BIRO KLASIFIKASI INDONESIA

ANALYSIS
TECHNIQUES STRENGTH

1. **GUIDELINES FOR STRENGTH ANALYSIS OF SHIP STRUCTURES WITH THE FINITE ELEMENT METHOD**
2. **GUIDELINES FOR FATIGUE STRENGTH ANALYSIS OF SHIP STRUCTURES**

EDITION 2005

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Analysis
Techniques Strength

1. Guidelines for Strength Analysis of Ship Structures with the Finite Element Method

EDITION 2005

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evaluation. Further instructions and information can be obtained from the more detailed specialist literature and from the descriptions of the software.

4. The type and extent of the analysis depends primarily on the kind of structural response to be assessed. In general, the following structural responses are foremost in strength analysis:

- Stresses and deformations for specified load conditions
- Failure behaviour and the magnitude of the ultimate load
- Eigenvalues for determining critical structural responses. The structural response is either assessed directly or in subsequent calculations, e.g. the latter for a statistical analysis of the extreme values to be expected under stochastic load.

5. The loads are generally regarded to comprise the external forces and pressures, forces resulting from the dead weight and accelerated masses as well as the tank contents. In special cases, further load components are investigated, e. g. the over pressure in gas tanks or temperature loads in the case of ships with hot or cold cargoes. For loads varying with time, the vibration behaviour of the structure must be taken into account in the form of dynamically increased loads or structural responses.

6. It should be noted that the structural response can depend on the loading magnitude in a linear or a nonlinear manner. If the structural response is determined under specified load conditions, a linear analysis is usually sufficient, especially in the case of thick-walled structures. Nonlinear effects can be of significance in the following cases:

- Generally for an analysis of the failure behaviour of the structure
- For relatively flexible structures with large deformations (geometric nonlinearity)
- When investigating the partial failure of structural members, e.g. buckling of plate panels
- If plastification of structural areas occurs (material nonlinearity)

7. In ship structures the deformations and stresses can usually be subdivided into the following categories, depending on the structural conditions:

- Global deformations and stresses of the hull girder and the primary structural components

- Local deformations and stresses of the primary and secondary structural components

- Locally increased stresses at structural details and discontinuities. The objective of the strength analysis and the kind of modeling, loading and evaluation can refer to one of these categories, which are described in more detail in C. – E.

B. Determining the Objective, Type and Extent of the Strength Analysis

1. The objective, type and extent of the strength analysis must be laid down clearly, since these aspects have a decisive effect on the modeling of the structure and the loading.

2. The objective of the analysis results from the alternatives described in A.4., whereby the category of the deformations and stresses to be considered in the analysis must be determined; see also A.7. and C. – E.

3. The type of analysis comprises either a linear or a material-related and/or geometric nonlinear analysis; see A.6.

4. The extent of analysis is mainly oriented towards the selected scope of the model and the necessary mesh fineness; see also Section 2, A. – C.

C. Global Deformations and Stresses

1. The structural response of the hull girder and the primary structural components under normal, shear, bending and torsional loads consists of global (i. e. large-area) deformations and stresses. In the case of beam-like structures, these follow the beam theory. Deviations from this are mainly to be expected for complex loads or structural geometries.

2. The primary structural components in this sense are the floors, bottom girders, side and deck transverses, stringers, longitudinal and transverse deck strips, deck girders and comparable components, each including the effective part of the plating and stiffeners.

3. The effective plate widths must be considered when calculating the global deformations and stresses. These must be expected, in particular, for bending combined with shear, at points of load introduction and re-directioning, as well as in asymmetrical or curved flanges and platings.

4. The resulting stresses are nominal stresses, i. e. stresses which would also result from integral quantities of the sectional forces and moments and of the cross-sectional properties. Global nominal stresses generally include the effective widths, but not locally increased stresses. These must be superimposed additionally, as is the case for the local nominal stresses in secondary structural members; see D. and E.

D. Local Deformations and Stresses

1. In secondary structural components, such as stiffeners and plates, the local loads can give rise to additional local deformations and stresses which follow the beam and plate theory.

2. The secondary structural members include all frames, stiffeners, beams and the plating with their bending, shear and torsional stiffnesses as well as the associated tripping and supporting brackets.

3. Effects of the effective width (see C.3.) must be taken into account. These must be expected particularly for bending with shear, at points of load introduction and re-directioning, as well as in asymmetrical or curved flanges and platings.

4. The resulting stresses are nominal stresses (see C.4.) which are superimposed to the global stresses. In addition, locally increased stresses can arise at structural details.

E. Locally Increased Stresses

1. At structural details and discontinuities, locally increased stresses which must be assessed especially in respect of fatigue strength can occur. Here a distinction is made between three types of stresses:

   - Maximum stress in the notch root; see 2.
   - Structural or hot spot stress, defined additionally for welded joints; see 3.

- Special parameters for assessing the stress at crack tips; see 4.

2. The maximum stress in the notch root, e. g. of the rounded edges of cut-outs, can already exceed the elastic limit of the material for realistic load assumptions in typical structural details of shipbuilding. Instead of the nonlinear notch stress σ and strain ϵ, the notch stress σ_k can be determined and assessed for normal cases under the assumption of linear elastic material behaviour. In the case of very sharp notches, the local supporting effect of the material can be considered with a correspondingly enlarged notch radius. Additional notes are given in the applicable literature.

3. In complex welded structures, only the stress increase as a result of the structural geometry is generally considered in the analysis, whilst that caused by the weld toe is considered during the assessment. This leads to the structural or hot spot stress σ_s at welds, and this is determined under the assumption of elastic material behaviour.

4. In the assessment of crack tips, special parameters are used, for example the stress intensity, the J-integral or crack tip opening. In calculating these parameters, special techniques are applied; these are described in the applicable literature.

5. Apart from a direct calculation of the locally increased stresses, it is possible to use catalogued stress concentration factors or detail categories. When using concentration factors and detail categories, the associated nominal stresses must be determined with sufficient accuracy in accordance with their definition. Moreover, the ranges of application and validity for the catalogued data must be observed.

6. Further notes on the definition and determination of locally increased stresses are given in the fatigue strength requirements of the " Rules for the Classification and Construction of Seagoing Steel Ships, Volume II Rules for Hull " as well as in " Analysis Techniques Strength and Stability, Guidelines for Fatigue Strength Analysis of Ship Structures ".

Section 2

Modeling the Structure

A. Extent of Modeling

1. Models of ship structures can generally be classified into the following types:

   a) Global models of the hull girder

   b) Partial models of the hull girder

   c) Grillage models

   d) Frame models

   e) Local models.

2. For the models b) – e), it must be ensured that meaningful boundary conditions are introduced, in order to represent the interaction with the neighbouring structural areas in a suitable way. If there is any risk that the results can be impaired by idealized boundary conditions, a correspondingly enlarged distance should be provided between the model boundary and the structural area under consideration.

3. A global model of the hull girder is normally used for the global strength analysis of the entire hull girder and its primary structural components. For 3D modeling of all the primary structural components, the loads can be applied very realistically, and the structural behaviour of complex ship structures, including the interactions between the individual components, can be taken into account (Fig. 2.1).

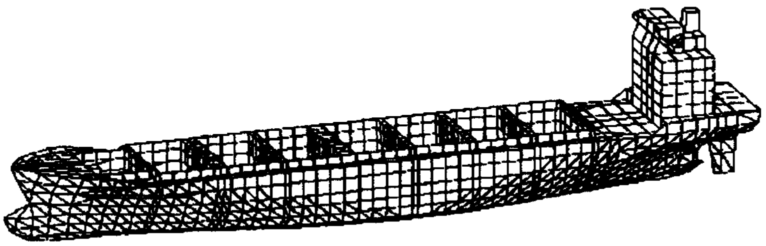


Fig. 2.1 Global model of the hull girder

4. Partial models of the hull girder are used for global strength analysis of parts of the hull girder and its primary structural components, for example a cargo hold area in the parallel part of the hull (Fig. 2.2). Like 3D global models, hold models are generally used to analyze the complex, three-dimensional strength behaviour of the primary structural components.

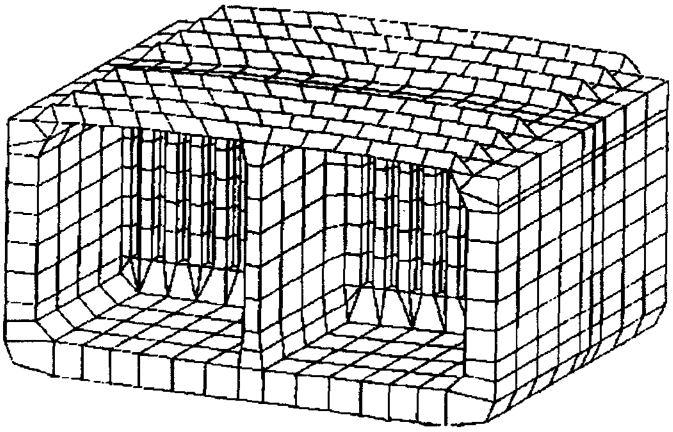


Fig. 2.2 Partial model of the hull girder

5. Grillage models are used for global and/or local strength analysis of plane structures with plates on one or both sides and reinforced by stiffeners and/or webs, e. g. double bottoms, bulkheads or decks (Fig. 2.3). The focus of the investigations is generally on the transfer of lateral loads to the boundaries of the grillage and on the associated deformations and stresses.

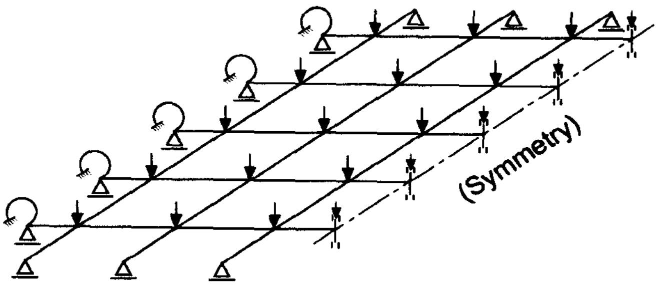


Fig. 2.3 Grillage model

6. Frame models are used for the strength analysis of beam-like structures, for instance of transverses in the hull girder (Fig. 2.4). The objective of the investigations is generally the analysis of the bending behaviour of the structure in the plane of the transverse webs.

7. Local models are used for the strength analysis of secondary or special components as well as structural details. The main focus of the investigations is usually on the analysis of the local structural behaviour and/or the locally increased stresses at structural details and discontinuities (Fig. 2.5).

