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# Lessons Learnt from Structural Reliability Research and Applications in Marine Structures

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Abstract

The first significant applications of reliability theory to aspects of structural design appeared about two decades ago. Since then, interest in such methods has continually grown, and we are now at a stage where several existing design codes are being rewritten on reliability precepts and new ones are anticipated. This paper briefly notes the motivation and reasons for such effort, with particular emphasis on marine structures. The potential benefits of such methods to both the designer and the decision maker are noted. Broad lessons and issues of interest evident from reliability research and applications are outlined. The paper concludes with discussion of a recent effort in developing probability based design assessment criteria for tension leg platforms.

## Introduction

Conventional structural design assessment methods have evolved through an interplay of knowledge and experience, a noteworthy example being ship classification rules [1][†]. Regardless of a perception otherwise, such traditional deterministic criteria have always considered loads and strength to be variable, i.e. random, in some sense. The methods aim to determine a lower bound strength and an upper found load, and provide an adequate but usually unquantified separation between the two. The separation becomes necessary because the "bounds" in fact contain uncertainty, whether due to workmanship or for reasons of economy. In time, and with experience, these deterministic design criteria are continually refined as knowledge related to loads and strength progresses, as material properties and manufacturing procedures improve, and as the profession's confidence in its technology grows. As a result, structures continue to become more efficient. The section moduli required of ships, for example, has in some cases seen a 15 to 20% decrease over the last two decades.

What is lacking in traditional design, then is not that it does not recognize uncertainties. It is also not that the methods are not rational, for rationality merely implies judgments appropriate to the circumstances. Neither is it that such methods are inherently unresponsive to changing situations. The degrees of that recognition and flexibility do vary, however. This was primarily because the methods do not evolve through a basic consideration of the uncertainties, but rather, through experience. Also, particularly when global safety factors are employed and a detailed accounting of various uncertainties is not the norm, the methods are less particular to the problem at hand. As a corrolary, it may be said that the resulting design is one that is not necessarily the most efficient possible. It is, however, one that is adequate under the circumstances, and certainly, one that works.

## Reliability Methods and Structural Design

Reliability techniques provide a framework for decision making in light of uncertainties. They provide a consistent means for verifying whether a structure is acceptable in some sense. This acceptability ultimately depends on a probability of failure which is affected and determined by the entire possible spectrum of loads and strength. As an ideal case, a reliability method would treat the problem of optimal design of a structural system under uncertainty and risk, considering not only structural parameters, but also human factors and costs, both tangible and intangible. The possibility of failure over the economic lifetime of the structure would be considered, and all modes of failure as well as their interactions would be treated. In current practice, however, reliability methods treat a specific number of failure modes, e.g. plastification, buckling, corrosion and fatigue, and often in isolation. Also, structural considerations alone usually exist in such analyses.

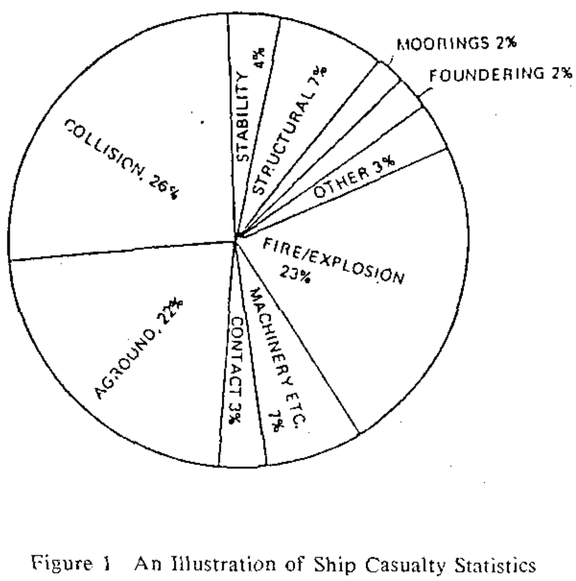



Figure 1 An Illustration of Ship Casualty Statistics

[†]Numbers in brackets designate references at end of paper.

Structures fail for many reasons. The statistics of the Figure 1, [2], which relate to over 2000 vessel casualties (not all of which were necessarily losses) from the Liverpool Underwriters Casualty returns for the years 1969 through 1975, show 7% of them to be attributable to structural causes. Other data, e.g. [3], show a somewhat higher rate, and any data such as this may be interpreted in many ways. Nevertheless, it is fairly clear that instances related to human and other unanticipated causes are perhaps an order of magnitude greater than those from anticipated causes. Similar conclusions can also be stated regarding casualties in various offshore structures, and in fact, just about any well engineered marine structural system today. This indicates the somewhat limited scope of the type of reliability assessments now practiced.

History of Structural Reliability Applications

Tracing the history of any area of human endeavor is fraught with difficulties, particularly if that effort takes place at a time when global communication is not what it is now, and barriers of language were more prevalent. In any event, early pioneers in the treatment of design uncertainties have included Mayer, [4], who as early as 1926 considered the safety of structures using means and variances, and Weibull [5], who in 1939 presented a statistical theory of the strength of brittle solids. According to [6], the relationship of the traditional safety factor to variabilities in loads and strength was also stated in the late 1920s in a series of papers by Khotsialov and Streletskii. In this country, early applications of reliability theory involved electronics and aerospace hardware, and interest in structural reliability applications began with a paper by Freudenthal of Columbia University in 1947, [4], to "analyze the safety factor in engineering structures, in order to establish a rational method for evaluating its magnitude". In 1966, there appeared the monograph by Sir Alfred Pugsley in the U.K., [8], and a second noteworthy paper from the Columbia team [9].

