CODEN:TRITA/SKP-91/1070

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# Combined Wave Induced Stresses in Ships

## Application of a Rationally Based Direct Calculation Method

## Summary

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Akademisk avhandling, som med tillstånd av Kungliga Tekniska Högskolan i Stockholm framlägges till offentlig granskning för avläggande av teknisk doktorsexamen onsdagen den 29 maj 1991 kl 10.00 i sal K2, KTH, Teknikringen 28, Stockholm

# COMBINED WAVE INDUCED STRESSES IN SHIPS;

## APPLICATION OF A RATIONALLY BASED DIRECT CALCULATION METHOD

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## ABSTRACT

Calculations of combined wave induced stresses in longitudinal and transverse primary members of ship structures have been performed with a direct method. The wave loads are calculated with linear strip-theory and include global hull girder moments and shear forces, and local loads from external hydrodynamic pressure and internal inertia forces from the cargo. Structural response is calculated by ordinary hull beam idealization for global loads and finite-element analysis for local loads. Results from the linear structural analysis are coupled to wave loads with discrete influence coefficients. Transfer functions of combined stress response in regular waves are obtained by superposition of the different wave induced stress components considering their phase lag. Non-linear stress response from hydrodynamic pressure fluctuation close to the still-water line is evaluated by a simplified time step procedure where the ship motions and global loads are assumed to be linear. Short-term and long-term linear stress responses are calculated for standard wave energy spectra and wave statistics for the North Atlantic. The statistical correlation between different stress components is analysed and shown to be important to take into account at the design stage. Of special importance is the counteracting effect of external hydrodynamic pressure and internal mass forces in full cargo holds. The influence of different load conditions, speed reduction, and non-linear effects on the long-term stress distribution is discussed. Fatigue analysis of a few typical hot-spots are performed considering local geometric stress concentrations and the correlation between nominal normal and shear stresses.

The direct calculation method is found to yield reasonable results and could be advantageous to introduce in the design process especially for novel type of ship structures and for highly optimized structures where the specific ship characteristics must be considered.

***Key words:***
ship structural design, wave loads, stress response, direct analysis, long-term distribution, fatigue

CODEN: TRITA/SKP-91/1070 ISSN 0349-0025

# CONTENTS

**Summary:**

## INTRODUCTION

In the three separate parts of this thesis, results are presented from direct calculations of wave induced stresses in different members of ship structures. The main purpose has been to evaluate the correlation and the combined effect of the wave load components. Examples are also given on how to estimate the local fatigue life considering long-term nominal normal and shear stress distributions and local geometric stress concentrations. The calculation method used is based on a synthesis of well established methods and is directly applicable to ordinary design works.

A fully rational method for determining the strength of a ship structure at the design stage should be direct in the sense that it is governed by the structural arrangement and expected cargo distributions, as well as the ship's behaviour and handling in the expected environmental conditions. It should furthermore be based on probabilistic methods with proper modelling of the uncertainties in the estimates of conditions, loads, and strength during the ship's service life. Criteria for strength evaluations should be established based on optimum or acceptable reliability levels with regard both to safety and economy.

Although the design work today is far from fully rational, development of refined calculation methods and accumulating service experience continuously improves the process. During the last decades, reliability-based methods have become accepted and used for new types of marine structures, especially for offshore oil and gas exploration. Direct calculations of ship's strength are today accepted by the codes as an alternative or complement to traditional formula-based design methods. For the development of new or better optimized structural designs a direct approach is a necessity.

Advanced numerical methods for strength analysis such as the finite-element method for calculation of stress levels have become an everyday tool. However, a detailed stress analysis is of little value if not the external loads are adequately modelled. Direct analyses of ship structures are today still generally based on assumptions of quasi-static loads which should be equivalent to worst expected conditions. These quasi-static conditions do not represent the actual dynamic load distributions determined by the ship's behaviour at sea, and are hence not sufficient for a truly direct analysis.

Even though the dynamic behaviour of the individual ship is not accounted for in the quasi-static loads, the dynamic effects are implicitly included in the choice of acceptable nominal stress levels based on experience from ships in service. One advantage of standardized static loads is that the effect of different structural arrangements is easily evaluated. This may, however, give the false impression that an extensively optimized structure with respect to static loads and nominal stresses will have an acceptable risk of structural failure. This is not at all certain since structural failure - especially fatigue - arise from local stresses rather than nominal stresses. The criteria reflect sufficient strength of previous designs and do not tell about specific risk levels in arbitrary designs.

The main loads acting on the ship structure can be split up in different types distinguished by their frequency of variation: still-water loads, wave induced low-frequency (first order) loads, and wave induced high-frequency and transient loads. Still-water loads are in general deterministic in the sense that they are exclusively determined by the cargo distribution and floating condition of the ship. At the design stage, the forthcoming sequence of still-water conditions are however uncertain. In recent years the stochastic character of the still-water loads have been analysed by Guedes Soares and Moan e.g. [1], [2].

The wave induced loads are to their general character stochastic due to the stochastic character of irregular seas. The stresses induced in the structure from wave loads depend on both the load levels, and on the correlation in time of the various load components. The main topic of this thesis is to illustrate how the correlation between low-frequency wave load components can be taken into account at the design stage in a direct way. The stress levels induced by still-water loads and wave loads are of the same magnitude and both must be taken into account when determining the ultimate strength of the ship. Due to the large number of wave encounters during a ship service life, the low-frequency wave loads are furthermore the most important ones for the fatigue strength of the structure.

Transient non-linear wave loads can be critical especially for the local strength of the foreship subjected to bottom or bow flare slamming, but also for the general hull girder strength by inducing high-frequency hull girder vibrations - whipping.

All load types are in general coupled since they are all affected by the ship condition. They can usually be predicted separately because of their difference in frequency of variation, but should in a complete reliability analysis be considered together. Of special importance is the influence of ship speed on the combination of low frequency hull girder bending and whipping, [3].

The present study treats the low-frequency wave induced stresses as the linear time-coupled combined structural effect of global dynamic loads acting on the hull girder as a rigid body, and local loads from hydrodynamic pressure and mass inertia forces acting on the local structural members. In comparison with traditional design methods based on equivalent static loads this approach gives an improved possibility of predicting extreme stress levels as well as a possibility of predicting fatigue damages anywhere in the structure.

New ship designs tend to include a larger proportion of high strength steel to reduce the scantlings. The consequently increased stress levels requires a more thoroughly fatigue-based design procedure. The major problem will be - in a reasonably simple way - to accurately predict the stress history from wave loads in the structure. Just like it became necessary to use direct methods for calculations of hull girder loads due to the rapidly increasing ship sizes in the 1960's, it is now becoming necessary to achieve knowledge about the local stress distribution over the ship's lifetime in primary and secondary structural members.

Below will follow a brief description of the direct calculation method, a summary of the results, and some comments on the application of the method in an ordinary design procedure.

## A DIRECT CALCULATION METHOD

Ever since the pioneering paper of St.Denis and Pierson [4], a rational method has been available for calculation of ship responses in irregular seas. The energy spectrum method together with the strip method became the predominant tool for naval architects for prediction of ship motions and hull girder bending moments. It thus delivered the necessary theoretical base for the tremendous development of ship designs during the 1960's and 1970's. Within the cooperative activities of ISSC and in innumerable separate papers, direct design procedures for ship strength were outlined. Results from full scale measurements and model tests were compared with theoretical calculations and the general applicability of the methods was verified. After these golden years followed a period of stagnation in the shipbuilding industries and research activities were to a large extent directed towards the upcoming offshore technology. Now again the international market has changed and the need for new ship designs is steadily increasing. The modern computer technology has radically changed the conditions for the design process, and previous research activities can now be generally applied.

Within the work of this thesis a general computer program has been developed for the calculation of combined low-frequency wave induced stresses. Although the method has been discussed in principle for many years, surprisingly few results from complete analyses have been published. This is the reason why such a large number of stress response functions are presented in the appendices of Part 1 and Part 2. Descriptions of the calculation method are included in all three parts of the report series. Here is discussed only the general properties of the method.

### *Linear deterministic stress response*

The direct method outlined in this work is based on a general assumption of linear load - response relationship. Although the method can be expanded to include non-linear load components with respect to the wave height, the structural response is always treated as linear. This assumption is no major obstacle when dealing with high cycle fatigue but is certainly a limitation when dealing with ultimate strength analysis.