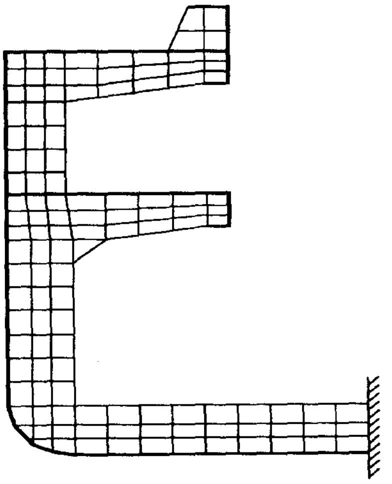


Fig. 2.4 Frame model

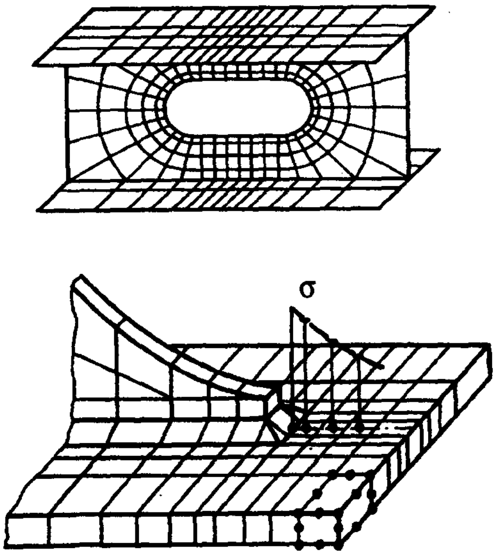


Fig. 2.5 Local models

B. Selecting the Elements

1. Selecting the type of element used primarily depends on the objective of the analysis. The characteristics of the selected element type must be able to reflect with sufficient accuracy the stiffness of the structure and the stresses to be analyzed. When carrying out a strength analysis, adequate knowledge of the characteristics of the elements used is a prerequisite; the program documentation and applicable literature should be consulted.

2. Usually, the following types of elements are used for strength calculations of ship structures:

   - Truss elements (1D elements with axial stiffness, but without bending stiffness)
   - Beam elements (1D elements with axial, shear, bending and torsional stiffness)
   - Plane stress elements (2D elements with membrane stiffness in the plane, but without bending stiffness about the axis lying in the plane)
   - Plate and shell elements (2D elements with membrane, bending and torsional stiffness)
   - Solid elements (3D elements)
   - Boundary and spring elements.

   When using different element types, attention should be paid to the compatibility of the displacement functions as well as the transferability of the boundary loads and stresses, particularly for the coupling of elements with and without bending stiffness at the nodes.

3. The selected element types must reflect the deformations and stresses for the load cases or the eigenvalues to be analyzed or reflect the failure behaviour when determining the magnitude of the ultimate load. In some cases, certain effects of secondary importance can be excluded by suitable selection of the elements. A number of notes on the element types commonly used in modeling ship structures are given below.

4. In general, it must be determined how and how far the bending of components must be considered in the strength analysis. In cases of pure bending behaviour in accordance with beam or plate theory - especially

for plate panels, stiffeners, grillages and web frames, as well as for the entire hull girder - beam and plate elements are suitable. When using plane stress or solid elements, a higher-order displacement function (e. g. with additional mid-side nodes) or a finer mesh may have to be chosen, if a corresponding bending behaviour of plane stress elements in their plane or of solid elements is to be permitted.

5. 3D models of the hull girder or of individual primary structural components are frequently produced with plane stress elements if only the global deformations and stresses are to be determined, cf. Section 1, A.7. Here the membrane stiffness of the modeled plane structures is taken into account. In addition, the relevant parts of the stiffness of secondary components must be considered in the model. In particular, the longitudinal stiffness of stiffeners must be accounted for with additional truss elements or anisotropic plane stress elements. It should be observed that in some cases the bending stiffness of stiffeners can also be relevant; this should then be considered through beam elements.

6. In local models, all stiffness components are generally of significance - even those of secondary components - so that here plate, shell or solid elements are suitable. An exception is presented by plane structures that are mainly loaded within their plane and which can thus be modeled with plane stress elements, e. g. in the analysis of local stress increases at the edges of cut-outs. Further information on selecting elements in the calculation of locally increased stresses is given in " Analysis Techniques Strength and Stability, Guidelines for Fatigue Strength Analysis of Ship Structures ".

7. With a view to evaluating the results, the arrangement of truss elements with a negligible cross-section can be useful to indicate the strain between two nodes, for example at free plate edges. Since here the stress is uniaxial, the edge stress can be determined in a simple manner for linear analysis.

C. Element Subdivision

1. The mesh fineness must be chosen by considering the element characteristics in such a way that the stiffness conditions of the structure, the types of stresses to be analyzed and possibly also the failure behaviour are modeled with sufficient accuracy. The selection of the element type and the mesh fineness exert a particularly great influence on the calculation of locally increased stresses and also of the ultimate load. Insufficiently fine mesh subdivision frequently leads to a considerable under estimation of the local stress peaks and over estimation of the ultimate load. A few notes on the mesh subdivision normally used in modeling ship structures are given in the following.

2. In subdividing the mesh, the structural geometry and the positions of load introductions or supports must be taken into consideration as far as possible.

3. 3D models of the entire hull girder or of parts must often be modeled very coarsely, by selecting the spacings of the primary structural components for the element dimensions. This is permissible for global strength analysis, provided that the bending behaviour of the primary structural components is reflected with sufficient accuracy by the element types that are used. Furthermore, it should be observed that for this modeling process the effects of reduced effective widths must be considered separately. The same applies for grillages and local strength analysis of stiffeners if the width of the elements in the plating corresponds to half or the whole stiffener spacing.

4. Whilst observing the element characteristics, the element proportions must be selected so that the stiffnesses and the resulting deformations and stresses are not falsified. For simple displacement functions, the ratio of the edge lengths of the element should be not greater than 3:1.

5. In calculating locally increased stresses, the mesh fineness must be increased gradually in accordance with the stress gradient. Further notes on mesh fineness in the calculation of locally increased stresses are given in " Analysis Techniques Strength and Stability, Guidelines for Fatigue Strength Analysis of Ship Structures ".

D. Simplifications

1. Owing to the complexity of the ship structure, simplifications are generally necessary in modeling, especially for global strength analysis. These simplifications are permissible, provided that the results are only impaired to a negligible extent.

2. A common simplification for global strength analysis concerns the combining of several secondary components (of stiffeners, for example) or, in some cases, even of primary structural components. The combined components should lie at the geometrical centre of the affected components, if possible, and should be modeled with an equivalent stiffness.

3. Small secondary components or details that only affect the stiffness to a lesser extent can be neglected in the modeling. Examples of this for global strength analysis are the brackets at frames, sniped short buckling stiffeners and small cut-outs.

4. Large cut-outs, for instance lightening holes, must always be considered. For coarse mesh subdivision, the reduction in stiffness can be considered by a corresponding reduction in the element thickness or, better, through a reduction in the shear modulus and Young's modulus in the longitudinal and transverse directions of the cut-out.

5. Steps in the plate thickness or scantlings of profiles, insofar as they do not lie on the element boundaries, must be taken into account through correspondingly adapted element data or characteristics to obtain an equivalent stiffness.

6. Plane elements should generally be positioned in the mid-plane of the corresponding components. For the global strength analysis of thin-walled structures, the elements can also be arranged at moulded lines, as an approximation.

7. Plane 2D elements in inclined or curved surfaces should be positioned at the geometrical centre of the modeled area if possible, in order that the global stiffness behaviour can be reflected as correctly as possible.

E. Boundary Conditions and Supports

1. The provision of supports for the model by suppressing or prescribing of displacements or rotations serves several purposes:

   - To suppress rigid body displacements and rotations of the model
   - To model physically existing supporting points
   - To model the interaction with the adjacent structural areas at the model edges

   It must be ensured that the supports do not cause any unrealistic constraints of the displacements or rotations.

2. To prevent problems with accuracy, the suppression of rigid body displacement and rotation of the model should - if possible, and insofar as this is not provided in the program - be performed with translational

supports that are arranged with relatively large spacings from each other. Forces in these supports can be eliminated through the generation of balanced load cases. Alternatively, rigid body displacements and rotations can also be suppressed by distributed spring elements which are adapted to the real conditions, e. g. the reaction forces to submersion of the hull girder.

3. Physically existent supports that take up forces and moments should be modeled as realistically as possible with the actual supporting length and spring stiffness.

4. For the strength analysis of the parts of the ship structure, the interaction with neighboring structural areas at the model edges should also be modeled as realistically as possible. This can be done at planes of symmetry by means of symmetry or asymmetry conditions, insofar as the load is distributed symmetrically or asymmetrically. In certain cases, the interaction can also be portrayed by prescribed stresses, or forces and moments, at the boundary. These parameters can be obtained, for example, from the structural analysis of larger areas or from beam forces and moments.

5. When using certain types of elements, it may become necessary to suppress individual degrees of freedom at the nodes, owing to non-existent stiffness. It must be noted that special care is required here, in order that deformations are not constrained unintentionally. If, instead of the suppression of degrees of freedom, additional elements are arranged to generate the required stiffness, the dimensions should be chosen to yield stiffnesses that do not falsify the results. For the case that nodal degrees of freedom are suppressed, it has to be ensured that applied loads/ masses are preserved in the system.

F. Checking the Input Data

1. The input data used for modeling the structural geometry and for the material characteristics must be checked thoroughly for errors. The effectiveness of the data check can be increased appreciably with the aid of suitable testing programs and visualization of the data.

2. The geometry of the finite element mesh should generally be reviewed by visual inspection. Here the possibility that individual elements have been entered twice should also be taken into account. Furthermore, geometry data which are not immediately visible, such as the thickness of 2D elements or the cross-sectional properties of 1D elements, should also be checked.

3. In addition to the geometry data, the material data as well as the boundary conditions and supports that were introduced should be checked carefully. Note that these parameters generally exert a considerable influence on the results.

4. The tests performed must be documented.

Section 3

Loading of the Structure

A. General Notes

1. The relevant loads for the strength analysis of ship structures can generally be classified into the following types:

   - Static (stillwater) loads from the dead weight of the ship and cargo and from the hydrostatic pressure caused by the buoyancy and tank contents.

   - Wave-induced loads, i. e. dynamic pressure, loads from accelerated masses and tank contents, as well as internal and external hydrodynamic impact forces

   - Other variable loads from the ship's operation, e. g. from the action of the engines or the rudder, and also wind loads and ice loads

   - Loads of cargo handling or from special cargo types, e. g. overpressure in gas tanks or temperature loads

   - Loads in extraordinary situations, e. g. during collisions, grounding or unintended flooding of compartments.