These early works were instrumental to the renewed interest in structural reliability research in the early 1970s. Among the promising developments, Cornell in 1969, [10], suggested the use of a mean value first order second moment method (MVFOSM) based safety index, which could be used to obtain load and resistance safety factors in conventional form. It was subsequently recognized that the MVFOSM index was not invariant to mechanically different forms of the limit state function. This limitation was overcome when in 1973, Hasofer and Lind [11] presented their generalized safety index $\beta$ which was now defined as the minimum distance from the origin to the limit surface in the space of reduced normal coordinates. The research and applications interest then quickened, see [12], and there have since then been several improvements in both the computation scheme and the treatment of non-normal variables, with the result that very efficient and accurate second moment reliability methods, e.g. [13], are now available and widely used.

In the marine structural field, American Bureau of Shipping as a major classification society recognized early the potential for structural reliability methods. To ABS, such methods seemed an ideal way to manage uncertainties in a basic and logical manner, while at the same time providing considerable insight because of the detailed accounting of all aspects of the design assessment procedures, and thus as an ideal support mechanism for rule development. Thus it was in 1969, about the same time that Cornell stated the MVFOSM safety index, and at a time the very notion of a "probability of failure", however notional it was qualified to be, was an anathema to many in the profession, that ABS first sponsored marine structural reliability research at the Massachusetts Institute of Technology under the guidance of Professor Mansour.

The MIT project developed an analytical framework for the reliability of ship structures, in particular considering hull girder strength [14-15]. From this work, Figure 2 shows the MVFOSM safety index for 18 vessels, 12 of which were tankers. Tankers were a type of structure which at that time was showing significant increases in size, necessitating levels of direct calculation and extrapolation of service experience not usual before. As evident from the figure, the study demonstrated that there was scope for more uniformity in safety margins for various vessel types and sizes. The work continued at MIT and later at the University of California at Berkeley, and delved into various questions of uncertainty in loads and strength of marine structures, and eventually on possible code formats, see [16-18]. There had in the meantime been related projects including structural model tests, full-scale instrumentation programs, and other studies that ABS has either participated in, sponsored or conducted. Many of these had reliability components, and all certainly were designed to enhance the profession's understanding of various aspects of the design process.

In addition to Professor Mansour, another enthusiastic proponent of the application of reliability methods to marine structures, in particular semi-probabilistic or less than full distributional techniques, has been Professor Faulkner, who first collaborated with Mansour in 1973 at MIT, [19], and later independently continued his work at the University of Glasgow, [20-21].

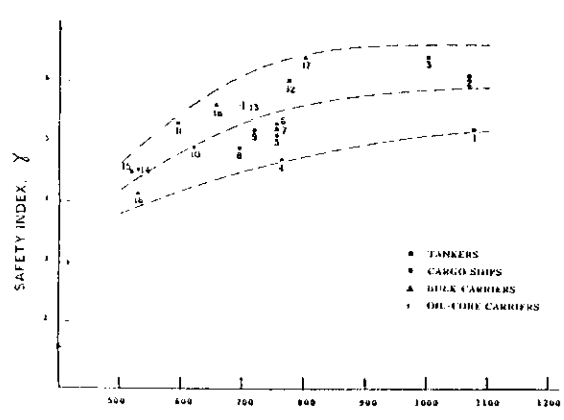



Figure 2 Safety Index for the Hull Girder Strength of 18 Vessels, from an early study by Mansour.

After an initial emphasis on ship structures, reliability research at ABS later expanded to cover the offshore field as well. Recent research has thus also aimed at questions of inspection and condition maintenance of ocean structures, in particular fixed offshore platforms. Companion papers being presented at this symposium outline related work led by Professor Shinozuka of Columbia University, [22,23]. Another paper, [24], is based on work led by Professor Wirsching of the University of Arizona on treating fatigue reliability aspects of marine structures, with emphasis on Tension Leg Platforms.

While ABS reliability research of early days successfully tackled basic questions, the more recent efforts have concentrated on the translation of such experience to workable design assessment schemes. A case in point is a recent Probability Based Model Code for Tension Leg Platforms, [25], result of a joint industry effort led by Conoco and ABS, and discussed subsequently.

Concurrently, other marine research organizations and regulatory bodies in the states had recognized the potential benefits of implementation of a reliability-based design standard and had devoted efforts toward establishing necessary frame works and practical procedures, as well as improving communication between researchers and engineers/designers. Among many of those organizations, the Ship Structure Committee, the U.S. Coast Guard and the Minerals Management Service have made significant contributions with respect to commercial application in recent years [30,31,69,84,85]. The successful implementation of a new design standard depends not only on the soundness of its scientific basis and logic process upon which the standard is developed, but also on the familiarity and confidence of the engineers in applying it. It is of vital importance to bridge the gaps between various sectors of the industry during the course of development.

## Uncertainty in Structural Design

It can be safely said that perfect knowledge does not exist. If it did, decisions would be obvious, elements of judgments eliminated, and many professions ranging from economicists to soothsayers would not exist as we know them today. Uncertainty, then, is an inherent part of any decision problem, including that of structural design. In this context, reliability methods appear particularly well suited to marine structures, primarily because many of the phenomena involved are random in nature and imperfectly known, and because for reasons of location, economics and logistics, the structures need to be relatively more efficient than, say, land-based buildings. One benefit of the increasing interest in reliability methods is that there has in the past few years been several interesting studies of the various uncertainties in marine structural design.

One class of uncertainties in marine structural design arise from imperfect knowledge related to structural loads, and inaccuracies in the design procedures that translate known loads into load effects. A lesson that reliability applications have made more obvious time and again is that there is a significant amount of conservatism in some aspects of this analysis process. Consider also the fact that, to start with, one does not often know the exact wave environment the structure will be subject to in its lifetime. Ocean-going merchantships, for example, are nominally designed to extrapolated 20 year wave bending moments resulting from a "standard" wave environment typically based on North Atlantic data. The extent of human control on vessel operation is not taken into account to any large extent. Figure 3, from a recent study of various full-scale deck stress measurements [26], illustrates that for various reasons, the wave bending moments used in ship hull girder design assessment may not always be met in service. In such cases, the loads used in design of course serve the aim of consistent comparative assessments of structural performance.