In a condensed form the linear load - response relationship can be described by a general equation for deterministic stress response in regular waves

$$\sigma_i = \mathbb{C}_{ij} \ \mathbb{L}_j \qquad (1)$$

where

$\sigma_i$ = vector of stress responses at positions i

$\mathbb{C}_{ij}$ = matrix of influence coefficients

$\mathbb{L}_j$ = vector of fluctuating load components j

The load vector $L_j$ can include all relevant dynamic load components, each fluctuating with the wave encounter frequency but with different phase lags. In a linear load analysis, the $L_j$-components are numerically treated as harmonic complex quantities while in a non-linear load analysis $L_j$ are the time-step values of the load components and $\sigma_i$ becomes the time-step value of stress response at position $i$. The influence coefficients $C_{ij}$ are constant values representing stress (normal or shear) at position $i$ per unit load component $j$. $C_{ij}$ are hence not influenced by whether the load is linear or non-linear.

The local structural responses to unit loads are usually adequately evaluated from a similar model as would be used for a direct analysis based on quasi-static load cases. The complexity and extent of the model shall be established based on whether the objective of the stress analysis is to evaluate nominal or detail stresses. The major difference from a static analysis is that a larger number of separate load cases must be considered. With the finite-element method the extra time necessary for this is small however, compared with the time needed to generate the model. Another difference that must be noted is that local static design loads are often symmetric with respect to the centerline and/or the mid-hold section, and the size of the models can be reduced by applying proper boundary conditions. The same cannot be done for unsymmetrical local unit loads, but again, with modern computer programs this is not a big obstacle.

The approach of using influence coefficients in a total structure analysis system has previously been discussed and exemplified by e.g. Söding [5], Nagamoto et al. [6], and Kawamura et al. [7]. Direct calculations of wave induced stresses in longitudinal and transverse members have also been presented by Hattori et al. [8].

***Loads in regular waves***

The low-frequency wave induced structural loads originates from the external hydrodynamic pressure variation and from inertia forces due to the ship motions. The integrated effect of these loads over the ship length result in global moments and shear forces. The hull girder bending moments and shear forces give rise to stresses in longitudinal strength members directly proportional to the load values at the hull girder cross section considered. The influence coefficients for these loads are directly determined from the instantaneous cross sectional load and from the cross sectional properties at the stress position considered. For non-continuous or badly supported longitudinal members the generated stresses might differ substantially from stresses obtained from a simple beam theory analysis of the hull girder. In this case a more refined analysis is necessary.

The warping stresses generated from global torsional moments cannot be determined directly from the sectional load but must be determined with account for the total instantaneous moment distribution over the ship length. This can be done by applying several unit moment distributions over the ship length with separate influence coefficients for each unit distribution as suggested in [5], and used for local loads in this study. However, if also the local deformations at the connection between open and closed sections [9], [10], are to be taken into account, the structural model will become rather extensive and different from the limited models used in the ordinary structural analysis. In Part 1, the torsional stress response in an open hold of a lo/lo containership is treated in a simplified way by assuming that the sectional torsional moment is coupled to a fixed - in this case trapezoidal - moment distribution over the ship length (see Part 1, fig.3.6). This simplification makes it possible to treat hull girder torsional stress response in a similar way as stresses from hull girder bending moment and shear forces. It can be justified for long waves where the torsional moment distribution is slowly varying along the hull, but in waves with lengths significantly shorter then the ship length, this simplified approach is not applicable. However, in short waves, or rather short wave projections along the hull, the torsional moment amplitude is small and consequently the error introduced in the combined long-term stress distribution will be of minor importance.

In addition to the hull girder loads, the local structure will be subjected to local external pressure fluctuations and local internal mass forces from the cargo forced to follow the ship motions. For transverse members such as side frames and bottom floors, the local loads exclusively will determine the dynamic stresses. For longitudinal members the local stress response must be superimposed on the global response with the relevant phase lag between the components taken into account.

While the global loads have been thoroughly examined during the last decades by full-scale measurements, model tests and theoretical calculations, the general knowledge of local load effects is still limited. One main reason for this is that hull girder bending moments and corresponding measurable strains and stresses in e.g. the deck, can be generalized to any ship with ordinary beam theory. The local loads and corresponding strains and stresses are however dependent on the actual local structure and cannot in a simple way be generalized to other ships with other structural arrangements. This is the reason why a direct calculation method shows its major advantage in the calculation of local wave induced stresses and especially for the analysis of transverse structural members.

To fit into equation (1), the local distribution of fluctuating pressure and mass inertia force is divided into discrete unit loads for which influence coefficients can be determined. The degree of division must be found with respect to both the structure and the gradient of the load distribution. While for instance the external pressure distribution varies slowly and continuously along the ship in long waves, the mass forces might be totally discontinuous at a transverse bulkhead with a full cargo hold on one side and an empty hold on the other side. The two different ship structures studied in Part 1 and Part 2 need different unit load divisions. The containership hold analysed in Part 1 is a typical 3-dimensional structure which needs a large number of unit loads to be accurately modelled, while the structural members of the OBO carrier studied in Part 2 and Part 3 can be modelled as in-plane loaded and hence only need a few unit loads.

The local inertia forces become generally different for liquid cargo and for solid cargo. In Part 2 is shown how dynamic liquid cargo forces can be modelled as fluctuating quasi-hydrostatic pressures induced by coupled motions in all degrees of freedom. In the case of low viscosity cargo there might also appear transient sloshing loads which are not included in this linearized model. Solid cargo mass forces in the containership, Part 1, are directly transmitted to the side and bottom structure through the container-guide framework.

The calculation of hydrodynamic forces and motions of floating bodies in waves is a classical problem to which a lot of research effort has been spent. The most frequently used method is the well known so-called strip method originating from the work of Korvin Kroukowsky and Jacobs [11], further developed by several others. In its basic form the method is limited by several harsh assumptions such as small wave and motions amplitudes, 2-dimensional flow around transverse hull sections, and linear response. During three decades of development and practical use, the strip-method has however proved to be able to sufficiently well predict motions and loads far beyond its theoretical limitations. In this study two different strip-program have ben used, in Part 1 the wide-spread SCORES program developed Kaplan and Raff [12] [13], and in Part 2 and Part 3 a modern program based on the theory of Salvesen, Tuck, and Faltinsen [14].

For the purpose of stress analysis, some general limitations of the linear strip method can be identified for larger waves. Firstly, the assumption of linear harmonic time variation of hydrodynamic pressure on the ship hull below the still-water line and no hydrodynamic loads above is obviously not in accordance with the physical reality close to the still-water line. Secondly, symmetric sagging and hogging bending moments based on a linear response assumption is not sufficient when the ship sectional form at the aft and fore ends has significant flare, as is the case particularly for slender ship forms, [15]. The consequence of the first limitation is studied in Part 1 and Part 2 where a simplified non-linear, non-harmonic pressure variation close to the still-water line is simulated in a time-step procedure. The second limitation does mainly affect the mean value of the dynamic vertical bending moment while the peak-to-through value still can be modelled as approximately linear. Comparisons between linear analysis, non-linear analysis, and model tests in regular waves, [16], further indicate that the roll motion and the horizontal bending moment are overestimated, while the peak-to-through amplitudes of other motions and global load components are rather well predicted by the linear approach.

### *Stochastic stress response in irregular seas*

With the assumption of linear load response in regular waves a combined stress transfer function $T_\sigma(\omega)$, representing the ratio between stress amplitudes and wave amplitudes over the wave frequency range, is achieved according to equation (1). The stress transfer function will be unique for the specific load condition, speed, and wave heading, i.e. $T_\sigma(\omega, LC, V, \beta)$. Several such transfer functions for different structural members and stress positions are shown in the figures of the first appendices to Part 1 and Part 2.

For a short-term stationary irregular sea defined by a wave energy spectrum $S_w(\omega)$, the stress response spectrum $S_\sigma(\omega) = S_w(\omega) T_\sigma(\omega)^2$ is calculated. From this the probability distribution of short-term stress amplitudes can be determined. When the stress response spectra are relatively narrow banded in the frequency range, the probability distribution of stress response amplitudes will approximately follow a Rayleigh-distribution.

