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System-based calibration of North West European annex environmental load factors for the ISO fixed steel offshore structures code 19902

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System-based calibration of North West European annex environmental load factors for the ISO fixed steel offshore structures code 19902

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This report presents results of the simplified system approach used in the Joint Industry Project (JIP) to derive environmental load factors for a North West European Annex to the ISO fixed steel offshore structures Code 19902.

The ISO 19902 Code introduces new provisions and changes in design practice; these changes, together with a new understanding of the NW Europe environment, means that it was necessary to review the levels of safety and economy of structures that may be achieved by the use of the new Code for the design of NW European fixed offshore steel structures. The main objective of this JIP was to calibrate the load factors for the NW European environment, although the other load and resistance factors were assessed also.

The project was been developed in collaboration with a broad industry grouping of consultants, oil companies and regulators from across Europe; BOMEL led the JIP load factor calibration phase. The JIP involved calibration using both a system-based approach and a component-based approach. The methodology developed for a 'simplified' system-based calibration is described in this report and results are presented.

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CONTENTS

EXECUTIVE SUMMARY

This report presents results of the simplified system approach for the Joint Industry Project (JIP) to derive environmental load factors for a North West European Annex to the ISO fixed steel offshore structures Code 19902.

The ISO 19902 Code introduces new provisions and changes in design practice; these changes, together with a new understanding of the NW Europe environment, mean that it is necessary to review the levels of safety and economy of structures that may be achieved by the use of the new Code for the design of NW European fixed offshore steel structures. The main objective of this JIP is to calibrate the load factors for the NW European environment, although the other load and resistance factors are assessed also.

The project has been developed in collaboration with a broad industry grouping of consultants, oil companies and regulators from across Europe; BOMEL led the JIP load factor calibration phase. The JIP involved calibration using both a system-based approach and a component-based approach [1]. The methodology developed for a 'simplified' system-based calibration is described in this report and results are presented.

To carry out a system-based calibration, the relationship between the reserve strength ratio (RSR) for a structural system and the environmental load factor needs to be established. Clearly, since the load factor is being calibrated for use with the ISO Code, it is necessary to consider values of the RSR for structures designed to the ISO Code. Since it is not practical within this project to redesign complete structures and undertake pushover analyses to evaluate RSRs, it is necessary to derive a theoretical methodology for adjusting values of RSR to reflect design to the ISO Code.

The report considers how the RSR of a structural system is built up from a number of sources including implicit and explicit Code safety factors, and system redundancy. A system reliability study has been carried out for theoretical values of minimum RSR for typical jacket structures designed to ISO. The reliability analysis has been undertaken using environmental load modelling derived to be representative of NW European waters. Unless noted otherwise, an annual reference period has been used; thus annual probabilities of failure have been evaluated.

The results show a wide variation in reliability across the range of environment-to-gravity load ratios and for different values of theoretical RSR. This means that it is not possible to choose an environmental load factor such that it can achieve consistent system reliability across a wide range of parameters.

To keep the exercise meaningful, an intelligent interpretation of the results based mainly on lower bound values of RSR is required. Lower bound values are expected to control failure for many optimally designed structures, but for some cases it is recognised that reliabilities assessed on the basis of theoretically-derived lower bound values will be conservative.

The failure probabilities evaluated from a reliability analysis are to some extent dependent on the level of Type II uncertainty included in the probabilistic modelling; Type II uncertainty is uncertainty that arises from lack of knowledge or information rather than uncertainty related to the inherent natural variation in the environment, material, etc., which is termed Type I uncertainty. One of the most significant sources of Type II uncertainty concerns the evaluation of the 100-year design load. The main system reliability analyses were undertaken with a CoV of 16.5% for this variable (this modelling was also used in the component-based calibration study). A study to assess the implications of increased environmental design loading uncertainty was undertaken; the CoV was increased from 16.5% to 25% to reflect concerns of some Participants.

On the basis of selected results, an extreme environmental load factor of 1.25 could be suggested for the design of structures in North West European waters. This value of the load factor corresponds to an annual target failure probability of 3×10^{-5} (using a CoV of 16.5% for design load uncertainty). This target value was first suggested by Efthymiou et al in 1996 for structural systems. A load factor of 1.35 will lead to a small increase in system reliability, or reduction in annual failure probability.

The results of the component-based calibration study suggest that an extreme environmental load factor of 1.25 leads to lower bound values of failure probability (rather than weighted averages) evaluated using compatible probabilistic modelling for tubular members that are an order of magnitude higher than the target suggested by Efthymiou for structural systems. From past experience and accepted practice, an order of magnitude between component and system failure probabilities is reasonable for redundant structures.

Applied in this way, the system level approach gives load factors compatible with the component-based approach, and can be a practical methodology that may be used in calibrating environmental load factors for other geographic regions of the world.

However, increasing the CoV of environmental design load from 16.5% to 25% leads to more than an order of magnitude increase in evaluated failure probability. These results cannot be reconciled with the base case results, and this makes the selection of a target reliability very difficult, particularly if cost-benefit considerations are used. (Cost-benefit considerations may be used to define targets for different Exposure Levels and for reassessment). Consequently, a consensus could not be achieved on a suitable value of target reliability.

The results suggest that adoption of a 1.35 factor on quasi-static extreme environmental loading with other ISO 19902 partial factors and provisions would result in structures being designed which deliver reliability levels for extreme weather at least consistent with traditional practice in all NW European regions.

For design use with NW European offshore structures, it is proposed by the Participants of the JIP to retain the existing value of environmental load factor at 1.35. However, there should be an option to derive structure-specific partial load factors using detailed analysis; this analysis should use site-specific environmental data and take into consideration the specific form of the structure.

1. INTRODUCTION

1.1 BACKGROUND

The Joint Industry Project (JIP) concerns the derivation of extreme environmental load factors for a North West European Annex to the ISO fixed steel offshore structures Code 19902. With the new provisions and changes in design practice introduced into the ISO 19902 Code, together with a new understanding of the NW Europe environment, it is necessary to review the levels of safety and economy of structures that may be achieved by the use of the new Code for the design of NW European fixed offshore steel structures.

The project has been developed in collaboration with a broad industry grouping of consultants, oil companies and regulators from across Europe. BOMEL is leading the JIP load factor calibration phase.

The JIP is using calibration approaches based on both system and component methods. By following both approaches it is believed that concerns with each of the system and component-based methods can be addressed and enough information generated to be able to make an informed judgement on the value(s) of the extreme environmental load factor(s).

The method developed for system-based calibration is described in this report.

The scope of work originally envisaged for the simplified system calibration approach was as follows:

- Develop RSR statistics. Assemble a database of pushover analyses for a wide range of modern structures in the region. Screen and validate the results to ensure results are reliable and on a consistent basis. Apply a range of weighting criteria.
- Perform reliability analysis using first-order second-moment reliability method (FORM).
- Target assessment based on generic Cost Benefit Analysis.
- Sensitivity analyses.
- Prepare report.

For brevity, throughout this report, the term “Code” is used to refer to the ISO and API design documents. All work in this report has been based on the Committee Draft of the ISO Code dated June 2001 [2].

2. SYSTEM-BASED APPROACH TO CALIBRATION

2.1 SUMMARY

This section discusses the basis of the system-based approach to the calibration of the environmental load factor. One of the most important inputs to the method is statistical information on the uncertainty in the ultimate strength of structures. The ultimate strength of structures is evaluated using non-linear pushover analyses, and is usually expressed as the reserve strength ratio (RSR) of the structure - the ratio of the ultimate load to the design load (see Section 3.2). However, there are a number of important concerns that mean that it is not valid to simply collate values of RSR for use in the calibration analysis; these concerns are discussed in Section 2.3.

2.2 BASIS OF SYSTEM-BASED APPROACH

The system approach, based on system failure and generally referred to as the 'Shell method', is described in a 1996 OMAE paper by Efthymiou et al [3]. The method is based on evaluating the probability that the extreme environmental load will exceed the Reserve Strength Ratio (RSR) of a structure within a specified reference period. In essence, this can be evaluated by structural reliability analysis using a failure function of the form:

$$Z = \mathrm{RSR} - W\,f \qquad (2.1)$$

where W is the maximum hydrodynamic load in the reference period (1-year) normalised by the 100-year load,

and f is the uncertainty in wave force modelling.

The failure probability may be expressed graphically in the traditional reliability format shown in Figure 2.1, in which

- the resistance probability distribution function (pdf) represents the uncertainty in the RSR of the structure (designed to the ISO Code), and
- the loading pdf represents the inherent variability in the maximum environmental loading due to the climate in the reference period (e.g. annual) and also the uncertainty in defining and evaluating the 100-year design load.

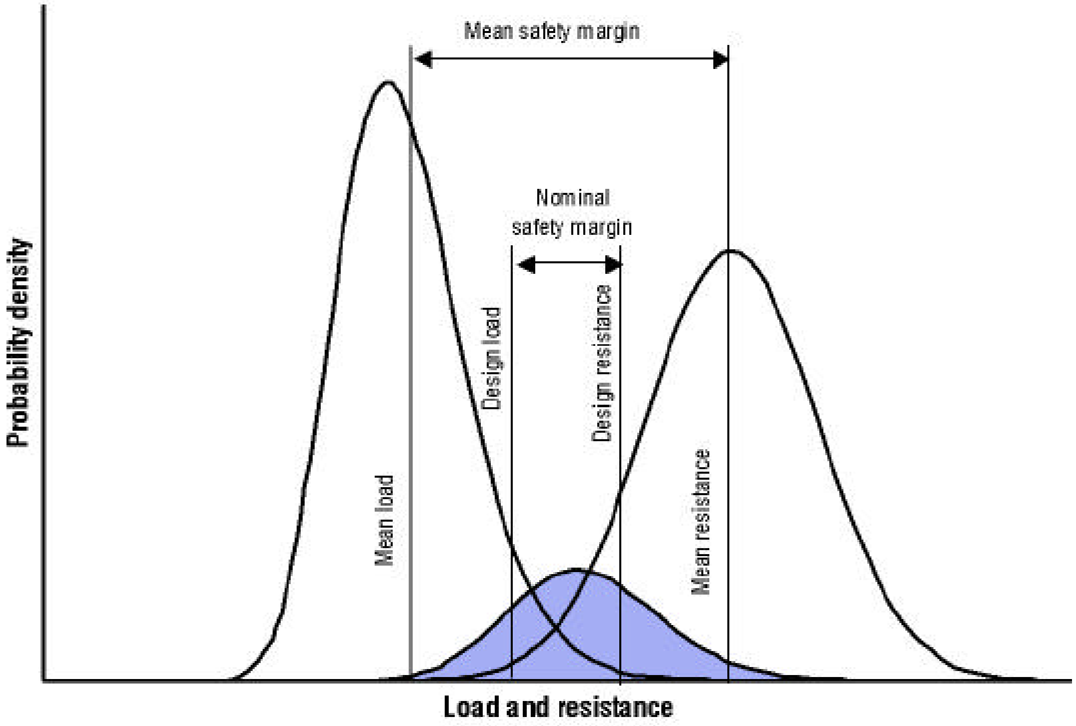

Figure 2.1 Illustration of Probability of Failure

In principle RSR is directly related to the environmental load factor, and thus the value of the partial load factor can be calibrated to achieve a target reliability. The main advantage of the method is that it is a direct approach to evaluating the environmental load factor, and it is simple to apply and understand.

