Direct Calculations for Special Service Craft of Metallic Construction

August 2015
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DIRECT CALCULATIONS FOR SPECIAL SERVICE CRAFT OF METALLIC CONSTRUCTION, August 2015

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Glossary of Symbols

\( k_L \) = Higher tensile steel factor (see Pt 6, Ch 2,2.4 of the Rules and Regulations for the Classification of Special Service Craft)

\( \rho \) = Density of sea-water in t/m\(^3\)

\( g \) = Gravitational constant to be taken as 9.81 m/sec\(^2\)

\( h \) = Local head for pressure evaluation in metres

LCG = Longitudinal Centre of Gravity

\( \sigma_0 \) = Specified minimum yield stress or 0.2 per cent proof stress (as appropriate) of material in N/mm\(^2\)

\( \tau_{\text{shear}} \) = Shear stress in N/mm\(^2\)

\( \sigma_x \) = Direct stress in element x direction in N/mm\(^2\)

\( \sigma_y \) = Direct stress in element y direction in N/mm\(^2\)

\( \tau_{xy} \) = Shear stress in element in xy plane in N/mm\(^2\)

\( \sigma_e \) = Von Mises equivalent stress in N/mm\(^2\) = \( \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3 \tau_{xy}^2} \)

\( \sigma_{cr} \) = Critical buckling stress in N/mm\(^2\)

\( \sigma_{\text{axial}} \) = Axial stress in N/mm\(^2\)

\( \sigma_{\text{extreme fibre}} \) = Stress in extreme fibres in N/mm\(^2\)

\( \sigma_{\text{actual}} \) = Equivalent design stress in N/mm\(^2\)

\( E \) = Materials - Young’s Modulus

\( L_e \) = Effective length of pillar, in mm (generally taken as 0.8 overall length of pillar)

\( r \) = Least radius of gyration of pillar cross-section, in mm

\( \lambda \) = Factor against elastic buckling = \( \frac{\sigma_{cr}}{\sigma_{\text{actual}}} \)

\( t \) = Thickness of the thinnest plate in way of area of interest in mm

\( \delta_n \) = Translation in the n direction in metres

\( \theta_n \) = Angular rotation in the n direction in radians

NOTE: Compressive stress is to be represented as a negative value.

Introduction

Section 1
General requirements

1.1 The guidance set out in this document is to provide direction on the suitable modelling, assessment and presentation of the strength structure of Special Service Craft (SSC) of metallic construction using finite element methods.

1.2 SSC are those defined in the Rules and Regulations for the Classification of Special Service Craft (hereinafter referred to as Rules for Special Service Craft), Pt 1, Ch 2, Section 2.

1.3 This guidance is intended to be used in conjunction with the Rules for Special Service Craft and does not cover trimarans. Rules and procedures for the direct calculation of trimaran structures can be found in Volume 4 of the Rules for the Classification of Trimarans.

1.4 In addition, this document does not extend to providing specific guidance on fatigue calculations. Although direct calculation may take a number of forms, e.g. formulaic calculation, matrix analysis etc., for the purposes of this document, it is assumed that where direct calculations are discussed in the Rules for Special Service Craft, the reference is to Finite Element Analysis (FEA) methods.

1.5 Direct calculations are required for craft with Rule lengths (as defined in Pt 3, Ch 1, Section 6 of the Rules for Special Service Craft) greater than:
1.6 Direct calculations may also be specifically required for craft of a novel or unconventional design (as per Pt 3, Ch 1,1.2 of the Rules for Special Service Craft), or for specific features of a craft where the craft has novel features, or in support of alternative arrangements and scantlings. Examples may include but are not limited to the following scenarios:

- Where it is required to utilise the load carrying capability of the superstructure for longitudinal strength.
- Where openings are proposed in the webs of stiffeners or primary stiffeners, and the openings are not in compliance with rule requirements.
- Local structural support for equipment foundations.
- Arrangements with large side openings, e.g. large side shell openings or superstructures with large cut-outs for windows or doors.