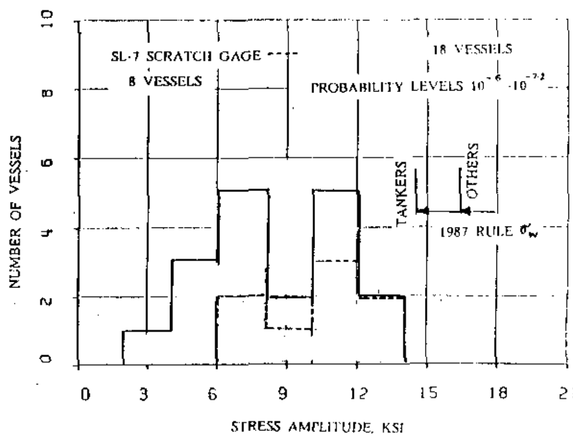
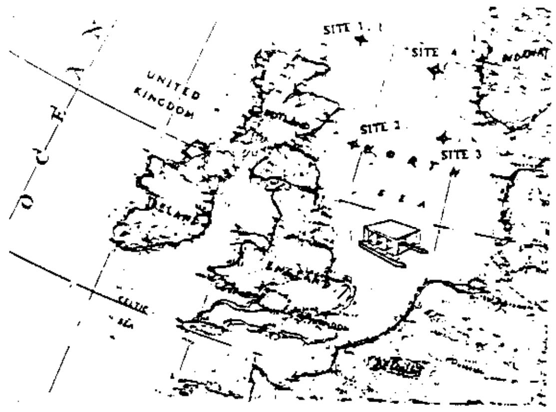



Figure 3 A Comparison of Deck Stress Measurements in Ships, with Wave Load Criteria Nominally used in their Design Assessment.

With the long term wave environment known, the situation is somewhat better, ever since St.Denis and Pierson [27], successfully demonstrated the applicability linear frequency domain procedures. Still, the load effects and structural response are computed through idealized engineering models. Various assumptions need to be made in these calculations, including in the spectral representation of the seas, and in the quasi-static or dynamic analyses that follow. Consider the case of semi-submersibles, another class of mobile structure where the lifetime wave environment may not be precisely known at design. Here, experience has generally shown that the effect of uncertainties, whether in the wave environment, the calculation of the lifetime extreme loads, wave spectral representation or the use of idealized models of wave spreading, appear considerably more exaggerated. This is primarily because of the period sensitive nature of such structures. For the same set of assumptions, Figure 4, obtained from [28], illustrates the net effect in the case of fatigue lives for a recent twin hull semi-submersible for continuous operation at different sites in the same general area of the North Sea. As noted in [37], it can be said that the effect of load related uncertainties on design estimates occasionally surprises even some experienced practitioners.

Equally important uncertainties exist in strength as well. A considerable amount of early research at ABS, for example, was spent




SAMPLE OF 21 BRACE TO COLUMN FATIGUE POINTS

| | SITE 2 | SITE 3 | SITE 4 | SITES 2-4 | SITES 1-4 |
|---|---|---|---|---|---|
| BIAS | 1.5 | 1.4 | 1.0 | 1.1 | 1.4 |

Figure 4 Effects of the Wave Environment on Fatigue Lives, in the case of a Semi-submersible for North Sea Operation.

in a painstaking collection of data related to variability in the strength aspects, such as material yield strength, modulus of elasticity and plate thicknesses, see for instance [17,18]. Uncertainties in fatigue strength are another example. Figure 5, from [28], illustrates one such uncertainty aspect in the case of welded structural details. In the figure, the slope parameter m for Stress-Life (S-N) curves is shown to vary significantly between two existing collections. Here, while one collection of S-N data show slope parameters close to but less than 4, the other indicates slope parameters significantly greater, although both sets of data are meant to be applied to the same general class of welded fabricated structural details. Of course this does not translate to a similar disparity in fatigue lives, since the slope and intercept constants are strongly correlated. However, it does mean that the sensitivity of fatigue life estimates to errors such as those in stress concentration factor determination, for example, will be different for the two sets of data. And it is a fact that the estimation of stress concentration factors is an area of considerable uncertainty, particularly when parametric equations are used, as they often are in structures such as fixed offshore platforms.

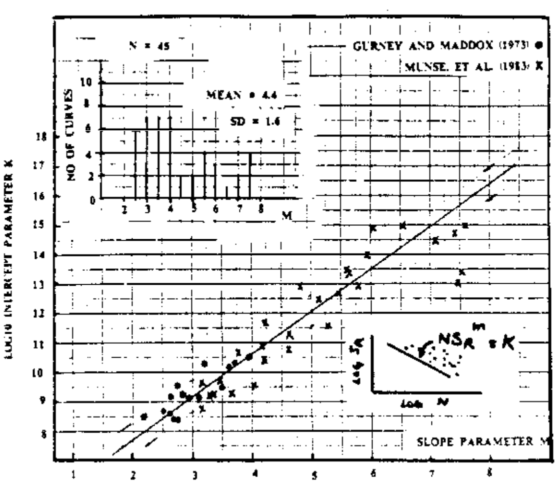



Figure 5a Trends of Fatigue Strength in S-N Data for Weld Fabricated Structural Details.