For this JIP, the uncertainty in the environmental loading in the NW European region has been derived by Tromans et al [4]. The assessment of the resistance uncertainty, and in particular the mean value of RSR, is discussed in Section 3.

2.3 CONCERNS WITH THE COLLATION OF RSR STATISTICS

Originally it had been intended to collate values of RSR from pushover analyses. However, recent work has shown that there is a very wide range of published RSR values, due to differences in:

- reasons for undertaking the pushover analyses
- software used, analysis methodology followed, experience of analyst
- finite element formulation
- detail of modelling, modelling of joint eccentricities and offsets, etc.
- assumptions for foundation modelling

- material properties (e.g. whether or how strain hardening is included)
- whether joint failures, foundation failures, local buckling, hydrostatic pressure effects, etc. were included
- basis of environmental load (and topside load) applied
- original design Code or Edition
- degree of optimisation in the original design.

Blindly collating all published values of RSR would lead to a histogram that would be dominated by the variability and uncertainty associated with all of the above points – it would **not** reflect the uncertainty in the 'true' RSR of modern structures (designed to the ISO Code), which is what is required for safety factor calibration.

It should be possible to screen the RSR results and analyses. Unfortunately, in many of the published papers concerning pushover analyses much of this basic information and assumptions are not presented, making it very difficult to collate values of RSR that have been evaluated on a consistent basis.

One of the most significant problems with using RSR results for existing structures is that the selected structures should be designed to be fully utilised, since for safety factor calibration it is necessary to assume that future designers will use the Code to its optimum. Thus, the influence of Operator or designer 'conservatism', 'engineering judgement', 'other design requirements' (e.g. transportation, installation, other wave directions, etc.), non-optimal design (e.g. due to fast-track design, etc.), etc., on RSR should be minimised.

Furthermore, the design should reflect the provisions of the ISO Code. Thus, the RSR of interest to the present system-based reliability analysis is the minimum RSR for a structure where the critical members initiating structural failure are designed to be fully utilised to the ISO Code for the 100-year design environmental load.

Clearly, it is not practical within this project to redesign complete structures to reflect the new provisions in the ISO Code and to undertake pushover analyses to evaluate the RSR for structures. Thus, it is necessary to derive a theoretical methodology for adjusting values of RSR to reflect design to the ISO Code.

In principle, it should be possible to consider a smaller set of pushover analyses in which all of the assumptions and details are presented; by considering the failure path small adjustments could be made (by hand) to the RSR.

However, in many cases the design load information required to carry out this conversion for the critical members in the failure path might not be readily available from a pushover analysis report.

Information such as length, diameter, thickness, characteristic yield strength used for design, material strength used for pushover analysis, Young's modulus, K-factor used for design, ratio of environmental-to-gravity load (unfactored), and ratio of original design load to true 100-year return period environmental load for the critical members would be required.

A method for determining system reliability based on calculation of theoretical reserve strength ratio (RSR) values is derived. The method uses a derived relationship between environmental load factor and RSR. Sets of analysis results for the Kittiwake and Tern structures are examined, and typical pushover analysis results are used to determine the range of likely RSR values.

3. METHOD FOR CHARACTERISING MINIMUM RSR

3.1 SUMMARY

This section discusses structural reserve strength and the sources of reserve strength that exist in a structure above the design strength of the components. A methodology is then presented for adjusting values of RSR to reflect fully optimised designs to the ISO Code, and a relationship between RSR and the environmental load factor is developed. The assumptions inherent in this approach are discussed, and finally an example is given of the sources of reserve strength based on the results of pushover analyses for two structures.

This method for characterising minimum RSR is clearly *not* intended to replace pushover analysis. Amongst other reasons, it is necessary to undertake pushover analyses in order to determine the failure path.

It is notable that the methodology to characterise RSR has some parallels with that adopted by the industry-wide API Task Group when determining acceptable reserve strength levels for the API RP2A Section 17 for the assessment of existing structures [5].

3.2 STRUCTURAL RESERVE STRENGTH RATIO

The definition of reserve strength ratio of a jacket structure is:

$$\mathrm{RSR} = \frac{\text{environmental load at collapse}}{\text{original design environmental load}} \tag{3.1}$$

RSR is evaluated using non-linear FE analysis of the structural model, often termed pushover analysis. Typically the analysis is undertaken by applying the gravity loading as an initial load step. The environmental design load for the chosen direction is then applied to the model, and the environmental loading is factored incrementally until the ultimate strength of the structure is reached, typically characterised by a plateau in the global load-deflection behaviour of the model. Alternatively, the wave height or storm severity is increased rather than factoring the design load. The latter method is often applied if the air gap of the structure is small, such that wave-in-deck loading may affect the ultimate response.

A structure will have different values of RSR for different directions; the most important value of RSR for a structure is the lowest, which is the typically the value associated with the weakest direction or most severe environmental loading. From pushover analyses carried out over a number of years it may be concluded that optimised structures designed to API WSD exhibit an RSR in the range 1.8-2.5 [3]. For structures designed to an LRFD format, the minimum RSR will be somewhat higher than 1.8 (about 1.9) because the LRFD format removes the least reliable components of the WSD format.

The RSR of interest in the present study is the RSR of a structure (or structures) optimally designed to the ISO Code formulations and ISO 100-year environmental load (i.e. where the principal members initiating failure are fully utilised to the ISO Code).

For modern structures designed to the ISO Code the 'original design environmental load' will be the ISO 100-year load. Furthermore, new structures designed to the ISO Code should have sufficient air gap, such that the effects of wave-in-deck loading on failure probability do not need to be considered.

3.3 SOURCES OF RESERVE STRENGTH

Offshore structures are traditionally designed on a component-by-component basis, such that under all combinations of design loading every component in the structure has a utilisation ratio derived using the strength formulations recommended in the Code of unity or less.

The sources of reserve strength that exist in a structural system above the basic 100-year storm loading condition are identified in Table 3.1 below.

	Source	**Examples**
1	Explicit Code safety factors	For compression members this is: 1.41 for API-WSD (KL/r=80), 1.29 to 1.59 for API-LRFD
2	Implicit safety in Codes	Analytical/empirical equations for joint/member strength, K factors, lower bound joint strength
3	Actual material strength	Actual yield strength, strain rate effects
4	System redundancy	X bracing, multiple rows, multi pile foundations
5	Steel work included for temporary phases	Load out, launch framing, installation, mudmat bracing
6	Other design conditions/requirements	Other wave attack directions. Load out, transportation, installation, boat impact, pile sizing, fatigue requirements, etc.
7	Engineering practice	Non-optimisation of member sizes, fast-track design process, Operator or designer conservatism, etc.

Table 3.1 Sources of Reserve Strength Beyond Basic 100-year Storm Loading Conditions

The calculation of each of the factors in Table 3.1 is discussed in more detail below. The method of combining the factors to calculate the theoretical RSR to the ISO Code is then set out in Section 3.5.

3.3.1 Explicit Code Safety factors

Where system failure is initiated by one principal member (e.g. a compression brace), it is straightforward to calculate the explicit Code safety factor or margin of safety (MOS) for the member to the original design Code (e.g. API RP2A-WSD or LRFD) and if the member had been designed to the ISO Code. For ISO and LRFD this is simply based on the partial load and resistance factors; for WSD the explicit safety factors are the 'obvious' factors applied to the classical strength formulae along with the one-third increase in allowable stresses for the extreme storm condition. It is thus implicitly assumed that for the relevant Code the maximum utilisation in the component is one under the 100-year loading condition.

3.3.2 Implicit Safety in Codes

Assuming that most modern jacket structures have strong joints and that the system failure is dominated by member failure, the implicit Code safety factor (ICSF) (Item 2 Table 3.1) will be dominated by the differences between the Code-based effective length factor (K-factor) and the actual K-factor for compression members. For slender compression members, use of a K-factor = 0.8 (API) can overestimate the actual member strength by up to 25% [6], since the actual K-factor can be around 0.55 for typical brace members. This effect will be less marked for ISO where the recommended K-factor for braces is 0.7.

Other sources of implicit safety include the differences between the actual strength of the component and the Code strength predictions, i.e. the model bias and uncertainty. For members under combined compression & bending the expected value of model uncertainty is close to one (~1.03).

3.3.3 Expected Material Strength

The expected (average) material strength (Item 3 Table 3.1) is around 20% higher than the nominal yield strength for 36 ksi steel (248 MPa) and 15% for 50 ksi steel (345 MPa) [6].

3.3.4 System Redundancy

System redundancy (SR) is the capacity of a structure to provide alternate load paths after failure of a member. The system redundancy (Item 4 Table 3.1) may be estimated from the ratio of first member failure (or rather first member initiating failure) to peak load. For modern optimised jacket structures (e.g. 4 leg X-braced), this is likely to be less than 10% after all of the above explicit and implicit factors have been removed.

3.3.5 Other Sources

The remaining part of the RSR (OF) accounts for a combination of other design requirements (Items 5 and 6 Table 3.1), and engineering practice and conservatism (Item 7 Table 3.1). Clearly, the influence of Operator and designer conservatism and non-optimisation should be removed. However it is less clear whether the effects of steel introduced for other design requirements (e.g. due to temporary phases, boat impact and fatigue) should be removed. Clearly, this additional steel contributes to the strength of real structures. However, future technology and practice may lead to even more optimised designs with reduced steelwork requirements for these other design requirements.

Unfortunately, from pushover analysis results it is very difficult to differentiate between the influences of steel necessary for other design requirements and that due to non-optimised design or conservatism.

In calculating the RSRs to reflect ISO in a manner relevant to load factor calibration, it is important to be aware of the factor due to other sources; this factor should either be eliminated or a *small* allowance made to account for the effects of the other design requirements. This factor is one of the main uncertainties with the approach.

3.4 RELATIONSHIP BETWEEN RSR AND LOAD FACTOR

In order to carry out a system-based calibration, it is necessary to establish the relationship between the RSR and the load factor.

A method for calculating the RSR of a structural system is described by van de Graaf et al [6]. The RSR is assumed to be directly related to the load factor. The method assumes that structural failure will be initiated by failure of a single member such as buckling of a compression brace. Furthermore, it is assumed that the failure mode leading to system failure involves other similar structural members, and that any effects due to foundation failure or weak joints do not significantly influence the failure mode.

Hence, if the ranges of likely failure mechanisms, environmental-to-gravity load ratios and likely system redundancies for typical modern jacket structures are known, then a range of values of theoretical RSRs to the ISO Code may be calculated.

Typical ranges of values based on the results of two example structures are derived below. A study of the results of a wide range of pushover analyses undertaken in a consistent manner would confirm that the range of parameters chosen is representative of modern jacket structures. However the results presented in Section 5 show that this exercise is not necessary.

3.4.1 Gravity-to-Environment Load Scaling Effect

In order to establish a relationship between environmental load factor and RSR it is necessary to account for the fact that only the environmental load is scaled in a pushover analysis. This factor will be designated the ‘PDPE factor’. (P_d=unfactored gravity load, P_e= unfactored environmental load for fully utilised member), and is derived below.