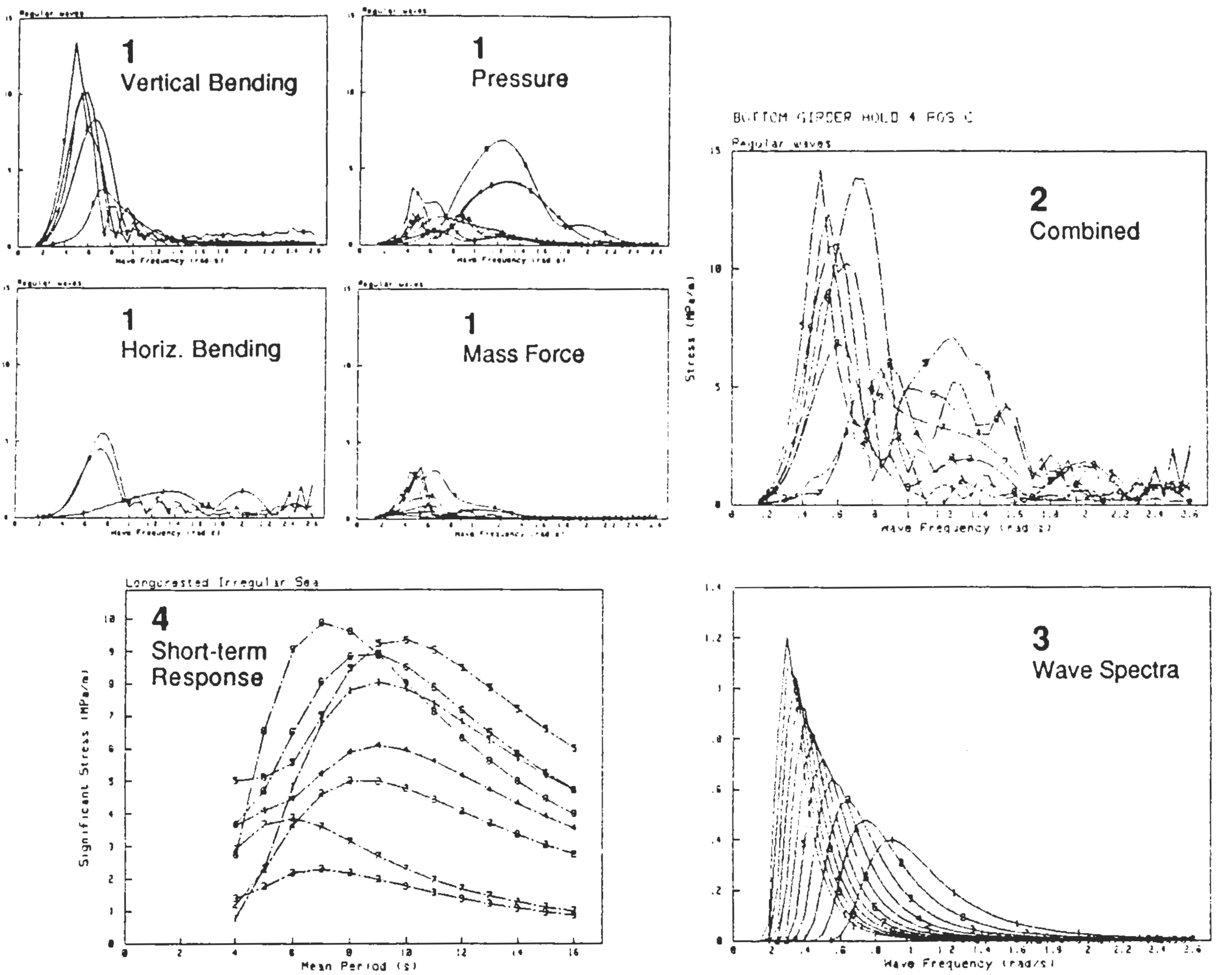
The short-term linear stress response in irregular seas is described by the ratio between significant stress amplitude and significant wave height. For design purposes it is convenient to use a simple wave spectrum formulation based on mean wave period $T_z$ and significant wave height $H_s$. In this way the short-term response becomes a function of the mean wave period together with the ship condition, speed, and the predominate wave heading angle, $\sigma_s / H_s = f(T_z, LC, V, \beta)$. Response functions in irregular longcrested seas are presented in the second appendices to Part 1 and Part 2.

Finally, the long-term probability function of stresses is obtained by summation of short-term probabilities of exceedance for different stress levels in all possible combinations of sea states, load conditions, speeds, and heading angles, multiplied with the predicted relative frequency of the different conditions during the ship's service life. Joint probabilities of significant wave heights and mean periods can be found for different ocean areas in collective reference books, such as the extensive Global Wave Statistics [17]. The number of different load conditions must at the design stage be limited to a few typical conditions for the ship class considered. For an OBO carrier these could for example be full homogeneous load, ballast, ore cargo in every second hold, and perhaps a few more. The long-term percentage of each load condition is naturally uncertain and difficult to foresee. It can be based on assumptions of the future use of the ship or it can be based on statistics from existing ships of the same type. The estimate of speeds and wave headings can be even more complicated since they might be voluntarily changed in rough seas.

There are two types of speed reduction in heavy weather. In moderate severe sea states the speed will be reduced due to added resistance and reduced propulsion efficiency, while in very severe seas, the speed will be further voluntarily reduced by the operator to reduce the ship motions and the probability of cargo damage, slamming and deck wetness, [18]. The involuntary reduction is believed to have little effect on the stress history while the voluntary reduction might have a significant effect on the extreme long-term stress levels. Beside speed reduction, also voluntary course changes can be initiated by the operator to reduce ship motions. Course changes are generally made in the direction from beam seas to head or following seas to avoid large rolling motions and cargo shift. Hence, course changes may increase the wave induced vertical bending moment in extreme seas significantly, [19]. The number of voluntary speed reductions and course changes is much larger for small ships then it is for larger ships. It is possible that the future use of weather routeing systems will increase the heavy weather maneuvering effect on the long-term stress distribution.

From the calculated long-term distribution of wave induced stresses, the probability of fatigue damage and the probability of exceeding a certain maximum stress level can be assessed. For ultimate strength evaluation, the extreme dynamic stresses are to be added upon the still-water stresses. The long-term stress distribution is usually well represented by a single 2-parameter Weibull distribution. In Part 2 is shown that a superior representation can be achieved by separating the distribution in two parts, one for the high-cycle stresses governing the fatigue strength, and one for the extreme low-cycle stresses.

Figure 1 below illustrates the different steps included in the determination of a combined long-term stress distribution.

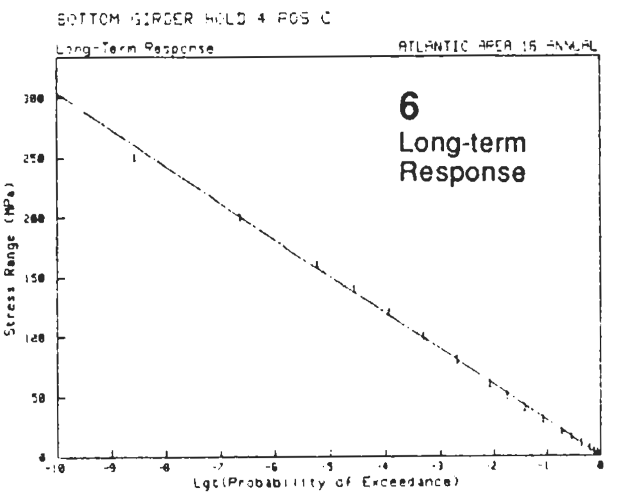



5

ALL DIRECTIONS

PERCENTAGE OF OBS = 100.00%
(INCLUDING 0 70% DIRECTION UNKNOWN)