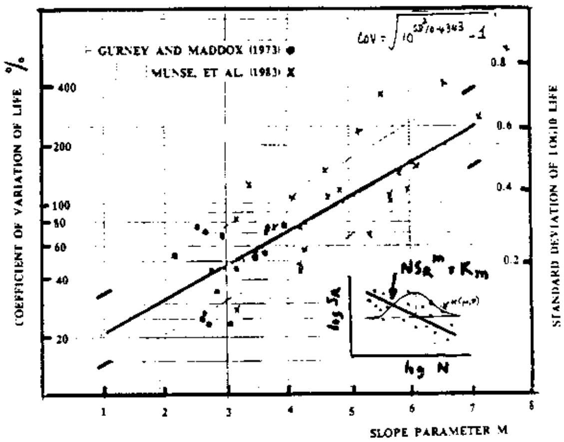



Figure 5b Trends of Scatter in S-N Data for Weld Fabricated Structural Details.

The above are but a few illustrations of design process related uncertainties in marine structures. Regarding such uncertainties, we can say that many of them are quantifiable to varying degrees with the requisite effort. Some of this effort has already taken place. In addition to the references previously cited, examples include Ang, [29], and Kaplan, [30], in the case ship hull performance, and Munse, [31] and Wirsching [32], on fatigue effects in ships and fixed offshore structures, respectively.

The use of a reliability framework in structural design does not need to await the elaborate and exact quantification of the various uncertainties. To recognize and treat all uncertainties may not even be possible, and occasionally, hazards unrecognized at the design stage can appear later in life. Some of these uncertainties appear more important than they should be, in part because practitioners have in the past been reluctant to consider redesign and reassessment schemes in numerical terms. In fact, reliability methods are also ideal for such applications.

A point to be noted is that any safety measure, whether deterministic or probabilistic, is a function of procedural details. That is to say, if two structures need to be designed to the same level of performance, comparisons are meaningful and consistent only if the same procedural details are used. For marine structures, there exists the need to select, identify and validate design procedures and obtain and catalog relevant data necessary to make possible the consistent assessment of structural reliability. This is undoubtedly a difficult and perhaps controversial task, and likely to be a long one.

## Why a Reliability Design Framework?

Given the apparent success of deterministic methods in marine structural design, an obvious question to ask is why one should opt for a new and different way of thinking. The answer to this is manifold. To some, there is of course the fact that the new approach is philosophically more appealing. There is also the argument that some types of structural failure are not obvious, one such "failure" being the inefficient use of material or other resources, [33]. The most immediate technical argument that one can profess for the use reliability theory in structural design is, however, that it has the potential for enhancing the quality of the system being engineered. This can occur because of the detailed accounting of uncertainties the method requires. It can also occur because safety margins within a class of structures can now be made more consistent. As studies on offshore structures [34-37] appear to indicate, these attributes have the potential for more efficient use of resources, one obvious result being reduced steel weight in some cases.

Reliability based deterministic design would usually involve split safety factors being applied to various components of load and strength. These split or partial safety factors would depend on the relative uncertainty in the variable to which they are applied. In such a split safety factor format, since one places safety where it should be, the resulting structure can be more efficient, and more particular to the needs at hand. In addition, it is much easier in such formats to account for effects such as workmanship and the consequences of failure of a member or sub-system, if one wished to do so. The quality of engineering analyses can also be readily accounted for in such formats. For example, it may be required that with a less refined stress analysis, the load effect safety factor would be higher. On another level, as previously noted, reliability methods are better suited for structural reassessments and life extension studies. They provide a rational basis for incorporating the effects of factors such as inspection and service experience, given, of course, that one accepts the tenets of Bayesian statistics!

It is evident, however, that a reliability approach to design is inherently more involved, and requires an amount of retraining on the part of the engineer. Also, to some who have thus far been able to design structures using conventional determinism quite successfully, it may appear that reliability technology is somewhat "fuzzy", with judgments playing a major role, and "probabilities of failure" and related safety indices being employed in cases where the actual data is scarce, as is the case at the tails of the load and strength variates. Another important reason for the slow move toward reliability based codes in marine structures is that in some cases, existing design assessment procedures, e.g. ship classification rules, have tended over time to consider certain failure modes such as fatigue in an implicit rather than an explicit manner. While such approach certainly results in procedural simplification, it also makes existing interrelationships between failure modes less obvious. In any event, there is now the added effort of having to rewrite codes so as to treat different failure modes specifically. There are answers to all these concerns. Apart from focused research, these answers include more effective communication and re-education.

## Classification of Reliability Approaches

There is now somewhat of a consensus that the most immediate use of structural reliability techniques today is in the development work leading to design codes. In this context, reliability approaches can for convenience be thought of at three levels, as noted in Table 1. Details of the approaches may be found in [38,12]. Level-II fast probability integration methods are now the most common, and form the basis for Level-I deterministic safety checks using partial safety factors as previously referred to. Level-III methods have found limited use because of the necessity for a multivariate probability description and subsequent integration, whether exactly, numerically, or through Monte Carlo techniques. Reliability applications at the American Bureau of Shipping (ABS) have generally used the Level-II fast probability integration technique, e.g. [39], leading to a Hasofer-Lind Safety Index. This is because of the following attractive characteristics of the Level-II method.

(a) A relatively good accuracy

(b) Statistical information needed is generally limited to means, coefficients of variation and forms of the probability distribution, and

(c) The ready determination of Level-I partial safety factors as well as sensitivity information.

Table 1. Levels of Reliability Application

| Level | Description |
|---|---|
| I | Uses Deterministic Safety Factors Obtained from a Level II analysis. A conventional safety check is employed. |
| II | First and Second Order (FORM and SORM) fast probability integration techniques to calculate notional safety measures given basic variables and corresponding uncertainty information. |
| III | Exact integration over the load and strength domains to obtain the notional safety measure. Requires multivariate probability distributions. |

An additional valuable feature is the ability to use most existing Level-II procedures in a "black-box" type manner, with what may be called a "randomization" of deterministic models.

