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Abstract

The objective of the project is to develop reliability based methods which are to be used for the design of ship structures, in particular by calibration of the safety factors in design rules. The project concentrates on the primary strength and thus it deals with the hull behaviour under longitudinal bending and aims at the design of the midship section, as representative of the parallel middle body,

The approach taken in this project is to develop further the state of the art concerning the methods to predict the limit-states which are the basis of the reliability formulation. Roughly one third of the project was devoted to the improvement of the load effect models, another third dealt with the strength assessment and only the last third dealt with the reliability analysis, reliability based design and code formulation.

The SHIPREL project has explored a new way of formulating rules for ship structural design through the development of a methodology for rule development, by determining the methods to quantify the uncertainty in the variables, by performing reliability analysis of ship structures and by deriving partial safety factors for the design of the primary structure. Having identified the new formulations, they were applied to typical cases of containerships and tankers ascertaining how a coherent set of Rules were developed and applied to ships of varying load and structural behaviour.

1. *Introduction*

The objective of the project is to develop reliability based methods which are to be used for the design of ship structures, in particular by calibration of the safety factors in design rules. The project concentrates on the primary strength and thus it deals with the hull behaviour under longitudinal bending and aims at the design of the midship section, as representative of the parallel middle body.

The reliability based approach is based on the calculated probability of failure, a concept that requires the answer to many difficult problems such as: what is the ultimate failure of the hull in which possible modes can the hull fail, how are defined the extreme conditions under which failure occur, how does one combine extreme events probabilistically, how accurate are present day calculation methods and so on. Many of these questions have been raised along the years and have motivated much important research in the various areas which are necessary before a realistic reliability calculation can be made.

The initial proposals of reliability formulation of the ship hull date back to the early 1970's. However, they have not been widespreadly used by the industry and a good indication is that the Classification Societies have not yet used them to formulate and to calibrate their Rules for Ship Design. It is felt that the reason for this unsatisfactory status of affairs is not the reliability methods, which are mature now, but on the load effect and strength models that have been adopted to calculate the ship reliability. If they are too simplified, the profession will not adopt them. ”

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A set of simplified procedures and formulas have been developed to use in design for the prediction of design loads and for the assessment of the strength of primary structural components, Research software packages have also been developed to quantify loading, response and strength for the primary specific ship hull structures components. A methodology for code development and guidance notes for ship structural design have been established.

2. *Probabilistic Modelling of Load Effects*

2.1 Modelling still-water load effects

The still-water load effects result from the longitudinal distribution of the cargo on-board and thus they are likely to change at each departure and even smaller changes may occur during a voyage. Once the distribution of cargo is known, the still-water load effects become known. However, the value that they will have at a random point in time is not known at the design stage and can only be described by a probability distribution.

This probabilistic formulation was already established and results were already published from a significant database of tanker voyages. However, not so much data was available from [1] containerships and this has been one of the contributions of SHIPREL. A database of about 3200 voyages from 40 containerships has been analysed in order to provide the parameters of the probability distributions describing the load effects in containerships [2].

It was found that the bending moments in the most loaded midship region can be described by a normal distribution with a mean of 62% of the rule design value and a standard deviation of 14%. A more detailed model that represents the effect of the carried deadweight (w) and of the ship length (L) is:

$$X_t = A_0 + A_1 W + A_2 L$$

where A_0 = 79.7 and A_1 = -21.5 and A_2 = .049 for maximum mean bending moments and A_0 = 15.2 and A_1 = .043 and A_2 = -.015 for the corresponding standard deviation.

In the case of shear forces, which have maximum occurring around L/4 and 3L/4, the applicable model has a mean of 54% and a standard deviation of 13%. The corresponding coefficients of eqn(1) are A_0 = 67.7 and A_1= -10.9 and A_2= -.049 for the mean values and A_0= 16.0 and Al = 6.2 and A_2 = -.038 for the standard deviation.

For the first time the voyage data of containerships has been grouped in the different routes and analysed in those subsets. It was found that the still-water data in some routes can be described by the same probabilistic model but in some cases the differences are significant and require different models to describe the load effects. This means that more than one load condition needs to be considered in the modelling of still-water loads of containerships. This is a known situation in tankers which normally operate in two significantly different conditions, i.e. loaded and in ballast. The differences in containerships are not so large.

A new model was also proposed to describe the still-water loads in tankers as a consequence of the analysis of new operational data from tankers and of the load manual of another tanker. In both cases It was detected that there existed significant differences between the still-water load effects at departure and arrival, a feature that was not apparent in the previously reported data,

The model developed took into account the variation of the load effects during the voyage and, based on simulated data, proposed a normal distribution with parameters that represent an average between departure and arrival conditions. It is based on the assumption that both departure and arrival conditions can be described by normal distributions and that the load effects change monotonically between one value and the other during the voyage. It is proposed that the still-water load effects at a random point in time can be described by a normal distribution with a mean and standard deviation which are the average between the respective values of the distributions of departure and of arrival conditions,

2.2 Modelling low-frequency wave induced load effects

Linear strip theory is the established method of predicting wave-induced load effects despite the emerging availability of codes based on the discretization of the hull in panels and on the application of three dimensional diffraction theory. To assess the uncertainty of existing methods to predict first-order wave induced load effects, a comparison was made among the linear response in waves predicted with two-dimensional strip theories with three-dimensional diffraction theory with experimental results from model tests, Motions and wave induced sectional loads were considered for a large high-speed containership advancing with constant forward speed in regular waves. This ship, subsequently referred to as the Flokstra ship [3], was chosen because a relatively complete set of model test measurements are available for comparison.

The strip theory methods are standard codes based on the proven method of Salvesen Tuck and Faltinsen [4]. The non-linear strip theory is an advanced method that incorporates an improved pressure formula developed by Hachmann to account for the steady perturbation of the forward speed flow, which is generally neglected in common strip theory methods [5]. The diffraction theory is a panel method that efficiently solves the boundary value problem on the basis of the zero-speed Green function [6].

No clear tendency was observed in the results indicating that more accurate results are obtained with the strip theory methods or the panel method. Predicted motions generally show less scatter than predicted sectional loads. Vertical wave induced loads predicted by the strip theories are generally higher than those predicted by the panel method; for horizontal wave induced loads, the opposite is generally true.

A convenient way to assess the effect of the uncertainty on the transfer functions is by calculating the corresponding long-term distributions and quantifying the uncertainty on the characteristic values. In this work long-term distributions of wave induced sectional loads were determined based on transfer functions obtained by the different methods and it was found that a relatively large degree of uncertainty was associated with the predicted midship wave induced sectional loads. Table 1 summarises some of the characteristic values,

Comparison with experimental measurements from model tests indicated no clear tendency that more accurate results were obtained by the two-dimensional strip theories or the three-dimensional panel method used, Calculated long-term distributions of sectional loads based on transfer functions obtained by the different methods demonstrates that a relatively large degree of uncertainty was associated with the predicted midship wave induced sectional loads [7].