The PDPE factor occurs because part of the member strength arises from (Code) strength requirements for gravity load and part from (Code) strength requirements for environmental load. The margins on the gravity load allow the environmental load to be increased beyond its factored values before failure occurs.

3.5 METHOD FOR CALCULATION OF RSR

Where system failure is initiated by one principal member (e.g. a compression brace) or a small set of similar members, it is possible to calculate the theoretical minimum RSR by multiplying the individual contributing factors as follows:

$$RSR_{ISO} = MOS_{ISO} \times ICSF \times MF \times SR \times PDPE_{ISO} \quad (3.2)$$

where RSR_{ISO} = Reserve Strength Ratio to ISO

MOS_{ISO} = margin of safety (explicit Code safety factor)

ICSF = implicit Code safety factor

MF = material factor

SR = system redundancy factor

$PDPE_{ISO}$ = factor which accounts for the fact that only the environmental load is scaled in a pushover analysis

This equation may be simplified as follows

$$RSR_{ISO} = MOS_{ISO} \times RSR' \times PDPE_{ISO} \quad (3.3)$$

where

$$RSR' = ICSF \times MF \times SR \quad (3.4)$$

For a structure designed to ISO, where failure is initiated by a member primarily in compression, the factors MOS_{ISO} and $PDPE_{ISO}$ are derived as follows (based on the procedure outlined in the Appendix of Reference 6).

Using ISO practice, the minimum design strength of a member (for a member dominated by axial compression for instance) is given by:

$$\frac{R_{ISO}}{\gamma_{Rc}} \leq (\gamma_d \times P_d + \gamma_w \times P_e) \quad (3.5)$$

where R_{ISO} = (characteristic) member resistance based on the ISO formulae

P_d = load component due to gravity loads (i.e. dead and live loads)

P_e = load component due to extreme environmental loads

γ_d = load factor on gravity load (1.10 in ISO)

γ_w = load factor on environmental load

γ_{Rc} = resistance factor for the component and load type

The total (unfactored) loading on the member is $P_d + P_e$. Thus, the explicit margin of safety for a member designed to achieve full utilisation to ISO can be defined as:

$$MOS_{ISO} = \frac{(\gamma_d \times P_d + \gamma_w \times P_e)}{(P_d + P_e)} \times \gamma_{Rc} \tag{3.6}$$

The explicit margin of safety to ISO will be in the range 1.29 to 1.59 for γ_{Rc} = 1.18 (member axial compression), γ_d =1.1 and γ_w =1.35.

Due to other implicit factors, the expected material strength, etc, the actual expected ultimate strength of the member initiating failure, P_{ult}, is:

$$P_{ult} = \{(\gamma_d \times P_d + \gamma_w \times P_e) \times \gamma_{Rc}\} \times MF \times ICSF \tag{3.7}$$

Hence from Eqn (3.6):

$$P_{ult} = MOS_{ISO} \times (P_d + P_e) \times MF \times ICSF \tag{3.8}$$

During a pushover analysis the gravity load is applied first, and then the environmental load is incremented until collapse. The member initiating collapse fails at a lower load than the ultimate load, given by:

$$P_{ult} = P_d + P_e \times \frac{RSR_{ISO}}{SR} \tag{3.9}$$

where SR is the ratio of ultimate load to load at first member failure (or rather at first member initiating failure)

From Eqn (3.8), (3.9) and (3.4):

$$RSR_{ISO} = \{MOS_{ISO} \times (P_d + P_e) \times MF \times ICSF - P_d\} \times \frac{SR}{P_e} \tag{3.10}$$

$$RSR_{ISO} = MOS_{ISO} \times \left\{1 + \left(1 - \frac{1}{MOS_{ISO} \times MF \times ICSF}\right) \times \frac{P_d}{P_e}\right\} \times RSR' \tag{3.11}$$

The PDPE factor is defined as:

$$PDPE_{ISO} = \left\{1 + \left(1 - \frac{1}{MOS_{ISO} \times MF \times ICSF}\right) \times \frac{P_d}{P_e}\right\} \tag{3.12}$$

The PDPE factor tends to 1.0 for components dominated by environmental loading. However, it becomes more significant with higher proportions of gravity loading and could typically be around 1.5 for ratios of environment-to-gravity load of one.

From Eqn (3.11)

$$RSR_{ISO} = MOS_{ISO} \times PDPE_{ISO} \times RSR' \tag{3.13}$$

Eqn (3.13) is the same as Eqn (3.3). Hence a direct relationship between environmental load factor and RSR has been derived. For cases dominated by environmental load the relationship between load factor and RSR is linear.

Thus,

$$RSR_{ISO} = \begin{pmatrix} \text{Explicit margin} \\ \text{of safety} \end{pmatrix} \times \begin{pmatrix} \text{Gravity - to - environmental} \\ \text{load scaling effect} \end{pmatrix} \times \begin{pmatrix} \text{Other} \\ \text{effects} \end{pmatrix}$$

The equations for RSR when the structure is designed to API WSD or LRFD are similar and are derived in the Appendix of Reference 6. The main difference occurs for the margin of safety term (MOS), which also affects the gravity-to-environmental load effect term (PDPE). The other material and system effects (RSR′) are assumed to be constant between Codes.

3.6 ASSUMPTIONS

This study examines steel jacket structures in intermediate to deep waters. It is assumed that the environmental loading on the structures is dominated by drag loading; the load factors derived on this basis are likely to be conservative for (the small number of) structures dominated by inertia loading. It is also assumed that the structures are not significantly affected by dynamic response under environmental loading. Other structures (e.g. mono-columns, tri-pods) have not been investigated; because of their reduced levels of structural redundancy these require particular consideration.

It is assumed that structural failure will be initiated by failure of a single member such as buckling of a compression brace, and that the failure mode leading to structural collapse will involve (primarily) other similar members.

Failure mechanisms initiated by, or significantly affected by, joint failure, and pile or foundation failure have not been considered. For most modern structures the joints are stronger than the members. However, it is important to note that foundation failure is not included, since the inherent margin of safety and levels of uncertainty in foundation design are somewhat different to general member design.

It is assumed that there are no significant changes in 100-year environmental storm load between the original design and the ISO Code definition. This is reasonable for structures designed to modern practice using recent Editions of API RP2A, i.e. with loading based on the 100-year load recipe with drag factors based on 1.05 for rough members, kinematics reduction, etc.

It is also assumed that any changes made to load factors etc. influence collapse only via the members participating in the failure mode, all other members and joints are assumed to remain elastic. Furthermore, any redistribution of force due to non-linear foundation behaviour is assumed to be a secondary effect such that it can be neglected; this is an important assumption that is necessary for this type of calibration study based on generic structural behaviour.

3.7 EXAMPLE CALCULATION OF RSR

The method of calculation of the RSR based on the results of pushover analyses for the Tern and Kittiwake platforms is described below (these structures were chosen because full results were available to BOMEL). The results are summarised in Table 3.2.

The results of the pushover analyses are used to determine the mode of failure of the platform and the principal members initiating failure. Both platforms were originally designed to API RP2A-WSD. The explicit Code safety factors for these members to this Code are derived. The material factor for 50 ksi (345 MPa) steel is 1.15 (1.13 used in Kittiwake pushover analysis). Knowledge of the P_d/P_e ratio in the principal member initiating failure enables the PDPE factor to be calculated. The system redundancy factor is estimated from the pushover analysis results from the ratio of first member failure to peak load.

The remaining factors account for the implicit Code safety factors (ICSF) and other design requirements. The product of these factors can be determined by back-calculating the factor required to give the pushover RSR result. However from the information obtained from the pushover analyses, it is not possible to determine the breakdown of this factor into separate contributions from ICSFs and other design requirements or engineering practice. A lower bound case may be taken in which these factors are set to one, and another case may be investigated where the implicit Code safety factors (ICSF) and other design requirements are included in full.

Having used the pushover analysis results to determine the system redundancy factor and the remaining factors, the explicit Code safety factors and PDPE factors to ISO are calculated. The factors are then combined to give the RSR to ISO.

Structure	**NNS- Tern**	**CNS- Kittiwake**
Reference	Reference 6	Reference 7
Loading Condition	Diagonal wave attack	North wave
Failure Mode	Leg compression failure	VDM failure
P_d/P_e ratio in critical member	0.94	1/4.5 = 0.22
Sources of reserve strength to API WSD		
Explicit Code safety factor (MOS)	1.32 on leg compression (KL/r=31)	1.37 on brace compression (KL/r=50)
System redundancy (SR)	1.04	1.07
Expected material strength factor (MF)	1.15 (50 ksi)	1.13 (50 ksi)
Factor to account for P_d/P_e ratio (PDPE)	1.32	1.09
RSR obtained from pushover analysis	**2.10**	**2.06**
Remaining factors: Implicit safety in Codes, Engineering practice, or other design requirements	2.10/(1.32×1.04×1.15×1.32) = 1.00	2.06/(1.37×1.07×1.13×1.09) = 1.14
Sources of reserve strength to ISO		
ISO explicit Code factor (MOS_{ISO})	1.45	1.53
System redundancy (SR)	1.04	1.07
Expected material strength factor (MF)	1.15 (50 ksi)	1.13 (50 ksi)
Remaining factors: Implicit safety in Codes, (Engineering practice, or other design requirements)	1.0	1.14 (1.0)
Factor to account for P_d/P_e ratio ($PDPE_{ISO}$)	1.38	1.11 (1.09)
RSR to ISO Code assuming remaining factor = ICSF (assuming remaining factor = other design requirements)	1.45×1.04×1.15×1.0×1.38 **=2.39**	1.53×1.07×1.13×1.14×1.11 **=2.38** (1.53×1.07×1.13×1.0x1.09 **=2.06**)

VDM – Vertical diagonal member

Table 3.2 Breakdown of sources of reserve strength beyond nominal design load for manned North Sea structures

4. METHOD FOR SYSTEM-BASED CALIBRATION

4.1 SUMMARY

This section describes the calibration procedure for the system-based calibration approach. The probabilistic modelling of the basic variables is presented, and the theoretical values defining the range of RSR are suggested.

4.2 CALIBRATION PROCEDURE

The failure function was defined as:

$$Z = MOS_{ISO} \times PDPE_{ISO} \times RSR' \times X_m - \left(dD + lL + wW / X_w\right) \quad (4.1)$$

where X_m is the model uncertainty associated with RSR

d, l and w are the proportions of unfactored dead, live and environmental load in the critical member initiating failure ($d+l \equiv P_d$, $w \equiv P_e$)

D, L and W and the random variables for dead, live and environmental loading

and X_w is the model uncertainty in the evaluation of the environmental design loading

The failure function was programmed into a spreadsheet and levels of reliability calculated for a realistic range of structural systems based on a limited number of pushover analysis results and estimated upper and lower bounds for RSR for typical modern jacket structures. The failure of the structures was assumed to be initiated by a single member in axial compression.

4.3 PROBABILISTIC MODELLING

Probability distributions have been assigned to both loading and resistance terms. All basic variables have been assumed to be independently distributed, i.e. uncorrelated. The modelling of the uncertainty in gravity and environmental loading is the same as that adopted in the component-based calibration approach [1].