1.7 Additional areas and scenarios which may require direct calculations may be found throughout the relevant sections of the Rules for Special Service Craft.

1.8 Direct calculations may also be carried out on a voluntary basis.

1.9 Where submitted and contracted, direct calculations will receive individual consideration based on the general standards of the Rules for Special Service Craft.

1.10 Lloyd’s Register (hereinafter referred to as LR) may, when requested, undertake calculations on behalf of designers or Builders and make recommendations in regard to suitability and verification.

1.11 Direct calculation for SSC craft or components requires:

- A detailed analysis of load cases that the craft and or component will be exposed to, or a suitable estimation based on an agreed model, e.g. Lloyd’s Register Global strength model.
- A structural idealisation of the craft or component.
- Calculation carried out using FEA, including mesh refinements as applicable.
- Presentation of model, load cases, results and analysis in report format.

1.12 Direct calculations considered herein are to be based on three-dimensional finite plate elements and carried out in accordance with the procedures contained in this guidance. Models consisting only of beam elements are not covered by this document.

1.13 The full craft (global analysis) direct calculation procedure comprises two parts:

- PART A, which considers verification of global strength and identification of high stress areas using a model of the full craft.
- PART B, which considers verification of the structural response of components and details using follow-up fine mesh models.

1.14 The analysis of the local details, direct calculation procedure comprises a single part:

- PART B, which considers verification of the structural response of components and details using fine mesh models.

1.15 Analysis of primary structure may also be undertaken using a limited extent model created in accordance with the guidelines in PART A and, where necessary, followed up with local detail analysis in accordance with the guideline in PART B.

1.16 A detailed report of the calculations is to be submitted and must include the information listed in Section 2 of this INTRODUCTION.

1.17 If the computer programs employed in creating and solving the structural model are not recognised by LR, then full particulars of the program will also require to be submitted (see Pt 3, Ch 1.3.1.3 of the Rules for Special Service Craft).

1.18 LR may, in certain circumstances, require the submission of computer input and output to further verify the adequacy of the calculations carried out.

1.19 Where alternative procedures are proposed, these should be agreed with LR before commencement of calculation to ensure acceptable submission (see also 1.21).

1.20 Craft of unusual form or structural arrangements may need special consideration, and additional calculations to those contained in this procedure may be required.

1.21 It is recommended that the designer discusses the proposed calculation with LR at an early stage of the design process. A calculation proposal may be submitted to the local office for review prior to the commencement of the analysis.

1.22 The responsibility for error free specification and input of program data, and the subsequent correct transposal of output, rests with the designer/Builder.

1.23 For craft of an unusual hull form, a suitable ‘loads and motions’ study may need to be performed, in order to verify the applicability of the Rule design vertical wave loadings.
Section 2
Direct calculation report

2.1 A report is to be submitted to LR for approval of the primary structure of the craft and/or the local supporting structure of a component, which is to contain the following information:

- A list of plans used, including dates and versions.
- A detailed description of structural modelling, including all modelling assumptions.
- Acceptance criteria.
- Plots to demonstrate correct structural modelling and assigned properties.
- Full details of material properties used for all components, including acceptance criteria.
- Plots showing the extents of each material (and condition, where appropriate) used in the structure.
- Details of boundary conditions.
- Details of all loading conditions applied with calculated shear force and bending moment distributions.
- Details of applied loadings, and confirmation that individual and total applied loads are correct.
- Details of boundary support forces and moments.
- Plots and results that demonstrate the correct behaviour of the structural models to the applied loads.
- Summaries and plots of global and local deflections.
- Summaries and sufficient plots of von Mises, and directional (mid-plane or extreme fibre as required) surface) and shear stresses to demonstrate that the design criteria has not been exceeded in any member.
- Summaries and sufficient plots of direct element stress in longitudinal, transverse and vertical directions for each member of relevance.
- Summaries and plots demonstrating compliance with any additional strain and elongation acceptance criteria where present.
- Stress plots showing maximum stress and all areas where the allowable stress is exceeded (where applicable).
- Figures that are suitably clear and sized to allow easy interpretation.
- Plate buckling analysis and results.
- Pillar buckling analysis and results (where applicable).
- Tabulated results showing compliance, or otherwise, with the design criteria.
- Conclusion that the stress/deflection criteria are not exceeded under the given loads.