Transfer function based on	Vertical shear force Probability level		Vertical bending moment Probability level	
	10^{-4}	10^{-8}	10^{-4}	10^{-8}
Experiments	0.812	1.585	1.023	2,058
GL3D	1,010	2,045	0.720	1.497
GL2D	1,032	2.081	1.001	2.007
1ST	1.406	2.636	0.924	1.901
RINA	1.111	2.089	1.158	2.385
IACS Rules	1.000	1.000	1.000	1.000

Table 1 - Normalized characteristic values of long-term midship vertical shear force and bending moment for the Flokstra ship

An experimental program has been conducted to collect service data of strains, stresses and temperatures on a containership performing voyages between France and America, during two years. The aim of the fill-scale measuring program concerning this task was to assess the model uncertainty in the long-term prediction methods, by comparing measurements with calculations. The measured wave induced stresses have been used to construct the long-term distribution corresponding to the voyages performed, This distribution was compared with a calculated one and with the unified rule requirement for this ship. It was found that the calculated values were higher and that the experimental values were in the range of the rule requirement.

However, the calculated values have to be interpreted with care because the exact data of the ship was not available and they were calculated with transfer function from a similar ship. Furthermore, since information was not available on the exact sea conditions experienced by the ship, the calculations were made for the average North Atlantic scatter diagram and therefore the measurements cannot be used to verify the calculation method, but instead they give an indication relative to the standard method of long-term calculations adopted in the project.

2.3 Modelling non-linear low-frequency wave induced loads

Methods have been developed to calculate non-linear wave induced load effects both in the frequency and in the time domain, Long-term formulations were also developed.

The non-linear frequency domain method of Jensen and Pedersen [8] has been extended from the case of head seas to all headings and has been applied successfully to study the wave induced load effects in the reference containership hull [9].

A study was made to assess the applicability of the Kac Siegert method for the evaluation of both the marginal and the extreme distributions of the pure quadratic vertical wave bending moment predicted by that theory. Long crested sea has been assumed and the pure second order contribution has been addressed in order to avoid the very complex algorithmic aspects connected with a formulation able to include the linear response. A method has been developed to determine the long-term distribution of the non-linear predictions of the frequency domain program and the combined linear and the quadratic terms [10]. Comparisons with a more accurate method gave good results [11].

A time domain formulation was applied to the ship motion problem. All the components of the hydrodynamic forces are represented and calculated in the time domain, and the equations of motion are solved by a numerical procedure. The radiation forces are represented by infinite frequency added masses, convolution integrals of memory functions, and radiation restoring force coefficients. The time domain description of these forces is obtained from Fourier analysis of the equations of motion both in the time domain and in the frequency domain. The hydrostatic forces are calculated taking into account the instantaneous wetted surface of the hull [12-14]. The method was then extended to calculate in the time domain the non-linear sectional shear forces and bending moments. Calculations have been made for a tanker and a containership and important non-linear effects were found for the second ship.

A method of incorporating the non-linearity of wave induced load effects into the long-term predictions has been proposed [15]. It is based on having a modeling factor which affects the linear transfer function to transform it into a non-linear one before performing the long term calculations. The model correction factor will affect the predictions of linear theory $H(\omega)$ to predict the non-linear “pseudo transfer function” $H_{NL}(\omega)$ calculated with Hachman’s method:

$$\hat{H}_{NL}(\omega) = \phi_{NL} H(\omega)$$

The inspection of the results of the non-linear transfer functions has suggested the use of a model factor composed of one term dependent on the frequency and another one dependent on the significant wave height:

$$\phi_{NL}(\omega, H_S) = \phi_1(H_S)\cdot\phi_2(\omega)$$

Using the model with separation of variables has a distinct advantage in the formulation of the long-term procedure. In fact, it allows the existing methods of calculation of long-term distributions to be used by only multiplying the variance of the response to each sea state by a function ϕ_2 depending only on H_s. The resulting long-term distributions are shown in figure 1 where it is apparent that the changes in the sagging moment are more substantial that in hogging.

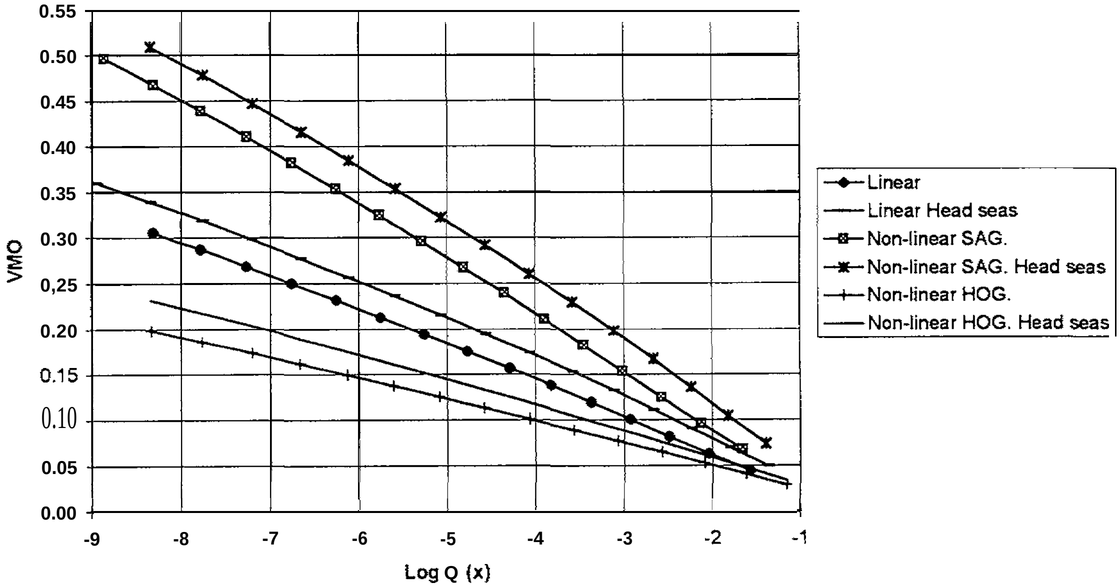


Figure 4- Long-Term Distribution of linear and non-linear Vertical Bending Moments.

The comparison of the results of the two methods of long-term predictions applied to the reference containership were very satisfactory, with differences on the order of 10°/0, [16] while the differences between non-linear and linear predictions are in the order of 30% to 40%.

2.4 Modelling high-frequency wave load effects

A theoretical study is undertaken on the determination of wave-induced ship hull vibrations. The study is limited to springing vibrations, characterised by a continuous excitation from the waves.

The calculations are performed within the framework of a non-linear, quadratic strip theo formulated in the frequency domain. The hull is modelled as a non-uniform Timoshenko beam vibrating in the vertical plane.

The stochastic nature of the sea and therefore also of the response is described by the first four statistical moments through a Hermite series approximation to the probability density function. The peak value distributions of the low frequency and high frequency response are treated independently, due to the large separation between the dominating wave frequencies and the lowest two-node frequency of the hull beam.