| SIGNIFICANT WAVE HEIGHT (m) \ ZERO CROSSING PERIOD (s) | <4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | 10-11 | 11-12 | 12-13 | >13 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TOTAL | - | 1 | 13 | 79 | 208 | 282 | 227 | 122 | 48 | 15 | 5 | 1000 |
| >14 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| 13-14 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| 12-13 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| 11-12 | - | - | - | - | - | - | - | 1 | 1 | - | - | 2 |
| 10-11 | - | - | - | - | - | - | 1 | 1 | 1 | 1 | - | 4 |
| 9-10 | - | - | - | - | - | 1 | 2 | 2 | 2 | 1 | - | 8 |
| 8-9 | - | - | - | - | - | 2 | 4 | 4 | 3 | 1 | 1 | 15 |
| 7-8 | - | - | - | - | 1 | 4 | 8 | 8 | 5 | 2 | 1 | 28 |
| 6-7 | - | - | - | - | 3 | 10 | 16 | 13 | 7 | 2 | 1 | 53 |
| 5-6 | - | - | - | 1 | 8 | 23 | 30 | 21 | 9 | 3 | [illegible] | 94 |
| 4-5 | - | - | - | 3 | 19 | 45 | 47 | 27 | 10 | 3 | 1 | 153 |
| 3-4 | - | - | - | 8 | 41 | 72 | 58 | 26 | 8 | 2 | - | 216 |
| 2-3 | - | - | 2 | 20 | 68 | 81 | 46 | 15 | 3 | 1 | - | 236 |
| 1-2 | - | - | 5 | 35 | 60 | 41 | 14 | 3 | 1 | - | - | 159 |
| 0-1 | - | 1 | 6 | 12 | 8 | 2 | - | - | - | - | - | 29 |




| | |
|---|---|
| 1 | Stress component transfer functions with phase lags |
| 2 | Combined stress transfer function for different headings $T_{\sigma}(\omega,\beta)$ |
| 3 | Family of short-term irregular sea spectra $S_W(\omega,H_S,T_Z)$ |
| 4 | Combined short-term irregular stress response for different headings $\sigma_S/H_S = f(T_Z,\beta)$ |
| 5 | Long-term sea statistics $p(H_S,T_Z)$ |
| 6 | Long-term stress distribution $Q_{LT}(\sigma)$ |

**Figure 1** Principal steps in the calculation of a long-term stress distribution. The example shows stresses in a bottom side girder for one specific load condition and speed

## SUMMARY OF RESULTS

The main advantage of a direct analysis is that the results reflect the specific ship characteristics and conditions. Because of this one should, however, be careful in drawing extensive general quantitative conclusions from a specific direct analysis. This summary of the results presented in Part 1, Part 2, and Part 3, is therefore concentrated on discussion of typical patterns and relative importance of different stress components and their correlations, rather then on the derived stress levels.

Two entirely different ship structures have been analysed. In Part 1 is analysed the midships hold of a lo/lo containership with a double shell structure. The side stringers, bottom girders, webs, and floors have approximately the same stiffness, and there is a strong coupling between transverse and longitudinal strength members of this structure. The second ship that has been analysed is an OBO carrier with single side shell and double bottom. Between hopper tank and top wing tank the side shell is stiffened by vertical frames only, while the double bottom is solely longitudinally stiffened by closely spaced full height girders. In Part 2 is examined the nominal stress responses in the side frames and in one bottom side girder in four holds forward of amidships. In Part 3 is further analysed in detail the local long-term stress distribution in the bottom side girder in the hold where the hull girder bending moments show their maximum values. Both ships have a length of about 200 m and a "Panamax" breadth of 32,2 m.

Transfer functions for stress response in regular waves are in Part 1 and Part 2 presented for wave frequencies up to 2,6 rad/s which corresponds to a wave length of about 9 m. For such short waves in comparison with the ship dimensions, neither the strip-theory nor the longitudinal division of pressure unit loads is good enough for determining realistic stress response. However, the dominating wave energy of ocean seas is found in the frequency range 0,25 - 1,50 rad/s corresponding to wave lengths between 30 m and 1000 m, and it is therefore in this range the transfer functions should be validated. But even though the transfer functions reflects the physical deterministic load effects, for design purposes it is of more interest to study the response in irregular seas in terms of significant stresses.

Longcrested irregular seas have been chosen in the evaluation of significant responses since they more clearly show the influence of wave heading. Shortcrested seas are usually modelled with a spreading function $f(\mu)$ independent of the frequency, and the response in shortcrested seas can be derived directly by weighing the responses in longcrested seas for different relative headings.

In order to illustrate the coupling effect of different stress components in irregular seas, a statistical correlation coefficient is defined from the significant values of two components and of their combined effect

$$\rho_{AB} = ((\sigma_A + \sigma_B)_s^2 - \sigma_{As}^2 - \sigma_{Bs}^2)/(2\,\sigma_{As}\,\sigma_{Bs}) \quad (2)$$

where
$\sigma_{As}$, $\sigma_{Bs}$, $(\sigma_A + \sigma_B)_s$, are statistical significant values of stress components and combined stress

This correlation coefficient is used both for the correlation between stresses induced by different wave load components and for the correlation between nominal normal and shear stresses which can be of importance for the local hot-spot stresses as shown in Part 3.

***Linear stress components in longitudinal members***

In continuous longitudinal members of the deck and bottom structure, stresses induced by hull girder vertical bending dominate amidships. The largest response in regular waves occurs in head waves with length 1,0 - 1,2 times the ship length, corresponding to wave frequencies 0,50 - 0,55 rad/s (see e.g. Part 1 p.A1.106 and Part 2 p.A1.4). In irregular head seas the largest significant response will occur for mean periods 8 - 10 s (see e.g Part 1 p.A2.51 and Part 2 p.A2.14). The horizontal hull girder bending stresses have maxima in bow or quartering seas with a mean period of about 7 s (e.g. Part 1 p.A2.50 , Part 2 p.A2.17). The longitudinal distribution of vertical bending moment show a maximum about 0,1L forward of amidships. The maximum of horizontal bending moment is about 0,05L forward of amidships (Part 2 fig.5.3).

The correlation between short-term horizontal and vertical bending moments is found to be strong. This has also been verified by several other studies e.g. [20]. The correlation is not very sensitive to the mean period of the sea state (Part 2. pp.A2.11-A2.13). In quartering seas the correlation increases forward along the ship, while in beam and bow seas the correlation is in practical terms constant along the ship (Part 2 fig.5.5a). The absolute value of the correlation coefficient is about 0,6 amidships for all directions, with positive values when the waves are coming in on the same side as the stress position and when the stress position is below the neutral axis of the hull girder.

The statistical correlation between long-term extreme stresses from horizontal and vertical bending moment is calculated for two different load conditions in Part 2 under the assumption of equal probability for all headings. The long-term correlation is shown to be significantly less than the short-term correlation (Part 2 figs.5.16,5.20). The reason for this is that in head and following seas, the vertical bending moment will be large while the horizontal bending moment will be low - in longcrested seas theoretically zero. Hence, in the long-term run the relative importance of the horizontal bending moment will decrease. The correlation will, however, also be affected by the relative maximum values of the two components. For the bulk cargo condition shown in Part 2 fig.5.20, the wave induced vertical bending moment is less than for the oil cargo condition and the long-term combined stress distribution will be relatively more influenced by the bow sea headings where the correlation is strong. In consequence the long-term correlation between extreme values is increased compared to the oil condition. This is a typical example on the advantage of a direct analysis, and on the difficulty to draw general conclusions from specific studies.

Stress response from hull girder torsional moment has been included in the analysis of the open container ship. The warping stress component is important only in the hatch side coaming where it is the second largest component after the vertical bending moment for quartering and beam seas (Part 1 pp.A2.52-A2.54). The torsional response is, however, strongly affected by the resonance peak in quartering regular waves with frequency 1,25 rad/s which gives an encounter frequency exactly equal to the ships natural frequency of roll (Part 1 figs.4.3c,4.4c, and e.g. pp.A1.96,A1.101). At this frequency the response amplitudes are very uncertain and the derived irregular stress responses for short mean periods from torsion and local pressure are believed to be conservative (cf. Part 1 figs.2.19,2.20 from [16]).