NOTE: Where deficiency is identified, proposed amendments to structure may be presented. In such a case, a revised assessment of stresses and buckling capabilities is also to be detailed. However, care should be taken that inclusion of amendments in the Report is limited, as the Report should generally be limited to the analysis of the final proposed structural arrangement only.

Section 3
Model extents (full craft/PART A models)

3.1 Full craft models are typically to extend over the full length and depth of the craft, including all pillars, hull and superstructure, structural longitudinal members and plating. Similarly, all transverse primary structures, e.g. watertight and other structural bulkheads, are to be included in the model.

3.2 Where the craft is a multi-hull, the extents of transverse structure required in the model will be specially considered. When run, the model should accurately represent the torsional and splitting behaviour of multi-hull craft.

3.3 The model is to represent, with reasonable accuracy, the actual geometric shape of the hull and superstructure.

3.4 Weld throats and deck equipment need not be modelled, see also PART A, Section 4, 4.3.

3.5 The model may be full or half-breadth, depending upon the degree of structural symmetry. Asymmetric designs may not be modelled using a half-breadth model.

3.6 Openings, such as portlights, windows, hatches and shell doors, should be represented.

Section 4
Model extents (primary structure/ PART A models)

4.1 For models considering truncated areas of the hull for the purposes of primary structure analysis, the model should extend longitudinally and transversely between the bulkheads and/or the shell, and vertically between decks and/or shell. The model should include all pillars, hull and superstructure structural longitudinal members and plating. Similarly, all transverse primary structures, e.g. watertight and other structural bulkheads, are to be included in the model, within the model extents. Care should be taken not to over constrain such bounding supporting structure.

4.2 Primary structure models are to comply with 3.2 to 3.6 of this INTRODUCTION.

4.3 The acceptance requirements in this case are to be considered as those listed in the failure modes control Chapters of the Rules for Special Service Craft Parts 6 and 7, for steel and aluminium structures respectively.
Section 5
Model extents (local detail/ PART B models)

5.1 For detail models, the model extents are to be such that the effect of the local/ component loading dissipates, at model boundaries, to a level lower than that associated with the relevant SSC design loading. Alternatively, the extent of the model is to be chosen carefully such that its boundaries coincide with bulkheads or primary members, such as girders and floors, provided these items are additionally modelled to allow visibility of the stresses induced in the supporting structure by the component. Care should be taken not to over constrain such bounding supporting structure.

5.2 The model should accurately represent, with reason, all local structure appropriate to the item of investigation, subject to the requirements of 4.1 of this INTRODUCTION, including brackets, pillars, plating, stiffeners, primary members and rider bars (sniped, as required).

5.3 Weld throats and deck equipment need not be modelled, see also PART A, Section 4, 4.3.

5.4 Where applicable, the model may be suitably truncated, providing the correct application of a symmetric boundary condition is applied.

5.5 All openings and appendages should be accurately modelled. Such items include, but are not necessarily limited to:

- Portlights, windows, doorways, hatches, shaft-lines and bulwarks.

5.6 Openings in primary and secondary member webs are to be modelled, including compensation arrangements. Note that it may not be necessary to model openings such as drainage or limber-holes; the requirement for such should be discussed with LR.
PART A – Global Response Analysis

Section 1
Application

1.1 For the application of PART A, see 1.1 and 1.13, of the INTRODUCTION.

Section 2
Objectives

2.1 The objectives of PART A of this guidance are:
(a) To derive the stress distribution over the complete cross-section and length of the craft, taking due account of the behaviour and effectiveness of the superstructure; and further, to ensure that the global hull stresses are in compliance with the Rules for Special Service Craft.
(b) To provide boundary conditions for the fine mesh models required by PART B of this guidance for the investigation of the detailed stress and deflection response of important structural components, e.g.:
   • Structure in way of windows and other significant shell, superstructure or bulkhead openings.
   • Hull cross-deck structure and cross-deck hull connections for multi-hulls.