For a fast containership the springing response is calculated in stationary seaways taking due account of different forward speeds and different headings. Included are also non-linear effects due to changes in added mass, hydrodynamic damping and water line breadth with the sectional immersion in waves. Both extreme value predictions and fatigue damage are considered.(fig. 2)

The main result is that springing is relatively more pronounced in head or near head sea in lower sea states where the zero-crossing wave periods are small. Also it is found that the non-linear contributions to the springing response are at least as important as the linear contribution [10].

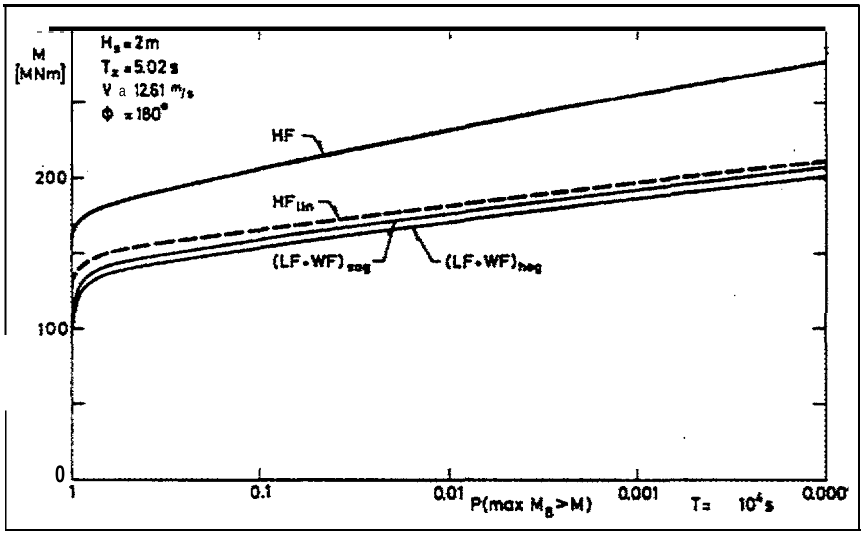


Figure 2- Probability distribution of extreme values of wave induced vertical bending moments during a sea state of Hs= 6m

A method was developed to assess the slamming loads and the slam induced whipping response [17, 18]. The method works in the time domain and assumes that the slamming forces will not modify the wave induced motions. Therefore, the ship motions are calculated by a strip theory which determines the characteristics of the ship response to regular waves. This is used to perform the time simulation of the ship motions in irregular seas from which the time history of the relative motions is calculated. The relative motions indicate when a slam occurs and exactly in which section. This is used to determine the time history of the slamming force at that location.

The slamming loads are calculated with a method that was developed from previous results of Ochi [19], Stavovy and Chang [20], Kawakawi et al [21] and by Zhao and Faltinsen [22]. The slamming loads are defined in terms of their intensity, spatial distribution on the hull bottom and sides as well as their time variation. A comparison of different methods to predict the vertical force on a section as a function of the relative angle between the hull and water showed that Ochi's method is consistently lower than the others which tend to coincide for angles up to about 25°. For larger angles, the method of Stavovy and Chang starts to diverge from the results of Zhao and Faltinsen and the ones based on the derivative of the added mass.

To assess the ship structural response to the vertical slam induced forces the ship is considered like a beam with varying cross section and mass distribution. The method used to find the natural frequencies and the dynamic response is based on the finite element method using a Timoshenko beam theory, which accounts for the effect of shear. The response is calculated with the modal superposition method and the time response is obtained by using the central difference method in the time domain,

The slamming stresses are combined with the low frequency wave induced components in the time domain simulation which accurately accounts for the phase relations. The combined stresses (M_c) are represented by a load combination factor K, which modifies the wave induced stresses (M_w) as:

$$M_c = M_w (1+K)$$

An example of a probability density function of this slamming coefficient derived from time simulations is shown in Figure 3 for one sea state.

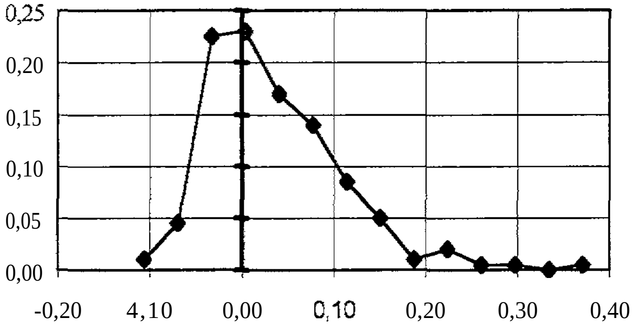


Figure *3- Probability density of the slamming coefficient (Hs = 8 m, Tz = 8 s)*

2.5 Modelling Thermal Loads

An experimental program has been conducted in complement to the stress monitoring by recording temperatures on the ship hull. A containership has been instrumented with temperature gauges which allowed correlations to be made between the temperature on the deck and the stress levels. In some location values of 30 to 40 MPa have been measured which can be significant taking into account that for steels of yield stress of 240 MPa the levels allowed for primary longitudinal stresses are of the order of 140 MPa. A good correlation was obtained in the initial set of measurements, which led to the decision of obtaining additional information of the temperature gradients during a limited time period.

The analysis of the measured data showed a large correlation between the variation of the thermal stresses and the external temperature. Statistical analysis has been performed as a basis to develop probabilistic models that describe the variability of' the thermal loads.

2.6 Modelling Load Combinations

A new method of calculating the statistics of the combined low-frequency wave induced bending moment with the high-frequency slamming induced bending moment was proposed [23]. The method is more complete than previously suggested methods because it accounts for the clustering effect of the slamming impacts. The probabilistic model takes the non-Poissonian character of slamming impact into account - more specifically the clumping effect, Further, the probabilistic model gives a combination rule for the low-frequency wave-induced bending moment, and the hig frequency slamming induced bending moment.

The basic idea is to model the joint density function of the wave amplitude and the frequency for those waves that give local maximum wave-induced slamming response within a clump of slamming impacts. The procedure followed is to consider an envelope process for the process of relative motion at the bow section in order to take the clumping effect into account, For a regular sinusoidal wave with fixed values of amplitude and frequency, the maximum/minimum value of the combined moment response is calculated.

Given the joint density function for the wave amplitude and the frequency, this density can be used to weigh the calculated combined response, so that the response statistics (say, the first four moments) are obtained, Thus the analysis is quasistationary. Finally, the extreme-value distribution is found based on the theory for first-passage time distributions in Poisson pulse processes. The mean inter-arrival times of the pulses is approximated by use of the uncrossing rate of the envelope process, modified for so-called “empty” envelope excursions.

The procedure was applied to a fast containership. From the numerical results it is found that the spectral density of the wave bending moment response can be divided into a low wave frequency part and a high frequency part. Also springing is relatively more important in the lower sea states and increases with ship speed. However, springing has only minor influence on the extreme values in severe sea states.