That the various reliability integration approaches will inevitably give somewhat different results is an obvious conclusion. Table 2, from [18], illustrates this for the very simple case of the nominal first yield limit state for a ship hull girder, with the limit state equation given by

$$M_s + M_w = SM\ \sigma_y$$

where $M_s$ and $M_w$ are the still water and wave bending moments, SM is the elastic section modulus at deck, and $\sigma_y$ is the yield strength. Table 2 presents probabilities of failure resulting from a MVFOSM analysis, as well as those corresponding to a Hasofer-Lind index. Also, because of the simplicity of the limit state expression, an exact integration was possible for the notional probability of failure. The results indicate that in this particular case, the "exact" method was more conservative than the other two methods, and that

Table 2. Probability of Failure for 18 Sample Ships

| Ship | Notional Probability of Failure $p_f$ | | |
|---|---|---|---|
| | MVFOSM | Hasofer-Lind | Exact |
| 1 | 1.528E-7 | 1.611E-7 | 3.541E-7 |
| 2 | 6.0E-10 | 1.2E-9 | 9.356E-9 |
| 3 | 1.5E-10 | 5.5E-10 | 8.398E-9 |
| 4 | 1.301E-6 | 1.581E-6 | 3.767E-6 |
| 5 | 1.699E-7 | 1.699E-7 | 3.372E-7 |
| 6 | 7.205E-7 | 6.825E-8 | 1.233E-7 |
| 7 | 8.48E-8 | 8.03E-8 | 1.465E-7 |
| 8 | 5.58E-7 | 7.178E-7 | 1.784E-6 |
| 9 | 9.965E-8 | 1.303E-7 | 3.868E-7 |
| 10 | 5.305E-7 | 7.178E-7 | 2.100E-6 |
| 11 | 7.605E-8 | 2.852E-7 | 1.586E-6 |
| 12 | 7.21E-8 | 9.45E-8 | 1.688E-7 |
| 13 | 1.795E-8 | 2.82E-8 | 1.197E-7 |
| 14 | 3.398E-6 | 6.212E-6 | 1.968E-5 |
| 15 | 3.732E-6 | 3.732E-6 | 7.011E-6 |
| 16 | 2.90E-4 | 5.770E-4 | 1.099E-3 |
| 17 | 1.0E-10 | 4.0E-10 | 7.438E-9 |
| 18 | 1.075E-8 | 2.01E-8 | 1.130E-7 |

the mean value method deviates more from the exact result than the Hasofer-Lind results. Note, however, that these indications are not necessarily general. They depend, for example, on whether the limit state function is linear, and on details of treatment of non-normal variables. In considering their accuracy, one must also not loose sight of the fact that the calibration exercise usual to code development is also not by any means exact.

## Reliability Methods and Code Development

In structural codes, Level-I safety checks are made for various limit states, broadly classed as serviceability and ultimate limit states. The *serviceability limit states* typically consider structural behavior that do not affect load carrying capacity. Examples include local deformations, machinery and hull vibrations, etc. Ultimate limit states relate to the load carrying capacity of the structure, and treat plastification, buckling, some fatigue effects, and fracture. The safety check made implies that

$$g(Z_i) > 0 \quad , \quad i=1,..n$$

where $Z_i$ are the n design variables defining loads and strength. The variables used in the safety check equation are characteristic values (e.g. Rule minimum values) modified (either divided or multiplied) by partial safety factors. The Level-I split safety factors are usually based at least in part on Level-II analysis.

Among the first tasks in reliability based code development is the selection of the Level-I safety check format, an example of which is shown in the Appendix. A review of a few different split safety factor code formats may be found in [18]. In a Level-II analysis leading to partial safety factors, there can in principle be as many partial safety factors as there are design variables. There also must be load combination factors to account for the possible non-simultaneous nature of extreme values. *Code formats, however, need to be simple*, yet accurate. These are conflicting requirements, and are often met in codes only to a limited extent. This is because in such situations, pragmatism necessarily governs, since even the ultimate representation of reality is meaningless if it cannot or will not be used. Ideally, however, the accuracy of reliability models used in obtaining the partial safety factors for any given code format would have been judged against the results of a more sophisticated reliability analysis.

The determination of partial safety factors depends on a target value of the safety index $\beta$, which in turn is related to a notional failure probability $p_f$ through the expression

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

An elaboration may be found in [38]. With the present state of knowledge of uncertainties in loads and strength, it is in general not possible to obtain "real" failure probabilities with any confidence. Thus the safety index is typically used as a calibration device against successful past experience relevant to the present situation. This *practice of pegging the new code format details to past experience* also satisfies a need for continuity, which can be overriding when existing codes are being rewritten on probability precepts. Figure 6, obtained from [40,41] shows typical notional safety indices representing various types of marine and land based structural experience. As noted in the Appendix, the Conoco/ABS Model Code effort related to Tension Leg Platforms tentatively used a target safety index of 3.72, corresponding to a notional probability of failure of 1 in 10,000. In the offshore field, values about 3 as a target safety index are more common, see for example [35] related to the Load and Resistance Factor (LRFD) translation of the API RP2A, [42], for Fixed Offshore Structures.

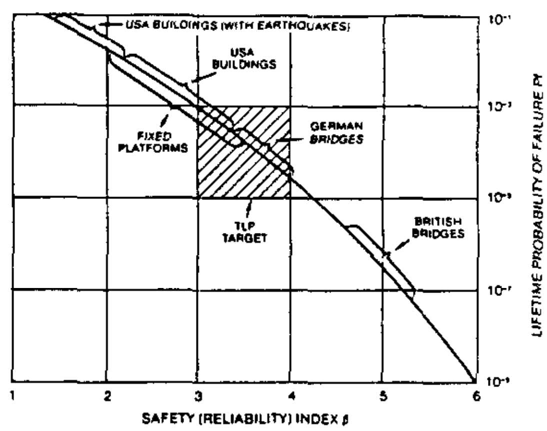



Figure 6 Safety Indices for Various Marine and Land Based Structures.

