the model significantly.

2. **Repeatability:** It is desirable that the results from an estimator be repeatable for comparisons. In this respect a weighted least squares fit is not necessarily satisfactory since the parameter estimates will in general be dependent on the chosen weighting function. However, this caution applies more when modelling extremes of random processes[4] such as wave excitation.

3. **Appropriate Equations:** Much of this section is most relevant to the selection of ***statistical distributions*** which best fit truly random processes such as extreme wave loading. But it is also important when determining analytical ***strength models*** to avoid the usual polynomial curve fit and to adopt models which reflect the ***mechanics of failure*** and where appropriate the effects of fabrication imperfections. More specific guidance will be given later.

4. **Avoid Unsafe Features:** Potentially unsafe features of design codes have been recently reviewed[6]. These include incorrect formulae, omissions (including limits of applicability), invalid criteria, incorrect data, misleading information, inconsistencies and anomalies, incorrect treatment of slenderness effects (main components and stiffener proportions), and incomplete scope (which encourages "shopping around").

5.3 Recommended Strength Modelling Criteria

Some general requirements for good codes are given in the Appendix. This section outlines the principles set out in 5.1 and 5.2 above in more specific terms.

Statistical Criteria

(a) mean value formulations are preferred, and are essential for meaningful in-service assessments,

(b) the modelling parameter X_m should be close to unity over the geometry and material range of interest; its mean bias should be within $0.95 < X_m < 1.05$,

(c) the modelling uncertainty v_{Xm} should be kept as low as possible, and overall values < 0.15 should be achievable for the ultimate strength of most components,

(d) X_m should show low correlation with any basic variables or their non-dimensional ratios, that is, no skewness should be inherent in the model,

(e) where the modelling uncertainty v_{Xm} varies noticeably with some of the basic variables or slenderness parameters then it should be evaluated in ranges,

(f) sample sizes are to be quoted; for sample sizes less than 15, goodness of fit tests should be applied and confidence limits determined.

Strength Requirements

(g) formulations should be 'strength of materials' type whose parameters reflect the *mechanics of failure*; curve fitting should be restricted to secondary terms (such as shell knockdown factors) and *not* for failure predictions, inelasticity effects, etc.,

(h) models should be relatively *simple* to apply; but over simplification may neglect important factors which may restrict the range of applicability and often leads to lack of robustness,

(i) avoid different levels of sophistication and cater for average imperfections,

(j) the ranges of relevant geometrical parameters and material properties should be clearly stated – normally based on test data ranges,

(k) restrictions based on ultimate stress for metals are to be avoided (σ_u/2.35 in lieu of σ_y is still used in some codes to this day),

(l) all important modes of component collapse failure should be catered for and all assumptions clearly stated,

(m) for multiple loads acting simultaneously empirical or analytical *interaction* failure equations are generally suitable; these should be consistent and give rise to no anomalies when checking safety,

(n) cross-section slenderness proportions of stiffeners should be properly restricted where buckling collapse can occur,

(o) test data should be checked as being reputable and relevant and any limitations are to be carefully noted.

5.4 Examples from Four Design Codes

During the late 70s and early 80s many tests were conducted on large welded stiffened cylinders in the UK and the USA under axial load, radial pressure and combined loads. Defining the modelling parameter in the usual way as X_m = Test result/Prediction, the following Table shows the mean bias and scatter (cov %) for the strength predictions as given for four design codes:

Model Code Number of tests	Axial Load 52	Radial Pressure 11	Combined Loads 22
API Bull 2U (1987) Orthotropic Discrete	 0.87/24.0% 0.99/18.4	 0.87/46.2% 1.21/14.5%	 0.82/35.5% 1.14/23.3%
RCC (1983)	1.02/13.3%	0.97/10.3%	1.05/11.9%
DNV Tech. Note CN 30.1 (1982)	 1.01/25.1%	 1.40/39.0	 1.39/42.9%
ECCS (1983)	1.27/27.7%	-	-