3 Probabilistic Modelling of Structural Strength

3.1 Model Uncertainty in the Analysis of Stress Distribution

Linear elastic. stress analysis is based on well established mechanical principles that are applied at a high mathematical level to ship structures. There are, however, significant modelling uncertainties due to different reasons.

First, one must realize that model and real structure may differ significantly because of simplifications necessary to adopt the degree of detailing of the model to available computer storage capacity and necessary running time.

Second, advanced modelling of the whole ship structure by finite elements requires exceptionally high manpower of well trained personnel, which is very costly. Thus, more restricted modelling of only the midship section of the structure is frequently used, thereby introducing additional modelling uncertainty.

Third, high cost may give reason to apply a totally different method of analysis as, e.g., the beam model. Here the hull girder is modelled as a beam with slowly varying properties. Differential equations take into account effects such as warping deflections due to shear and rotary inertea. The abrupt changes in cross-sectional properties occur at the transitions between open and closed parts of the ship, and where deck beams or transverse girders are situated they are introduced as discontinuities. Such discontinuity conditions introduces strong couplings between torsion and bending. The mathematical problem consisting of the system of differential equations with boundary conditions and discontinuities is self-adjoint and semi-definite and thus a well posed problem that can be solved rather exactly. The modelling uncertainty stems from the mathematical description of, e.g. discontinuities in relation to the real structure they are meant to describe.

Fourth, a model structure can always be analyzed rather exactly, However, since the model structure is not the real structure, the results obtained for the model structure have to be correctly interpreted when assessing stresses or deflections in the real structural components.

Finally, a significant source of uncertainty is the application of sectional loads to the structural model: the ideal procedure is to apply wave and motion induced (external) hydrodynamic pressures and related inertia loads to every finite element, but the normal procedure is to apply sectional loads as derived from the integration of hydrodynamic pressures and inertia loads over one end of the structure.

To assess the combined effect of all those uncertainties a series of calculations have been made, two used the same full 3-D finite element model of the ship with two different methods of load definition, two calculations were made using only finite element models of the parallel middle body and two calculations adopted a beam model of the whole ship [24].

Five load cases were calculated using a classic linear strip method, The resulting loads were defined as sectional moments and shear forces. These loads were used by all participants, except in one study where pressure and inertia forces were applied directly at the finite elements using a full 3-D model.

The stresses were determined at 5 points in the hull plating adjacent to two selected frames. The points were numbered 1, 2, 4, 5, 6 as indicated in Fig. 4. For each point the principal stresses and shear stress were calculated by each participant with their particular stress analysis model and method. The results for direct stresses are indicated in Table 2.

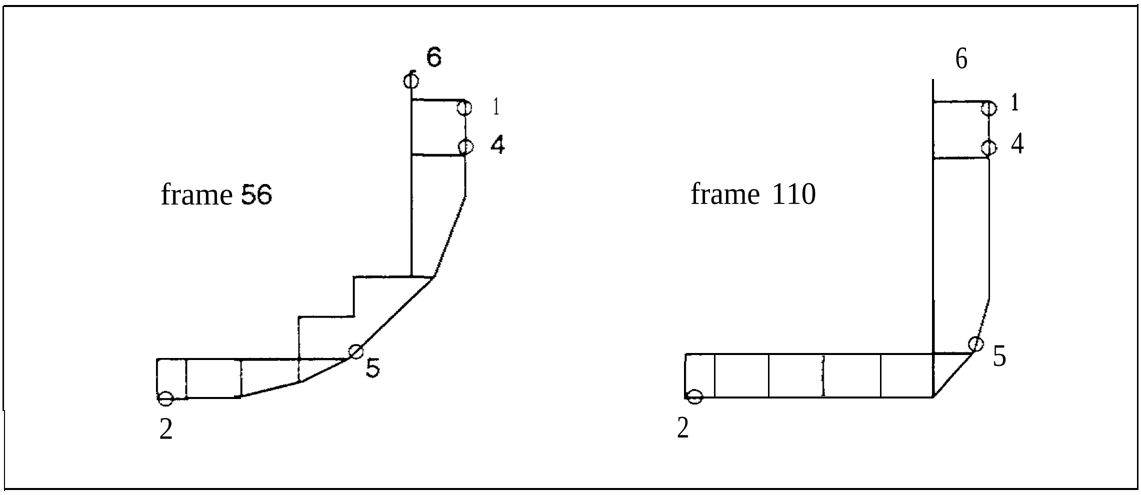


Figure 4- Position of Calculated Stresses in Frame 56 and 110

Participant	Frame 56						Frame 110					
	sig I	sig2	sig3	sig4	sig5	sig6	sig1	sig2	sig3	sig4	sig5	sig6
1	66. S	-61.1	83.8	42.8	-49.	%3.8	163.	-131.	203.	109.	-103,	203.
2	71.0	-72.8	91.0	44.7	-59.	91.0	160.	-132.	200.	106.	-104.	200.
.3	7(1.0	-60.(!	92.0	39.0	-42.	92,0	157.	-12s.	204.	95.	-98.	204.
4	67.0	-62.0	90.0	43.0	-49.	90.0	167.	-128.	202.	112.	-100.	202,
5	80.0	-68.0	1(?5.0	44.0	-49.	105.0	150.	-120.	193.	91.	-93.	193.
6							167.	-137.	216.	97.	-105.	216.

***Table 3**- Calculated axial stresses for load case 1.*

It is seen that for this case of predominantly symmetric loading on the ship hull girder there is a reasonable good agreement bet ween the results obtained by the different calculation procedures.

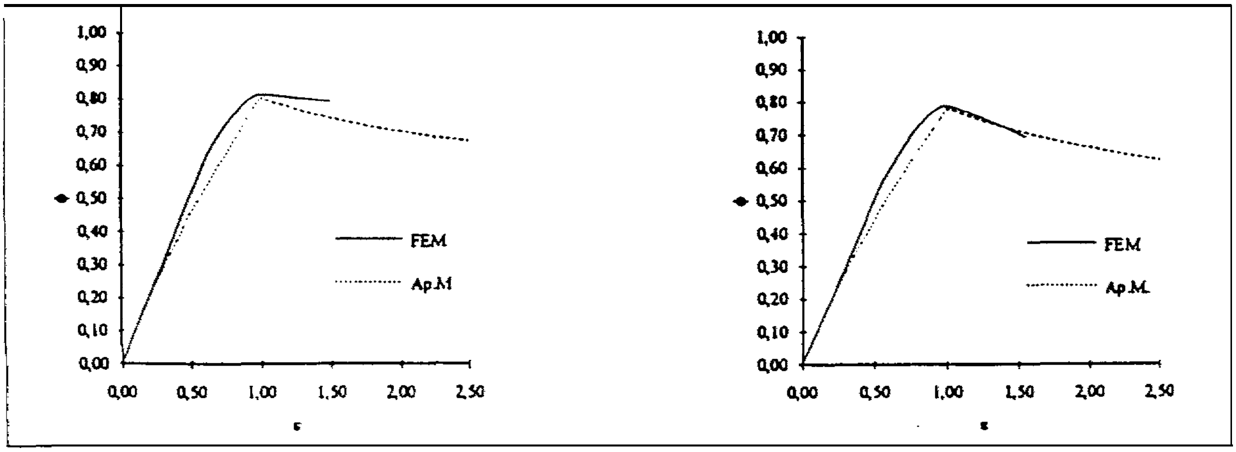
The a priori logical assumption that model uncertainty should not be a function of the location any considered structural element within the structure, was confirmed within the limits of the available data base, excluding elements close to boundaries and to locations where sectional or other lumped loads are applied, The investigation yielded meaningful measures of uncertainty for use in reliability analyses, be it the average coefficients of variations or the standard deviations of stresses, applied independently of the actual stress level, In fact, the results indicated that model uncertainty does not depend on the stress level. So the definition of a unified measure of model uncertainty for use in systematic reliability analyses was found to be reasonable,