An aspect of partial safety factors that experience has emphasized time and again is their fidelity (or the lack of it) in reproducing in design, the level of notional safety they were meant for. This variability is a direct result of the *simplification* usual in design code formats, where the number of partial safety factors needs to be a practical minimum. It is now clear that partial safety factors in such applications are a strong function of the composition of the load, e.g. the *ratio of static to dynamic load components*. Figure 7, from [43], shows trends of this "load ratio effect" in a particular case of the flat plate structures in TLPs. If such trends had not been accounted for over the relevant load ratio range, the variability in the safety indices for structures resulting from the code may in some cases be unacceptable. In any case, partial safety factors for limit state structural codes need to be optimally obtained, e.g. by minimizing the sum of the squared difference of actual and target safety levels, $(\beta - \beta_T)^2$, considering such effects as the load ratio, as well as the possible range of structural parameters.

One must at this time point out that experience indicates the partial safety factor format to be not always the most appropriate one for all limit states. In the case of fatigue design, for example, while partial safety factor formats have been proposed, the ABS Tension Leg Platform rule development effort, [25,24,44], as well as other fatigue reliability studies, indicate that deriving allowable Miner linear cumulative damage criteria for a target safety index is a simpler and viable approach, with the added advantage of being consistent with present design procedures.

On the subject of code formats, it should also be pointed out that while partial safety factors and reliability based Miner criteria could eventually become the most common option, the possibility of direct design using reliability analysis for a target safety level using codified sets of uncertainty description also exists. This is an attractive option, since structural variability related to applying a limited set of safety factors would then not exist. The approach was at one time considered by the Conoco/ABS Rule Case Committee for Tension Leg Platforms, and is in fact still a possible alternative. Unless various procedural and other details are standardized or specified, the direct design approach should of course be used with some caution, and possibly by appropriately trained personnel, so as to obtain designs whose notional safety is not less than that resulting from conventional design codes.

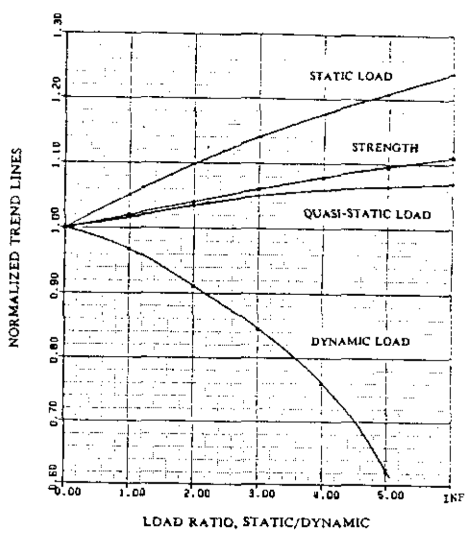



Figure 7 Trends of Partial Safety Factors with the Ratio of Static to Dynamic Loads in TLP Flat Plate Structures.

## Progress in Structural Reliability Applications

There have now been a number of structural code development efforts using reliability theory at least in part. While one would think that obvious candidates for this technology would be structural concepts such as Tension Leg Platforms, where little prior experience exists, many of the efforts in question are actually rewrites of existing ones, with accumulated experience being transfered through a code calibration process using an appropriately selected target safety index $\beta$. In related fields, some such codes, code proposals or model codes are listed as references [45-53], and include the newly released Load and Resistance Factor Design for Buildings, from the American Institute for Steel Construction, the American National Standard A58 for Building Loads, Comite Euro-International du Beton effort related to concrete structures, the National Building Code of Canada, and the Building Code of the Canadian Standards Association, which, in 1974 published the first limit state code based on probabilistic precepts. While many of the above are not yet working codes, and not all universally employ structural reliability theory in deriving the partial safety factors, there various attempts do represent a significant change in thinking and approach in structural design. These efforts were made possible by a realization that, while any change is a nuisance, it can have its advantages.

There has been a significant amount of research and applications interest in the marine structural field as well. The effort has covered diverse areas such as uncertainty assessment, the development of simplified reliability models, system reliability applications, issues of design, inspection and redundancy, and of course code development. Some of these efforts were previously noted, and others may be found in [54-76]. It must at this time, however, in all candor be admitted that completely reliability based marine structural codes used on a day-to-day basis do not exist, although considerable progress has been made in that direction. Examples include the API fatigue reliability work, [32], the recent pilot study at the University of Glasgow on calibrating the U.K. Bridge Design Code BS-5400 for fixed offshore platforms, [57], the API LRFD RP2A related project, [37], the LRFD rewrite of the CSA code for fixed offshore structures, [62], the proposed DnV offshore standards, [67], and the various ABS projects, Conoco/ABS Rule Case Committee Model Code and subsequent work related to tension leg platforms, e.g. [24,25,40,41,44], as well as other studies previously referred to, all of which undoubtedly will support the ongoing effort towards formal reliability based design guides.

## Concluding Remarks

The general state of marine structural reliability applications is an optimistic and promising one. This is so, even considering that in present structural design, some failure modes are in some cases still implicitly rather than explicitly treated, and deterministic approaches are the norm. The necessary analytical tools for development and calibration of structural design codes on a reliability basis, using limit state precepts, now exist. Also, significant progress has been made in the quantification of uncertainties in loads and strength. Many examples now exist where design assessment procedures have been calibrated using in part reliability technology, even if the resulting products are not yet formal working codes. Most of these applications have tended to use a partial safety factor format rather than direct design for a particular level of reliability. For reasons of simplicity, consistency and continuity, this trend is expected to continue in the future.