X_m Resistance Model Uncertainty LN[1.0, 0.10]

The resistance uncertainty for a structural system is smaller than for a single member since, at least for ductile structures, failure of the structure arises from several members. The member strength is effectively averaged over the members controlling the mechanism, and the coefficient of variation (CoV) in system strength is less than that of member strength. A CoV of 10% for system strength has been used, as recommended by Efthymiou et al [3]; this value may be conservative. A bias of 1.0 has been used, since mean yield stress is assumed in the pushover analysis. A lognormal distribution is assigned to resistance.

W Annual Environmental Loading Tromans[A=0.327, B=0.146]

The probability distribution for environmental loading is based on recommendations by Tromans & Vanderschuren [4]. The annual probability of exceedence of extreme load, normalised on its 100-year value, is

$$Q(L^*) \quad = \quad \exp\left\{-\left(\frac{L^* - A}{B}\right)\right\}$$

where $L^* = L/L_{100}$, $A = 0.327$ and $B = 0.146$.

The cumulative probability distribution is given by:

$$F\left(L^*\right) \quad = \quad 1 - Q(L^*) \quad = \quad 1 - \exp\left\{-\left(\frac{L^* - A}{B}\right)\right\}$$

This is an exponential distribution, which is only valid for $L^* \geq A$. The mean of the distribution is $A + B = 0.473$, and standard deviation is $B = 0.146$; the coefficient of variation (CoV) is thus 0.31.

A distribution based on annual exceedence has been used, and thus annual probabilities of failure have been evaluated.

X_w Design Load Uncertainty Truncated N[1.09, 0.18, truncated at ±1.5s]

The design load arising from the ISO Code and standard practices is estimated to be subject to a 9% conservative bias and a CoV of 16.5% relative to the ‘true’ 100 year value. The uncertainty is modelled by a normal distribution truncated at ±1.5 standard deviations, as suggested by Tromans [4]. The truncation is introduced because it is considered that any values beyond the truncation limit will be filtered out during the course of the design process.

Uncertainty and bias in the environmental design load arise from two main sources:

- the application of the wave force recipe
- the environmental design criteria themselves.

The interpretation of questionnaires undertaken by Tromans & Vanderschuren of oceanographers [4] is that there is a CoV of 15 % on design wave load arising from uncertainty in extrapolation of metocean data, and a conservative bias of 9 % from the wave force recipe. The uncertainty in the load arising from the recipe is a matter of application details; study by Digre et al [8] suggests that it can be represented by a CoV of 7 %.

D Dead Load N[1.0, 0.06]

The uncertainty in the dead load component in members participating in the failure mode is proportional to dead loading on the structure. Uncertainty in dead loading includes rolling tolerances, fabrication aids, paint and fire protection, approximations in weight take-off, marine growth, etc. Based on calibration work undertaken for the North Sea adaptation of the Draft LRFD Code in 1990, the uncertainty in dead loading has been modelled by a normal distribution with a bias of 1.0 and a CoV of 0.06.

This modelling was assumed to cover all permanent load on the structure; for the ISO Code, it was assumed to encompass both categories of permanent load (action) (i.e. G_1 and G_2).

L Live Load N[1.0, 0.10]

Uncertainty in live loading arises from variation in fluid volumes and densities, drill pipe volumes, drill rig position, load distribution, etc. Based on calibration work undertaken for the North Sea adaptation of the Draft LRFD Code in 1990 [9] the uncertainty in live loading has been modelled by a normal distribution with a bias of 1.0 and a CoV of 0.10.

The assigned probability distributions are summarised in Table 4.1.

Basic Variables		Distribution	Mean Bias	Standard Deviation	Other parameter	Source of data
RSR uncertainty	X_m	Lognormal	1.0	0.10		Reference 3
Load model uncertainty	X_w	Truncated normal	1.09	0.18	±1.5	Reference 4
Environmental load	W	Annual	A = 0.327	B = 0.146		Reference 4
Dead Load	D	Normal	1.0	0.06		Reference 9
Live Load	L	Normal	1.0	0.10		Reference 9

Table 4.1 Load and Resistance Probability Distributions

4.4 RANGE OF PARAMETERS

The range of parameters used in the calculation of the typical RSRs are summarised in Table 4.2. The parameter RSR′ is defined in Eqn (3.4) above. Lower and upper bounds for each of the factors that make up the combined RSR′ factor have been assumed and typical values from the results of the Kittiwake structure pushover analysis have been calculated (see Table 3.2) for comparison.

	Lower Bound	Typical jacket (Kittiwake pushover analysis)	Upper Bound
Material Factor (MF)	1.13	1.13	1.15
Implicit Code Safety Factor (ICSF)	1.00	1.15	1.25
System Redundancy (SR)	1.04	1.07	1.10
RSR′ (=MF × ICSF × SR)	1.175	1.390	1.581

Table 4.2 Ranges of Parameters Used in System Reliability Study

The material factor for structural steel with a minimum specified yield strength of 345 MPa (50 ksi) has been chosen for this study based on the assumption that most modern jacket structures would use this grade of steel. A material factor of 1.15 is expected for this grade of steel [6] but a factor of 1.13 was used in the Kittiwake pushover analysis so a range of 1.13 to 1.15 has been used in the present study.

Reference 6 states that the implicit Code safety factor (ICSF) for slender compression members may be up to 1.25, hence this has been used as an upper bound. (Note the factor of 1.25 is based on the API K-factor of 0.8 for slender compression members. The ICSF to ISO will be less than this as the corresponding ISO K-factor has been reduced to 0.7. However 1.25 has been used in this study as the upper bound. A typical value of 1.15 is likely for a slender member that fails via buckling; vertical diagonal braces with typically high ratios of environmental to gravity load often fall in this category. A lower bound of 1.0 for the ICSF has been used (i.e. no implicit safety in Code). This is more appropriate to stocky members that fail by crushing/local buckling; such members are typically legs of jackets with relatively low ratios of environmental to gravity load.

Modern jacket structures (e.g. 4 leg X-braced frames) dominated by bracing failure do not have high levels of system redundancy once all of the other factors have been accounted for. Hence an upper bound of 1.10 for this factor has been assumed. (Non-optimised structures may have higher levels of system redundancy.) It is assumed most modern steel jacket structures will have at least some system redundancy so a lower bound of 1.04 has been assumed. The Kittiwake structure falls between these bounds.

The resulting lower and upper bounds for the combined RSR′ factor are 1.18 and 1.58 respectively. In the context of the present study, the lowest value of 1.18 should be regarded as an absolute lower bound; real jacket structures will exceed this. It is expected that most well-designed, optimised jackets will reach an RSR′ value of 1.39. It is possible for RSR′ to reach 1.58, though this is unlikely for a well-optimised structure. (RSR′ may exceed 1.58 for non-optimised structures and as a result of other factors.)

The range of environmental load factors examined was 1.2 to 1.4. The range of environmental to gravity load ratios (W_e/G ratio) used was 1 to 25. These values gave minimum RSRs in the range 1.68 to 3.67.

5. RESULTS OF RELIABILITY STUDIES

5.1 SUMMARY

Reliability levels have been calculated for upper and lower bound theoretically estimated RSRs and also for a typical jacket structure based on the results of the Kittiwake structure pushover analysis. Variation of reliability index with environmental load factor and environmental-to-gravity load ratio has been studied, and the results presented. The results show a wide variation in reliability across the range of environment-to-gravity load ratios and for different values of theoretical RSR. This means that it is not possible to choose an environmental load factor such that it can achieve consistent system reliability across a wide range of parameters.

In order to derive a load factor it is necessary to interpret the results selectively. On the basis of the most significant results, an environmental load factor of 1.25 is selected. For most structures designed and optimised to the ISO Code, this load factor should achieve a minimum reliability of 3×10^{-5} / year. This reliability level is compared with the results of the component-based calibration study, and is shown to be compatible.

It should be noted that it is assumed that joint and foundation failures do not participate (significantly) in the failure mechanism of the structural system, and that the calculations are based on a theoretical derivation for RSR that assumes that system failure is initiated by a single member in axial compression (see Section 3.6).

5.2 INDIVIDUAL RELIABILITY ANALYSIS RESULTS

To illustrate the reliability analysis results obtained, typical results for an individual case based on the Kittiwake pushover results are presented in Table 5.1. The value of RSR′ has been assumed to be 1.390, the (unfactored) W_e/G load ratio has been taken as 4.5, and for the table the gravity and environmental load factors of 1.10 and 1.35 have been taken. The value of RSR is 2.39. In this case, the equivalent reliability index, β, is 4.77.

The values of the basic variables at the β-point, i.e. the most likely failure point, are shown in Table 5.1, along with the sensitivity coefficients (α-factors). The reliability is influenced most by the variable with the highest value of sensitivity coefficient. Thus, in this case the most sensitive variable is the environmental loading, followed by the uncertainty in RSR and design load modelling; of negligible influence on the reliability are the dead and live loads.

Basic Variables		**β-point values** **(x^* values)**	**Sensitivity coefficient** **(α-factors)**
RSR uncertainty	X_m	0.863	0.299
Load model uncertainty	X_w	0.882	0.313
Environmental load	W	2.03 equivalent to 110,000-year return period storm	-0.901
Dead Load	D	1.00	-0.014
Live Load	L	1.00	-0.003

Table 5.1 Reliability Analysis Basic Variable β-point Values and Sensitivities

The curvature of the failure surface was investigated at the β-point using second-order reliability analysis, but this had very little effect on the failure probability. Thus, first-order reliability was considered adequate for the present purposes, and was used for all analyses presented in this report.

5.3 GENERAL RESULTS

On the basis of the range of RSR′ parameters discussed in Section 4.4, Figure 5.1 shows that minimum RSRs for typical jacket structures designed to the ISO Code using an environmental load factor of 1.35 may vary between 1.9 and 3.6, depending on the (unfactored) environmental-to-gravity load in the member initiating failure.

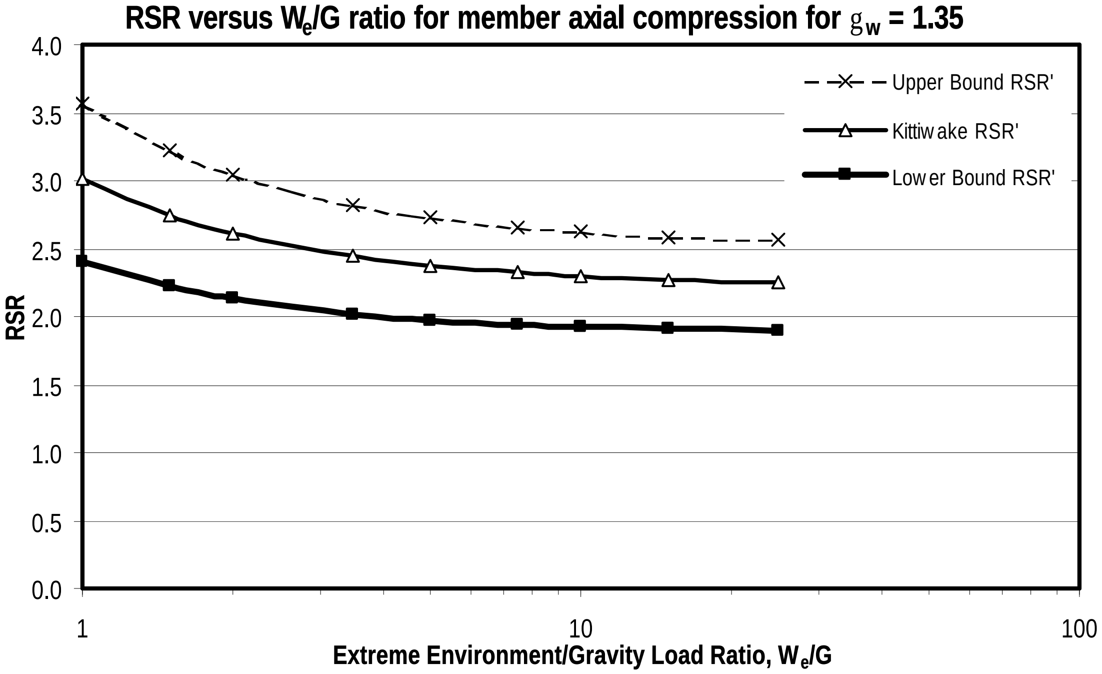

Figure 5.1 Effect of Variation in Values of RSR′ on RSR for γ_w = 1.35

The variation of RSR with environmental-to-gravity load ratio is significant over lower values of the W_e/G ratio where initiating members are heavily influenced by gravity loading, e.g. structures with failure sequences initiated by leg failure. Values of W_e/G ratio greater than ten imply that the initiating member has very little gravity load component.