3.2 Collapse Strength of Stiffened Plates

The interest in knowing the load carrying capacity of plates together with the stiffener under compressive load is to develop design rules to be incorporated in codes and to provide the information about plate behaviour which allows the study of the strength of systems with plated elements such as the complete ship hull girder,

The method used in the collapse analysis is a beam-column approach to the actual behaviour of the structure [25]. It is assumed that collapse occurs locally between two adjacent frames, which means that any overall deformation behaviour of the structure is neglected. The structure is divided into a number of beam-column each consisting of a stiffener and a part of the plating. A beam-column is assumed to react independently of adjacent beam-columns, which implies that the behaviour of a beam-column is only a function of how the ends of the beam are displaced and rotated. The procedures developed are able to take account of initial deflection of the stiffeners, initial deflection of the plating between stiffeners, residual stresses caused by welding..

The simplified procedures has been verified by comparison to experimental results and numerical finite element analysis results, As an example on the degree of accuracy which has been achieved by the simplified procedures we can consider results obtained using a comprehensive non-linear finite element formulation and the simplified procedure for two different stiffened panels subjected to inplane uniaxial compression in Fig, 5.



$\beta = 2.32$ and $\lambda = 0.6$ $\beta = 2.32$ and $\lambda = 1.20$

***Figure 5** - Average stress-strain curves for two different panels by F.E.M. and simplified procedures.*

It can be said that the developed approximate methods for predicting the load-shortening curves of stiffened plates under predominantly uniaxial loads seems to represent quite well the behaviour of the stiffened panels both on the ultimate strength prediction as well as in the pre and post buckling behaviour, specially when the column buckles by flexural collapse.

The main advantage of the approximate methods relatively to the finite element method results is evident when comparing the time consumption both in the creation of the model and in the CPU time, which ranges from few seconds in one method to 10 hours typically on the other, On the other hand, with a finite element program one must be very careful about the imposed boundary conditions, plate and stiffeners imperfections if a realistic load-end shortening curve is desired. With the proposed approximate methods average distortions can be automatically accounted for, and residual stresses are easily incorporated.

The uncertainty of the predicted collapse loads can be determined from the approximate formulations but a more correct approach is obtained by using a finite-element code together with a Monte-Carlo simulation of the values of the initial variables [26].

3.3 **Fatigue Strength of Structural Connections.**

A comprehensive search was conducted in order to gather data on typical welded joints in ships to be considered in the study. With this background material a rational, probabilistic FORM model for fatigue reliability assessment was developed and applied the procedure to actual ship designs.

This approach accounted for the uncertainties in the loading model, on Miner's model and on the assessment. of the geometric stress uncertainty. The long-term distribution of wave induced load effects was calculated from a wave scatter diagram of the North Atlantic but the resulting characteristic value was multiplied by a model uncertainty factor. The uncertainties in the response calculations leading to the geometric stresses involved a model factor that accounted for workmanship, structural analysis and a geometric stress concentration factor. A model uncertainty factor was used for the Miner sum limit value as was as to the material coefficients of the weld and on the fatigue limit stress range.

The results of this comprehensive analysis have given much insight in the influence of the many uncertain parameters involved in a consistent fatigue analysis of ship structural details. The analysis has also shown that the presently applied loading assessment procedure leads to considerable overestimation of the fatigue damage.

The reliability against fatigue failure formulated above is a local mode. This limit state is a problem of maintenance and inspection planning and as such not directly comparable with the hull girder collapse mode.

In developing a design criterium for the longitudinal strength of ships, it is necessary to formulate the effect of the cracks on the hull section modulus which is the design variable for the assessment of the hull longitudinal strength. The increasing number of cracks and their growing in size will decrease the net area of the section resisting the longitudinal loads, decreasing the section modulus. This decrease maybe such as to increase the nominal stress levels amidships which in turn will increase the rate of crack growth and will precipitate a failure [27].

The midship section failure due to the widespread growth of cracks is a very unlikely mode of failure and a correct formulation of the problem requires the inspection and repair process to be adequately taken into account, which was achieved by a time variant formulation, including also the effect of corrosion,

3.4 **Strength of Structural Systems**

Models have been developed to quantify the strength of systems composed of several stiffened plate elements subjected to different failure modes [26-28]. These models have been validated against existing small and Ml-scale experiments and against complex non-linear finite-element collapse analyses. They have been specially developed to predict the longitudinal collapse strength of midship sections.

Simplified, non-linear, incremental calculation procedures for the ultimate hull girder strength have been developed. These models are based on the previously described analysis procedure for load-deflection behaviour of inplane loaded stiffened panels. The resulting system analysis procedure have been verified through comparison with experimental results from model scale experiments of thin-walled girder previously performed in Japan by Nishihara and in UK by Dowling.

In Dunfermline, UK, Dow tested a 1 /3-scale steel model representing a typical warship hull structure subjected to a sagging bending moment. The total dimensions of the model were 18m x 4.1 m x 2.8 m. The developed calculation procedure have also been compared to the results of this experiment, As seen from Fig. 6 for the ultimate capacity, good agreement is found between the experimental results obtained by Dow and the analytical curve with residual stresses and initial deflections, However, some difference between the slopes of the curves are noticed. There may be two reasons for this, one is the idealised model used for describing the residual stresses in the analytical method and another is the way the a-mature of the hull is calculated for both curves. Which of these explanations is the most significant is difficult to decide,

In these procedures the influence of horizontal bending moments and vertical shear forces can be taken into account using interactions formulas developed in the project. It has been found that the torsional induced warping stresses have nearly no effect on the ultimate vertical hull girder bending moment.