Shear stresses from hull girder shear forces are insignificant in all the studied longitudinal girders (cf. transfer functions for shear stress components Part 1 pp.A1.3-A1.53)

Local pressure and mass force fluctuations contribute significantly to the normal stress response in the bottom girders of both ships and in the side stringer of the containership. The shear stress response is entirely determined by the local loads. The distributions of stress response amplitudes due to local loads follows approximately the distribution that would have been achieved with a static constant distributed load (Part 1 figs.4.11-4.12, Part 2 figs.5.4,5.6), with the largest values at the connection to transverse bulkheads. The significant pressure stress component per significant wave height decreases in irregular seas with increasing mean period for all directions except for beam seas. In beam seas coming in on the same side as the stress position, the pressure component reaches its maximum and dominates the combined normal stress in the side stringer (Part 1 pp.A1.14,A2.8) and in the bottom side girder (Part 2 p.A2.8). In the latter, the combined normal stress level in beam seas is however only about one third of combined stress in head seas. Due to increased relative motions, the local pressure stress component increases forward in the ship in head and bow seas (Part 2 fig.5.4).

The external pressure induced stress component can be compared with a stress induced by an equivalent hydrostatic pressure addition. For the bottom side girder of the OBO carrier, 1 m hydrostatic pressure corresponds to 4,4 MPa normal stress at position A close to the bulkhead and -3,2 MPa at position C in the centre of the hold. The separate most probable extreme long-term stress range from dynamic pressure at position A is calculated to 92 MPa for the oil condition and 102 MPa for the bulk condition (Part 2 figs.5.16,5.19). This equals the static stress response from a hydrostatic depth variation of ±10,4 m and ±11,6 m respectively. However, as discussed below, the combined stress will not at all be that much affected.

The stress component due to local mass inertia forces is found to be of the same magnitude as the pressure component in the bottom girders, but generally less in members of the side structure. For solid cargo (containers in Part 1), the mass forces are directly determined by the accelerations in the direction normal to the panel considered, while mass forces from liquid cargo includes coupling terms from accelerations in all directions. For the bottom side girder, the vertical acceleration component naturally dominates but with liquid cargo the transverse acceleration component contributes significantly to the combined mass force stress in beam seas (Part 2 fig.3.5).

A very strong correlation is found between pressure induced and mass force induced stresses and this is of significant importance for the combined stress response. With an equal distribution of cargo over the holds, the two components counteract each other and the combined stress is generally less than the largest of the components. This phenomenon is important especially for the shear stress response (e.g. Part 1 p.A2.9, Part 2 figs.5.4-5.6 pp.A2.2-A2.9), and appears also in the long-term distribution (Part 2 figs.5.16-5.17). For an ore load condition with empty holds surrounded by full cargo holds, the two normal stress components counteract each other in the bottom girder at the transverse bulkheads, but add to each other fully in the middle of an empty hold (Part 2 fig.5.19-5.20). The strong correlation between internal and external local loads is also reported in [7] and [8].

The total normal stress response in longitudinal members is achieved by combining the global hull girder bending stresses with stresses from local loads with account for their phase lags. The statistical correlation between global and local components in irregular seas is, except for beam seas, generally found to increase with increasing mean wave periods (Part 2 pp.A2.10-A2.17). The degree of correlation varies with the wave heading, but for a condition with evenly distributed cargo the correlation coefficient for local/global stress components in bottom girders at bottom shell is in general positive at mid-hold and negative at the bulkheads (Part 2 fig.5.5). The relative importance of the local components is largest in following or quartering seas but there is a significant contribution from local loads also in head seas (Part 2 fig.5.2). This is also reflected in the long-term stress distribution (Part 2 figs.5.16,5.19). The derived combined distribution of extreme normal stress along the bottom girder shows the same general pattern as has previously been found in [8], (Part 1 fig.2.25). This pattern is found for all three load conditions - oil, ore, and ballast - studied in Part 3 (Part 3 fig.3.8), even though the values of the correlation coefficient depends on the load condition.

***Linear stress components in transverse members***

Dynamic stresses in transverse members are determined only by local loads. The pressure component is found to be significantly larger than the mass force component. This is valid both at bottom and side in the containership web (Part 1 pp.A1.54-A1.93,A2.28-A2.48) and at different positions in the side frames of the OBO carrier (Part 2 A1.6-A1.9,A2.18-A2.29). The largest combined stresses in the side structure occurs for beam or bow seas heading towards the stress position side (e.g. Part 1 pp.A2.33-A2.34,A2.41-A2.42 and Part 2 figs.5.9-5.11). There is, as could be expected, a full correlation between combined shear and normal bending stresses in the side web of the containership. In the bottom floor at centre line, however, shear and normal stresses are in practical terms statistically uncorrelated (Part1 pp.A2.45-A2.47). The correlation between mass force and pressure components is found to be very strong for the side structure in both short-term, (Part 2. fig.5.12), and long-term, (Part 2. fig.5.22), distributions. For the highest stressed positions in the side frame, internal mass forces will to a large extent reduce the effect of external pressure fluctuation (Part 2 fig.5.21).

***Non-linear stress response***

The effect of fluctuating water level at side is the only non-linear effect studied in this work. Although this effect is usually not important for the responses of the ship as a whole, it is found to be important for the local structural response. From time simulations in regular waves with different amplitudes, equivalent transfer functions have been evaluated. These indicate that combined stresses in the side structure is significantly affected by the non-linearities while the bottom structure is unaffected. The largest influence is naturally found for the headings when the pressure component is largest (e.g. Part 1 pp.A1.12-A1.15 and Part 2 pp.A1.8-A1.9). The position of the still-water level and the side structural arrangement will govern if the non-linear effect will cause higher or lower stress levels than those obtained from a linear approach. In the double shell side structure of the containership, hydrodynamic pressure above the still-water line will have a larger influence on the bending stresses in side girder and side web, than pressures below the still-water line, and hence the non-linear stress response is generally higher than the linear response for these members (e.g. Part 1 pp.A1.12,A1.64). The OBO carrier has a full load still-water line close to the bottom of the stiff top wing tank (Part 2 fig.2.2), and consequently the dynamic pressure above the still-water line will affect the bending stresses in the side frames very little. The non-linear pressure induced stress response is therefore significantly less then the linear response. In most cases this is also true for the combined stress (e.g. Part 2 pp.A1.8-A1.9). However, in certain conditions when the mass force component is large and acts against the pressure, the combined stress may increase when the pressure component is reduced (Part 2 fig.5.25-5.26).

***Influence of voluntary speed reduction and course change in heavy weather***

The influence of speed reduction in an extreme short-term sea condition is examined in section 5.3.2 of Part 2. In head and bow seas, which are the most probable ones in this severe sea states, the extreme stress response is reduced about 20% in the bottom side girder and 40-50% in the side frames when speed is reduced from (unrealistic) service speed to zero speed (Part 2 figs.5.23-5.24). The influence of speed reduction on the long-term stress distribution has also been examined with the simple assumption that the speed is reduced to zero when the significant wave height is above a certain value independent of the wave heading (Part 2 figs.6.14-6.15). The results indicate that speed reduction should be accounted for in a direct design procedure, especially in the prediction of extreme stresses. The influence of speed reduction on fatigue is found less important.

The influence of voluntary course changes is not believed to be critical. The upper tail of the long-term stress distribution for an assumed equal probability of wave headings is already determined by the headings where the short-term responses are largest - usually head or bow seas. Hence, the long-term extreme stress is not much affected by wether these headings occur with a probability of 0,25 or say 0,9. Even if we assume that all severe sea states are met by the head or bow, the characteristic extreme stresses at the probability level $10^{-8}$ will increase about 7% as a maximum.

***Fatigue analysis***

The most important advantage of a direct analysis of wave induced stresses is that the complete long-term dynamic stress distribution can be calculated. Both the slope and the curvature of this distribution is decisive for the fatigue strength. At the design stage a simplified analysis method based on linear cumulative damage and SN-curves for different classes of weld joints is most appropriate. When the long-term stress distribution at the local hot-spot is described by a Weibull-distribution, the cumulative damage ratio can be directly obtained from the parameters of the distribution and the relevant SN-curve.

The synthesis method based on influence coefficients that is developed and applied in this thesis can be used either for direct calculations of hot-spot stress distributions or for calculation of nominal stress distributions to which geometric stress concentrations are applied. In both cases the local hot-spot stresses must be uniaxial, otherwise the principle of linear superposition will not be valid. In Part 2 and Part 3 examples are given on how direct fatigue analysis can be included in the method. Part 2 presents results from fatigue analysis based on nominal normal stresses in the bottom side girder at bottom shell along the ship, and in the side frames at three different positions representing different joint classes. In Part 3 the bottom side girder "as built" is further analysed in detail with respect to the combined effect of local shear stresses and normal stresses.