It is seen that the Rule Case Committee (RCC) formulations are far and away the best as judged by the above criteria. Cylinders designed using the other formulations for the same notional safety index would be about 20% to 40% heavier, and the ECCS rules did not cover radial pressure loads. Even the API discrete stiffened-shell formulations are not as good as the RCC ones on which they were based because the person who transcribed them had his own "minor improvements" which in fact made matters worse. Also obvious is that orthotropic stiffener-shell theory incurs large scatter and is unsafe. Interestingly, the combined loads result shows up the advantage of the Odland-Faulkner equation(7) which interacts between elastic buckling and von Mises yield, and caters also for tension loads.

On the Predictions vs. Tests plots of Fig. 1, it is also seen that the DNV and ASME formulations are substantially skewed, as would be the ECCS equations, had they also been included.

Reference (6) shows up the weakness of over simplified equations. In particular, polynomial curve fitting is taboo, except perhaps for secondary terms. SSC-375 is guilty of this, but neither of the above reports has considered strength modelling seriously.

6. LOAD MODELLING

It is interesting that ship hydrodynamicists are particularly guilty of polynomial curve fitting and often assume there are no serious modelling errors in their work! In principle, many of the requirements outlined for strength modelling apply equally to hydrodynamic forces. The offshore industry at least has been alive to the existence of large modelling errors. This section will briefly refer to the two most serious omissions on the ship loading aspects of the current studies.

6.1 Real Sea Uncertainties

It is unfortunate that the only uncertainty the investigators associate with the use of sea spectra appears to be the *initial* distribution, that is, the uncertainty inherent in the statistical distribution of the spectra itself. But, in any narrow wave frequency increment, the spectral energy value is an *expectation* or mean value of the wave energy. The actual wave heights and energy experienced in that narrow increment will vary about that mean with a random component substantially greater than that of the initial uncertainty in the spectrum itself.

We may call this frequency dependent component the *real sea* uncertainty and values of say 12% to 18% cov may be expected. In contrast, the initial uncertainty may vary between say 6% and 10%, so assuming independence the total uncertainty is likely to vary between say 13% and 20%. For fully arisen long-crested extreme storm seas values of 15% or 16% would be expected. For intense cyclonic storms higher values may be expected. Such values would have a direct influence on the partial safety factors required for extreme wave-induced loads.

6.2 Non-Linear Waves

Ships are rarely sunk by linear seas. Leaving aside self-induced capsize, trawlers are more frequently lost by steep, elevated local waves induced, for example, by wave caustics (Pierson, 1972) from shoaling waters or bottom topography, from coastline refraction and reflection effects, from wave-current (or tide) interactions, etc. Such waves may become breaking plungers, and their damaging power is very high.

For larger ships in certain regions, where wave-current interactions are known to occur (Agullas current off SE Africa, Peruvian current, Denmark Strait current off SE Greenland, Kuro Siwa current off S. Japan), major ship damages and losses have occurred from steep elevated waves. Sometimes, these combine with typhoons. For example, between 25-30% of ship losses occur in a 2,000 mile stretch of ocean south of Japan.

Such waves also occur naturally in revolving tropical storms (hurricanes, typhoons, etc.) and these can migrate northwards in the N. Atlantic and S. Pacific oceans or southwards in the S. Pacific, drawing in yet more energy from other depressions, to cause monstrous seas far away from the tropics. Figure 2 shows a steep wave recorded during hurricane CAMILLE in 1969.

Work on the *DERBYSHIRE* investigation has shown what many mariners and some oceanographers have always known that such Abnormal or Freak waves are not curious and unexplained quirks of nature. Their occurrence can be calculated with an acceptable degree of precision. And yet, naval architects ignore them in design. Moreover, weather routing is simply not working as a safeguard to prevent ships from meeting abnormal seas.