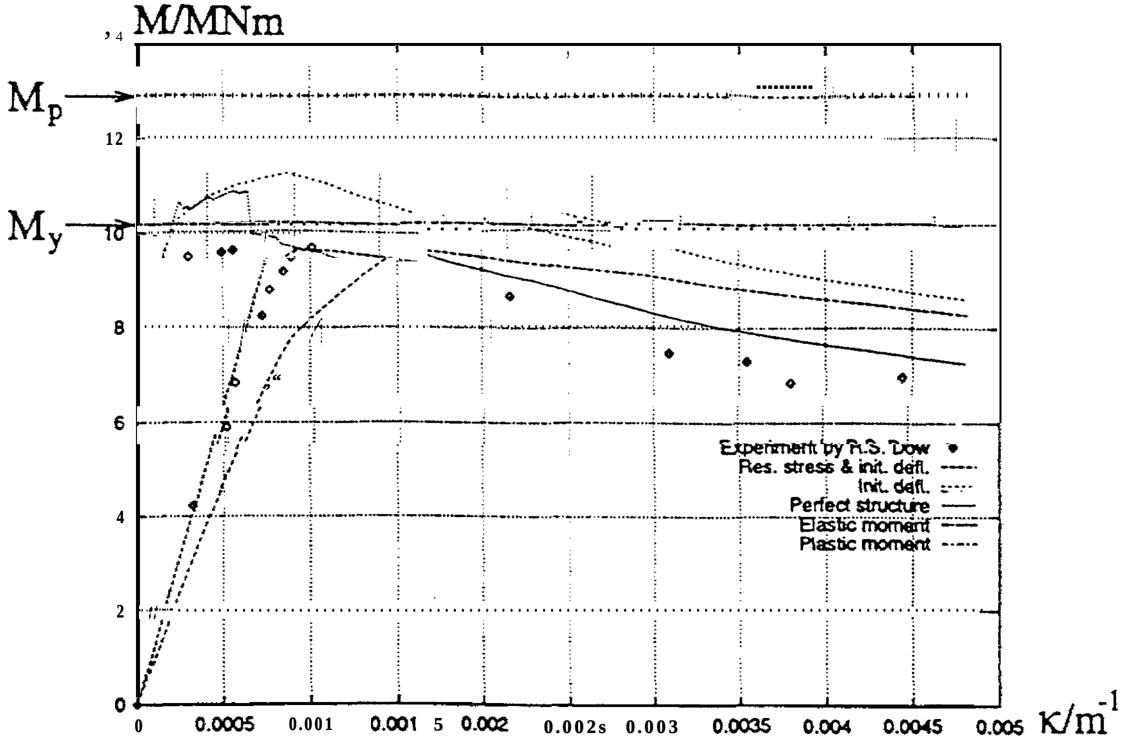


Figure 6: Analytical and experimental moment-curvature relationship for Dow's 1/3 fregate model.

The contribution of the different stochastic variables to the uncertainty of the ultimate strength predictions was estimated by first order second moment methods. It accounted for the uncertainty in plate imperfections, stiffened imperfections, residual stresses, yield stress and young modulus of the material, The results showed that the yield stress contributed with about 90% of the uncertainty which confirmed earlier results, obtained for individual plate elements. The results suggest that all but the uncertainties in the yield stress can be omitted and replaced by their mean values in a probabilistic collapse analysis. Typical COV values for the yield stress are 8- 10%.

4. *Derivation of New Rules and Calibration of Safety Factors*

4.1 Formulation of the Reliability Approach

Different reliability formulations can be considered for ships and several examples have been given in the literature. However a standardised and generaly accepted reliability formulation for ship longitudinal strength, which is one of the ultimate goals of the project, was not available when the project was initiated, The main reason being that, for most items, different more or less equivalent solutions existed and several discussions were underway to select the best one. Within SHIPREL, a general consensus was reached around the following formulation:

- *Ship operational service*

  A ship is generally allowed (and designed) to operate world-wide under unrestricted navigation and restricted navigation conditions are considered as special cases for which specific (less demanding) requirement have to be met,

  IACS (International Association of Classification Societies) philosophy is to consider a regular trade from Northern Europe to Northern North America extended for all ship life and to adopt a suitable scatter diagram.This approach was kept within the project.

- *Ship types*

  The basic approach followed by Classification Societies, consisting in considering specific formulations for each ship types was kept within the project, More specifically, tankers and containerships were considered,

- *Wave scatter diagram*

  Considerable debate is ongoing on a world-wide basis to formulate an appropriate conventional scatter diagram to be used in conjunction with direct evaluation of wave induced loads on ships. Within SHIPREL, what is judged for the time being the most appropriate scatter diagram was adopted, based on a weighted sum of different Global Wave Statistics Areas.

- *Reliability formulation*

  Based on a review of existing formulations to assess the reliability of ship structures, it was concluded that the most adequate method to apply in the reliability assessment of ship longitudinal strength is a time independent first order formulation (FORM) corresponding to one year of ship operations.

  This time independent formulation has the advantage of allowing the use of existing widely used software for the assessment of the reliability y index and at the same time it can also account for the effect of strength degradation,

  The time dependent reliability assessed in this fashion is a very good approximation to the time variant reliability and therefore appropriate for code calibration as it provides a good compromise between the ease of computation involved using FORM methods and the need of relating it to more accurate time variant methods.

  The Hasofer and Lind reliability index β was adopted. A one year ship life is taken as reference period for the evaluation of β; in other terms the annual probability of failure is considered in. ‘This is not the case for fatigue limit states where a reference ship life of 20 years is considered.

– *Design format*

The format selected for reliability based design code is basically a load and resistance factor (LRF) one where partial safety factors are considered for loads and resistance. More specifically, a partial factor was selected for the capacity and two separate factors for wave induced and still water loads respectively,

The main advantage of this format with respect to traditional ones is to allow flexibility in design by a better allocation of safety depending on the ship characteristics.

4.2 Reliability Analysis of Existing Shim

– *Corrosion*

Formulations of the reliability of ship hull need to take into account the different mechanisms of degradation of the structural resistance. Corrosion wastage, in particular, is very difficult to handle: firstly because of the lack of detailed corrosion data appropriate to be treated in a reliability analysis; secondly for the difficulties involved in modelling in a satisfactory way the strength degradation physical process due to corrosion.

As far as the second point is concerned, detailed investigations have been carried out within this task resulting in a suitable model to evaluate the reliability index as a function of time for a ship subject to corrosion wastage and repair (see e.g. Fig, 7).