Thus far, however, marine structural reliability applications have tended to be confined to the performance of components rather than of the system, although the number of examples where system reliability is treated is on the increase. A significant amount of future research effort can be expected to be in this area, both in the development of appropriate analytical tools, and in the treatment of issues such as structural redundancy and system ultimate strength. The designer's feed back is no doubt an important element which may add to the realism of any reliability based code and broaden its applicability. This practice was exemplified in the development of the API LRFD code. Research will also be focused on the application of reliability theory to questions of in-service inspection and maintenance, and related fitness for purpose and life extension issues. Eventually, the state-of-the-art in reliability applications will progress to a stage where factors related to economy and intangibles such as the societal and human consequences of failure can also be systematically considered in design.

Acknowledgements

The application of reliability theory to marine structural design is a collective effort, spanning many organizations, individuals and countries. In this regard, this paper could never have been made even reasonably exhaustive, and it clearly has not been the intention of the authors to try to do so.

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## APPENDIX

## DEVELOPMENT OF RELIABILITY BASED DESIGN CRITERIA FOR TENSION LEG PLATFORMS

### Scope of Work

Recognizing the importance of probabilistic methods in the design of marine structures, the American Bureau of Shipping (ABS) and Conoco, together with other industry participation, initiated an intensive effort to develop reliability-based design criteria for tension leg platforms. TLPs, Figure 8, are a type of structure with which little prior experience exists. This appendix describes aspects of the effort, including some experience gained from that endeavor. An expanded description of the following material may be found in Mansour, Jan, Zigelman, Chen and Harding, [18].

The TLP project aimed to utilize state-of-the-art technology and results of extensive structural model tests to develop design criteria. For this purpose, a Rule Case Committee (RCC) was formed in 1981, consisting of members drawn from ABS, Conoco, and the associated organizations [40,41], with Professor Faulkner of the University of Glasgow at the helm. Their scope of work covered several areas, including the selection of appropriate reliability methods, development of strength formulations for the various failure modes in the proposed limit state code, formulation of a statistical model of the environmental disturbances, and the quantifications of all relevant uncertainties.

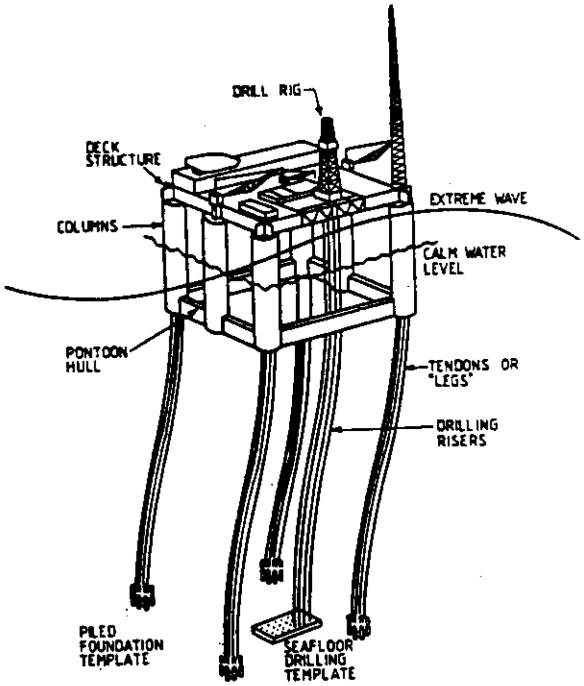


Figure 8 The Tension Leg Platform, the Focus of a Recent Reliability Based Code Development Effort.

The primary emphasis at this stage of the effort was on the major cylindrical components of the structure, including the corner columns and the pontoon. Flat plate assemblies were later considered. The RCC work focused on ultimate limit states. Work related to serviceability limit states, to reliability in the fatigue limit state, and to system reliability were also to be subsequently undertaken by ABS.

In the RCC work, the code format was developed along the Level-I approach utilizing partial safety factors, which were obtained through Level-II analyses for a given target safety index, $\beta$. A review of the many possible analytical methods for treating structural reliability may be found in [38,18]. The RCC treatment of non-normal variables followed that of Rackwitz and Fiessler [77]. Reliability calculations were made using the Horne and Price [39] algorithm, which offers an iteration scheme that is more attractive than that of [77].

The Rule Case Committee tentatively selected a target safety index $\beta$ of 3.72. This compares favorably with the $\beta$ range of 4.2 to 4.6 calculated for a stiffened cylindrical column structure of an existing mobile offshore drilling unit in the as-built condition. The committee further recommended that, when a direct calculation using the Level-II algorithm is employed, the possibility of reducing the target safety index to 3.0 can be examined.

## Environmental Model and Load Effects

Ideally, the occurrence of relevant environmental events such as wind, waves, tide, and current should be characterized by their joint probability. There are theoretical and practical reasons as to why this is beyond the present state-of-the-art. The most pressing problem is one of lack of sufficient data especially in the regions corresponding to extreme values of the variables [78]. Considering this, a simplified model [79] for the combined environmental disturbance was proposed in the TLP work. In the model, the significant wave height and the characteristic wave period are regarded as the prominent environmental parameters, and their joint distribution is first developed. The distribution of other parameters are taken dependent or conditional on given values of the significant wave height.

Another consideration of interest is related to the nonsimultaneous occurrence of the environmental events. For instance, in wind-driven waves, measurements suggests that there can exist a time lag between extreme wind and extreme waves. Nor would the wind or current directions necessarily coincide with the predominant wave direction. In these cases, it is possible that usual treatments of the load combination problem, e.g. Turkstra's Rule, can be non-conservative. Other approaches to the problem have also been proposed, e.g. [80]. In the TLP work, the issue was by-passed in light of the fact that the load effects on the structure, due to the action of environmental events other than waves, are generally small.

In the context of reliability analysis, one aspect of the simplified environmental model used is worth noting, namely, that wave effects were treated as dynamic while effects of wind, current, tidal level, mean wave drift, etc., were considered quasi-static. The load effect extreme values within each of these groups and those corresponding to the static loads were considered fully correlated within any given group. All load effects in a group were assumed to have the same coefficient of variation. The number of partial safety factors was thus reduced to a manageable set, with resulting simplifications in the safety check equations.