The results indicate that the studied ship structures would not fulfil the strict offshore codes based on design SN-curves corresponding to a 97,7% probability of survival. The most critical positions for fatigue damage in the side frames are found at the connection of a tripping bracket to the flange at about midpoint between hopper tank and top wing tank. With rough estimates of influence of speed reduction and non-linearity, the theoretical design fatigue life for a full oil load condition in North Atlantic is found to be 15 - 45 years for holds midships, and 10 - 30 years for the forward hold, dependent on the quality of the actual weld joint. If one hold would be constantly empty and internal mass force induced stresses omitted, the design fatigue life would be further reduced by 50% (Part 2 pp.50-54).

In the detailed analysis of the bottom side girder, local geometric stress concentrations are calculated with a separate fine-mesh finite-element model. The fatigue life is calculated for six different positions around a man-hole, corresponding to the positions where the highest stress concentration occurs for nominal shear and normal stresses in the girder. Due to the correlation between combined shear and normal stress, the fatigue damage ratio is found to be about constant along the girder, in spite of the significant variation of the nominal stress components (cf. Part 3 figs.3.8-3.9, fig.3.16). The most critical position around the hole was found to be where the stress concentration for shear is highest, at the lower side of the hole nearest to the bulkhead. The design fatigue life in North Atlantic service is at this position calculated to be 6 - 8 years dependent on the load condition. The difference in fatigue damage ratios obtained for full load oil, ore, and ballast conditions is generally found to be small, the oil condition giving the highest normal stress level and the ballast condition the highest shear stress level. The bottom fillet weld adjacent to a rat-hole, which corresponds to a class F joint with geometric stress concentrations accounted for in the SN-data, is estimated to have a minimum design fatigue life of 10 - 12 years solely based on the normal stress distribution.

The cumulative fatigue damage ratios presented in Part 2 and Part 3 are calculated in a simplified way without considering the proposed fatigue limit $S_0$ at $N = 2 \cdot 10^8$ for steel with cathodic protection. However, for large damage ratios the fatigue limit will have little influence on the fatigue life (Part 2 fig.6.3). It must , however, be emphasized that the calculated fatigue lifetimes are pure theoretical estimates. In practice corrosion and maintenance can change these results significantly.

## SOME NOTES ON LONG-TERM STRESS DISTRIBUTIONS

The long-term probability of exceeding a certain stress level is in Part 2 and Part 3, calculated for a specific load condition and speed, by summation of short-term probabilities of exceedance in all possible combinations of sea states and heading angles.

$$Q_{LT}(\sigma) = \sum_i \sum_j \sum_k p_s(H_{si}, T_{zj})\, p_h(\beta_k)\, (1 - F_{STijk}(\sigma)) \qquad (3)$$

where

$Q_{LT}$ = long–term probability of exceedance

$p_s(H_{si}, T_{zj})$ = long–term joint probability of significant wave heights and mean zero–crossing wave periods

$p_h(\beta_k)$ = relative probability of heading angle $\beta_k$

$F_{STijk}(\sigma)$ = short–term cumulative probability distribution of stress peaks (Rayleigh distribution)

$= 1 - e^{-(\sigma^2 / 2m_{0ijk})}$

$m_n$ = n:th moment of the stress response encounter spectrum

$= \int_0^{\infty} \omega_e^n S_\sigma(\omega_e)\, d\omega_e$

$\omega_e$ = wave frequency of encounter

This probability is independent of the mean periods of stress fluctuation in the different short-term sea states. It can be understood as the average long-term probability that one specific cycle will exceed the level. However, for design purposes the relevant long-term distribution should be based on time instead of cycles, and hence the different mean frequencies of responses in the different short-term sea states should be taken into account. Furthermore, a relevant design criteria should be based on time and not on "probability level" as usually done in the codes, and therefore also the long-term mean frequency of the response should be taken into account.

$$Q_{LT}(\sigma) = \frac{\sum_i \sum_j \sum_k \left( \frac{1}{T_{z\sigma ijk}} \right) p_{sij}\, p_{hk}\, (1 - F_{STijk})}{\sum_i \sum_j \sum_k \left( \frac{1}{T_{z\sigma ijk}} \right) p_{sij}\, p_{hk}} \tag{4}$$

where

$T_{z\sigma}$ = short–term mean zero–crossing period of stress response

= $2\pi \sqrt{m_0 / m_2}$, with $m_n$ defined above

In table 1 below is compared the long-term distributions of combined stress in the bottom girder and the side frame of the OBO-carrier (Part 2 figs.2.2,2.3 positions C and M in hold 4) obtained from equation (3) and equation (4) respectively. The examples indicate that the influence of short-term stress periods on the long-term distribution is insignificant. It is therefore sufficient to use the simplified equation (3), although it is not much more complicated to use the theoretically more relevant equation (4). Table 1 also shows the influence of long-term mean stress period. The North Atlantic Area 16 wave statistics used in the examples (Part 2 fig.5.14) has a long-term mean wave period of 8,4 s. If we choose $10^8$ waves cycles as a life-time design value, it thus equals a mean service time of 26,6 years in the North Atlantic. The most probable single largest stress range during this time is the one coupled to the long-term probability *1/N*, where *N* is the number of stress cycles. This value is in table 1 compared with the usual extreme stress value at "probability level" $10^{-8}$.

| Table 1<br>Influence of response period on the long-term distribution | North Atlantic Area 16 | | | |
|---|---|---|---|---|
| | Bottom side girder Combined stress | | Side frame Combined Stress | |
| Equation for long-term calculation | eq.(3) | eq.(4) | eq.(3) | eq.(4) |
| Stress range at probability level $Q_{LT} = 10^{-4}$ [MPa] | 122,8 | 122,1 | 103,7 | 104,8 |
| Stress range at probability level $Q_{LT} = 10^{-8}$ [MPa] | 235,2 | 236,1 | 205,1 | 205,5 |
| Mean long-term stress period | 8,9 s | | 5,3 s | |
| No of stress responses in $10^8$ wave cycles | $10^{7,97}$ | | $10^{8,20}$ | |
| Most probable largest stress range in $10^8$ wave cycles [MPa] | 234,4 | 235,4 | 209,0 | 209,4 |

The Rayleigh probability distribution used for short-term peak responses is valid for narrow-banded spectra. The bandwidth of a spectrum can be described by a bandwidth parameter $\varepsilon$ defined from the moments of the spectrum according to

$$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0\, m_4}} \tag{5}$$

If the response spectra are wide-banded (say bandwidth parameter $\varepsilon > 0,6$) a more general probability distribution function for the peak values should be applied, [21]. This general distribution of response maxima tends from the Rayleigh distribution for narrow-banded spectra to the Gaussian distribution when $\varepsilon \rightarrow 1$. As shown in [22], the extreme peak values expressed in terms of time will still be independent of the bandwidth even for broad-banded spectra with a bandwidth parameter $\varepsilon < 0,9$. This is explained by the fact that while the probability for larger peaks is reduced for a wide band spectrum, the number of peaks increases. For fatigue estimates, however, a wide-banded stress spectrum is difficult to analyse since the peak distribution is not valid for the crest-to-trough time sequence which governs the fatigue damage. A broad-banded spectrum will have several crests below the mean value and several troughs above the mean value and the number of peaks will be significantly larger than the number of zero-crossings. The problem of fatigue under wide band random stresses has been highlighted in connection with design of offshore structures. Often used is the rainflow method applied on time simulations of the stress response. Wirsching has shown [23], [24], that sufficient results can be obtained with an equivalent narrow-band method together with an explicit correction factor on the cumulative damage. For SN-curves with slope $m$=3 the correction factor for broad-banded spectra, $0,6 < \varepsilon < 0,95$ was found to be approximately 0,85 compared with results obtained with the rainflow method.