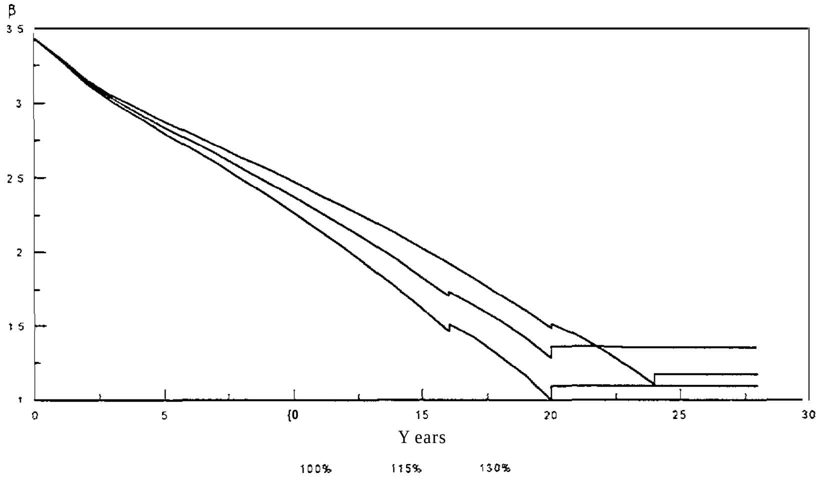


Figure 7 - Time Variant **Reliability** *Index of a tanker* **subjected to corrosion**

- *Reliability calculations; ultimate collapse*

Reliability calculations were carried out on several ships selected in such a way to conveniently represent typical oil tankers and containerships design. The aim of the exercise was mainly to test the formulation and to modify those items requiring improvements.

Table 4 present results of calculations made for a double hull (DH1) and a single hull tanker (SH2), showing the target index (β_t) the index for the full load condition (β_{FL}) the ballast (β_{BL}), the partial load (β_{PL}) and the resulting overall value.

CONDITION	SHIP	β_t	β_{FL}	β_{BL}	β_{PL}	β
Sagging	DH1	3.00	2,S5	3.61	3.18	2.74
	SH2	3.70	3.39	5.64	6.15	3.39
Hogging	DH1	3.00	5.20	3.03	3.44	2.97
	SH2	3,70	4.40	3.55	3.80	3.46

Table 4- *Target reliability index and results of calculations.*

– *Reliability calculations: fatigue reliability*

The failure equation for the fatigue limit state is given by:

$$F(\underline{x},T) = B_{\Delta}\overline{\Delta} - D^{WB}_{LT}(\underline{x}, T)$$

where:

$D^{WB}_{LT}(\underline{x}, T)$ is the stochastic long term fatigue damage;

B_{Δ} is Miner's model uncertainty;

$\overline{\Delta}$ is Miner's sum;

$\underline{x}$ is the vector of random variables;

T is the operational period of time considered (typically 20 years).

Fatigue reliability calculations were carried out for three critical details (A, B, and C) located at starboard side of the middle reinforced webframe of hold # 4 of the DH1 double hull tanker.

Both transverse and longitudinal plate weldings were considered. Results can be summarised as follows:

- for transverse welds of structural details participating to the longitudinal strength and submitted to global loads, 20 years reliability indices fall within the range [2.35; 3.94] which means a very good fatigue reliability;
- for longitudinal welds of the same details, reliability indices fall within the range [-0,15; 5.08] at waterline level, [0.56; 4.26] at longitudinbal stringer level and [-0.77; 2.57] at inside bottom level (negative values mean that a crack is expected to occur before the expiry of the 20 years period); this means that these details have not a very high reliability and should be conveniently inspected during her life.

It should be underlined that effects of inspection and repairs - which would definitely increased the reliability - have not been considered: in other words, in real life these details would have higher reliability.

4.3 Assessment of the target safety levels

The objective of this task, namely to establish suitable safety levels to be applied in ship design to safeguard against hull structural collapse, was approached into two distinct ways:

- by analysing the world-wide casualty return records
- by considering the level of structural safety implicitly in built in present ship design practice.

A detailed investigation was carried out by considering both Lloyd's Casualty Returns (regularly published on yearly basis since the last 20 years) and IMO's (International Maritime Organization) database of serious casualties (working and constantly updated since 1978).

The analysis covered all ship types and not only tankers and container ships which are of concern within the project. The reason for this was mainly to have a glance of the differences between different ship types in order to assess the explainability of the methods developed within SHIPREL to other ship types.

The following conclusions were obtained:

- structural related casualties (i. e, those for which weather the initiating event or the final one was imputed to structural reasons) account for 13. 5°/0 of total casualties;

- casualties caused by structural failure as first events only account for 8.50/0 of total;
- apart from general cargo ships (GEN), bulk carriers (BCA) and tankers (TAN) are the ships types which most frequently are subject to structural induced casualty; containerships (CON) are less frequently involved;
- medium sized-tankers (10000 -50000 DWT) are those more likely subject to hull failure;
- structural failure normally occurs during navigation (94%); roughly half (43%) occur under bad weather conditions and 1/4 (23%) involve either loss of life or pollution or both,

An evaluation of the inbuilt safety in present practice was obtained by performing reliability calculations, based on the above described formulation, carried out for different existing ships under different loading conditions,

From comparison of these results, it was found appropriate to set the following targets reliability indices to be used in connection with the reliability formulation above (Table 5).

	As built	Corroded
Tankers	10^{-4}	10^{-3}
Containerships	10^{4}	/

Table 5: Target annual probability of failure.

4.4 Development of Semi-Probabilistic Design Rules

Based on a comprehensive investigation and on extensive benchmarking exercises carried out throughout the whole project, the following conclusions were reached:

- in view of the importance of the choice of the scatter diagram and of related aspects (bad weather avoidance, voluntary route and speed changes), it is suggested that Global Wave Statistics (GWS) is considered the most consistent set of data available and is assumed that this data already has inbuilt the above aspects;
- a “standard” scatter diagram is recommended, taken from GWS by averaging North Atlantic areas (cf. Table 6) [14];