2. The selection and generation of the load cases to be analyzed must be done in such a way that, with respect to the sum of the forces and moments, either fully balanced load conditions or clearly defined, realistic sectional forces and/or deformations are obtained at the model boundaries or supports.

3. Nonlinearities in the load components must be considered to the extent that they are relevant. It must be observed that the linear superposition principle does not apply here. In some cases, forces that only arise for certain deformations - e. g. through the contact of structural areas - can be analyzed in the form of additional load cases and superimposed whilst taking into account the nonlinear behaviour of the structure.

4. Since several of the load components mentioned are of a stochastic nature, and because the selection and determination of the relevant load cases can be a very complex undertaking, there are simplified procedures which can be used for practical cases; see B. Moreover, there are special

procedures which refer particularly to wave-induced loads, but can also be applied to other stochastic load effects; see C.

B. Simplified Procedures

1. In the simplified procedures, selected (deterministic) load situations are considered that are decisive for the strength of the structural areas under analysis. In general, these load situations consist of unfavourable, but physically meaningful, combinations of diverse load effects. For assessments of the fatigue strength, load situations should be considered that generate both maximum and minimum stresses at the critical points.

2. For the definition of the load cases, there are two approaches:

- Application of the load components and load combination factors specified in the Construction Rules.
- Direct computation of the loads using the procedures given in C., and selection of unfavourable load cases for which certain design load parameters attain extreme values, e. g. bending and torsional moments or pressures as well as acceleration components at defined positions of the hull girder.

3. In general, the load cases should represent unfavourable loading conditions and the following unfavourable wave situations:

- Wave from astern and wave from ahead (with respect to the vertical hull girder bending and loads on the forebody)
- Oblique waves from astern and wave from ahead when the ship is upright (especially for ship types which react sensitively to horizontal bending moments and torsional moments in the hull girder)
- Oblique waves from astern and wave from ahead when the ship is heeling (insofar as this is relevant for the ship structure or component under consideration).

The following paragraphs provide additional notes on the load cases to be selected. It may be necessary to consider further load cases for special ship types and/or other relevant load components.

4. With respect to the loading conditions, conditions with uniform and non-uniform cargo distribution at maximum draught should generally be considered. Furthermore, the relevant loading conditions with single holds or tanks loaded to the maximum or empty, as well as ballast conditions, must be included in the computations.

5. With regard to the situation of waves from astern and/or ahead, the load cases "ship on wave crest" and "ship in wave trough" must be analyzed in general, whereby the position of the crest or trough should be arranged unfavourably or possibly varied. The external pressure must correspond to the pertinent arrangements (phase relations between ship and wave). Moreover, vertical and longitudinal acceleration components must be applied that have an unfavourable effect on the masses of the ship and the cargo or tank contents.

6. The situations with oblique wave from astern or ahead when the ship is upright must be chosen so that the maximum torsional or horizontal bending moments to be expected are applied at various positions of the hull girder, whilst the vertical bending moment exhibits values that are generally reduced in relation to the peak value. Furthermore, the relevant vertically and longitudinally oriented acceleration components that have an unfavourable effect on the masses of the ship and the cargo or tank contents must be applied.

7. The situations for heeling of the ship must be selected so that the maximum transverse accelerations to be expected actually occur. For diverse components, different wave situations can be relevant. The vertical and horizontal acceleration components that have an unfavourable effect on the masses of the ship and the cargo or tank contents should be applied.

8. For direct computation of the load, the wave situations to be considered can be based on design waves whose data result from the requirement that the design load parameter(s) are attained. In general, first the vertical bending moment in the hull girder is considered, as the result of a wave the wavelength of which corresponds approximately to the ship length and the direction of which is parallel to the longitudinal ship axis. In an initial approximation, further design waves can be assumed with variable wave lengths that change proportionally to the cube root of the wave length.

C. Special Procedures

1. As an alternative to the simplified procedure with selected (deterministic) load cases, there are also special procedures which are especially suited to complete consideration of the wave-induced ship motions and loads. For specified irregular waves, there are two possibilities for calculating the motions and loads:

   - Computation in the frequency domain and assessment with the aid of the spectral method

   - Computation in the time domain by simulation.

The natural seaways are usually characterized by energy spectra. Here the use of the Pierson-Moskowitz spectrum is recommended. The results must be assessed statistically, whilst considering the frequency of occurrence of the seaways, cargo distributions, ship courses and speeds. The following sections give further advise on this and on both computation possibilities.

2. In general, the hydrodynamic loads and the ship motions must be calculated as realistically as possible by considering all influencing parameters, including the ship's speed. Here the linearized strip method can usually be applied. The hydrostatic and hydrodynamic pressure applied to the model should be determined up to the current waterline.

3. For computations in the frequency domain, the first step is to determine the structural response to harmonic elementary waves, in the form of transfer functions which apply for each case of a particular cargo distribution, ship speed and heading relative to the wave direction. Here a sufficient number of wave frequencies must be taken in order to consider the resonance peaks of the structural response with sufficient accuracy. For a specified natural seaway, the spectrum of the structural response is obtained from the transfer function and the wave spectrum.

4. For computations in the time domain, the loading process must be generated in a suitable manner from the characteristic data of the wave spectrum. The time domain for analysis of the structural response must be selected to be large enough, so that the subsequent statistical evaluation can be performed with sufficient accuracy with respect to the expected values.

5. The structural response for a natural seaway must be determined for a representative selection of waves, cargo distributions, ship headings and speeds, and these must be selected with reference to their frequency of occurrence and the structural response to be assessed. For the waves, the long-term statistics of the North Atlantic should be used in general. If the examination is not to be performed in detail, a uniform distribution for the ship courses and 2/3 of the maximum speed can be assumed. For the loading conditions, further instructions are given in B.4. In the statistical assessment of the structural response, the probability level specified in the Construction Rules must be used as the basis.

D. Modeling the Loads

1. The loads must be modeled realistically. If necessary, the modeling of the structure must be adapted to the modeling of the loads; see Section 2, C.2.

2. Distributed loads must be converted to the equivalent nodal forces and - if applicable - moments, considering the displacement function of the elements.

3. If the boundary deformations derived from coarse models of large structural areas are applied to local models, the correspondingly interpolated values must be specified for the intermediate nodes. In addition, the loads acting within the local structural area must be applied, insofar as they are relevant.

E. Checking the Load Input

1. The input data on the loads must be checked thoroughly for errors. As is the case for the structural geometry, here the effectiveness of the check can be increased considerably with the aid of suitable checking programs and visualization of the data.

2. It is particularly important to check the sums of the forces and moments. For balanced load cases, it must be ensured that the residual forces and moments are negligible.

3. The checks performed must be documented.

Section 4

Calculation and Evaluation of the Results

A. Plausibility of the Results

1. In the calculation, it must be ensured that the results are determined with sufficiently high numerical accuracy (e. g. checking the conditioning of the stiffness matrix).

2. Before and during the evaluation, the results must be examined for plausibility. This involves in particular the visual presentation and checking of the deformations to see whether their magnitudes lie within the expected range and whether their distributions are meaningful with respect to the loads and boundary conditions or supports.

3. Furthermore, it should be checked whether the forces and moments at the supports lie within the expected order of magnitude or can be neglected, respectively.

4. For local models with specified boundary deformations from the models of large structural areas, it is necessary to check whether the stresses near the boundaries correspond for the two models.

5. For nonlinear computations, it is necessary to check whether the solution was determined with sufficient accuracy in the nonlinear zone.

B. Deformations

1. The deformations of the structure should generally be plotted so that other persons can perform a plausibility check of the results. Here it must be observed that in a three-dimensional representation the direction of the deformation is not clearly defined.

2. A further evaluation of the deformations is generally performed with a view to special questions for certain structures, e. g. for deformations of the foundations of propulsion plants or supports of hatch covers.

3. For the strength analysis with specified load conditions, it must be observed that excessively large deformations are be avoided which impair the

load carrying capacity or the serviceability of the structure. For linear analysis in particular, it must be noted that in reality additional stresses can occur in components under simultaneous longitudinal and bending loads with increasing deformations.

C. Stresses

1. In strength analysis for specified load conditions, the stresses in the modeled components must generally be evaluated. An exception is the analysis of locally increased stresses, for which it is possible that only the maximum value may be relevant.

2. The stresses must be checked with respect to the permissible values, as defined in the Construction Rules. The corresponding stress category must be observed, cf. Section 1, A.7. – E. If necessary, stress components that are missing because of the selected models and element types must be superimposed in addition.

3. For the stress evaluation, the changes in stress between the element centre and the element edge or corner must be taken into account. Simplifications in the model in relation to the real structure must be included in the assessment. If cut-outs are considered in models with a coarse mesh in the simplified manner according to Section 2, D.4., the stresses must be referred to the residual cross-section next to the cut-out. This applies especially for shear stresses in the webs of primary structural members.

4. In models with relatively coarse meshes, the reduced effective width must be considered, if applicable. Furthermore, local stress increases at existing structural details and discontinuities must be included in the assessment, if their effect is not considered separately.

5. To improve the clarity, it is recommended that the assessment be carried out with the aid of usage factors, which are obtained from the relationship between the existing and the permissible stress. In the case of extensive models, result tables should be set up and sorted according to the usage factors.

6. For analysis that are nonlinear with respect to materials, the local strain must generally also be determined and assessed in addition to the local elastic-plastic stress.

D. Buckling Strength

1. In general, the safety with respect to the ultimate load must be assessed and found adequate. If in accordance with Section 1, A.4. the magnitude of the ultimate load or the corresponding eigenvalues are calculated directly within the extent of the strength analysis, these structural responses can be used directly for the assessment. However, if the stresses and deformations were calculated for specified load conditions, an adequate safety against buckling or the effects of an associated load transfer must be taken into account. The latter can generally only be assumed for redundant systems, e. g. for stiffened plate panels for which the stiffeners can take over part of the loads of the plates subject to buckling. The following paragraphs refer to the buckling assessment within the scope of calculation of stresses and deformations for specified load conditions.

2. The safety with respect to buckling failure must be determined by considering all calculated stress components in the member area under assessment, on the basis of the assumptions given in the Construction Rules. In the buckling analysis of stiffeners, the effective width of the associated plating must be taken into account.

3. The effect of the load transfer in the post buckling regime for plate panels can be estimated approximately with the assumptions given in the Construction Rules concerning effective width. The increased stress in the edge area of the plate or in the stiffeners must not exceed the relevant permissible values.

4. To improve the clarity, it is advisable to perform the assessment with the aid of tabulated usage factors, which are obtained from the ratio of the actual and the permissible stress or load.