The actual bandwidth of a response spectrum is determined by the transfer function and the wave spectrum. The combined dynamic stress in a ship structural member is the consequence of different wave loads with response peaks at different frequencies. The combined transfer function can therefore be rather wide in the frequency range. Typical values of $\varepsilon$ and of mean zero-crossing response period $T_{z\sigma}$ is shown below in table 2 and table 3. Stress response spectra are here evaluated for longcrested short-term seas defined by the 2-parameter Pierson-Moskowitz wave spectra used in this study. The bandwidth is shown to be relatively small for global stresses and for local stresses primarily induced by the ship motions. But for pressure induced stresses at side and for combined stresses in head seas, the spectra become rather wide. This can be explained by the transfer functions (Part 2 pp.A1.2-A1.9). Especially for pressure induced stresses at side the transfer functions show large responses to high-frequency (short) waves. At these frequencies the strip-method is not reliable as discussed earlier, and the actual bandwidth will probable be less then the calculated. The significant stress response amplitude is less affected by the high frequency part of the transfer function and the presented results of long-term stress distributions and fatigue damages is believed to be reasonable accurate, although on the conservative side.

| **Table 2**<br>Bandwidth parameter $\varepsilon$ for different short-term stress component spectra | 200 m OBO Carrier, 15 kn<br>PM 2-parameter spectra, $T_Z$=9s, longcrested sea | | | | |
|---|---|---|---|---|---|
| | following sea (0°) | quartering sea (-45°) | beam sea (-90°) | bow sea (-135°) | head sea (180°) |
| Bottom side girder, pos.C | | | | | |
| Vertical Bending | 0,09 | 0,15 | 0,32 | 0,40 | 0,52 |
| Horizontal Bending | - | 0,12 | 0,55 | 0,64 | - |
| Pressure | 0,17 | 0,11 | 0,37 | 0,77 | 0,61 |
| Mass Force | 0,13 | 0,20 | 0,39 | 0,28 | 0,24 |
| Global Combined | 0,09 | 0,14 | 0,45 | 0,50 | 0,52 |
| Local Combined | 0,17 | 0,14 | 0,56 | 0,57 | 0,55 |
| Total Combined | 0,09 | 0,14 | 0,43 | 0,66 | 0,80 |
| Side frame, pos.M | | | | | |
| Pressure | 0,80 | 0,13 | 0,56 | 0,94 | 0,93 |
| Mass Force | 0,13 | 0,15 | 0,48 | 0,53 | 0,24 |
| Local Combined | 0,80 | 0,14 | 0,54 | 0,93 | 0,91 |

| **Table 3**<br>Mean short-term response periods for different stress components, $T_{z\sigma}$ [s] | 200 m OBO Carrier, 15 kn<br>PM 2-parameter spectra, $T_Z$=9s, longcrested sea | | | | |
|---|---|---|---|---|---|
| | following sea (0°) | quartering sea (-45°) | beam sea (-90°) | bow sea (-135°) | head sea (180°) |
| Bottom side girder, pos.C | | | | | |
| Vertical Bending | 20,4 | 15,7 | 8,6 | 8,4 | 8,4 |
| Horizontal Bending | - | 14,9 | 6,0 | 6,5 | - |
| Pressure | 20,7 | 14,7 | 11,4 | 4,5 | 3,4 |
| Mass Force | 21,5 | 16,1 | 10,7 | 9,3 | 9,3 |
| Global Combined | 20,4 | 15,4 | 8,0 | 8,0 | 8,4 |
| Local Combined | 20,8 | 15,0 | 7,8 | 3,6 | 3,2 |
| Total Combined | 20,4 | 15,4 | 7,8 | 7,8 | 7,4 |
| Side frame, pos.M | | | | | |
| Pressure | 20,3 | 14,6 | 8,9 | 5,7 | 2,7 |
| Mass Force | 21,6 | 15,7 | 11,0 | 9,8 | 9,3 |
| Local Combined | 20,3 | 14,9 | 7,9 | 5,2 | 2,5 |

For design purposes, it is of interest to use a maximum stress level coupled to a specific confidence of not being exceeded, rather than to use the most probable largest stress level. If the long-term probability of stresses is described by a Weibull distribution

$$Q_{LT}(\sigma) = e^{-(\sigma/B)^h} \tag{6}$$

where

B and h are general parameters of the distribution calculated with regression analysis to fit the values obtained from equation (3) or (4)

then the cumulative probability distribution of the extreme value among $N$ will be

$$F_{LTextr}(\sigma) = (1 - Q_{LT}(\sigma))^N = 1 - \alpha \tag{7}$$

where

$\alpha$ = risk (probability of exceeding $\sigma$ among N cycles )

$1 - \alpha$ = confidence (probability of not exceeding $\sigma$)

From (6) and (7) the design extreme level with confidence 1-$\alpha$ is obtained

$$\sigma_{LT\alpha} = B\left[\ln\left(\frac{1}{1-(1-\alpha)^{1/N}}\right)\right]^{1/h} \tag{8}$$

It should be noticed that the long-term extreme value distribution is rather wide. With $h$ = 1 and $N = 10^8$, the largest value that has the confidence 99% of not being exceeded, is 25% larger than the most probable maximum value.

# APPLICATION IN AN ORDINARY DESIGN PROCESS

The direct method for calculation of wave induced stresses can be used in the design process either as a part of a total reliability analysis or as a separate semi-probabilistic method. In a total reliability analysis the criteria will be formulated in terms of acceptable risk levels, based on a description of the statistical distributions of loads and strength. This is different from a semi-probabilistic approach where the criteria may be described in terms of maximum stress levels or cumulative fatigue damage ratios where the acceptable levels include safety factors with respect to the statistical distribution of the strength. The load and the strength are here separated instead of being analysed together.

The author believes that the semi-probabilistic approach is the most realistic one in the near future for ordinary design purposes. A proper modelling of the strength reliability is extremely complicated if it shall be based on actual as-built structure and include different modes of failure. In many cases it must be determined from extensive test series.

The most important criteria that should be applied on the ship's structural strength is the ultimate strength, connected to the extreme loads or stress levels, and the high-cycle fatigue strength, connected to stress levels fluctuating with $N > 10^4$ cycles during the ship's service life. The ultimate strength can today with advanced computer systems for structural analysis, including post-buckling and plasticity, be rather accurately calculated for both the hull girder and for primary and secondary members. The main uncertainty here is associated with the extreme loads. Even if we knew the exact conditions and sequence of sea states that a certain ship will encounter in service, the statistical distribution of the extreme values would be rather wide. To this should be added the uncertainties associated with extreme wave statistics, response analysis for extreme waves, and the handling of the ship. Under extreme low cycle loads, the local stresses in structural details will reach the yield stress and there will be a redistribution of local mean stresseses. However, the redundancy in a ship structure is large, and the overall strength of hull girder and primary members will generally not be much affected by local yielding. Stress criteria for ultimate strength can therefore be formulated in terms of nominal stresses disregarding local stress concentrations.

For the fatigue strength, the situation is rather different as regards uncertainties and stress criteria. The high-cycle part of the long-term stress distribution is believed to be better predicted than the low-cycle part since the long-term sea statistics for moderate sea states is comprehensive and the stress responses is less affected by non-linear effects and operational decisions. The fatigue strength, as presented in standard SN-curves based on a large number of laboratory fatigue tests [25], is however very scattered. The standard deviation of $\log N$, where $N$ is number of cycles to failure, is 0,18 - 0,25 for typical joints in ships. A design fatigue life based on SN design curves with 2,3% probability of failure will hence be only 30% - 40% of the mean fatigue life. In further contrast to ultimate strength, stress criteria for fatigue must be based on local hot-spot stresses as long as the fatigue strength is established from tests of weld joint specimens and not from actual ship structural members. Due to the high tensile residual stresses at welds the dynamic stress range is in the codes assumed to pulsate downwards from yield stress in tension and no account is taken of the stress ratio. This assumption is usually conservative for a structure subjected to compression load, since the first heavy weather journey will have a "shake-down" effect on local residual stresses.

A semi-probabilistic direct design procedure based on the present method is outlined in figure 2. The shaded part of the design process chart is today incorporated in the interactive computer program WAIST (WAve Induced STresses) developed within this study. It includes all linear response calculations and an approximate non-linear simulation of pressure induced stresses close to the still-water line. It can easily be expanded to include also still-water combined stresses based on the same influence coefficients as used for combined dynamic stresses. The program system is fast and easy to use and can be directly applied in an ordinary design process for specific studies, and in parallel with traditional methods and the classification rules.