## The Treatment of Strength

For purposes of code design, the ultimate strength of stiffened cylinders are determined from simplified strength formulations, see [81]. These formulations were selected in part because they compared favorably with experimental data in terms of both bias and scatter. A sample comparison of the theoretical strength predictions to test data for the particular case of orthogonally stiffened cylinders under axial compression is shown in Figure 9. Such data are useful in defining the biases and coefficients of variation of the random "modelling error" parameters used in the reliability analysis for the partial safety factors.

The structural model tests during and subsequent to the RCC program, e.g. [82], were limited to cylindrical structures. With regard to plane structures, existing design formulae were considered acceptable, except when the panel carries both in-plane and transverse loads. In this case, experimental and/or analytical work seems desirable.

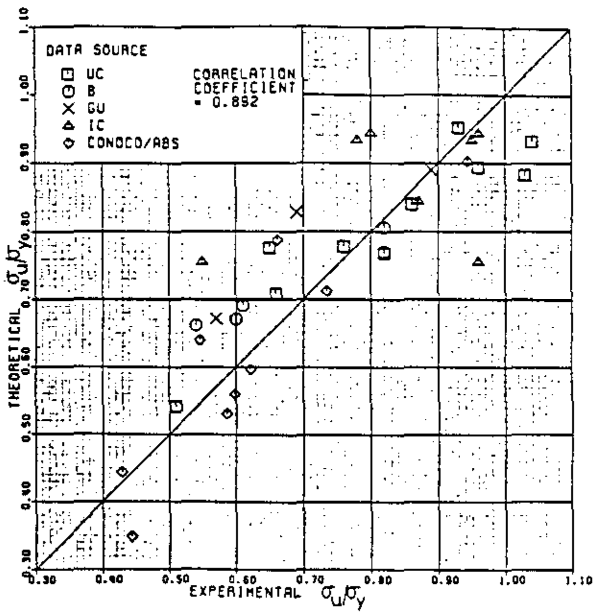


Figure 9 Comparison of Theoretical Strength of Orthogonally Stiffened Cylinders under Axial Compression with Test Data.

## Estimation of Uncertainties

Uncertainty estimation was one of the most difficult, but important tasks of the TLP work. With regard to the load effect uncertainties, the inherent variabilities were of less concern since they could be derived from the basic probability density functions. The estimation of the subjective uncertainties, however, needed heavy reliance on judgment. These subjective uncertainties arise from the imprecise knowledge related to environmental data, load prediction, motion and load analyses, and structural idealization.

With regard to the uncertainties in strength, other than the modelling errors discussed earlier, those due to material variability, mostly in yield strength and plating thicknesses, are important. Tentative values for the coefficients of variation of various uncertainties, suitable for use in the reliability analysis of TLP structural components, may be found in [83]. That reference also illustrates how the reliability approach can be applied in the direct design evaluation of offshore structures.

## On the Safety-check and Partial Safety Factors

In design, adequate structural performance in the various limit states is to be verified for each main structural component. For the cylindrical structures considered, this is demonstrated by meeting the requirement that design load effects do not exceed design resistance, according to the following safety-check expression.

$$\frac{(\gamma_s N_s + \gamma_q N_q + \gamma_d B N_d) + (2/R)(\gamma_s M_s + \gamma_q M_q + \gamma_d B M_d)}{N_u/(\gamma_m \gamma_N)} + \left\{\frac{(\gamma_s V_s + \gamma_q V_q + \gamma_d B V_d) + (2/R)(\gamma_s T_s + \gamma_q T_q + \gamma_d B T_d)}{V_u/(\gamma_m \gamma_V)}\right\}^2 + \left\{\frac{\gamma_s p_s + \gamma_q p_q + \gamma_d B p_d}{p_u/(\gamma_m \gamma_p)}\right\}^n \leq 1$$

Here, characteristic (mean) values are used for the following extreme load effects:

N = compressive axial force

M = bending moment

V = transverse shearing force

T = torsional couple

p = external radial pressure

The subscripts s, q and d denote static, quasi-static, and dynamic components of each load effect. $\gamma_s$, $\gamma_q$, and $\gamma_d$ are the corresponding partial safety factors. B is a systematic modelling or bias factor for the dynamic component.

Also $N_u$, $V_u$, and $p_u$ represent the characteristic (mean) values for the axial, shear, and pressure states, and $\gamma_m$ is the strength reduction partial safety factor to account for variability in material properties and plate thicknesses. $\gamma_N$, $\gamma_V$, and $\gamma_p$ are strength modelling partial safety factors for the axial, shear, and pressure loads. The power n, corresponding to interaction effects, is tentatively taken as n = 2. For a further discussion of considerations related to safety check criteria under interacting loads, see for example, [81].

Illustrative values for the various partial safety factors in the above safety check expression are shown in Table 3. As previously noted in the text, these partial safety factors can be quite sensitive to the relative magnitude of the load effects, here, the ratio of the static to the dynamic components of the load. The load factors of Table 3 are thus for values of load ratios typical to the problem at hand. It is observed that the load partial safety factors shown are significantly different for the different types of loading, reflecting the relative intensities of the three loading groups as well as the variability (coefficients of variation) of each group. It is in providing for such differences that a reliability based code format differs from a traditional working stress design format.

Table 3 Illustrative PSFs for Ring Framed Cylinders

| PSF | Typical Value |
|---|---|
| $\gamma_n$ | 1.20 |
| $\gamma_p$ | 1.00 |
| $\gamma_m$ | 1.35 |
| $\gamma_s$ | 1.05 |
| $\gamma_q$ | 1.00 |
| $\gamma_d$ | 1.95 |