Such waves have been defined for ships > 150 m as having design heights H_d:

$$H_d = 2.5 H_s \quad , \quad > 25 \text{ m} \qquad (1)$$

Where H_s is the significant height, crest elevations of 0.6 to 0.7 are not uncommon, and mean crest front slopes can be 0.5. Survivability design conditions for H_s and T_p have been defined, as shown in Fig. 3, where T_p is the peak or modal period. For typhoon ORCHID which sank the *DERBYSHIRE* H_s = 14 m, T_p = 13.5 s, so the most probable wave height in 12 hours is 28 m but with a 63% probability of being exceeded. Wave bending moments are then substantially higher than the IACS S11 standard. For offshore design West of Shetland oil companies are considering H_s = 18m, which implies design wave heights of up to 40 m or so.

For ships less than 150 m length the first equality in eq. (1) can still be used, and advice on this can be found in ref. (9).

At present, naval architects assume linear waves, never exceeding 10 m to 15 m in height. For wave induced loads which distress or sink ships this must surely change(9). Although the investigators have used moderately non-linear waves, what is really required is the use of large amplitude wave loading programs such as are now appearing. One such in the USA is the LAMP numerical simulation program of the SAIC Corporation which has been in development for some eleven years or more and has been, partly at least, validated experimentally and with full scale measurements.

It is of course not expected that the investigators would be using this yet, but no research program should totally ignore such developments. Associated with this is the need to examine critical conditions for design and operation(9). Structurally, this is less likely to be associated with primary hull strength than with loss of watertight integrity through breached side shell, hatch covers, etc. The reliability modelling of these processes has barely started.

7. REPORT BY DR. P.A. FRIEZE

7.1 It will be apparent from the foregoing that the Reviewer's concern that Dr. Frieze's report may be overly critical was unfounded. Whilst there is a great deal to admire in the many SSC documents, they are "patchy" and incomplete and fall short in several important respects, which are mentioned by Dr. Frieze.

7.2 As regards Dr. Frieze's Critical Review in his Final Report, this Reviewer:

- approves its Basis (2.1) which recognises the state-of-the-art at the time the various reports were written,
- broadly agrees with its Main Findings (2.2) regarding each document,
- agrees with its Summary (2.3).

This means that at present the SSC reliability thrust program has not yet met its aims and reached the stage when it can be confidently applied to ship structural design. Dr. Frieze also discusses this in his section 3.

7.3 Dr. Frieze outlines in Section 3 the framework for this development, and this reviewer has no quarrel with this, even though opinions are expressed.

7.4 Section 4 then generally goes into appreciable depth over each SSC Report or Project. An exception is SSC-322 which is dismissed rather cursorily, though justifiably so. The lead investigator was one very senior hydrodynamicist and none of the others had previously had any serious involvement in structures or reliability. They were on a learning curve and this is evident.

7.5 The reports by Mansour et al (SSC 351, 368, 373, 392 and 398) overlap to an extent with each other. But, more surprisingly, there is an overlap between some of them and SSC-375 by Hughes et al which concentrates on strength limit states. And yet there appears to be absolutely no cross-referencing between them. There is nevertheless an overlap insofar as Mansour uses some of the Hughes formulations. Neither set treats the effect of pressure, which is pretty fundamental for many ship applications. Nor is either set modelled satisfactorily for the reasons previously given. Dr. Frieze's remarks in this respect are agreed.

7.6 It is surprising that very little reference is made to offshore practice, which is ahead of ship practice in the use of reliability methods. Equally surprising, for the same reason, is the fact that Professors Mansour and Bea work in the same Department, and Bea has done so much in the offshore field, and more recently in tankers. They are of course two different personalities, and are no doubt often in competition.

7.7 Having made these somewhat random remarks, mostly to support or top up what Dr. Frieze has reported, it is appropriate to end this section by confirming that in this Reviewer's opinion Dr. Frieze has done an excellent job. His recommendations are broadly agreed, except for his final suggestion of working on a broader front. Alternative thoughts are offered in the Recommendations (Section 10).

8. FOOD FOR THOUGHT

8.1 If one examines ship loss statistics it is well known that most are caused by human error. Steps are now being taken to better understand this and to seek a remedy.