For the determination of fatigue strength at the design stage, the direct method is believed to be sufficiently accurate - but of course all the different levels within the system can be refined. The major obstacle is now the lack of explicit fatigue criteria for ships. The best way to verify direct calculations is to perform hindcast calculations on discovered damage. By such calculations and by comparisons with nominal stress criteria in the rules, it should be possible to formulate fatigue strength criteria that will result in a level of structural reliability that is found appropriate for existing ships.

Regarding the extreme stresses, an important future task will be to further develop time simulation procedures for non-linear responses in irregular seas. Preferable these should include non-linear motions, non-linear local pressure distributions, and non-linear vertical bending moments including whipping in extreme sea states. Although there are today methods available for calculation of all these effects, it is yet far from realistic to incorporate them in an ordinary design process. If they are used for systematic parametric studies of the non-linear effects, the results might be summarized in the form of correction factors on the extreme linear stresses and on the upper tail of the linear long-term stress distribution. This possibility is indicated in Alt.3 of extreme stress determination in the chart. This alternative is by the author expected to be the most realistic one - even if it in principle is a deviation from the direct approach.

Another possible use of the direct method is to incorporate stress analysis in a hull surveillance system installed on board. By continuous measurements of the ships motions, the actual present wave spectrum can be determined, and from this the cumulative damage and the probability of exceeding certain specified stress levels can be calculated for a few typical hot-spots in the structure. The results could be used directly for operational decisions and collected to serve as guidance for inspections.

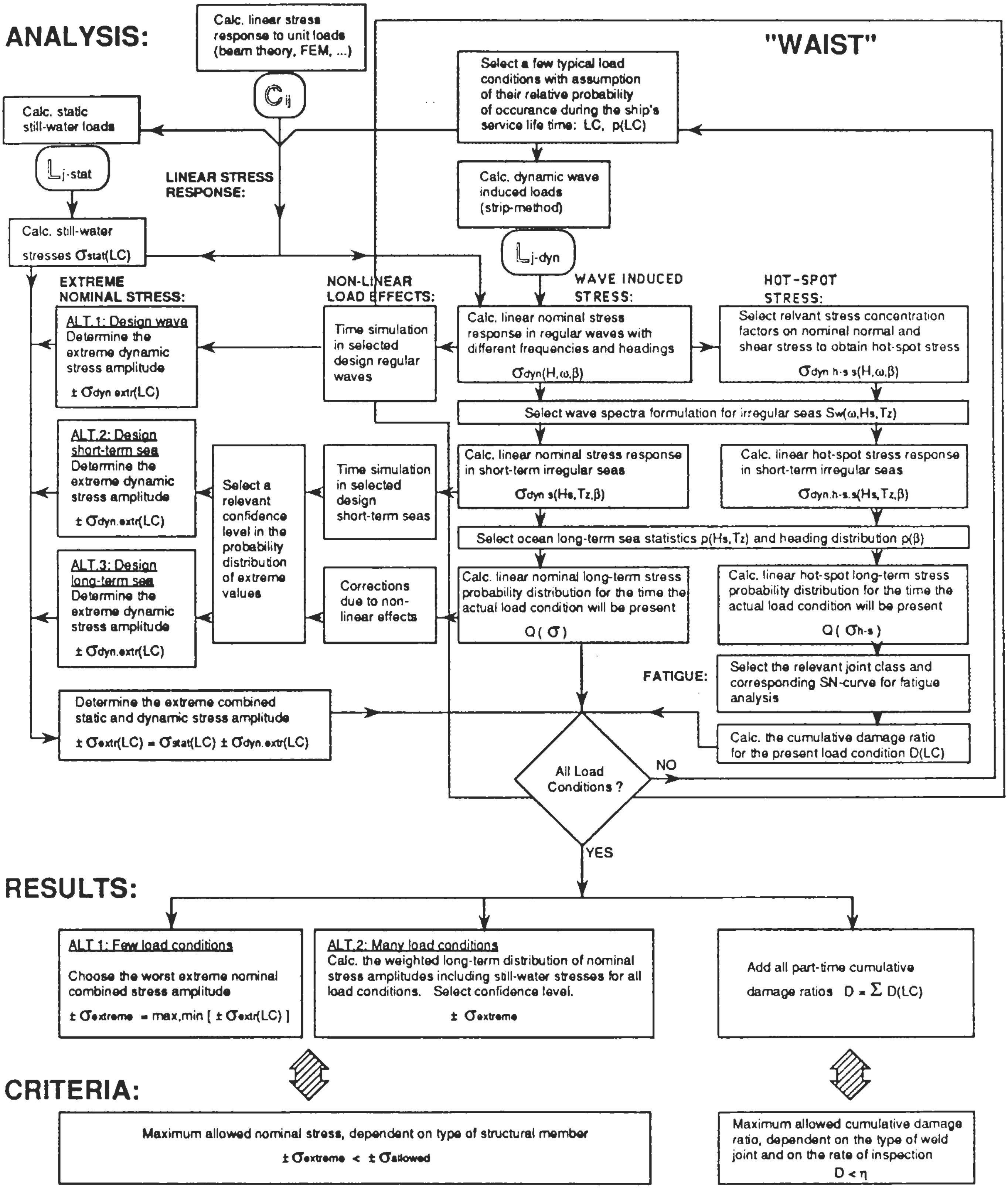



Figure 2 Flow-chart of a semi-probabilistic direct design procedure

## CONCLUSIONS

A direct calculation method for determining low-frequency combined wave induced stresses is found possible to use in the design process. The major advantages of the direct procedure compared with an ordinary "design load" procedure are:

The specific ship load conditions and sea-keeping performance is taken into account.

The relative importance of different dynamic load components and their statistical correlation in irregular short-term and long-term seas can be evaluated.

The complete long-term probability distribution of nominal and hot-spot stresses can be determined.

With a direct method it is possible to design in a rational way and to evaluate new types of ship structures for which lack of service experience is otherwise a design obstacle. Before a direct method can be generally utilized, results have to be verified by comparisons with experience from existing ships, and suitable design criteria have to be developed. For ultimate strength, further research work is also needed for tackling the problem of stress responses in extreme waves.

Some general conclusions can be drawn from the specific results obtained in this study:

For longitudinal primary structural members at amidships, the long-term normal stress distribution is primarily governed by the global hull girder loads. The long-term correlation between vertical and horizontal bending is small but might vary with the static load conditions. Local normal and shear stress components in longitudinal members are to a large extent correlated with the global components. The combined effect of global and local loads must be determined with respect to the stress position and the cargo distribution. The relative importance of local loads increases forward in the ship.

Normal and shear stresses in transverse members are solely governed by the local hydrodynamic pressure distribution and the internal inertia forces from cargo. The local components are firmly correlated and generally counteract each other in full cargo holds. The influence of non-linear pressure fluctuations close to the still-water line can be significant for stresses in the side structure.

The correlation between combined shear and normal stress must be considered in the fatigue analysis of local hot-spots.

The compound long-term stress distributions calculated with wave statistics for the North Atlantic, are found to be sufficiently represented by Weibull distributions.

Speed reduction might reduce the extreme stress levels in the long-term distribution considerably .

## ACKNOWLEDGEMENTS

This research project has been financially supported by the National Board for Technical Development (STU) and the Swedish Shipyard Association (SVF).

The synthesis computer program (WAIST) for direct calculations of wave induced stresses was developed at the Department of Naval Architecture, KTH, in two separate phases. The first phase took place in 1986 and led to a provisional version [26], that was used in a pilot study to verify the usefulness of the method (Part 1). In this work I got valuable assistance from my colleague Henrik Hannus. It was our early fruitful discussions that inspired me to carry on with this project. In the second phase 1989, I started from scratch and re-programmed an interactive version that was adapted to suit a direct design process. This second version has been used for the calculations reported in Part 2 and Part 3. The strip-theory calculation of hydrodynamic loads is in this version performed with a computer program developed by my colleague Jianbo Hua. I am very grateful for his assistance in adjusting this program for my purposes, and for all the time he has spent with me discussing wave induced loads. I also wish to thank my colleagues Anders Olander and Gustaf Lidvall who have contributed with several of the computer calculations included in this work.

I am sincerely obliged to my supervisor, Professor Erik Steneroth, for his longlasting and encouraging support of this project. His extraordinary experience from code development and from damage investigations has been invaluable to me.

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