Unfortunately, for real structures it is not easy to determine the environment-to-gravity load ratio in the initiating member for a number of reasons, including:

- In practice, members are not dominated by purely axial loading; the ratio of axial to bending stress under gravity loading will generally be different from the ratio of axial to bending stress under environmental loading.

- The gravity loading in members is sensitive to the position of the drill rig, for example, and distribution of loading on the topsides. However, the distribution of gravity load may be expected to have limited influence on minimum RSR, since a local increase in direct gravity loading may be countered by a reduction elsewhere, thereby increasing the capacity for load redistribution (system redundancy factor). However, this is difficult to allow for in a theoretical study in which member designs have to be 'adjusted' to achieve full utilisation.

- The elastic distribution of stresses is influenced by the non-linear stiffness of the foundation, as is RSR; but the effect on RSR may be more or less than on an individual component. For example, if the failure mode is a classical plastic mechanism it will not be influenced by foundation settlement/rotation or the load path. This should be manifested by a change in system redundancy factor, but again this is difficult to allow for in a theoretical study in which member designs have to be 'adjusted'.

Figure 5.2 shows that for a typical structure and for a particular environmental-to-gravity load ratio, the RSR varies by less than 0.4 for environmental load factors in the range 1.2 to 1.4 (i.e. what may be considered a reasonable range of values). However, the difference in RSR is over 0.7 between environment-to-gravity load ratios varying from 1 to 25 for the same value of load factor.

Comparison of Figures 5.1 and 5.2 shows that the influence of the environmental load factor on RSR is much less than that arising from the implicit Code safety factors and system redundancy, which implies that adjusting the environmental load factor is not the most direct method of influencing structural RSR.

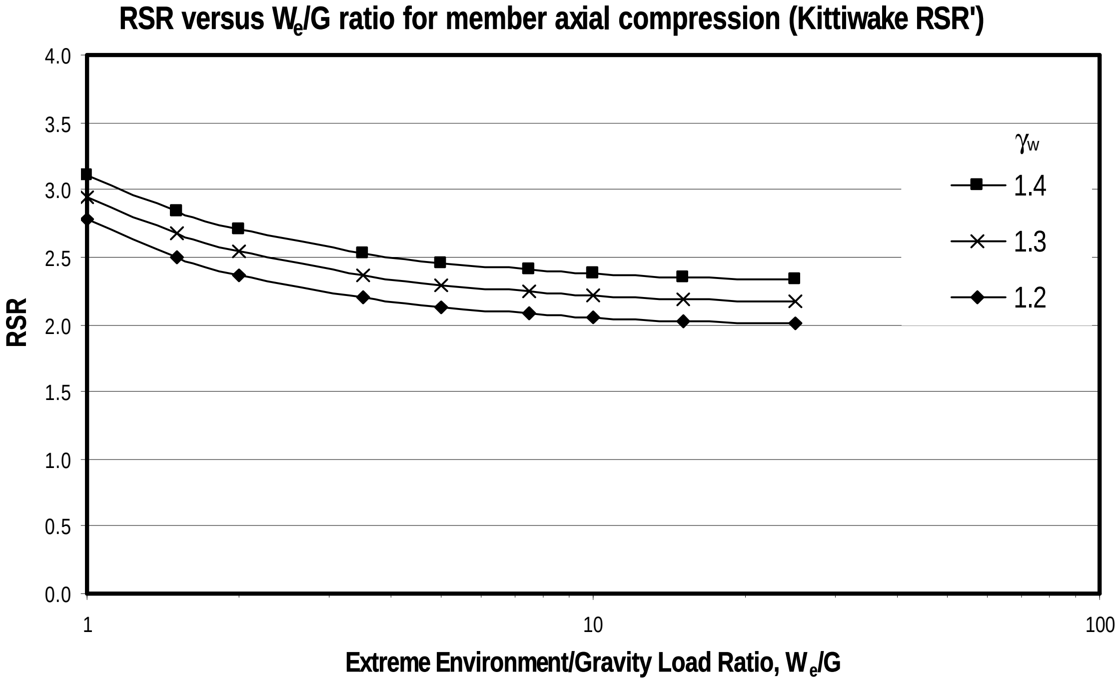

Figure 5.2 RSR Against Environmental-to-Gravity Load Ratio for Different Load Factors

Figure 5.3 shows variation of reliability index with environmental-to-gravity load ratio for a typical jacket structure. The reliability index varies from between 6.5 for W_e/G ratio of 1.0 to around 4.0 for cases dominated by environmental loading. However, for a particular W_e/G ratio the reliability index varies by less than 0.5 when the environmental load factor is changed within a range of 1.2 to 1.4. Clearly, the influence of the environment-to-gravity load ratio has much greater effect on reliability than load factor.

For illustration, a target reliability has been superimposed on the figure – the target has been drawn at an annual probability of failure of 3×10^{-5} as suggested by Efthymiou [3] for structural systems.

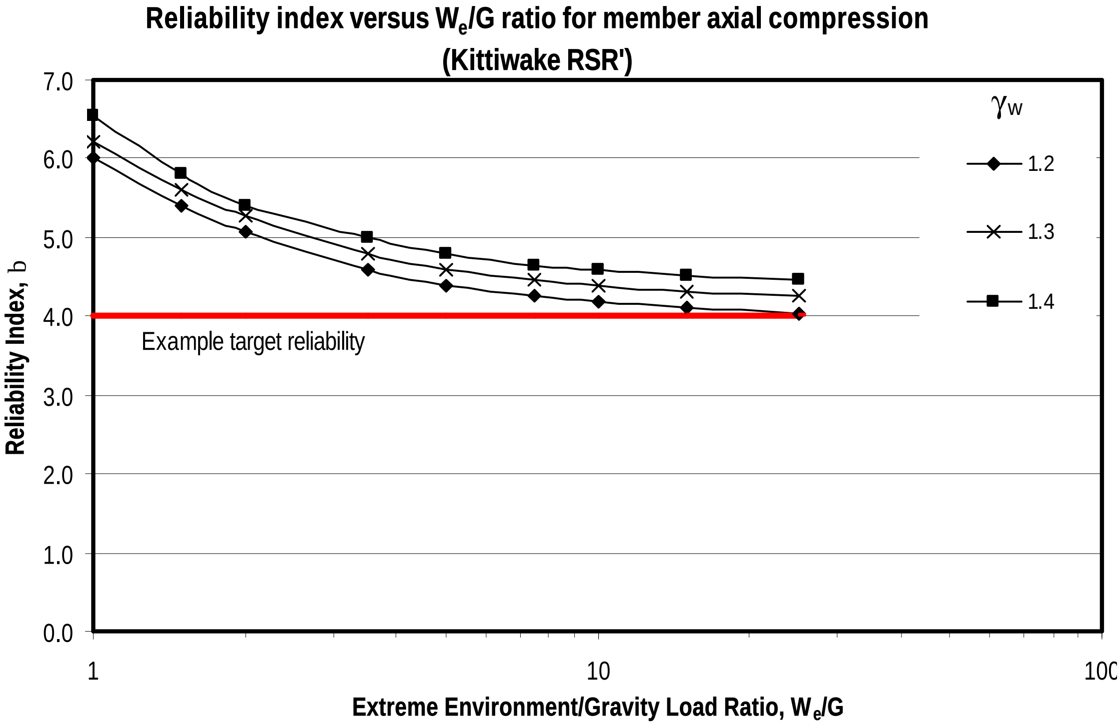

Figure 5.3 Reliability Index Against Environmental-to-Gravity Load Ratio for Different Load Factors

Figure 5.4 shows variation of reliability index with environmental load factor for a typical environment-to-gravity load ratio of 5.0 due to different values of RSR′. The difference in reliability index between the lower bound and typical values of RSR′ is around 0.6, but the difference between a load factor of 1.2 and 1.4 is only around 0.4 for the same value of RSR′.

The slope of the curves is small, which would make selection of an environmental load factor to achieve the required target reliability difficult on this basis.

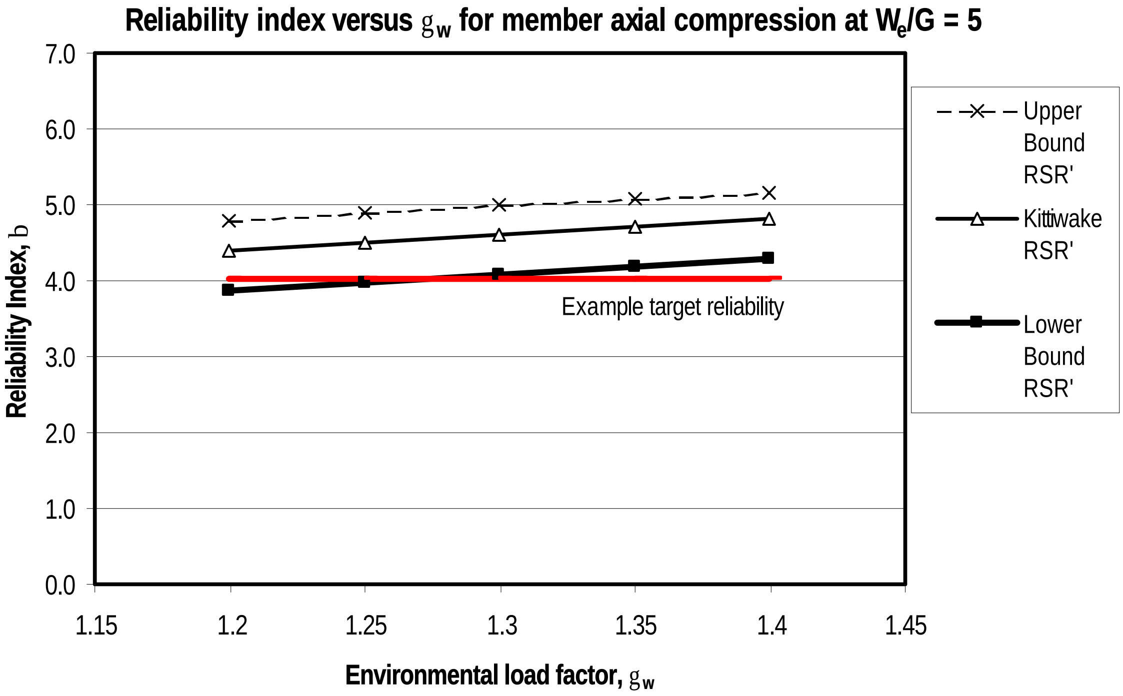

Figure 5.4 Reliability Index Against Environmental Load Factor for Different Values of RSR′

5.4 SELECTED RESULTS

From the discussion in Section 5.3, it might appear that the vagueness or lack of confidence in the environment-to-gravity load ratio means that there is uncertainty in the theoretical minimum RSR, and this in turn means that there is lack of confidence in the reliability evaluated on this basis. However, RSR sensitivity will be lower in reality.