E. Fatigue Strength

1. Fatigue strength aspects should generally be taken into account in the assessment of ship structures, owing to the cyclic stresses that are usually present. In strength analysis for specified load conditions, a simplified assessment can be performed if the load cases according to Section 3, B. are chosen such that the maximum stress ranges are approximately attained in the components under consideration. Then further assumptions can be made on the stress spectra and for assessment on the basis of the parameters prescribed by the Construction Rules.

2. In the assessment of the stresses with regard to fatigue strength, the stress type must be considered, i.e. whether nominal stresses or locally increased notch or structural stresses are calculated with the chosen model; see also Section 1, A.7.

3. For the assessment, it is recommended that usage factors be applied; these are obtained from the ratio of the maximum actual stress range to the permissible stress range for an equivalent stress spectrum of the same shape and number of load cycles.

4. Further notes, particularly on special strength analysis are given in "Analysis Techniques Strength and Stability, Guidelines for Fatigue Strength Analysis of Ship Structures".

F. Presentation of the Results

1. The results obtained and the conclusions made on the basis of these results must be documented as completely and clearly as possible.

2. The documentation can take the form of plots and lists. Lists are necessary for the case that a graphical presentation of results is not sufficiently accurate. Extensive lists should be sorted, for example according to usage factors.

3. All symbols and designations that are used should be explained, if possible in or before the plots and lists.

Section 5

Example

A. General

In the following, the procedure for a typical strength analysis of a ship structure is illustrated with the aid of an example. Here the hold area of a bulk carrier is subjected to a global structural analysis, with the load assumptions according to the Construction Rules. The following remarks follow the format of the Sections 1 – 4 above. Wherever there are several approaches, each is discussed briefly.

B. Objective, Type and Extent of the Strength Analysis

1. The objective of the strength analysis is to calculate and assess the global stresses and deformations in the hold structure mentioned above for specified load conditions resulting from the possible loading conditions and the wave-induced additional load due to vertical hull girder bending as per the Construction Rules.

2. For this case, a linear strength analysis is regarded as sufficient in order to achieve the objective; see also Section 1, A.6.

3. In this example, the stresses are to be analyzed in the longitudinal and transverse primary structural components as well as in the bulkheads of a typical hold. The case of alternate loading is viewed as especially critical; here every second hold remains empty with maximum draught, so that the highest loads occur there as a result of the missing counter pressure. Only this case is considered in the following, for reasons of clarity. A complete strength analysis would include further cargo and ballast distributions and possibly other wave situations.

4. For the above-mentioned analysis objective, the investigation of a hold model is regarded as sufficient for this type of ship, owing to the long parallel part of the hull. For an approximate consideration of the effective width and the stress gradient in the highly stressed areas, several plane elements should be arranged between the primary structural components.

C. Modeling the Structure

1. The modeled section of the hull girder is shown in Fig. 5.1. Hold 4 is analyzed; together with holds 2 and 6, it remains empty for alternate loading. By exploiting the structural symmetry that exists to a certain degree, the model extends up to the mid lengths of holds 3 and 5. For reasons of symmetry, only one half of the ship is considered.

2. As the element types, plate or shell elements are selected for the plane components (primary structural members) and beam elements for the stiffeners. The later are required if several elements are arranged between the primary structural members, in order to take up the pressure loads on the plane areas and to pass them on. Insofar as eccentrically located beams are available in the element library of the program used, these are recommended for the stiffeners arranged on one side only (here: bulb plate stiffeners). Otherwise the bending stiffness of the combined cross-section of the profile and the effective plate width must be taken for the beams. For the axial stiffness, however, only the sectional area of the profile need be considered. As a matter of principle, plane stress elements could also be used instead of the plate elements, owing to the thin-walled structure.

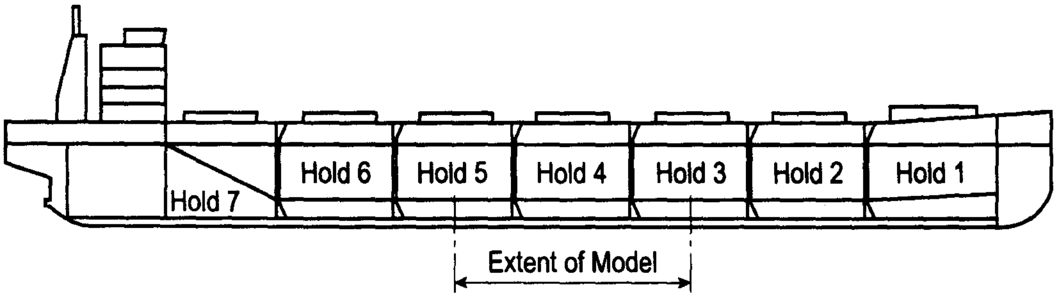


Fig. 5.1 Example

3. The modeling of the structure is shown in Fig. 5.2. All primary structural members and all frames and stiffeners are considered. In the transverse and vertical direction, the mesh fineness is oriented towards the spacing of the longitudinals. Three elements are arranged in each case between the primary structural components (e. g. floors). Through this subdivision, the effective widths are considered approximately and results are available directly in the individual plate fields for the subsequent buckling analysis. For the modeling, it should be observed that the elements lying in the planes of symmetry (the centre-line plane in this case) must be given half the normal thickness.

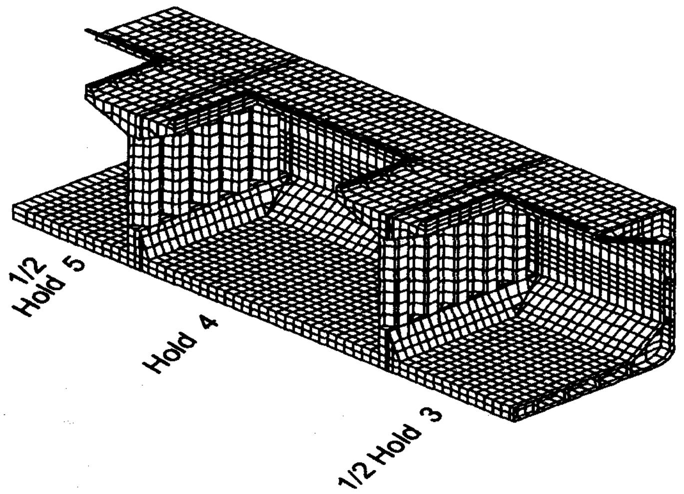
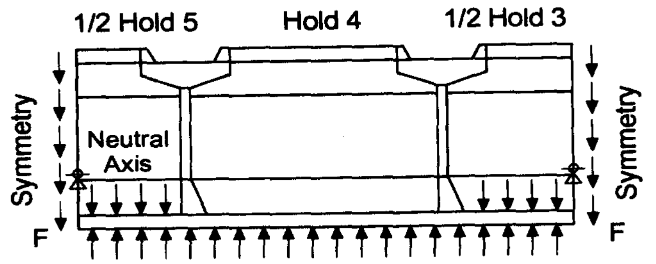


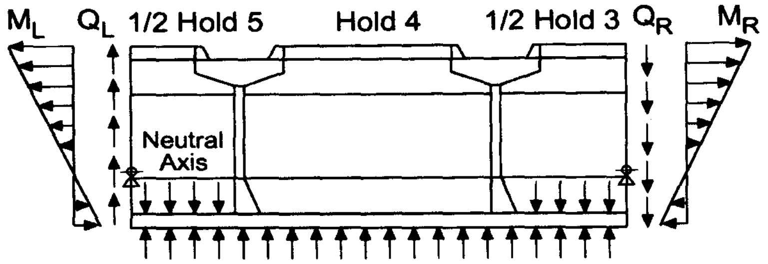
Fig. 5.2 Finite element model of the hold area

4. Simplifications in the modeling primarily affect the consideration of lightening holes through correspondingly reduced thicknesses or stiffnesses of the plates.

5. Symmetry conditions can be introduced at the model boundaries, if these conditions are valid both from the viewpoint of the geometry and the loads. In the example, this is true for the centre-line plane. However, the situation at the ends of the model is complex. Symmetry can only be applied if only lateral loads, as sketched in Fig. 5.3 at the top, are considered and the additional stresses from the global hull girder bending are superimposed onto the analysis results after the calculation. On the other hand, if sectional forces and moments are to be introduced into the model (Fig. 5.3, bottom), the ends must be able to shift and rotate. However, only idealized distributions of the stresses or deformations in the end cross-section can be assumed here, or estimated on the basis of beam theory. In the example in the question, the end sections are kept in the plane - as a simplification - by the corresponding program functions (or relatively stiff auxiliary structures). Through this practical solution, the compatibility of the deformations to the adjacent area is not fully satisfied (e. g. with respect to the shear-induced deformations), so that in the vicinity of the model boundaries the stresses will be disturbed somewhat. Here it may be assumed that these effects have decayed at the bulkheads.



F = Supporting Force to achieve Equilibrium



M_L, M_R = Bending Moment in Hull Girder
Q_L, Q_R = Shear Force in Hull Girder

Fig. 5.3 Model with and without hull girder bending

6. The structure is supported in space by two supports at the side shell in the vertical direction and one support in the longitudinal direction. Since balanced load cases are to be considered, no forces act at these points. Together with the symmetry conditions in the centre-line plane, the model is adequately supported in space with respect to the three translational and three rotational degrees of freedom. Regarding non-existent node stiffnesses, attention should be paid to nodes lying in inclined planes when modeling with plate and beam elements, if no beams are arranged here, and the plate elements used have no rotational degree of freedom about the normal to the surface. In the model in question, this affects several nodes in the inclined elements of the corrugated bulkheads, so that here an equivalent stiffness or corresponding support must be provided.

D. Loading the Structure

1. As mentioned initially, of the various possible loading conditions only the case of alternate loading for an empty hold 4 and maximum draught is considered, for reasons of simplification. Moreover, the additional pressures, accelerations, and sectional forces and moments in the hull girder are considered for the situations "ship on wave crest" and “ship in wave trough”.

2. For both load cases, Fig. 5.4 shows the pressure loads which are determined according to the Construction Rules to be acting on the cross-sections in holds 3 and 5. Only the external pressure has an effect on hold 4. In addition, the pressure loads on the bulkheads are also depicted, whereby only the worst case for the bulkhead (in which a hold is filled up relatively high) is considered here. The pressure loads are applied to all nodes in the affected areas, taking into account their load area.

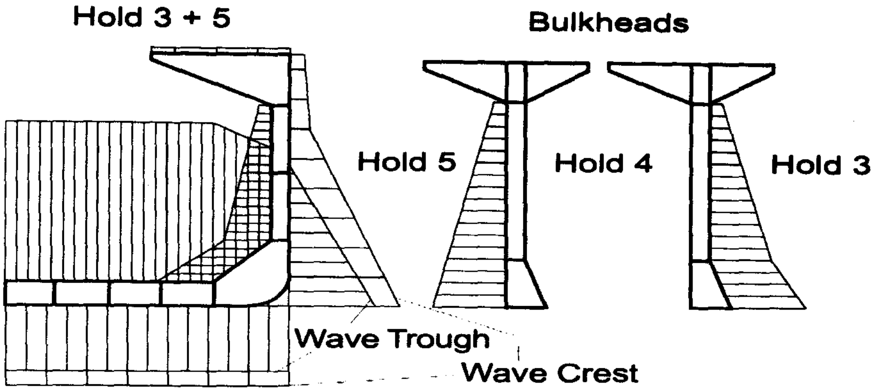


Fig. 5.4 Loading of the cross-sections and bulkHeads

3. The sectional forces and moments at the front and rear ends of the model are applied so that the worst-case values for the situations "ship on wave crest" and "ship in wave trough" are produced. In the definition of the sectional forces and moments, it must be observed that the conditions of equilibrium are maintained. For the example depicted in Fig. 5.5: if M_L and Q_L are specified at the left boundary, the sectional forces and moments are obtained at the right boundary as:

$$M_R = M_L - Q_L \cdot \ell - \Sigma\left[P_i\,(\ell - x_i)\right]$$
$$Q_R = Q_L + \Sigma P_i$$

Here P_i represents the vertical forces acting at a distance x_i from the left model boundary. The sectional forces and moments are selected so that the maximum hogging or sagging moments act in the hold area under consideration, and the maximum shear forces at the bulkheads. The shear forces Q_L and Q_R are distributed over the nodes of the cross-section in accordance with the shear flow, so that the correct distribution of shear forces can already result near the boundary.

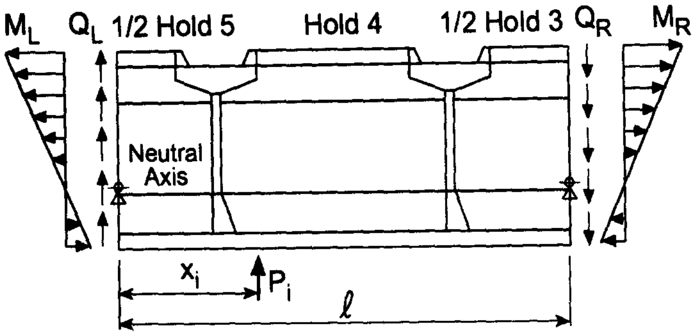


Fig. 5.5 Forces and moments acting on the model

4. After application of the loads described above, the sums of the forces and moments must be zero. Here the loads acting on the supported nodes (e. g. at the side shell) must be included in the summation process.

E. Calculation and Evaluation of the Results

1. Fig. 5.6 shows the calculated deformations for the load case "ship on wave crest" with a magnified scale. As expected, there are large vertical deformations of the bottom grillages. The local deformations of the longitudinals between the primary structural members and the deformations of the transverse bulkheads are also recognizable. The global hull girder bending is easy to see at the side of the deck. The plausibility check using the resulting deformations should also be performed with the aid of plots in the three main planes, whereby special attention must be paid to compliance with the boundary conditions.

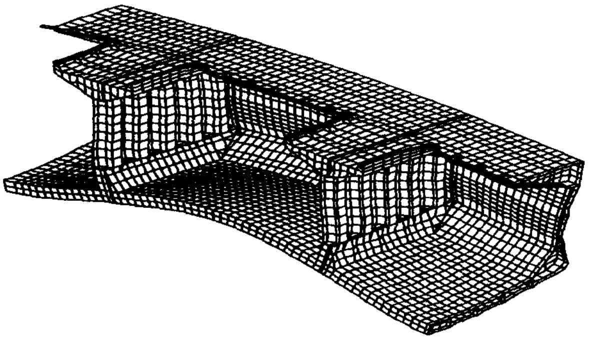


Fig. 5.6 Deformations (Magnified)

2. Apart from the plausibility check, the deformations are not evaluated any further in this example.

3. The element stresses are checked with respect to permissible limits. Here it should be noted that local stresses resulting from the pressure loads are only contained incompletely in the results, or not at all. For the beam elements, it may be necessary to make a correction to consider the parabolic curve of the moments and possible effective widths. The same applies to the plate elements, insofar as eccentric beam elements are used, otherwise only global stresses are determined. Fig. 5.7 shows the principal stresses found for the bottom shell. The stresses were assessed on the basis of the permissible limits for normal, shear and equivalent stresses, as specified in the Construction Rules. Here the type of stress calculated in each case must be taken into account; see Section 1, A.7. In this example, the largest normal stresses have occurred in the middle of the bottom shell, whereas the largest shear stresses in the webs of girders and floors naturally arise at the edges of the double bottom. An extrapolation of the normal stresses to the element edges or corners should be performed, to take into account the effects of constraining, especially at the boundaries of large component areas.

4. The buckling analysis is performed directly for the plate elements or fields, with application of the relevant Construction Rules. In this example, increased scantlings are obtained in the bottom shell, owing to the high compressive stress in the ship's longitudinal and transverse directions.

5. With respect to fatigue strength, an evaluation of the stress ranges from the two load cases (through subtraction) would yield information on the structural areas under high cyclic loading, whereby in addition the local stresses, localized stress concentrations and the detailed design must be taken into account

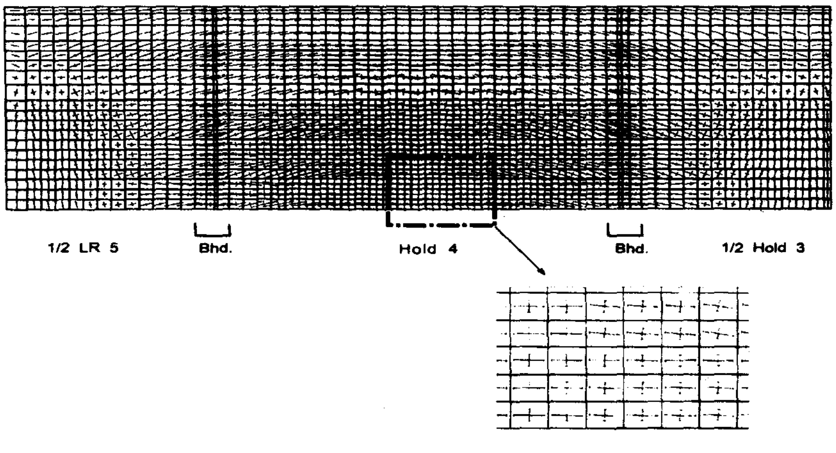


Fig. 5.7 Principal stresses in the bottom shell

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Analysis
Techniques Strength

2. Guidelines for Fatigue Strength Analysis of Ship Structures

EDITION 2005

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Section 1

General

Preamble

The proof of sufficient fatigue strength, i. e. the strength against crack initiation under dynamic loads during operation is useful for judging and reducing the probability of crack imitiation of structural members during the design stage.
Due to the randomness of the load process, the spreading of material properties and fabrication factors and to effects of aging, crack initiation cannot be completely excluded during later operation. Therefore among other things periodical surveys are necessary.

A. Objective of the Guidelines

1. These guidelines give further information about the performance of fatigue strength analysis of ship structures in addition to the Rules for the Classification & Construction of Seagoing Steel Ships (references of this kind hereafter are related to Section 20 of Rules for Hull, Volume II). In view of the great variety of ship structural details, different load effects and available analysis methods, it is necessary to keep these guidelines relatively general.

2. In accordance with the Rules for the Classification & Construction of Seagoing Steel Ships , it is assumed that the fatigue strength is assessed on the basis of design S-N curves and the Palmgren-Miner's Rule for the consideration of variable-amplitude loading. In cases, such as initiated cracks or welds with partial penetration, however, other approaches, e.g. those based on fracture mechanics, can be suitable for the assessment. They can require other calculation models and analysis procedures.

3. In addition to the information regarding the performance of fatigue strength analysis, which are illustrated by examples, attention should be given to the detail design to aim at a fatigue-resistant structure, an objective which is still of great importance because the complete assessment of all details under consideration of all possible load effects is not yet practicable.

B. Objective of a Fatigue Strength Analysis

1. The objective of a fatigue strength analysis is normally

   a) the identification of structural areas with high cyclic stresses,

   b) the analysis and assessment of critical structural details and

   c) the determination of structural alternatives.

2. The identification of structural areas with high cyclic stresses (a) requires the calculation of stress ranges and mean stresses in the areas under consideration for one of the stress types mentioned in D. together with a suitable representation of the results that allows the identification of critical details.

3. The analysis and assessment of critical structural details (b) and the determination of structural alternatives (c) is normally performed under consideration of the expected stress history as well as the local stress concentration or a corresponding detail category.

C. Analysis Methods

1. Three methods are available for considering the wave loads which dominate the fatigue behaviour of ship structures:

   – Simplified deterministic method; see 2.,

   – Spectral method; see 3.,

   – Simulation of the stress history; see 4.

   All three methods, which differ in their computation effort, will be dealt with in Section 3 in more detail.

2. In the simplified deterministic analysis, selected load situations are considered and from this, stress spectra for the whole service life are derived, adopting the assumptions in the Rules for the Classification and Construction of Seagoing Steel Ships for the subsequent strength assessment.

3. When applying the spectral method, the structural response to stochastic load processes is calculated in the frequency domain, and

the stress spectrum for the whole service life is determined with statistical methods for the subsequent fatigue strength assessment.

4. Contrary to the spectral method, the simulation of the stress history is performed in the time domain, making it possible to consider the direct calculation of nonlinear effects during the load and damage process.

5. The selection of the method depends primarily on the question as to whether acceptable results can be expected in view of the respective simplifications and assumptions. In the case of the simplified deterministic method, which ist at present mostly applied for practical reasons, the main question is whether the selected load situations consider sufficiently the relevant stresses and whether the shape and number of cycles of the stress spectrum can be estimated with satisfactory accuracy on the basis of experience and/or similar computations. When applying the spectral method, it is necessary to check how far simplifications such as the neglect or approximate consideration of nonlinear effects can be justified. In the case of a simulation of the stress history, the length of simulation time which allows extrapolation to the whole service life with sufficient accuracy is of primary interest.

D. Stress Types

1. Depending on the detail considered, the fatigue strength analysis is normally based on one of the following three types of stresses:

- Nominal stress σ_n; see 2.,
- Structural or hot-spot stress σ_s at the toes of welded joints; see 3.,
- Notch stress σ_k at rounded plate edges; see 4.

2. In welded structures, the fatigue strength analysis is normally based on the **nominal stress** σ_n in the structural member at the location of the detail considered and an appropriate relation to a classified detail according to the catalogue of details in the Rules for the Classification & Construction of Seagoing Steel Ships which also describes the direction of the relevant stress component.

The nominal stress is usually calculated from integral load quantities and sectional properties (force or moment per unit area or section modulus, respectively) or from relatively coarse finite element models. The effective width has to be considered. Further guidance for the computation of nominal stresses by finite element analysis is contained in Analysis Techniques Strength and Stability "Guidelines for Strength Analysis of Ship Structures with the Finite Element Method".

3. Welded structures which cannot be related to a classified detail or where additional stresses occur which are not or not fully considered by the catalogued detail can be assessed with respect to fatigue at weld toes on the basis of the **structural or hot-spot stress** σ_s, which contains the stress increase due to the structural geometry, but not that due to the weld toe. In some cases, structural stress concentration factors K_s can be used for the determination of the structural or hot-spot stress σ_s,

$$K_s = \frac{\sigma_s}{\sigma_n}$$

which result from parametric investigations. Here, the definition of the nominal stress and the validity ranges of the parametric formula or diagrams have to be considered. The fatigue strength assessment is performed using specific S-N curves or detail categories for structural stresses, as given in the Rules for the Classification & Construction of Seagoing Steel Ships

4. Free plate edges are usually assessed on the basis of the notch stress σ_k, which is computed for ideally elastic material behaviour. In some cases, the notch stress can be calculated with the aid of the theoretical stress concentration factor K_t resulting from parametric investigations:

$$K_t = \frac{\sigma_k}{\sigma_n}$$

Here, the definition of the nominal strees and stress and the validity ranges of the parametric formula or diagrams have to be considered. The fatigue strength assessment is performed by using specific S-N curves or detail categories for free plate edges.

5. As regards **further types of stresses**, e.g. the notch stress at weld toes, the elastic-plastic stress and strain in the notch root or the stress intensity at crack tips or sharp notches, reference is made to the specialist literature.

Section 2

Modeling of the Structure

A. General

1. The modeling of the structure has to be performed in such a way that, at the detail considered, the type of stress on which the fatigue assessment is to be based can be calculated with sufficient accuracy.

2. Two methods are normally applied in the calculation:

   a) Analytical methods, e.g. based on beam theory, which usually result in nominal stresses

   b) Numerical methods, such as the finite element method, which are particularly well suited for the stress analysis of geometrically complex structures as well as local stress increases.

3. The following sub-sections give special information about the modeling of a structure in view of calculating the desired type of stress; see Section 1, D. Further information is contained in Analysis Techniques Strength and Stability "Guidelines for Strength Analysis of Ship Structures with the Finite Element Method".

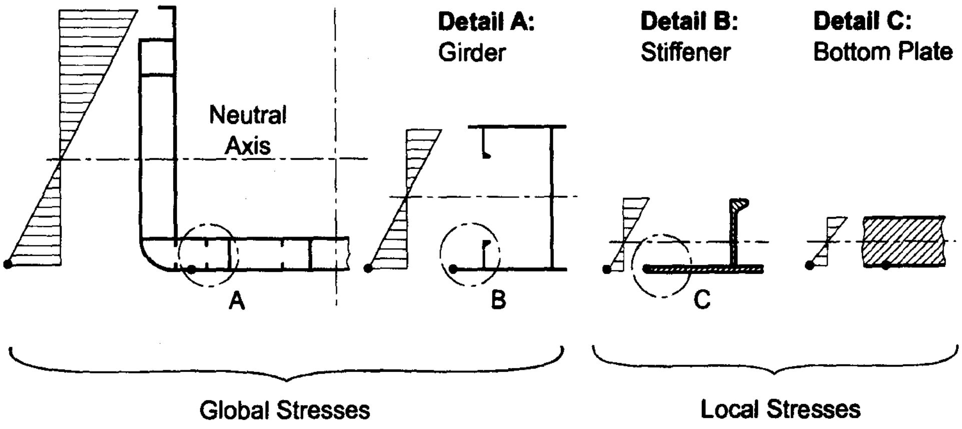


Fig. 2.1 Global Stresses and Local Stresses

B. Calculation Models for Global and Local Nominal Stresses

1. The calculation of nominal stresses is normally performed by using beam models of the ship's hull girder, of the primary structural members as well as secondary structural members, or by using relatively coarse finite element models to represent these structures. The latter method is recommended especially for more complex structures and load cases.

2. It is common to distinguish between global stresses in primary structural members and additional local stresses in secondary structural members; see Fig. 2.1. The latter include bending stresses in stiffeners and plates. In fatigue analysis, the combined effect of both components is to be taken into account.

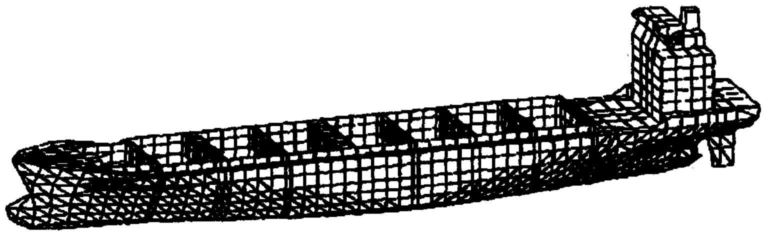


Fig. 2.2 Overall Model of a Ship's Structure

3. The extent of the model is primarily determined by the question of whether and how reasonable boundary conditions can be formulated for partial models of the structure. Fig. 2.2 shows a typical overall model of the ship structure with a relatively coarse mesh. As a result, global nominal stresses are obtained in the primary structural members; these have to be superimposed with local stresses as well as increased stresses due to reduced effective widths.

4. The resulting nominal stresses can

   a) be directly assessed in connection with a corresponding detail category,

   b) be multiplied by stress concentration factors K_t or K_s to obtain and assess locally increased notch stresses σ_k or structural (hot-spot) stresses σ_s (see Section 1, D.3 and Section 1, D.4),and

   c) serve as boundary conditions for local models of the structural details considered (alternatively, deformations are frequently prescribed at the model boundaries); see also C. and D.

5. If crack initiation from the weld root is assessed, it should be noted that the nominal stress has to be related to the cross-sectional area of the weld; see also the description of the respective detail categories in the Rules for the Classification and Construction of Seagoing Steel Ships.

C. Calculation Models for Structural Stresses at Welded Joints

1. Structural or hot-spot stresses are normally calculated by using local models of the ship structure.The extent of the model has to be chosen such that effects due to the boundaries on the structural area considered are sufficiently small and reasonable boundary conditions can be formulated.

2. Basically, it is necessary to distinguish between two types of weld toes at fillet or K-butt welds:

a) Weld toes on plate surfaces, e.g. at transverse stiffeners or at the weld around the toe of an attached plate

b) Weld toes at plate edges, e.g. at the termination of the cut edge of a scallop.

Fig. 2.3 shows both types of weld toes for the example of a scallop. It should be noted that local plate bending may affect the structural stress, especially with type a).

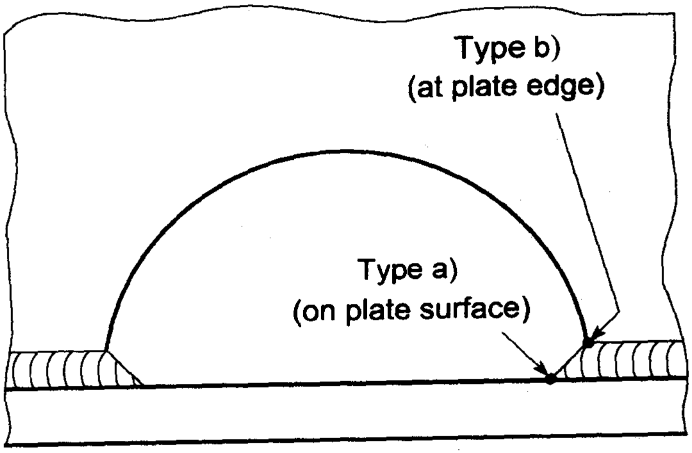


Fig. 2.3 Types of Weld Toes

3. When applying the finite element method, it is recommended in view of effects due to plate bending that models with plate or shell elements, or alternatively with solid elements, be used. It should be observed that on the one hand the arrangement and type of elements used have to allow the formation of plate bending, and on the other hand only the linear stress distribution in the plate thickness direction has to be evaluated in accordance with the definition of structural stress (i.e. neglect of the local stress increase due to the weld toe). Fig. 2.4 shows the relationship between different types of stresses at a weld toe.

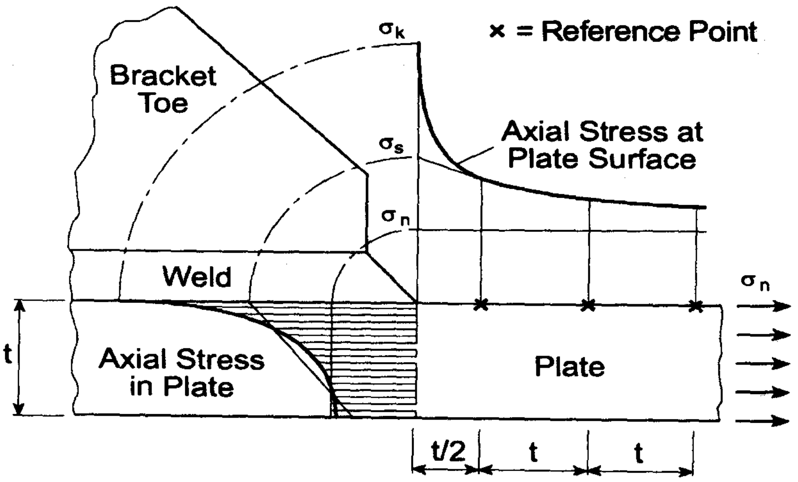
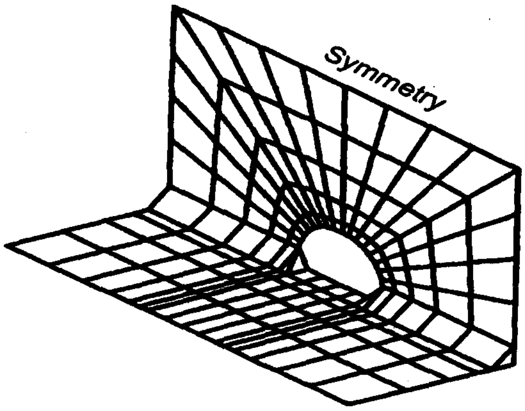


Fig. 2.4 Types of Stress at a Weld Toe

4. Recommended meshes with plate and solid elements are shown in Fig. 2.5. In connection with the type of modeling shown, solid elements have to be chosen such that they have a displacement function allowing plate bending with linear stress distribution in the plate thickness direction, e.g. isoparametric elements with mid-side nodes at the edges and two integration points in the thickness direction. The modeling of all welds is generally recommended. When using plate elements, it must be ensured that the plate elements at the weld toe are sufficiently clamped on the one hand, and that the axial and bending stiffness behaviour of the weld is realistic on the other. For the inclined elements, half of the thickness of the attached plate, plus the fillet weld area distributed over the element length (cf. Fig. 2.6), should be chosen. Warping of the weld sections modeled should be prevented by arranging fictitious transverse web elements within the weld sections and using elements with mid-side nodes.

(a) Plate elements



(b) Solid elements

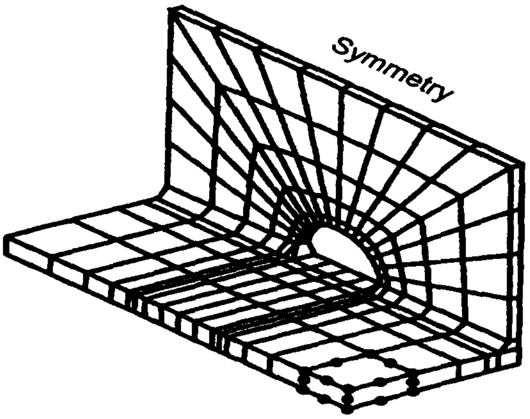


Fig. 2.5 Typical Mesh Subdivision for a Welded Detail with Plate and Solid Elements

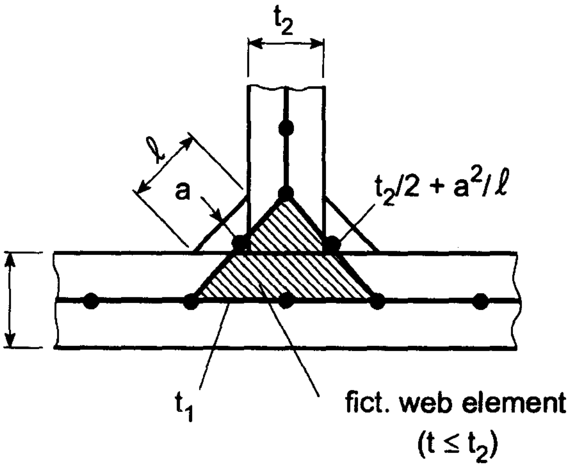


Fig. 2.6 Modeling of a Fillet Weld with Plate Elements

5. It is recommended that the first two or three elements in front of weld toes of type (a) (see Fig. 2.3) be modeled with a length equal to the plate thickness. In the transverse direction, the whole width over the welds may be chosen for the element width. At weld toes of type (b), the element length and width should not be larger than 2 · a (a = weld throat thickness). It has to be observed that the structural stress computed depends highly on the element sizes and that conservative results may be obtained from very fine meshes. Additional plate bending need normally not be considered for this type of weld toe.

6. Furthermore, it is recommended that the normal stresses perpendicular to the weld derived at the centre of the element surface or edge be extrapolated in a linear way over two elements or in a quadratic way over three elements to the weld toe; see Fig. 2.4. With quadratic extrapolation, an increased detail category or design S-N curve may be used in accordance with the Rules for the Classification and Construction of Seagoing steel Ships, provided that the bending component in the plate is significant. This condition may be assumed to be fulfilled if the bending portion of the total stress at the plate surface amounts to more than 30 %.

7. Probable cracks from the weld root may require the additional calculation and assessment of the nominal stress in the weld throat area; see B.5.

D. Calculation Models for Notch Stresses at Plate Edges

1. Notch stresses are normally calculated using local models of the ship structure. The extent of the model has to be chosen such that effects due to the boundaries on the structural area considered are sufficiently small and reasonable boundary conditions can be formulated.

2. For the calculation of the notch stress σk at plate edges (e.g. edges of cut-outs) assuming idealelastic material behaviour, it is mainly the stresses in the mid-plane of the plate that are significant. Therefore, modeling of plate areas with membrane elements is sufficient in most cases, as far as the bending stiffness does not significantly affect the load distribution.

3. In notched areas, the mesh fineness has to be chosen such that the stresses at the plate edge can be determined with sufficient accuracy. This means for example that at least eight elements with linear displacement function or five elements with quadratic displacement function should be arranged along the quarter of a circle. The subdivision

in radial direction also has to be sufficiently fine in view of the stress gradient. It is recommended that the element lengths in the radial direction be chosen no larger than in the tangential direction. The element arrangement for the stress analysis of a hole in the web of a girder is exemplified in Fig. 2.7.

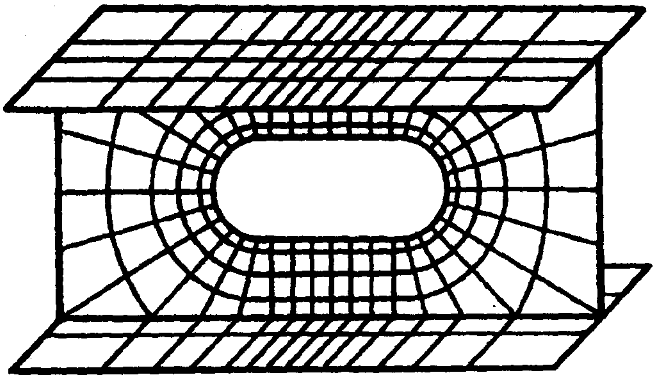


Fig. 2.7 Typical Mesh Subdivision for the Computation of Notch Stresses at Edges of Cut-Outs

4. Stiffeners on primary structural members in the vicinity of the analyzed notches are normally to be considered in the model. A three-dimensional model is recommended, with a realistic modeling of the terminations of the structural members, e.g. sniped stiffener ends.

5. The evaluation of the results can be simplified if truss elements with negligible cross-sectional areas (which do not affect the structural stiffness, but yield directly the edge stress) are arranged at the plate edges.

Section 3

Definition of Load Cases and Calculation of the Stress Spectrum

A. General

1. In the following sub-sections, further information is given on the three analysis methods mentioned in Section 1, C. Here, only wave-induced loads and loads due to different loading conditions are considered. Other load effects, which may be relevant for certain ship types, can be dealt with analogously.

2. Regarding the consideration of the loading conditions, two approaches are possible, according to Rules for the Classification and Construction of Seagoing Steel Ships:

   a) Assumption of the loading condition that is most unfavourable for the fatigue strength of the detail considered, i.e. with respect to the mean stress and the stress ranges.

   b) Assumption of several representative loading conditions which on the one hand are typical for the ship being considered and on the other include different cargo and ballast distributions within the hull and also different draughts. Frequently, 4 to 12 loading conditions are sufficient, if they

      - cause high hogging and sagging bending moments in the hull girder,
      - include the ballast and fully-laden conditions, as well as an intermediate condition, if appropriate,
      - include cargo distributions which cause high stresses in the bottom and in the bulkheads.

   Regarding consumables, consideration of the condition "50 % consumables" is normally sufficient.

   In extensive fatigue strength analysis for different structural areas, various loading conditions normally have to be analyzed because unfavourable conditions can result from different loading conditions for different details.

B. Simplified Deterministic Analysis

1. In simplified deterministic analysis, unfavourable situations in waves are selected for all loading conditions, considering the maximum stress range $\Delta\sigma_{max}$ and associated mean stress σ_m.

2. The assumed wave loads and the load combination factors result from the assumptions in the Rules for the Classification and Construction of Seagoing Steel Ships. It has to be noted here that certain load components (e.g. horizontal bending and torsional moments) may have to be superimposed with different signs.

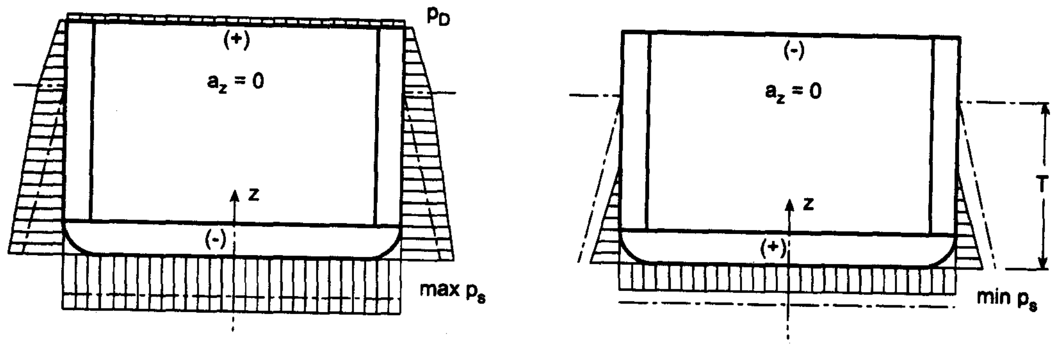
3. Generally, load combinations (cf. Fig. 3.1) with

- waves from ahead/astern (max. vertical bending moments in the hull girder, correspondingly increased or reduced side and bottom pressure in the forward, midship and aft part of the hull girder), and
- oblique head/stern waves (reduced vertical bending moments in the hull girder, max. horizontal bending and torsional moments, max transverse acceleration or tank pressures, with corresponding opposing pressure from outside)

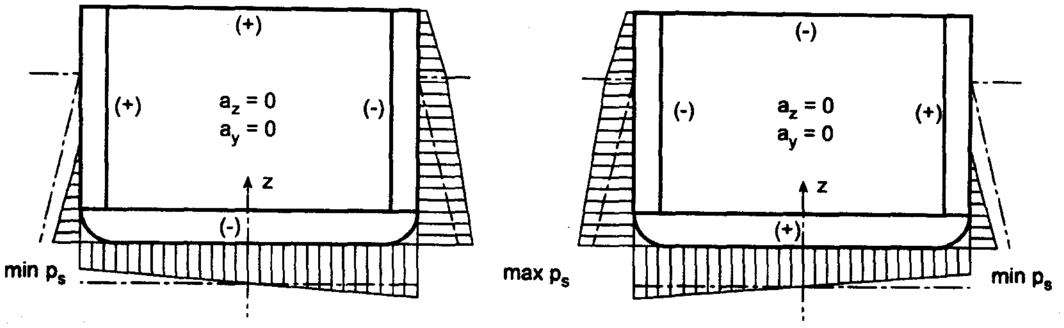
should be considered. In the latter case, the consideration of the upright and heeled ship position might be necessary, depending on the structural detail under consideration. Unfavourable load combination may occur at port or starboard side.

4. After calculating the highest stress range $\Delta\sigma_{max}$ and the associated mean stress σ_m for each loading condition, further characteristics of the stress range spectrum are estimated on the basis of the Rules for the Classification and Construction of Seagoing Steel Ships. For wave induced stresses, usually a straight-line spectrum in semi-logarithmic representation and a total number of load cycles $N_{max} = 5 \cdot 10^7$ during the service life of about 20 years are assumed.

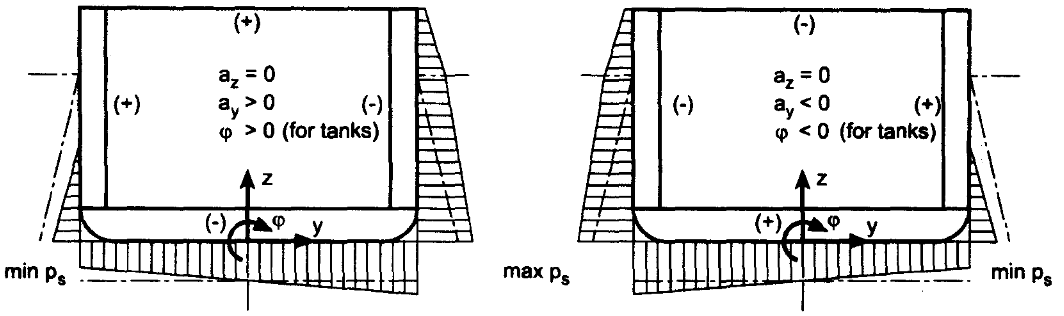
1. **Head Seas**



2. **Beam Seas, upright Position**



3. **Beam Seas, with Rolling**



Remarks :

- In cases 1. And 2., $a_z \neq 0$ may be considered in connection with mean external pressure.
- The signs (+) and (-) apply to the longitudinal stresses due to vertical and horizontal wave bending of the hull girder acc. to Rules for the Classification and Construction of Seagoing Steel Ships
- Torsion related stresses are to be included for ships with large deck opening

Fig. 3.1 Typical Load Situations for the Calculation of the Highest Stress Range

C. Spectral Method

1. When applying the spectral method, the following calculation steps are performed for each loading condition:

   1.1 Calculation of the structural response (stress) in the form of transfer functions (response amplitude operator / RAO) for waves of different length. Various angles of encounter are assumed for these waves.

   1.2 Calculation of the stress spectrum for all sea states considered and determination of the stress range distribution.

   1.3 Establishment of the long-term distribution of the stress ranges, considering the probability of occurrence of the individual sea states.

   Some information on the necessary assumptions are given in the following paragraphs. Further details are given in the specialist literature.

2. The wave load cases in the first step (see 1.1) should be calculated with a wave amplitude which lies within the range of the highest damage due to the number of load cycles (approx. 1 m). The ship's speed is usually assumed to be 2/3 of the service speed if no service profile is specified. The wave lengths should be chosen such that the pressure fluctuations due to shorter waves as well as the roll, heave and pitch resonances of the ship are covered, and such that enough values are available to allow for a sufficiently accurate representation of the transfer function between wave amplitude and structural response (normally 15 – 25 wave lengths). The angle of encounter should be varied in steps of 30 degrees, whereby waves running transversely to the ship's course usually require a special consideration. If only angles of encounter from one side of the ship are considered, the results for the corresponding detail on the other ship's side have to be included in the evaluation. For each wave situation, two cases with a phase difference are considered in order to obtain real and imaginary part of the harmonic load process.

3. In the second step (see 1.2), the stress spectra are calculated for all sea states considered by the longterm statistics, with all loading conditions and angles of encounter, by multiplying the quadratic transfer function with the individual wave spectra. For the wave spectra, a two-parameter standard distribution (e.g. according to Pierson-Moskovitz) can be assumed. The frequency distribution of the stress ranges

results approximately from the spectral moments and the assumption of a narrow-banded Gaussian process (Rayleigh distribution of the maxima). A correction for the wide bandedness of the loading process can be performed on the basis of published methods, whilst its neglect generally leads to slightly conservative results. Relevant nonlinear effects regarding the damage should be considered. This includes the pressure fluctuations at the ship's sides close to the still-water line which depend in a nonlinear way on the wave height, due to intermittent wetting of the structural area considered. Reference is made to the specialist literature concerning methods to account for this effect.

4. For the long-term statistics of the sea states, the data of the North Atlantic Ocean are usually used; see Table 3.1. The angle of encounter is normally assumed to follow a constant distribution, if more accurate data is not available. The total service life is usually set to 20 years. From this data, the total duration of the individual sea states is derived for the different angles of encounter and loading conditions. From this and from the mean period of the structural response follows the number of cycles of the associated spectrum of stress ranges. By summation of the partial spectra, the long-term distribution of stress ranges can then be calculated.

5. It is recommended that the long-term distribution of stress ranges at the structural detail considered be calculated separately for all different loading conditions, because they are assessed with different mean stresses. For each loading condition, the entire service life of 20 years should be assumed in a first step. In this way, the results can be directly compared and it is possible to assess them for various combinations of loading conditions as well as for the most critical loading condition.

D. Simulation of the Stress History

1. Different possibilities exist for the simulation of the stress history, inter alia:

a) Simulation of the stress history on the basis of computed stress range spectra for the individual sea states

b) Simulation of the complete motion and load process for the whole ship structure.

In any case, different sea states and angles of encounter are considered for all loading conditions investigated, from which the long-term distribution of stress ranges is evaluated in a similar way as that described in C.4.

2. Method (a) is based on calculations of the structural response, as described in C.2 – C.3 in connection with the spectral method, so that the prerequisites are the same. The advantage of simulation lies in the computation of the course of the stress history, which allows a refined assessment of the damage process, e.g. by considering sequential effects or material-related nonlinearities in corresponding concepts.

3. In addition to that, method (b) permits realistic consideration of nonlinearities in the load process, which may be significant for certain ship types.

4. The loading conditions and sea states considered as well as the simulation time are to be chosen such that significant statistical evaluations can be made with respect to the entire service life.

5. From the stress history evaluated, the relevant parameters for the assessment (e.g. largest stress range $\Delta\sigma_{max}$, shape of stress spectrum and associated mean stress σ_m) are to be determined using the rainflow counting method.

Table 3.1 Wave Scatter Diagram for the North Atlantic

hs \ tz	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	SUM
0.5	0.0	0.0	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050
1.5	0.0	0.0	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575
2.5	0.0	0.0	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810
3.5	0.0	0.0	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128
4.5	0.0	0.0	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13289
5.5	0.0	0.0	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328
6.5	0.0	0.0	0.0	0.0	0.0	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806
7.5	0.0	0.0	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586
8.5	0.0	0.0	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309
9.5	0.0	0.0	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	17.7	6.1	1.7	0.4	0.1	626
10.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
SUM:	0	0	1	165	2091	9280	19922	24879	20870	12898	6245	2479	827	247	66	16	3	1	100000

Values stand for time fractions of sea states characterized by tz and hs

tz = zero upcrossing period in s
hs = significant wave height in m

Section 4

Assessment of the Results

A. General

1. The calculation of stresses and their assessment with respect to fatigue strength should be performed for as many details as possible, so that critical areas can be identified with certainty and effective measures can be taken.

2. An overview of the probable danger of fatigue cracking is given by:

   a) The presentation of maximum stress ranges in the structure analyzed whereby, in the case of nominal stresses, local stress increases or detail categories of the structural details have to be observed.

   b) Existing experience for ships in service which indicates that primarily

      - longitudinal structural members in the upper and lower flange of the hull girder due to hull girder bending (except for the ship's ends),
      - longitudinal and transverse structural members at the ship's sides due to local pressure fluctuations, and
      - structural components in the vicinity of the main propulsion plant and manoeuvring system

   as well as, in general, discontinuities in continuous structural members are prone to fatigue. The probability of fatigue failure increases if higher-tensile steel is used due to the increased nominal stress as long as no compensation is achieved by an improved structural design and/or higher fabrication quality.

B. Assessment of the Fatigue Strength

1. The fatigue strength is assessed either

a) on the basis of a damage calculation using Palmgren-Miner's Rule, or

b) in the case of standard stress spectra, using the permissible highest stress range $\Delta\sigma_p$.

2. The damage ratio computed using Palmgren-Miner's Rule must generally not exceed the limit value defined in the Rules for the Classification and Construction of Seagoing Steel Ships ; this quantity is denoted by D* in the following:

$$D = \Sigma\left(\frac{n_i}{N_i}\right) \leq D^*$$

where

n_i = number of stress cycles for the block i of the long-term spectrum, which has to be subdivided into at least 20 blocks

N_i = number of endurable stress cycles which results from the design S-N curve of the detail considered. The design S-N curve has to be corrected for several factors in accordance with the Rules for the Classification and Construction of Seagoing Steel Ships with respect to the mean stress, amongst others.

The design lifetime results from

$$L = 20 \text{ years} / D$$

3. If more than one loading condition is analyzed the assessment can be performed in two ways, as long as the damage ratio D_j has been computed for each loading condition j for a service life of 20 years (cf. Section 3, C.5):

a) Only the most critical loading condition is considered:

$$\text{Max}\left(D_j\right) \leq D^*$$

b) The damage due to all loading conditions is considered, taking into account their probability of occurrence P_j ($\Sigma P_j = 1$).

$$\Sigma\left(P_j \cdot D_j\right) \leq 0{,}7\ D^*$$

Here, a reduced limit value of the damage ratio is used, because less favourable probabilities of certain loading conditions may occur in reality compared to the assumptions made, and because the additional damage due to the changes between the individual loading conditions is not considered.

Alternatively, the additional load cycles due to changing loading condition may be included in the damage calculation, by taking the rainflow counting method into account and making conservative assumptions for the probability of occurrence of the individual loading conditions.

4. For standardized stress spectra, the criterion for the assessment is

$$\Delta\sigma_{max} \leq \Delta\sigma_p$$

where

$\Delta\sigma_{max}$ = highest stress range within the spectrum
$\Delta\sigma_p$ = permissible stress range

The permissible stress range results directly from the Rules for the Classification and Construction of Seagoing Steel Ships, considering the appropriate detail category or design S-N curve, as well as various other factors, such as the mean stress.

5. It is recommended that the results be assessed on the basis of the usage factor U with respect to stress ranges:

$$U = \frac{\Delta\sigma_{max}}{\Delta\sigma_p}$$

When applying Palmgren-Miner's Rule, $\Delta\sigma_p$ results from the condition that with an equivalent spectrum of stress ranges, i.e. having the same shape and number of load cycles, the limit damage ratio D* according to B.2 is reached. The application of the usage factor has the advantage that - due to the relationship with stresses - direct conclusions can be drawn with respect to the necessary reduction of stresses or a possible increase of the detail category. For example, in case of U = 1,2, the stress has to be reduced by 20 % or the detail category increased by 20 %.