Tz

		2	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	
	0,5	6,2E-04	6,6E-03	2,5E-02	3,7E-02	2,2E-02	6,9E-03	1,2E-03	O, 0E+00	O, 0E+00	0,0E+00	O, 0E+00	1,0E-01
	1,5	1,7E-04	3,1E-03	2,0E-02	6,3E-02	8,2E-02	5,1E-02	1,8E-02	4,0E-03	1,1E-03	0,0E+00	O, 0E+00	2,4E-0 1
	2,5	8,8E-05	1,5E-03	1,0E-02	3,7E-02	7,4E-02	7,2E-02	3,8E-02	1,3E-02	3,3E-03	9,0E-04	0,0E+00	2,5E-01
	3,5	0,0E+00	7,2E-04	4,5E-03	1,7E-02	4,2E-02	5,4E-02	3,9E-02	1,7E-02	4,9E-03	1,4E-03	0,0E+00	I, SE-O]
	4,5	0,0E+00	2,9E-04	1,9E-03	6,9E-03	2,0E-02	3,1E-02	2,7E-02	1,4E-02	5,3E-03	1,5E-03	1,6E-04	1,1E-01
	5,5	0,0E+00	1,7E-04	6, SE-04	3,0E-03	8,4E-03	1,5E-02	1,6E-02	9,8E-03	4,0E-03	1,5E-03	3,2E-04	5,9E-02
[s	6,5	O. 0E+00	0.0E+00	3.5E-04	1.4E-03	3.5E-03	7.0E-03	8.3E-03	5. SE-03	2.7E-03	1.1E-03	3.2E-04	3,0E-02
	7,5	0,0E+00	0,0E+00	1,7E-04	4,3E-04	1,5E-03	3,4E-03	4,4E-03	3,4E-03	1,8E-03	7,2E-04	1,6E-04	1,6E-02
	8,5	0.0E+00	0.0E+00	O. 0E+00	2.2E-04	K6E-04	1.8E-03	2.1E-03	2. 0E-03	1.3E-03	4.9E-04	O. 0E+00	8,8E-03
	9,5	O, 0E+00	O, 0E+00	O, 0E+00	1,7E-04	1,7E-04	8,4E-04	1,2E-03	1,1E-03	7,3E-04	3,0E-04	O, 0E+00	4,5E-03
	10,5	O, 0E+00	0,0E+00	0,0E+00	O, 0E+00	0,0E+00	O, 0E+00	8,5E-04	6,9E-04	4,6E-04	O, 0E+00	O, 0E+00	2,0E-03
	11,5	0,0E+00	0,0E+00	O, 0E+00	O, 0E+00	0,0E+00	O, 0E+00	O, 0E+00	5,0E-04	0,0E+00	O, 0E+00	O, 0E+00	5,0E-04
	12,5	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	O, 0E+00	O, 0E+00	0,0E+00	0,0E+00	O, 0E+00	O, 0E+00	O, 0E+00
	13,5	0,0E+00	0,0E+00	0,0E+00	O, 0E+00	0,0E+00	O, 0E+00	O, 0E+00	0,0E+00	0,0E+00	O, 0E+00	O, 0E+00	0,0E+00
	19	0.0E+00	0.0E+00	0.0E+00	O. 0E+00	0.0E+00	O. 0E+00	O. 0E+00	O. 0E+00	0.0E+00	O. 0E+00	0.0E+00	0,0E+00
		8, 8E-04	1,2E-02	6,3E-02	1,7E-01	2,5E-01	2,4E-01	1,5E-01	7,1E-02	2,6E-02	7,9E-03	9,77s44	1,0E+00

Table 6- SHIPREL recommended scatter diagram

- the use of even sligthly different theories for calculating wave induced loads, produces considerable scatter. Based on a comprehensive benchmark exercise, it is however possible to derive suitable uncertainties in terms of bias and COV with respect to the averaged results obtained in the benchmarking [7];
- suitable simplified formulations to straighforwardly account for non-linearity in wave loading were provided [16],

4.5 Application of Design Rules and Code Adjustment

The draft rules developed within the project where applied to some ships with the aim of assessing their effectiveness and to modify them whenever necessary, This involved ship “redesign” according to the drafted rules in order to provide a minimum feed-back to the process of rule development.

The ship redesign was obtained by applying the developed rule checking formula at fill utilisation, evaluating, this way the minimum required strength. Based on this, partial safety factors were sligthly modified with the aim of making them more uniform and to avoid burdern to the designer obliging him to adopt several different partial factors.

As a result, rules were re-drafted, and reliability calculations were performed for the ships designed according to this revised version. The aim of this additional calculations was to check the influence of the modifications with respect to the target reliability adopted. As expected, the influence was small and always in the increasing safety side: this means that the assumed targets need not be modified. A glance of the results is given in Table 7 and 8.

SHIP	$M_{UV\ sag}$ (MNm)	$M_{UV\ hog}$ (MNm)	M_{UH} (MNm)
DH1	2970	3334	4802
SH2	346S	4211	4734

Table 7 - Value of ultimate moments for re-designed ships

CONDITION	SHIP	β_t	β_{FL}	β_{BL}	β_{PL}	β
Sagging	DH 1	3,00	3.35	3.61	3.66	3.20
	SH2	3,70	3.56	5.64	6,15	3,56
Hogging	DH1	3.00	5.’20	3.03	3.44	2.97
	SH2	3.70	4.40	3.71	3.96	3.62

Table 8 - Reliability indices for re-designed ships

5 Conclusions

This report has described the main achievements of the SHIPREL. This project has identified the significant uncertainties involved in the procedure to calculate the long-term distribution of wave induced load effects due to the different theories of predicting wave induced load effects. It is essential to conduct a series of model tests with accurate measurements of wave induced loads in order to clarify the accuracy of the different.

It was also shown that there are significant uncertainties associated with the reliability of the existing wave data which are an input to the calculations leading to design values of wave induced load effects.

The fill-scale measurement program was important to identify the significant difference between calculated and measured wave induced load effects. However due to budget limitations no on-line accurate information was obtained of the prevailing wave conditions which does not allow a definitive validation between the measured and calculated values.

More work is necessary to clarify the discrepancy between the calculated values and the ones measured as well as the ones used presently by Classification Societies as design values.

Important achievements were accomplished as concerns practical methods of predicting non-linear wave induced loads. This is specially important for ships of fine forms.

A method was developed to calculate the stresses developed in extreme situations associated with ship slamming. However, the approach still needs to be further extended because it does not account for the effect of water on deck which often occurs in the extreme situations.

The knowledge of the behaviour of stiffened panels was improved although there are still some aspects that need more work, namely the collapse under combined loading which had not been considered in the present project.

A major achievement with significant practical implications is the development of a simplified procedure to calculate the hull girder collapse accounting for the post collapse strength of each panel. This is a procedure that is bound to be quickly introduced in design practice and to be considered in the rule requirements of the Classification Societies.

A very complicated procedure was used to determine the fatigue reliability of important joints. While this procedure will give reference values, more simplified approaches are required for current design procedures. However, these approaches can be calibrated with the results of a more demanding analysis like the one proposed here.

A standard reliability approach has been proposed as a basis for comparative studies between different ships and for calibration of safety factors. The procedure was applied to some example cases, providing an indication of the nominal levels of safety in present ships. Partial safety factors have been determined based on that level of reference.

Although the methodology for reliability assessment and for derivation of safety factors was demonstrated, a larger series of analysis and additional refinements resulting from it are required before definite values can be proposed for design.

The project dealt briefly with the effect in the reliability assessments of strength degradation such as fatigue and corrosion. R also considered the interaction between those phenomena and the influence that maintenance and repair actions have on the level of reliability. However, this was not the main objective of the project which, however, has demonstrated the need of a more comprehensive study of the degradation mechanisms such as fatigue and corrosion as well as of the reliability of ship structures subjected to periodic maintenance actions.

The overall methodology developed in the project for reliability based design of ship structures has proved that this is feasible within the present state of the art. However, the procedure will only be used by industry if in addition it becomes also practical. The ship designers will not find it easy to use the various separate modules that are required to apply the complete methodology.

This means that it is necessary to develop an integrated software package that is able to perform the different aspects of the analysis, from prediction of loads effects to structural collapse and to reliability in an integrated way. This is the main follow up work that this project should lead to, which will certainly much enhance its present usefulness.

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