Section 3
Structural modelling

3.1 Model extents are to be in accordance with Section 3 of the INTRODUCTION.

3.2 The FEA model is to be represented using a right handed Cartesian co-ordinate system with:
   • \( x \) measured in the longitudinal direction, positive forwards of the aft perpendicular.
   • \( y \) measured in the transverse direction, positive to port from the centreline.
   • \( z \) measured in the vertical direction, positive upwards from the baseline.

3.3 The proposed scantlings, excluding Owner’s extras, are to be incorporated in the model. All primary structure, such as deep beams, girders, deck plating, bottom and side shell plating, longitudinal and transverse bulkhead plating, transverse floors, superstructure side and internal structural walls, are to be represented by membrane plate elements.

3.4 Secondary members, such as panel stiffeners, may be individually represented by line elements with appropriate axial and bending properties. Where appropriate, a single line element may represent more than one secondary stiffener.

3.5 Pillars are to be represented by line elements having axial and bending stiffness.

3.6 The size and type of plate elements selected are to provide a satisfactory representation of the deflection and stress distribution within the craft’s structure. In general, the plate element mesh is to follow the primary stiffening arrangement. Hence, it is anticipated that there will be:
   • Longitudinally, at least one element between web frames or main frames.
   • Transversely, one element between stiffeners or longitudinals.
   • Vertically, elements suitable for the locations of stiffeners and longitudinals and/or to maintain suitable aspect ratios.

3.7 It may be necessary to refine the mesh arrangement to achieve satisfactory aspect ratios in accordance with the remaining clauses of this Section. The basic mesh arrangement should also permit the inclusion of the features listed in 3.9 and the alignment required as per 3.8.

3.8 Meshing of the superstructure is to be similar to that of the hull, such that the alignment of the mesh at the intersection of the hull and superstructure is effectively continuous.

3.9 Window, door and large shell openings are to be modelled such that the deformation pattern under hull shear and bending loads is adequately represented. Any idealisation adopted is to be verified by means of check models and comparison with the performance of suitable fine mesh models; the overall deflection of the comparative models is to be of the same order of magnitude.

3.10 Where computing power, run time, model file size, and clarity of display and reporting allow, fine meshes at relevant areas may be incorporated into coarse mesh full craft models, without the need to create a separate models for specific areas of investigation.

3.11 Figures 1 and 2 illustrate an example of how a coarse mesh might be applied to a full craft model; note, however, that these images represent a first pass effort. The illustrated mesh was further refined to incorporate the above requirements before submission to LR.
Section 4

Loading

4.1 The FEA model is to be loaded in accordance with the global loading and design criteria defined in Pt 5, Ch 5 of the Rules for Special Service Craft. Alternative methods of establishing global loadings and design criteria will be specially considered, provided they are based on model tests, full scale measurements, or other generally accepted methods. In such cases, full details of the methods used are to be discussed and agreed with LR, before commencement of FEA modelling.
4.2 Additionally for multi-hull craft, design transverse and torsional moments are to be stipulated, and load combinations for head, beam and quartering seas are to be presented.

4.3 Deck equipment operational loading need not be modelled where it is not to be used at sea or where it is to be separately analysed as laid out in PART B. However, self-weight of such items (including the effect of shipboard accelerations) is to be included in the model.

4.4 Calculation and subsequent application to the FEA model of still water shear forces and bending moments is to cover the range of load and ballast conditions proposed. Still water, static wave, dynamic bending moments, and shear forces are to be calculated for both departure and arrival conditions. The extent of load cases may be discussed with LR, prior to submission of the FEA. Further guidance may be found in Section 2, Chapter 6, of Parts 6 and 7 of the Rules for Special Service Craft, respectively.

4.5 Additionally for multi-hulls, transverse and torsional moments should also be considered in accordance with the Rules. Load cases are defined for head, beam and quartering seas (see also Pt 5, Ch 5, Section 5 of the Rules). Further guidance may be found in Section 3, