RULES FOR CLASSIFICATION

Ships

Edition October 2015

Part 3 Hull

Chapter 7 Finite element analysis
FOREWORD

DNV GL rules for classification contain procedural and technical requirements related to obtaining and retaining a class certificate. The rules represent all requirements adopted by the Society as basis for classification.

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CHANGES – CURRENT

This is a new document.

The rules enter into force 1 January 2016.
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SECTION 1 FINITE ELEMENT ANALYSIS

1 General

1.1 Introduction
This chapter describes modelling techniques, loads, acceptance criteria and required documentation for finite element analysis. Reference is made to Ch.4 Sec.8 for definition of loading conditions and Pt.5 for ship type application when required.

1.2 Calculation methods

1.2.1 The rules cover four levels of finite element analysis:
a) Global direct strength analysis, to assess hull girder strength and to give correct boundary conditions to partial ship structural models and/or local FE models, when applicable.
b) Partial ship structural analysis, to assess the strength of longitudinal hull girder structural members, primary supporting structural members and bulkheads.
c) Local structure analysis, to assess local stress levels for Ultimate Limit State (ULS).
d) Very fine mesh analysis, to assess the local structural details for Fatigue Limit State (FLS), as described in Ch.9.

a) to c) are described in Sec.2 - Sec.4.
The objectives of the analyses together with their applicable acceptance criteria are described in Sec.2 - Sec.4.

1.2.2 For structures such as hatch covers, ramps etc., it will in general be sufficient to carry out a direct frame and girder analysis as described in Ch.6 Sec.6 [2].

1.3 Load scenarios

1.3.1 The calculations shall be based on the most severe realistic loading conditions for the ship, for instance:
— fully loaded
— partly loaded
— ballasted
— during loading/discharging.

1.3.2 General design loads are given in Ch.4 and FE design load combinations for the different ship types are given in Pt.5.

2 Net scantling

2.1 Net scantling application
FE models for ships with class notation ESP shall be based on the net scantling as defined in Ch.3 Sec.2 Table 1. Otherwise, gross scantlings shall be used in FE models.
Buckling capacity assessment shall be based on net scantling as defined in Ch.3 Sec.2 Table 1.
3 Finite element types

3.1 Used finite element types

3.1.1 The structural assessment shall be based on linear finite element analysis of three dimensional structural models.

3.1.2 Two node line elements and four node shell elements are, in general, considered sufficient for the representation of the hull structure. The mesh requirements given in this chapter are based on the assumption that these elements are used in the finite element models. However, higher order elements may also be used. The types of finite elements to be used are given in the Society’s document DNVGL-CG-0127, Finite element analysis, Sec.1.

4 Documentation

4.1 Reporting

4.1.1 When direct strength analyses are submitted for information, such analyses shall be supported by documentation satisfactory for verifying results obtained from the analyses.

4.1.2 The documentation for verification of input shall contain a complete set of information to show the assumptions made and that the model complies with the actual structure. The documentation of the structure may be given as references to drawings with their drawing numbers, names and revision numbers. Deviations in the model compared with the actual geometry according to these drawings shall be documented.

4.1.3 The modelled geometry, material parameters, plate thickness, beam properties, boundary conditions and loads shall be documented preferably as an extract directly from the generated model.

4.1.4 Reaction forces and displacements shall be presented to the extent necessary to verify the load cases considered.

4.1.5 The documentation of results shall contain all relevant results such as:
— type of stress (element/nodal, membrane/surface, normal/shear/equivalent)
— magnitude
— unit
— load case
— name of structure
— structural part presented
— evaluation of the results with respect to the acceptance criteria

5 Computer programs

5.1 Use of computer programs

5.1.1 In general, any computation program recognised by the Society may be employed for structural assessment according to these rules provided the software combines effects of bending, shear, axial and torsional response.
5.1.2 A computer program that has been demonstrated to produce reliable results to the satisfaction of the Society is regarded as a recognised program. Where the computer programs employed are not supplied or recognised by the Society, full particulars of the computer program, including example calculation output, shall be submitted. It is recommended that the designers consult the Society on the suitability of the computer programs intended to be used prior to the commencement of any analysis work.

6 Alternative procedures

Procedures other than those outlined in the rules and associated class guidelines issued by the Society may be accepted on a case by case basis.
SECTION 2 GLOBAL STRENGTH ANALYSIS

1 General

1.1 Introduction

1.1.1 A global FE analysis covers the whole ship and may be required if the structural response of the hull girder cannot otherwise be sufficiently determined, e.g. for ships:
— with large deck openings subjected to overall torsional deformation and stress response, as for Container ships
— without or with limited transverse bulkhead structures over the vessel length, as for Ro-Ro vessels and Car carriers.
— with partly effective superstructure and/ or partly effective upper part of hull girder, as for large Passenger vessels ($L > 150$ m)

Specific requirements for different hull shapes and ship types are given in Pt.5, including required scope for Ultimate Limit State (ULS) and Fatigue Limit State (FLS) analysis.

1.1.2 Global analyses are generally to be based on load combinations that are representative with respect to the responses and failure modes to be evaluated, e.g.: yield, buckling and fatigue.

1.1.3 The objective of the global strength analysis is to obtain a reliable description of the overall hull girder stiffness and to calculate and assess the global stresses and deformations of all primary hull members. Depending on the ship shape and applicable ship type notation, the scope of the global FE analysis is in general to assess and verify compliance with relevant criteria in [4] and Pt.5.

2 Structural model

2.1 General

2.1.1 The global FE model shall extend over the complete ship length, depth and breadth, and represent the actual geometry of the vessel with acceptable accuracy. All main structure contributing or partly contributing to the hull girder strength including all primary supporting members, transverse members, i.e. watertight bulkheads, non-watertight bulkheads, cross deck structures and transverse webs, shall be included in the model.

The omission of minor structures may be acceptable on the condition that the omission does not significantly change the stress response of the structure.

2.1.2 Modelling

The mesh size, model idealisation and boundary conditions to be as described in the Society's document DNVGL-CG-0127, Finite element analysis, Sec.2. Additional modelling requirements are given in Pt.5 and in the Society's class guidelines for the relevant ship types.

3 Loading conditions

3.1 General

The selection of loading conditions and the application of loads will depend on the scope of the analysis. For required ship type specific loading conditions, reference is made to Pt.5. Application of loads is specified in the Society's class guidelines for the relevant ship types.
4 Analysis criteria

4.1 General
The analysis criteria apply for global FE model are described in this section. Where the global FE model is partially or entirely refined to a mesh arrangement as used for partial ship analysis, the analysis criteria for partial ship analysis apply, as given in Sec.3 [4].

4.2 Yield strength
Nominal axial (normal), shear and von Mises stresses derived from a global analysis shall be checked according to the acceptance criteria given in Pt.5 for the relevant ship types. For all plates of the structural members the von Mises stress, $\sigma_{vm}$, in N/mm$^2$, shall be calculated based on the membrane normal and shear stresses of the shell element. The stresses shall be evaluated at the element centroid of the mid-plane (layer), as follows:

$$\sigma_{vm} = \sqrt{\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2}$$

where:

$\sigma_x$, $\sigma_y$ = Element normal membrane stresses, in N/mm$^2$
$\tau_{xy}$ = Element shear stress, in N/mm$^2$

4.3 Buckling strength
All structural elements in FE analysis shall be assessed individually against the buckling requirements as defined in Ch.8 Sec.4.

4.4 Fatigue strength
General assumptions, methodology and requirements for the fatigue strength assessment are given in Ch.9.
SECTION 3 PARTIAL SHIP STRUCTURAL ANALYSIS

Symbols
For symbols not defined in this section, refer to Ch.1 Sec.4.

1 General

1.1 Definitions

1.1.1 Partial ship analysis
The partial ship structural analysis is used for the strength assessment of a part of the ship.

1.1.2 Cargo hold analysis
For ships with a cargo hold arrangement, the partial ship analysis is defined as a cargo hold analysis.

1.1.3 Evaluation area
The evaluation area is an area of the partial ship model, where the verification of results against the acceptance criteria shall be carried out. For a cargo hold structural analysis, evaluation area is defined in [4.1].

1.2 Introduction

1.2.1 The partial ship structural analysis is used for the assessment of scantlings of longitudinal hull girder structural members, primary supporting members and bulkheads. This section gives the requirements for the partial ship structural analysis.

1.2.2 The FE model for partial ship analysis shall extend so that the model boundaries are adequately remote from the evaluation area. The FE model extent for a cargo hold analysis is defined in [2.2.2]. For partial ship analysis other than a cargo hold analysis, the model extent depends on the evaluation area and the structural arrangement and will be decided case by case when required.

1.3 Application

1.3.1 Cargo hold analysis of midship region is mandatory for ships with cargo hold arrangement with \( L > 150 \) m, novel design, or when required for specific ship types, ref. Pt.5 or when found necessary by the Society.

1.3.2 The scantlings assessment shall be carried out as found necessary to ensure the strength of PSM outside of midship is as a minimum equivalent to the area analyzed by FEA.

1.3.3 FE analysis outside midship region may be required if the structure or loads are substantially different from that of the midship region. This analysis is mandatory for some ship types, as given in Pt.5.

1.3.4 Primary supporting members for which FE analysis has not been carried out shall be assessed with a beam analysis as given in Ch.6 Sec.6.

1.3.5 For cargo hold analyses, the finite element model extent, boundary conditions, applicable loading cases and acceptance criteria are given in this section. For some ship types, additional analysis requirements are given in Pt.5. For ships without cargo hold arrangement, the analysis procedures given in this chapter may be applied with a special consideration.
2 Partial ship structural model

2.1 General

2.1.1 Finite element types
Shell elements shall be used to represent plates. Stiffeners shall be modelled with beam elements having axial, torsional, bi-directional shear and bending stiffness. The eccentricity of the neutral axis shall be modelled. Snipped stiffeners and face plates of primary supporting members and brackets shall be modelled using beam or rod elements.

2.1.2 Mesh
The element mesh shall follow the stiffening system as far as practicable, and shall represent the actual plate panels between stiffeners, i.e. \( s \times s \), where \( s \) is the stiffener spacing.

2.1.3 Model idealization
All main longitudinal and transverse structural elements shall be modelled. All plates and stiffeners on the structure, including web stiffeners, shall be modelled. Brackets which contribute to primary supporting member strength and the size of which is not less than the typical mesh size \( (s \times s) \) shall be modelled. Openings shall be represented in the model as specified in the Society’s document DNVGL-CG-0127, *Finite element analysis*, [3.2.2.8].

2.2 Cargo hold structural model

2.2.1 Mid-hold definition
For the purpose of the FE analysis, the mid-hold is defined as the middle hold(s) of a three cargo hold length FE model. In case of foremost and aftmost cargo hold assessment, the mid-hold represents the foremost and aftmost cargo hold including the slop tank if any, respectively.

2.2.2 Extent of model
The longitudinal extent of the cargo hold FE model shall cover three cargo hold lengths. The transverse bulkheads and webframes at the ends of the model can be omitted. Both port and starboard sides of the ship shall be modelled. The full depth of the ship shall be modelled including primary supporting members above the upper deck, trunks, forecastle and/or cargo hatch coaming, if any. The superstructure or deck house in way of machinery space and the bulwark are not required to be included in the model. Exceptions for individual ship types are specified in Pt.5.

2.2.3 Boundary conditions
The cargo hold model shall be supported at the ends to provide constraint of the model and support of the unbalanced forces. The boundary conditions applicable to cargo hold analysis are specified in the Society’s document DNVGL-CG-0127, *Finite element analysis*, Sec.3.

3 Loads and loading conditions

3.1 General

3.1.1 FE load combination definition
A FE load combination is defined as a loading pattern, a draught, a value of still water bending and shear force, associated with a given dynamic load case.
3.1.2 Design load scenarios
The combinations of the ship static and dynamic loads which are likely to impose the most onerous load regimes on the hull structure shall be investigated in the structural analysis. Design loads used for partial ship FE analysis shall be based on the design load scenarios, as given in Ch.4 Sec.7 Table 1. In general, two design load scenarios shall be considered:

— Seagoing conditions with extreme sea loads, where both static and dynamic load components (S+D) are applied
— Harbour and testing conditions, where only static load components (S) are applied.

Other loading scenarios may be required for specific ship types, as given in Pt.5.

3.1.3 Design loads
Design loads for cargo hold partial ship analysis are represented with FE load combinations. When FE Load combinations are specified in Pt.5 for a considered ship type and cargo hold region, these FE Load combinations shall be used in the cargo hold analysis.

3.1.4 Where the loading conditions specified by the designer are not covered by the FE load combinations given in Pt.5, these additional loading conditions shall be examined according to the procedure in the Society's document DNVGL-CG-0127, Finite element analysis, Sec.3.

3.1.5 FE load combination
Each FE load combination consists of a loading pattern and dynamic load cases as given in Ch.4 Sec.2. Each load combination requires the application of the structural weight, internal and external loads and hull girder loads as given in [3.1] and [3.3], respectively.

3.1.6 Load applications
All simultaneously acting hull girder and local loads shall be applied to the model. The application of local and hull girder loads to the FE cargo hold model shall be in accordance with the Society's document DNVGL-CG-0127, Finite element analysis, Sec.3. The application of the specific load for some ship types are given in relevant class guidelines.

3.2 Internal and external loads

3.2.1 External sea pressures
External pressure shall be calculated in accordance with Ch.4 Sec.5. External pressures include static sea pressure, wave pressure and green sea pressure.

3.2.2 Internal loads
Internal loads to be calculated for in accordance with Ch.4 Sec.5 and Ch.4 Sec.6. The specific internal loads for some ship types are given in relevant chapter of Pt.5.

3.3 Hull girder loads

3.3.1 General
The hull girder loads are the combinations of still water hull girder loads and wave induced hull girder loads as specified in Ch.4.

3.3.2 In general, each FE load combination shall be associated with a relevant component of hull girder loads i.e. vertical and horizontal bending moments, shear force and torsional moment. When FE load combinations are not specified in Pt.5 for a considered ship type, the required component of hull girder loads will be decided on case by case basis.
3.3.3 Target values for hull girder loads
For each FE load combination the hull girder loads shall be adjusted to the required target value and location in the model. The target locations for hull girder shear force are at the transverse bulkheads of the mid-hold of the FE model. The target location for hull girder bending moments is, in general, located at the center of the mid-hold of the FE model. The target location for hull girder torsional moments is, in general, located at one of the transverse bulkheads of the mid-hold of the FE model. The hull girder load target calculation procedures are given in the Society’s document DNVGL-CG-0127, *Finite element analysis*, Sec.3.

3.3.4 Application of hull girder loads
Hull girder loads shall be applied to the model according to the procedures for adjustments of shear force, bending moment and torsional moment as described in the Society’s document DNVGL-CG-0127, *Finite element analysis*, Sec.3.

4 Analysis criteria

4.1 Evaluation areas
Verification of results against the acceptance criteria given in [4.2] and [4.3] shall be carried out within the evaluation area of the FE model for all modelled structural members. In cargo hold analysis the mid-hold, as defined in [2.2.1], represents the evaluation area with the following structural members:

— all hull girder longitudinal structural members,
— all primary supporting structural members and
— bulkheads, inclusive forward and aft transverse bulkheads of the mid-hold.

4.2 Yield strength assessment

4.2.1 Von Mises stress
For all plates of the structural members within evaluation area, the von Mises stress, $\sigma_{vm}$, in N/mm$^2$, shall be calculated based on the membrane normal and shear stresses of the shell element. The stresses shall be evaluated at the element centroid of the mid-plane (layer), as follows:

$$\sigma_{vm} = \sqrt{\sigma_x^2 - \sigma_y^2 + \tau_{xy}^2 + \sigma_y^2 + 3\tau_{xy}^2}$$

where:

$\sigma_x, \sigma_y$: element normal membrane stresses, in N/mm$^2$
$\tau_{xy}$: element shear stress, in N/mm$^2$.

4.2.2 Axial stress in beams and rod elements
For beams and rod elements, the axial stress, $\sigma_{axial}$, in N/mm$^2$, shall be calculated based on axial force alone. The axial stress shall be evaluated at the middle of element length.

4.2.3 Yield criteria
The structural elements given in [4.1] shall comply with the following criteria:

$$\lambda_y \leq \lambda_{yperm}$$

where:
\[ \lambda_y = \text{yield utilisation factor} \]
\[ \lambda_y = \frac{\sigma_{vm}}{R_y} \text{ for shell elements in general.} \]
\[ \lambda_y = \frac{\sigma_{axial}}{R_y} \text{ for rod or beam elements in general.} \]
\[ \sigma_{vm} = \text{von Mises stress, in N/mm}^2 \]
\[ \sigma_{axial} = \text{axial stress in rod or beam element, in N/mm}^2 \]
\[ \lambda_{yperm} = \text{coarse mesh permissible yield utilisation factors defined in Table 1.} \]

a) The yield check criteria shall be based on axial stress for the following members:
   — the flange of primary supporting members,
   — the intersections between the flange and web of the corrugations, according to [4.2.5].

b) Where the von Mises stress of the elements in the cargo hold FE model in way of the area under investigation by fine mesh exceeds the yield criteria, average von Mises stress, obtained from the fine mesh analysis, calculated over an area equivalent to the mesh size of the cargo hold finite element model shall satisfy the yield criteria above.

c) In way of cut-outs, yield utilisation factor shall be obtained with shear stress correction, as given in [4.2.7].

4.2.4 Coarse mesh permissible yield utilisation factors
The permissible coarse mesh yield utilisation factors, \( \lambda_{yperm} \), given in Table 1, are based on the element types and the mesh size described in [2.1.2] and [2.1.3], respectively.

The yield utilisation factor resulting from element stresses of each structural component shall not exceed the permissible values as given in Table 1.

<table>
<thead>
<tr>
<th>Structural member</th>
<th>Acceptance criteria</th>
<th>Load components</th>
<th>( \lambda_{yperm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plating of all longitudinal hull girder structural members, primary supporting structural members and bulkheads. Dummy rod of corrugated bulkhead. Face plate of primary supporting members modelled using shell or rod elements.</td>
<td>AC-I</td>
<td>S</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>AC-II</td>
<td>S + D</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>AC-III(1)</td>
<td>A, T</td>
<td>1.00</td>
</tr>
<tr>
<td>Corrugation of corrugated bulkheads under lateral pressure from liquid loads, for shell elements only.</td>
<td>AC-I</td>
<td>S</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>AC-II</td>
<td>S + D</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>AC-III(1)</td>
<td>A, T</td>
<td>0.90</td>
</tr>
</tbody>
</table>

1) For members of the collision bulkhead, AC-I shall be used.

4.2.5 Corrugation of corrugated bulkhead
The stress in corrugation of corrugated bulkheads shall be evaluated based on:

a) The von Mises stress, \( \sigma_{vm} \), in shell elements on the flange and web of the corrugation.

b) The axial stress, \( \sigma_{axial} \), in dummy rod elements, modelled with unit cross sectional properties at the intersection between the flange and web of the corrugation.
4.2.6 Simplified shear stress correction for openings
The correction of element yield utilization due to presence of cut-outs may be carried out by a simplified correction. The yield criteria given in [4.2.3] shall be satisfied based on the following yield utilisation factor:

\[ \lambda_y = \frac{\lambda_{y, FE}}{C_r} \]

where:

- \( \lambda_{y, FE} \) = yield utilisation factor from FE assessment with openings not reflected in the model
- \( C_r \) = reduction factor for yield criteria as given in Table 2.

Where the shall not above is not satisfied, the criteria given in [4.2.7] shall be applied.

**Table 2 Simplified shear stress correction**

<table>
<thead>
<tr>
<th>Identification</th>
<th>Figure</th>
<th>Difference between modelled shear area and the effective shear area in % of the modelled shear area</th>
<th>Reduction factor for yield criteria, ( C_r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper and lower slots for local support stiffeners fitted with lugs or collar plates</td>
<td><img src="image1" alt="Figure" /></td>
<td>( \frac{h - h_{eff}}{h} \cdot 100% ) &lt; 15 %</td>
<td>0.85</td>
</tr>
<tr>
<td>Upper or lower slots for local support stiffeners fitted with lugs or collar plates</td>
<td><img src="image2" alt="Figure" /></td>
<td>( \frac{h - h_{eff}}{h} \cdot 100% ) &lt; 20 %</td>
<td>0.80</td>
</tr>
</tbody>
</table>
### 4.2.7 Shear stress correction for cut-outs

The element shear stress in way of cut-outs in webs shall be corrected for loss in shear area in accordance with the following formula. The corrected element shear stress shall be used to calculate the von Mises stress of the element for verification against the yield criteria.

\[
\tau_{cor} = \frac{h}{h_{eff}} \tau_{elem}
\]

where:

- \(\tau_{cor}\) = corrected element shear stress, in N/mm\(^2\)
- \(h\) = height of web of girder, in mm, in way of opening, see Table 1. Where the geometry of the opening is modelled, \(h\) shall be taken as the height of web of the girder deducting the height of the modelled opening
- \(h_{eff}\) = effective web height, in mm, deducting all openings, including slots for stiffeners, calculated in accordance with Ch.3 Sec.7 [1.4.7]
- \(\tau_{elem}\) = element shear stress, in N/mm\(^2\), before correction.

In case of difference between the effective thickness and the modelled thickness, the shear stress correction shall be adjusted by the ratio between the modelled thickness and the effective thickness.

### 4.2.8 Use of mesh other than s x s

Where the geometry cannot be adequately represented in the cargo hold model and the stress exceeds the cargo hold mesh acceptance criteria, a finer mesh may be used for such geometry to demonstrate satisfactory scantlings. The mesh size required for such analysis can be governed by the geometry. In such cases, the area weighted von Mises stress within an area equivalent to that specified in [2.1.2] shall comply with the shall nots given in [4.2.3].

### 4.3 Buckling strength assessment

All structural elements in FE analysis carried out in accordance with this section shall be assessed individually against the buckling shall nots as defined in Ch.8 Sec.4.
SECTION 4 LOCAL STRUCTURAL STRENGTH ANALYSIS

Symbols
For symbols not defined in this section, refer to Ch.1 Sec.4.

1 Objective and scope

1.1 General

1.1.1 Local structural strength analysis shall be carried out on structural details which are required by ship type specific rules in Pt.5 or optional class notations stated in Pt.6. Such analysis may also be required for other details considered critical.

1.1.2 Local FE strength analysis may be required for longitudinals subject to large relative deflections. Double brackets with soft toe may be sufficient to accommodate the increased bending stress at transverse bulkhead.

1.1.3 The structural details shall be assessed by fine mesh FE analysis according to the general principles stated in this section. Detailed procedures are given in the Society’s document DNVGL-CG-0127, Finite element analysis, Sec.4.

1.1.4 The selection of critical locations on the structural members and the fine mesh structural models shall be in accordance with the requirements given in the Society’s document DNVGL-CG-0127, Finite element analysis, Sec.4 in general and in class guidelines for specific ship types issued by the Society.

1.1.5 For details where very high surface stresses are expected, an advanced analysis of hot-spot stresses covering both low cycle and high cycle fatigue may be required, see the Society’s document DNVGL-CG-0129, Fatigue assessment of ship structures. Such analysis may also be accepted in lieu of local structural strength analysis according to this section.

2 Structural modelling

2.1 General

2.1.1 The fine mesh analysis may be carried out by means of a separate local finite element model with fine mesh zones, in conjunction with the boundary conditions obtained from the partial ship FE model or global FE model. Alternatively, fine mesh zones may be incorporated into the partial ship model.

2.1.2 Model extent
The extent of the local finite element models shall be such that the calculated stresses at the areas of interest are not significantly affected by the imposed boundary conditions and application of loads.

2.1.3 Fine mesh zone
The fine mesh zone shall represent the localized area of high stress. The finite element mesh size within the fine mesh zones shall be not greater than 50mm x 50mm. In general, the extent of the fine mesh zone shall not be less than 10 elements in all directions from the area under investigation.
3 Load combinations

3.1 General
The fine mesh analysis shall be carried out for all FE load combinations applied to the corresponding partial ship or global FE analysis.

3.2 Application of loads and boundary conditions
Where a separate local model is used for the fine mesh detailed stress analysis the displacements or forces from the partial ship model (or global model) shall be applied to the corresponding boundary contour on the local model. All loads, including local loads and loads applied for hull girder bending moment and/or shear force adjustments, in way of the structure represented by the separate local finite element model shall be applied to the model.

4 Analysis criteria

4.1 Reference stress
Reference stress is von Mises stress, $\sigma_{vm}$, which shall be calculated based on the membrane direct axial and shear stresses of the plate element evaluated at the element centroid.

4.2 Acceptance criteria

4.2.1 The acceptance criteria as given in [4.2.2] are applicable for structural details and conditions given in [1.1]. For other structural details, the acceptance criteria may be considered on a case by case basis.

4.2.2 The structural assessment shall demonstrate that the von Mises stresses obtained from the fine mesh finite element analysis do not exceed the maximum permissible stress, as follows:

$$\lambda_f \leq \lambda_{perm}$$

where:

$\lambda_f = \text{fine mesh yield utilisation factor}$

$$\lambda_f = \frac{\sigma_{vm}}{R_Y} \text{ for shell elements in general}$$

$$\lambda_f = \frac{\sigma_{axial}}{R_Y} \text{ for rod elements in general}$$

$\sigma_{vm} = \text{von Mises stress, in yield N/mm}^2$

$\sigma_{axial} = \text{axial stress in rod element, in N/mm}^2$

$\lambda_{perm} = \text{permissible fine mesh utilisation factor as given in Table 1}$

The structural assessment shall satisfy the following:
a) The maximum permissible stresses are based on the mesh size of 50 mm × 50 mm. Where a smaller mesh size is used, an average von Mises stress calculated in accordance with [4.1] over an area equal to the specified mesh size may be used to compare with the permissible stresses.

b) Average von Mises stress shall be calculated based on weighted average against element areas:

\[
\sigma_{vm-av} = \frac{\sum_{i=1}^{n} A_i \sigma_{vm-i}}{\sum_{i=1}^{n} A_i}
\]

where:

- \(\sigma_{vm-av}\) is the average von Mises stress.

c) Stress averaging shall not be carried across structural discontinuities and abutting structure.

**Table 1 Permissible fine mesh yield utilisation factor \(\lambda_{yperm}\)**

<table>
<thead>
<tr>
<th>Structural member</th>
<th>Acceptance criteria</th>
<th>Load components</th>
<th>(\lambda_{yperm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements not adjacent to weld</td>
<td>AC-I</td>
<td>S</td>
<td>1.36 (f_f)</td>
</tr>
<tr>
<td></td>
<td>AC-II</td>
<td>S + D</td>
<td>1.70 (f_f)</td>
</tr>
<tr>
<td></td>
<td>AC-III(^1)</td>
<td>A, T</td>
<td>2.04</td>
</tr>
<tr>
<td>Elements adjacent to weld</td>
<td>AC-I</td>
<td>S</td>
<td>1.20 (f_f)</td>
</tr>
<tr>
<td></td>
<td>AC-II</td>
<td>S + D</td>
<td>1.50 (f_f)</td>
</tr>
<tr>
<td></td>
<td>AC-III(^1)</td>
<td>A, T</td>
<td>1.80</td>
</tr>
</tbody>
</table>

where:

- \(f_f\) = Fatigue factor taken as:
  - \(= 1.0\) in general
  - \(= 1.2\) for details where fatigue strength is verified by hot spot stresses based on very fine mesh finite element analysis, ref. Ch.9 Sec.3 [4].

1) For members of the collision bulkhead, AC-I shall be applied.
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