Structures with failure sequences initiated by members with low environment to gravity load ratios, say unfactored W_e/G ratios less than 5.0, such as many legs, will tend to have low implicit Code safety factor (ICSF) values (since leg members tend to have low slenderness), that is they will be closer to the lower bound line. Whilst structures with classical brace failure mechanisms will often be initiated by members with high environment to gravity load ratios, say unfactored W_e/G ratios of 5.0 or more, such members may be expected to have typical ICSF values and consequently have values of RSR′ (and RSR) that are above the lower bound values. The transitional W_e/G ratio of 5.0 is subjective, but is believed to be a reasonable value.

On this basis, a realistic range of typical to lower bound values of RSR for optimised structures can be considered as being from 2.0 to 2.4 (with environmental load factor 1.35) (see Figure 5.1). This range is shown shaded in Figure 5.5.

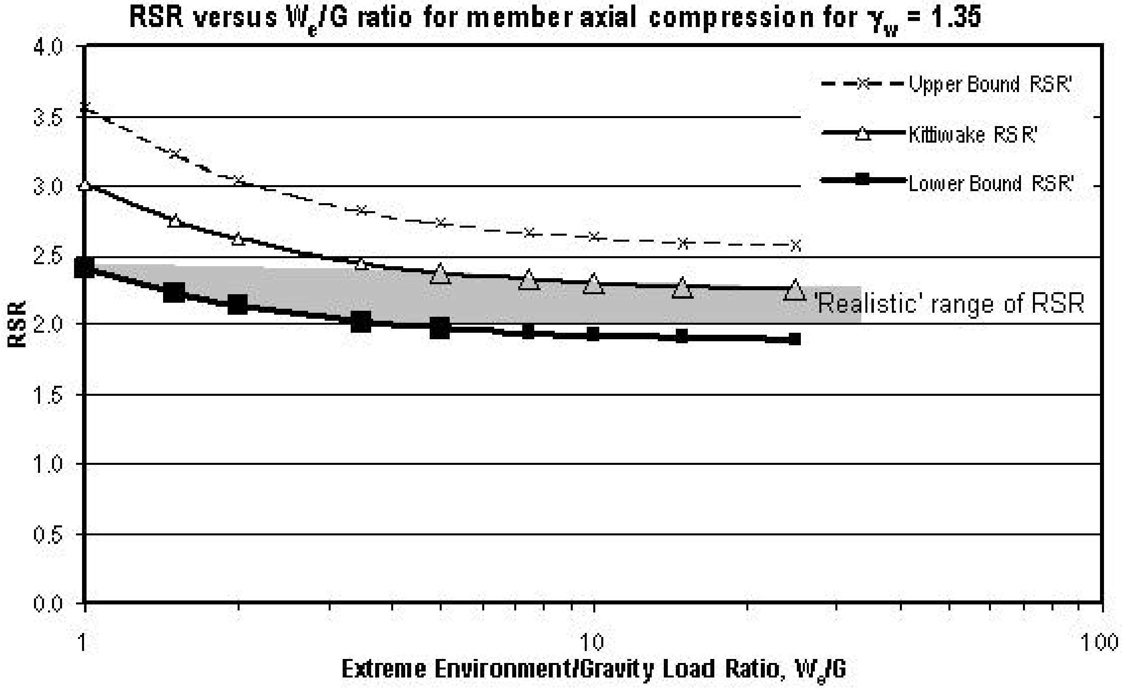

Figure 5.5 Significant RSR Values for γ_w = 1.35

Figure 5.6 and Figure 5.7 show the variation of reliability index with environmental load factor for lower bound and typical (Kittiwake structure) values of RSR′ respectively. The lower bound values (Figure 5.6) are shown for environment-to-gravity load ratios of 5.0 and below, and are expected to be representative of structures with failure sequences initiated by leg failure. The values in Figure 5.7 are expected to be representative of structures initiated by brace failures, and results are shown for environment-to-gravity load ratios of 5.0 and above.

Figure 5.6 shows that for W_e/G ratios less than around 5.0, an environmental load factor of 1.25 would achieve an annual target failure probability of at least 3×10^{-5} (as suggested by Efthymiou) for structures with lower bound RSR′ values. Figure 5.7 shows that for structures with more typical RSR′ values, an environmental load factor of 1.25 would achieve the same target for W_e/G ratios greater than 5.0.

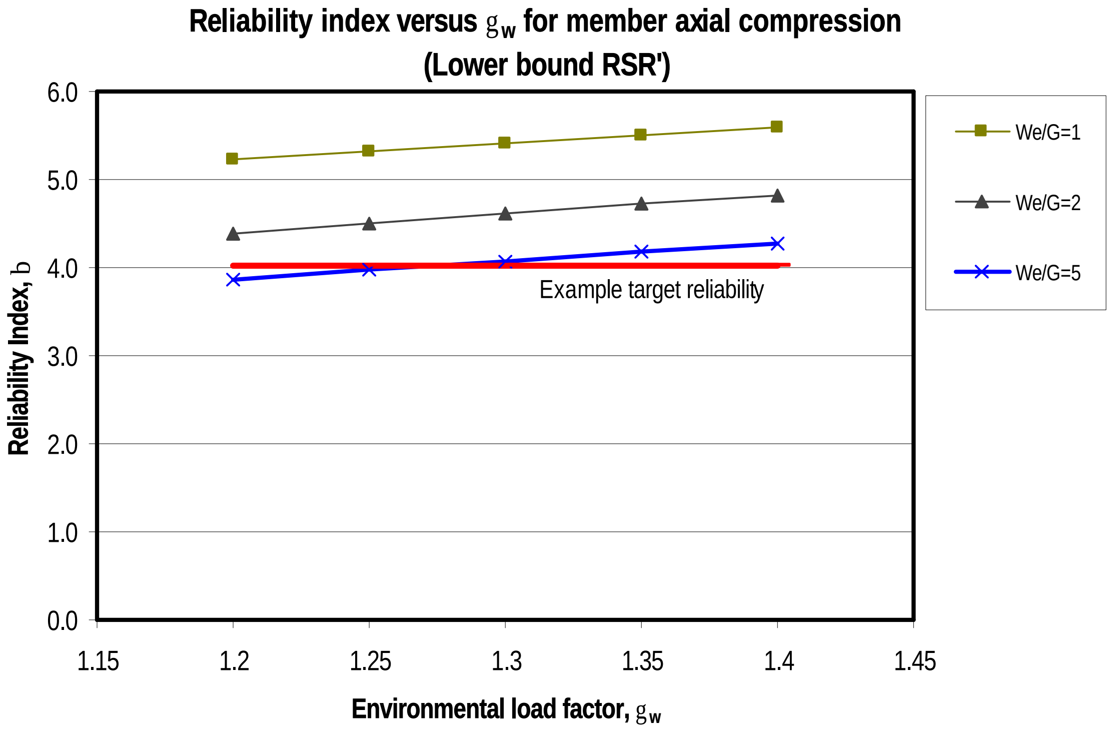

Figure 5.6 Reliability Index Against Environmental Load Factor for Lower Bound Values of RSR′

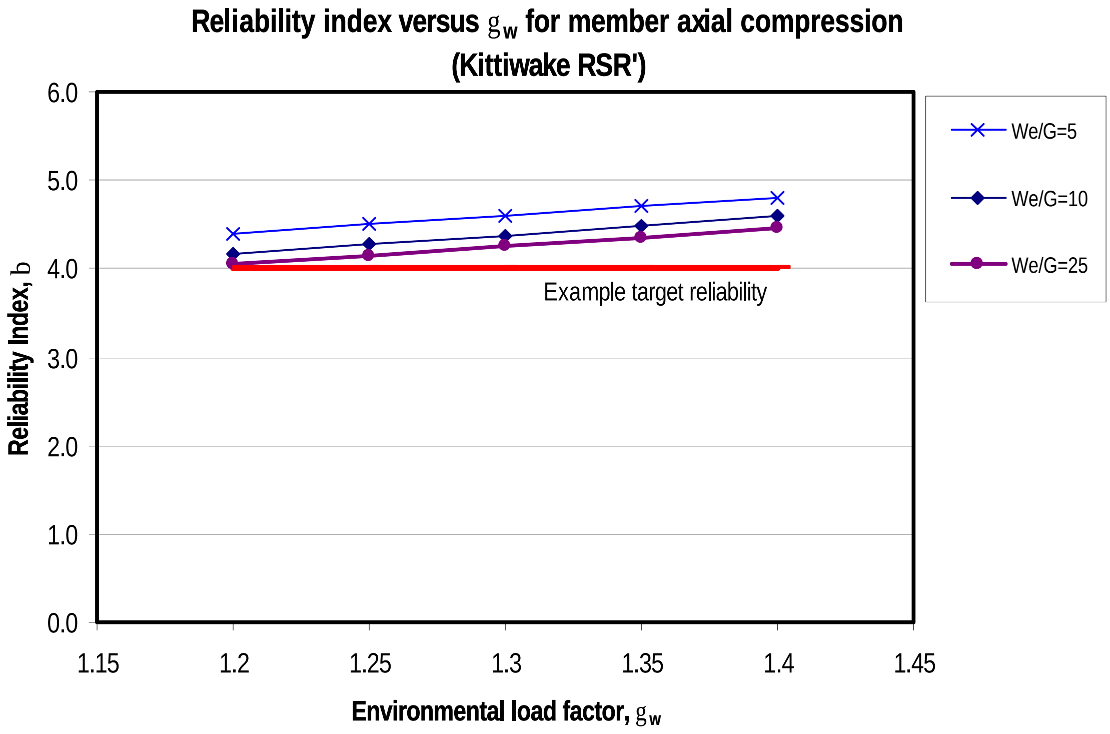

Figure 5.7 Reliability Index Against Environmental Load Factor for Typical RSR′ Values

Figure 5.8 shows the variation in reliability with environmental-to-gravity load ratio for a load factor of 1.25. The values suggested as significant are shown with larger symbols, i.e. lower bound RSR' values with W_e/G ratios of around 5.0 and less, and typical (Kittiwake) RSR' values with W_e/G ratios of 5.0 and more. The suggested target reliability of 3×10^{-5} / year is also shown.