8.2 At the more technical level, if one leaves aside the many losses due to poor navigation, fire or explosion, etc., one is left with three basic naval architectural categories of loss:

(a) inadequate primary strength leading to jack-knifing or brittle fracture of the whole cross section,

(b) lack of watertight integrity leading to foundering,

(c) inadequate stability leading to capsize.

Very few ships (relatively) suffer (a), and roughly speaking larger cargo ships are more prone to (b) than (c) whereas smaller ships are generally more vulnerable to capsize.

8.3 A point that arises is that historically, and perhaps still in present practice, structural design has been dominated by longitudinal vertical plane bending. The present studies are examples of that, and in-plane compression strength is then important. But ships very seldom sink at sea because of inadequate compression strength.

8.4 One wonders, therefore, if the emphasis should not be shifting to lateral pressure loading, in which bending and shearing actions generally lead to loss of water tightness. This is almost totally ignored in the present SSC-studies, although some excellent work is in hand in Japan and elsewhere.

8.5 This appears to have been recognised by one classification society nine years ago in an excellent report(10) which in the context of structural reliability methods:

- contains recommended practices for applying reliability in design, inspection and operation,
- points out sources of uncertainty and relevant probability distributions,
- has practical applications and examples and contains a rule proposal on the direct use of reliability methods in classification.

The formal presentation of this material is fitted into the format of classification notes.

8.6 This suggests that perhaps all that is needed for primary strength is a “tidying up” operation, to be followed by work on lateral wave-induced loads and response. This should be integrated with the best work worldwide.

8.7 As a closing comment to this section, it does seem that many owners are still looking to save the last 100 tons of steel through class societies. Presumably, this is because steel weight is thought to dominate acquisition costs. This Reviewer believes that the scope for saving steel weight from primary strength material (hull plating and longitudinals) is much less than from transverse stiffening, with the obvious exception of transverse side frames in single skin bulk carriers. This in turn would indicate a needed move toward rational design of laterally loaded structures.

9. CONCLUSIONS

9.1 The review by Dr. Frieze goes into appreciable depth, is justifiably critical, very perceptive, relevant, and his findings are generally agreed. The layout of the report is good and his conclusions and recommendations are generally excellent. Modified versions of the last paragraph of his recommendations are mentioned in Section 10.

9.2 Although the quality of the SSC work is generally good, it does vary considerably and falls short of several of the stated aims and research objectives. There are also several important omissions. The reasons suggested by Dr. Frieze are agreed.

9.3 Many of the reports involve one high standing academic researcher, and several other well respected academics. This is not surprising as academics have a vested interest in research. At the end of the day, however, it is the more practical designers and structural assessors who would use the methodologies recommended. Also, the heterogeneity brought about by the passage of time and the use of disparate, academically oriented consultants who prefer to use their own "models" has not helped.

9.4 It would have been preferable to involve practitioners in some way, either working with the academics or reviewing their work at key stages; it is, however, accepted that this is easier said than done.

9.5 There are several disappointing aspects of the SSC work, but three of the most important are:

- no clear and convincing outcome so far as application to ships is concerned and choice of target reliability,
- objective knowledge based uncertainties are generally adequately handled, but the far more important subjective modelling uncertainties are either ignored (very disturbing) or badly handled,
- very little appears to have been learned from offshore developments where reliability based design and assessment is used.

These have been discussed more fully above and have been mentioned by Dr. Frieze. The second is so important that it has been given more attention in sections 5 and 6 above.

9.6 SSC report 375 does home in on strength models with minimum bias and modelling parameter scatter, then spoils it by advocating the most conservative model! – presumably because this has been traditional engineering practice. Lower bound models are anathema in the development of reliability based codes, although they are more acceptable in the final code itself.

10. RECOMMENDATIONS

10.1 Dr. Frieze's Recommendations in Section 5 are perceptive as far as reasons for the disappointing outcome are concerned. He rightly suggests the need for customer (designer) involvement, but the problem is how to achieve this. He then ends with a perceived solution to engage in a wider involvement, such as IACS and IMO or, possibly under the umbrella of NATO or the European Union, a partnership to ensure a wide peer review and to augment North American efforts. This Reviewer feels these visions are, perhaps, too grand and unlikely to succeed. He therefore now offers two alternative suggestions and a final thought.

10.2 First Suggestion:

Place a contract with an acknowledged international expert or two. Synthesise the best features of the current work (there are many good features) and pull it together with specific ship design examples as a real demonstration of the process. It would be ideal if the investigators were able to work in close conjunction with a person in one of the major class societies who understands reliability, but also has sufficient internal standing to be able to press for implementation of the work. It would also be important that the work is critically reviewed by a small group of experts as it progresses. IACS should offer some financial support, as they are the beneficiaries.

10.3 *Second Suggestion*:

Persuade IACS to mastermind a longitudinal strength implementation study along the lines of 10.2 above. The Reviewer recalls with some satisfaction how effective were the "brainstorming" sessions of the Conoco-ABS Rule Case Committee (1982-83) when developing a structural design code for Tension Leg Platforms. Much of the outcome was adopted four years later by the API. The strength of the RC Committee was that most of its members were not only of international standing but were directly responsible to the beneficiaries (the sponsors Conoco and ABS).

10.4 *Third Suggestion*:

Give some consideration to initiating a research/implementation program in the reliability design of laterally loaded structures.

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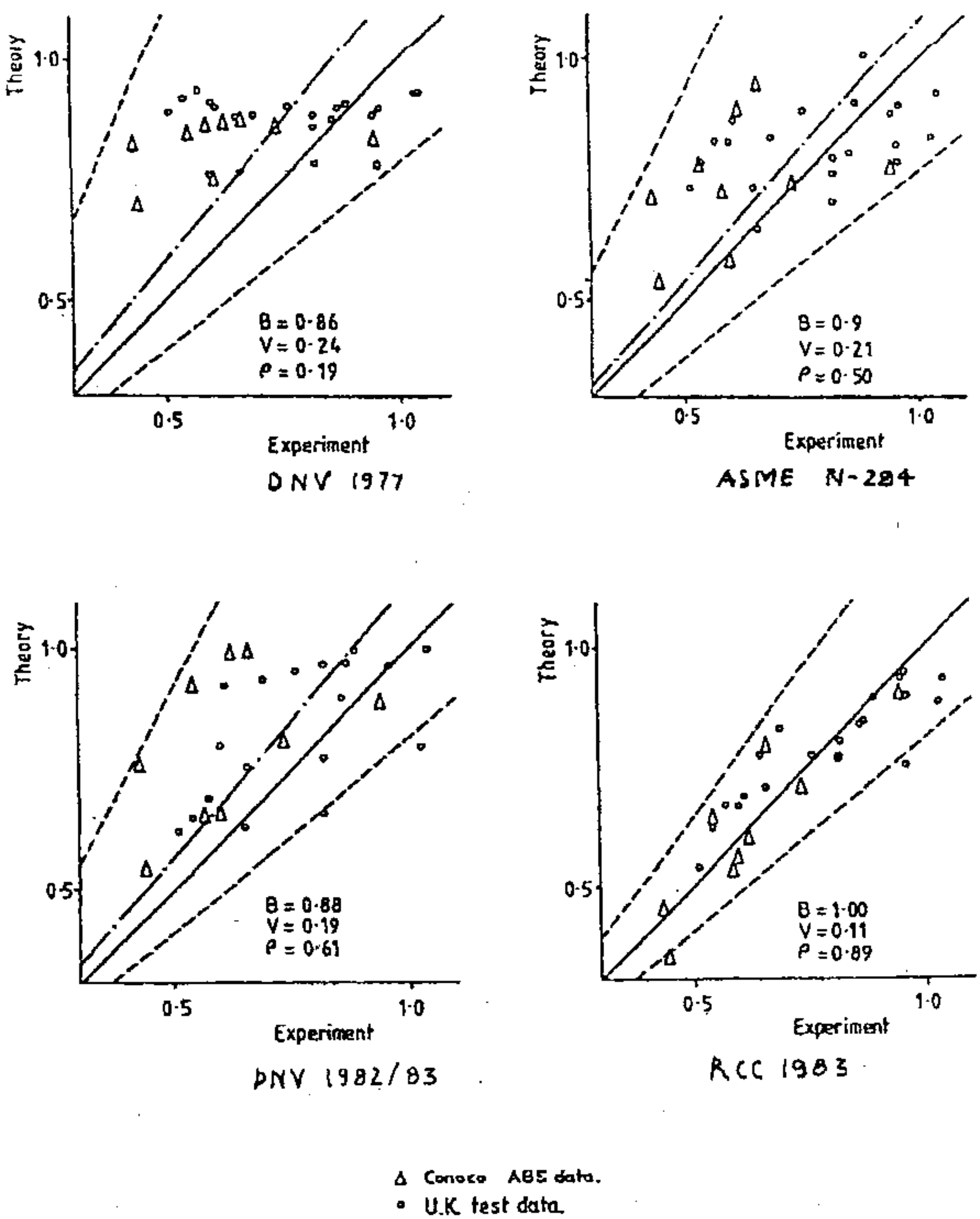

Fig. 1: Test Data and Modelling Uncertainties for compressed axially stiffened cylinders

Steep, Long-Crested Wave as seen from Unidentified Ship (Buckley, 1983)

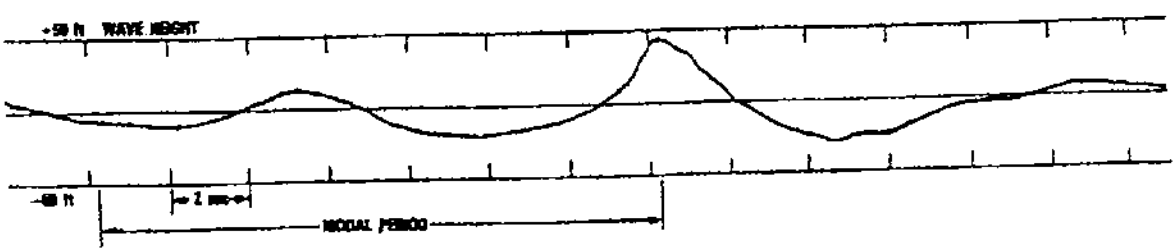

Fig. 2 Steep, Elevated Wave Record During Hurricane *CAMILLE* (Buckley, 1983)

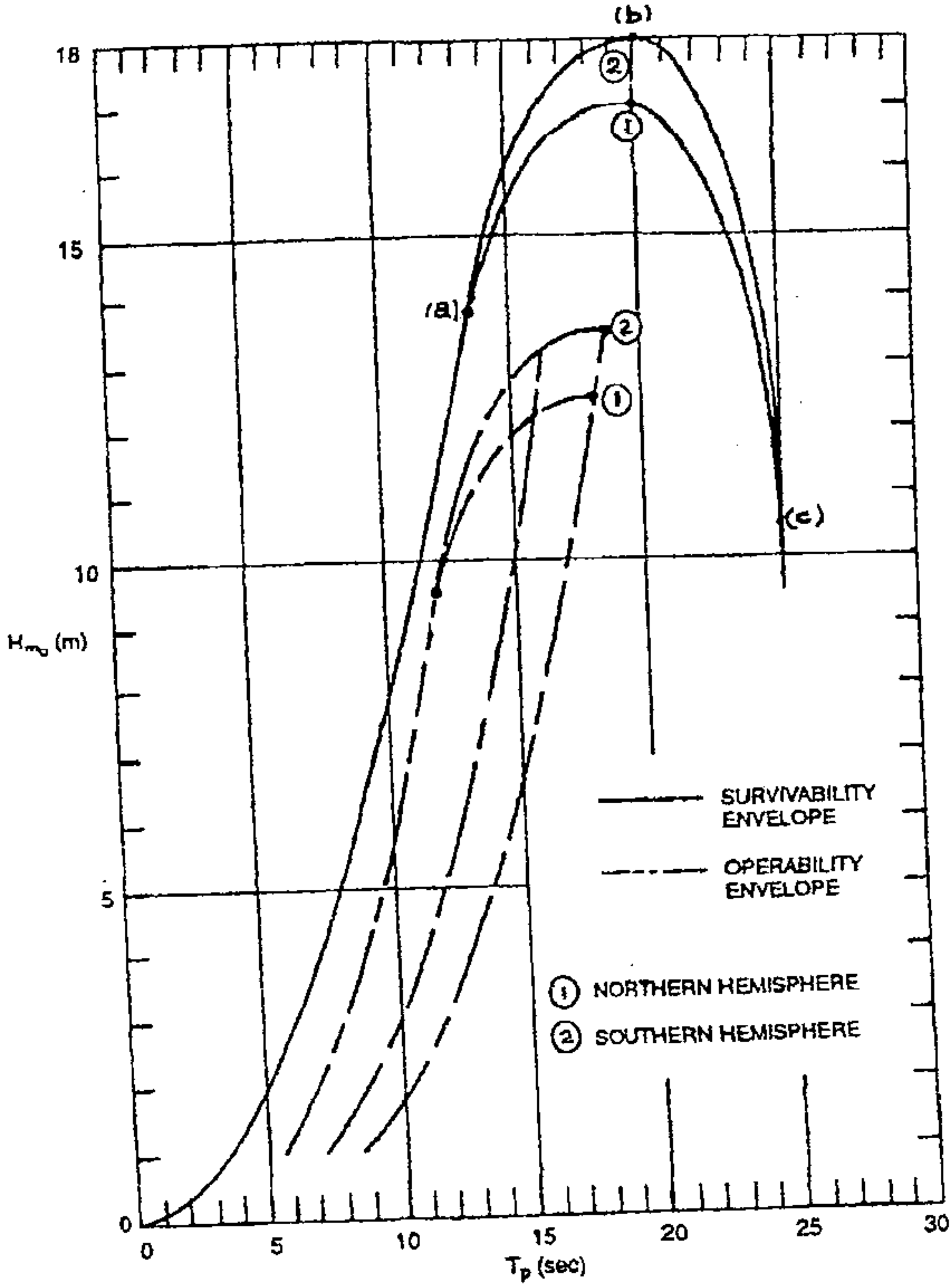

FIGURE 3 SURVIVABILITY AND OPERABILITY ENVELOPES FOR NORTHERN AND SOUTHERN HEMISPHERES

APPENDIX

GENERAL REQUIREMENTS OF DESIGN CODES

[1] need for a Commentary and regular updating

[2] unified internationally as far as can reasonably be accomplished

[3] ultimate limit state reliability based with derived partial safety factors for selected safety index

[4] review potentially unsafe features

[5] review level of safety required – adequate and appropriate to present knowledge and with which economic structures can be designed

[6] prima facie case exists for reducing notional safety factors for structural components, and this should certainly be encouraged especially where system reserve strength is high

[7] consider needs for in-service assessments by more explicit consideration of notional safety for components and the whole structural system

[8] the safety check equation format is perhaps the single most important decision to make with reliability based codes to minimise the spread of reliability

[9] balance simplicity with sensible computer based sophistication

[10] more explicit fatigue design procedures and guidance

[11] ensure the scope for the code is complete and unambiguous so far as what is covered for design, fabrication, installation and in-service assessment

[12] inspection and testing procedures should be rational and not excessive; consider possible arguments in favour of proof testing

[13] where equations are recommended it is important that their range of applicability is clearly defined

[14] as much validated state-of-the-art knowledge should be incorporated as possible

[15] ideally, the code should be illustrated with design examples.

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