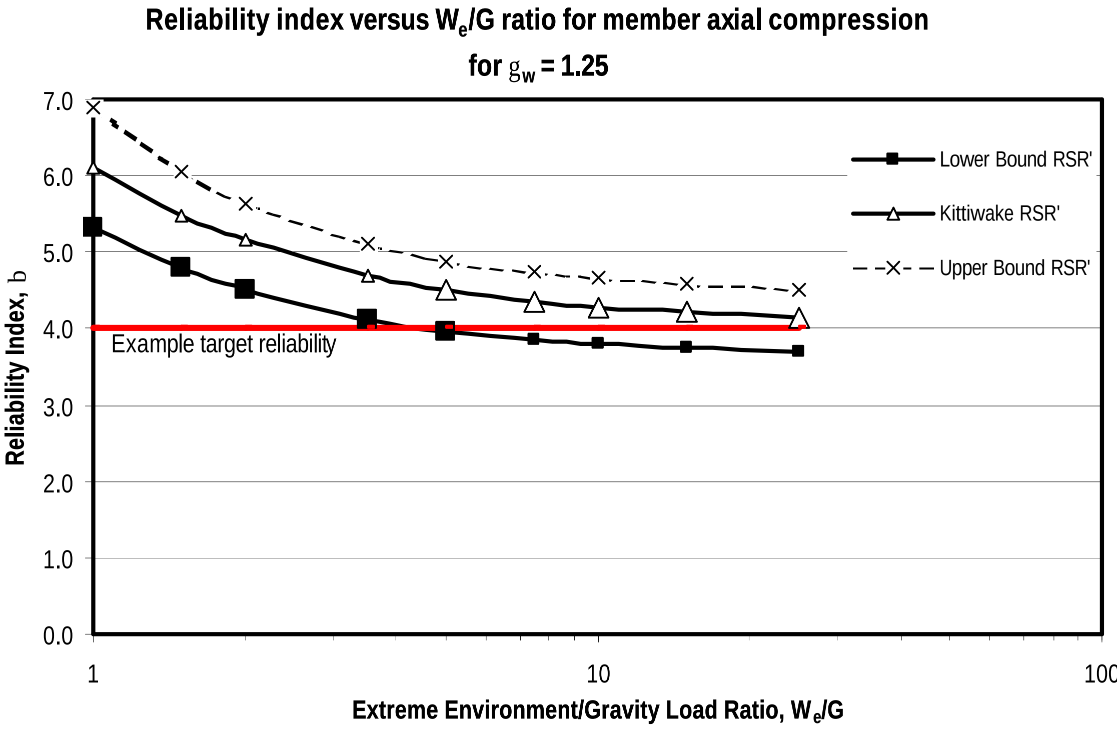

Figure 5.8 Reliability Index Against Environmental-to-Gravity Load Ratio for γ_w = 1.25

It may be seen from Figure 5.8 that some structures may achieve reliabilities that fall below the suggested target reliability. The figures are based on extreme theoretical values, and as discussed below, it is considered that in practice such structures are unlikely to occur.

For completeness, the corresponding figure to Figure 5.5 is shown in Figure 5.9 for an environmental load factor of 1.25. The significant or selected range of RSR is from 1.85 to 2.25 for a load factor of 1.25, and is shown shaded in the figure.

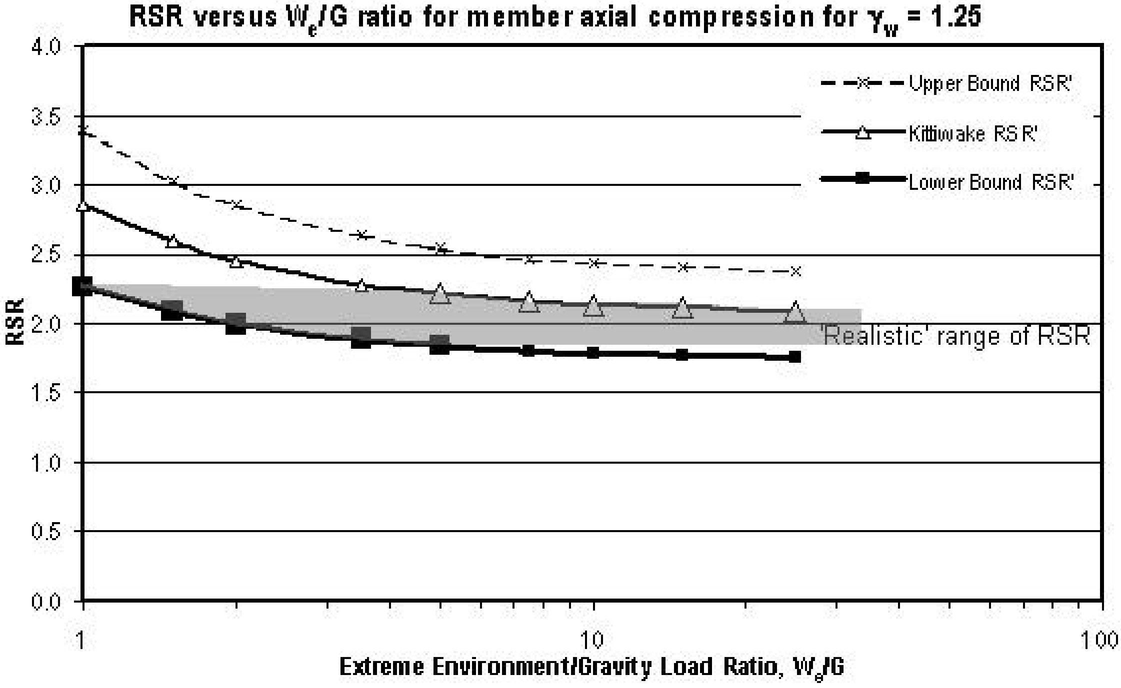

Figure 5.9 Significant RSR Values for $\gamma_w = 1.25$

Figure 5.9 shows that it is theoretically possible for some optimised structures to achieve RSR values of below 1.85 with $\gamma_w = 1.25$. As shown in Figure 5.8, these structures may also achieve reliabilities that are below the suggested target value. These values correspond to structures with failure sequences initiated by members with very high environment-to-gravity load ratios. In practice such members would be expected to be tubular braces (rather than legs).

Consider a structure initiated by failure of a compression member with W_e/G ratio of 25. From Eqn (3.6) it can be shown that the explicit margin of safety for the member designed to be fully utilised to ISO with a load factor of 1.25, MOS_{ISO}, is 1.47. Assuming a material factor, MF, of 1.13, and a system redundancy factor, SR, of 1.04, it can be shown from Eqn (3.10) that the implicit Code safety factor, ICSF, necessary to achieve a minimum RSR of 1.85 is only 1.05.

The implicit Code safety factor includes conservatism in effective length factors, as well as model uncertainty bias in the Code formulations. From the component-based calibration study [1] the resistance formulations themselves have a bias of at least 1.03 for compression and bending, and at least 1.05 for axial compression alone. Thus, it is considered very unlikely in practice that structures would achieve RSR values of less than 1.85.

5.4.1 Target reliability

The target of 3 × 10^{-5} /year suggested for structural systems compares well with the weighted average results from the component-based assessment [1]. The weighted average results from the component-based calibration study for tubular members and legs are shown in Table 5.2 for designs to API RP2A-WSD, and for the ISO Code with various values of the environmental load factor from 1.2 to 1.4.

Code		**brace members**		**brace members (compression & bending only)**		**leg members**	
		P_f	**Equivalent** b	**P_f**	**Equivalent** b	**P_f**	**Equivalent** b
API–WSD 20th		1.074E-04	3.701	1.063E-04	3.704	2.362E-04	3.496
ISO	γ_W-1.2	1.243E-04	3.664	1.093E-04	3.697	1.753E-04	3.575
	γ_W-1.25	8.588E-05	3.757	7.509E-05	3.791	1.218E-04	3.669
	γ_W-1.3	5.949E-05	3.848	5.171E-05	3.882	8.488E-05	3.760
	γ_W-1.35	4.131E-05	3.937	3.569E-05	3.972	5.927E-05	3.849
	γ_W-1.4	2.874E-05	4.023	2.468E-05	4.059	4.149E-05	3.936
	γ_W-1.45	2.004E-05	4.107	1.711E-05	4.143	2.912E-05	4.020

Table 5.2 Weighted Average P_f and Equivalent β for Different Environmental Load Factors (from [1])

From Table 5.2 it can be seen that a target failure probability of 3 × 10^{-5} / year corresponds to a load factor of between 1.35 and 1.40 for component design. However, for component design the target failure probability should be required to be somewhat higher. Past experience and accepted practice (see for example, DNV note on reliability analysis [10]) suggests that for redundant structures the component target failure probability may be expected to be one or two orders of magnitude (i.e. a factor of 10 or 100) higher than the system target. From Table 5.2 it can be seen that an environmental load factor of 1.25 corresponds to a lower ratio of component/system failure probability (i.e. between $8 \times 10^{-5}/3 \times 10^{-5} = 2.5$ and $1.2 \times 10^{-4}/3 \times 10^{-5} = 4$). However, Table 5.2 is based on weighted average results.

From the results of the component-based calibration study (Section 7 of [1]), the lowest reliability indices evaluated for components in the database designed to ISO with a load factor of 1.25 were:

- 3.4, equivalent to a failure probability of 3.2 × 10^{-4} / year for tubular members
- 3.27, which is equivalent to a failure probability of 5 × 10^{-4} / year for legs

Thus, for tubular members there is around an order of magnitude in failure probability between lower bound values for components and structural system. For legs there is slightly more than an order of magnitude between component and structural system failure probabilities.

It should be noted that the calibration points used in the component-based calibration study were selected as representative of designs for North Sea structures, they were not selected to produce lower bound values to the ISO Code. Nevertheless, the database contains a large number of designs, such that the reliabilities are believed to approximate to lower bound values.

6. ENVIRONMENTAL DESIGN LOAD UNCERTAINTY SENSITIVITY STUDY

6.1 SUMMARY

Some of the Participants were concerned about the level of uncertainty associated with the definition of the environmental design loading. A study was undertaken to investigate the effect of increasing the CoV of the environmental design load uncertainty from 16.5%, which was used in all of the other analysis in this report and in the component-based calibration study [1], to 25%.

6.2 ENVIRONMENTAL DESIGN LOAD UNCERTAINTY MODELLING

X_w Design Load Uncertainty N[1.0, 0.25]

In the previous analyses, the design load arising from the ISO Code and standard practices was estimated to be subject to a 9% conservative bias and a CoV of 16.5%; and the uncertainty was modelled by a normal distribution truncated at ±1.5 standard deviations.

Uncertainty and bias in the design load arise from two main sources:

- the application of the wave force recipe
- the environmental design criteria.

The accuracy of the environmental load recipe has been investigated in various research studies including: Heideman & Weaver [11], Atkins in the Tern project [12], etc. For this JIP, Kvitrud [13] has summarised the results of a number of full scale load measurement comparisons for different North Sea structures, including: Ekofisk 2/4-A and 2/4-W, Valhall QP, Draupner, Gorm, Magnus and Tern. A direct comparison of the results for the various studies is difficult because the studies were undertaken by a number of engineers/analysts/companies, at different times using different (sometimes un-stated) assumptions, and are reported in a variety of papers/reports. It is not even always clear from the published information whether the comparisons are on a wave-by-wave or a storm-by-storm basis. Kvitrud shows that there is considerable scatter in the bias and CoV statistics for the various studies, but suggests that 'the COV is high for a given sea state or wave, an average will be 25-30%'.

It has also been suggested by ExxonMobil [14] that there is generally a lack of familiarity and experience from operators and contractors in using the 'new' environmental load recipe within the ISO code, and this could lead to potential differences in interpretation and application. ExxonMobil traditionally model this Type II uncertainty in the environmental design loading with a CoV of 20-30% in reliability analysis.

In this study, a CoV of 25% has been considered. This has been assumed to be unbiased, and an un-truncated normal distribution has been used. This modelling was chosen rather arbitrarily, and is intended solely for the purposes of this study.

Whilst improved QA, better education or information could in principle reduce some of the uncertainty in the definition of the design load, there is an additional source of uncertainty that could be considered to affect the definition of the 100-year design load. This additional uncertainty arises from the dataset itself that is used to derive the 100-year parameters. For any particular site, the definition of the 100-year design parameters changes from year-to-year as a result of a longer dataset, and changes to the hindcast model, e.g. NESS, NEXT, NEXTRA, etc. Whilst an allowance for the uncertainty in statistical analysis or data-fitting has been included (e.g. distribution type, fitting method, etc), this additional uncertainty in the dataset itself has not been included. By its very nature, this uncertainty is very difficult if not impossible to quantify.

6.3 RESULTS

The system reliability analysis discussed in Section 4 was re-run with the above environmental design load uncertainty. Figures 6.1 and 6.2 show plots of reliability index evaluated using a design load CoV of 25% against environmental load factor for different values of environment-to-gravity load ratio. The results can be compared with the previous results for design load CoV of 16.5% presented in Figures 5.6 and 5.7.

Comparison between the two sets of figures shows that the difference in the evaluated annual failure probabilities is greater than an order of magnitude. This difference arises as a result of changes in the uncertainty modelling for the environmental design load. Given the nature of this uncertainty, it is very difficult to quantify it, and the uncertainty modelling for this variable must be based largely on judgement. This means that differences in evaluated reliability levels between models based on 16.5% CoV and models based on 25% CoV cannot easily be reconciled.

On the basis of the discussion in Section 5, the results satisfy a target reliability of 2.91, or corresponding failure probability of 1.8×10^{-3} / year. This is depicted in Figures 6.1 and 6.2.

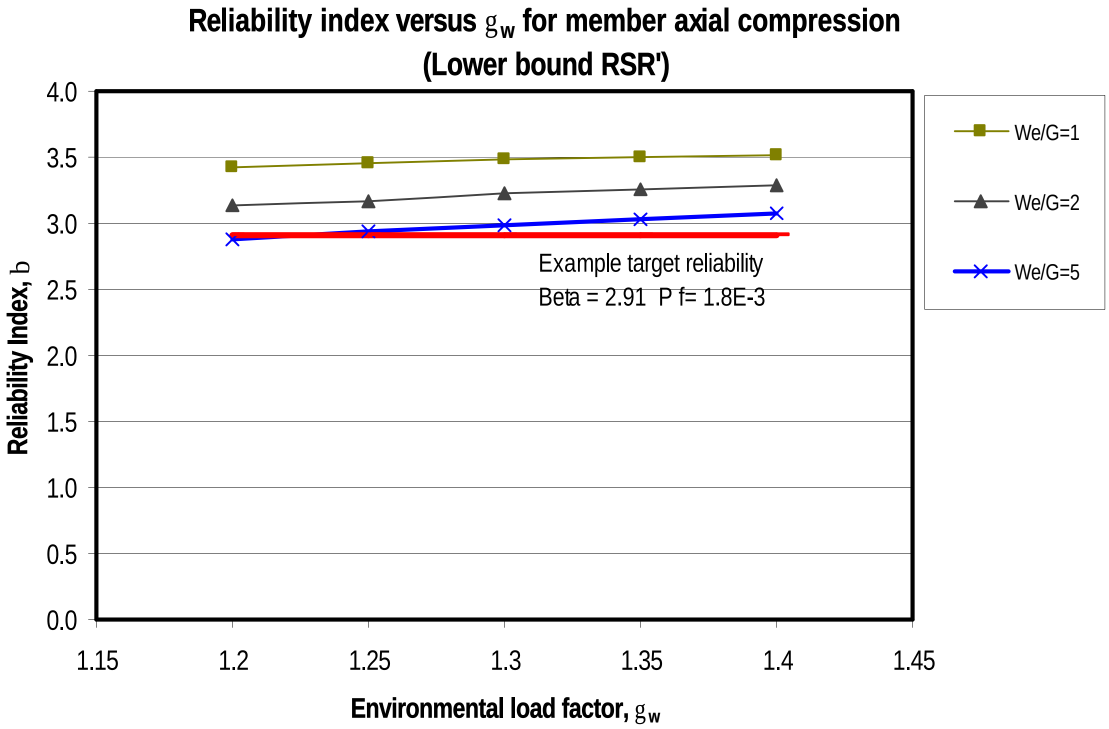

Figure 6.1 Reliability Index Against Environmental Load Factor for Lower Bound Values of RSR′ - evaluated with load model uncertainty of 25% CoV

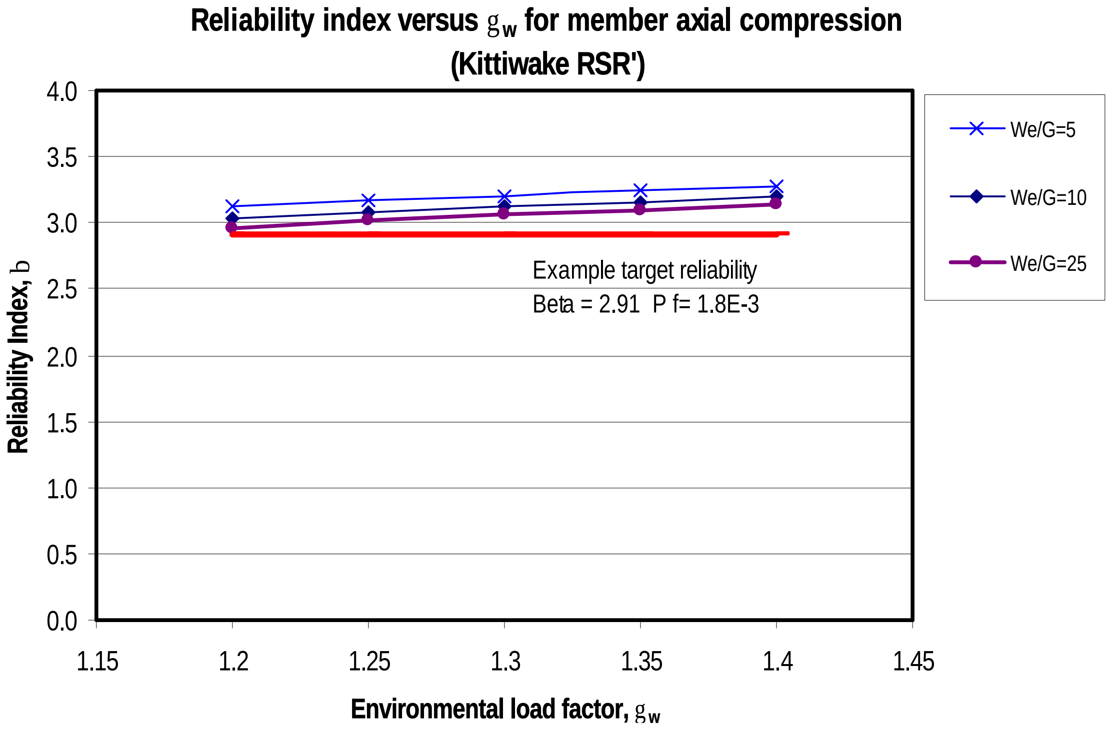

Figure 6.2 Reliability Index Against Environmental Load Factor for Typical RSR′ Values - evaluated with load model uncertainty of 25% CoV

7. CONCLUSIONS

A simplified system calibration approach has been presented.

A method for calculating the theoretical Reserve Strength Ratio (RSR) of a jacket structure to the ISO Code has been presented. A linear relationship between RSR and environmental load factor has been derived.

A system reliability study has been carried out for theoretical values of minimum RSR for typical jacket structures designed to ISO. Variation of reliability index with environmental load factor and environmental-to-gravity load ratio has been investigated for a range of typical RSRs.

The results show a wide variation in reliability across the range of environment-to-gravity load ratios and for different values theoretical RSR. This means that it is not possible to choose an environmental load factor such that it can achieve consistent system reliability across a wide range of parameters.

In order to derive a load factor the results have been interpreted judiciously. Lower bound values are expected to control failure for many optimally designed structures, but for some cases it is recognised that reliabilities assessed on the basis of theoretically-derived lower bound values will be conservative.

The failure probabilities evaluated from a reliability analysis are to some extent dependent on the level of Type II uncertainty included; Type II uncertainty is uncertainty that arises from lack of knowledge or information rather than Type I uncertainty which is related to the inherent natural variation in the environment, material, etc. One of the most significant sources of Type II uncertainty concerns the evaluation of the 100-year design load. The main system reliability analysis was undertaken with a CoV of 16.5% for this variable (this modelling was also used in the component-based calibration study). A study to assess the implications of increased environmental design loading uncertainty was undertaken; the CoV was increased from 16.5% to 25% to reflect concerns of some Participants.

On the basis of selected results, an extreme environmental load factor of 1.25 could be suggested for the design of structures in North West European waters. This value of the load factor corresponds to an annual target failure probability of 3×10^{-5}. This target value was first suggested by Efthymiou et al in 1996 for structural systems. A load factor of 1.35 will lead to a small increase in system reliability, or reduction in annual failure probability.

The results of the component-based calibration study suggest that an extreme environmental load factor of 1.25 leads to lower bound values of failure probability (rather than weighted averages) evaluated using compatible probabilistic modelling for tubular members that are an order of magnitude higher than the target suggested by Efthymiou for structural systems. From past experience and accepted practice, an order of magnitude between component and system failure probabilities is reasonable for redundant structures.

Applied in this way, the system level approach gives load factors compatible with the component-based approach, and can be a practical methodology that may be used in calibrating environmental load factors for other geographic regions of the world.

However, increasing the CoV of environmental design load from 16.5% to 25% leads to more than an order of magnitude increase in evaluated failure probability. These results cannot be reconciled with the base case results, and this makes the selection of a target reliability very difficult, particularly if cost-benefit considerations are used. (Cost-benefit considerations may be used to define targets for different Exposure Levels and for reassessment). Consequently, a consensus could not be achieved on a suitable value of target reliability.

The results suggest that adoption of a 1.35 factor on quasi-static extreme environmental loading with other ISO 19902 partial factors and provisions would result in structures being designed which deliver reliability levels for extreme weather at least consistent with traditional practice in all NW European regions.

For design use with NW European offshore structures, it is proposed by the Participants of the JIP to retain the existing value of environmental load factor at 1.35. However, there should be an option to derive structure-specific partial load factors using detailed analysis; this analysis should use site-specific environmental data and take into consideration the specific form of the structure.

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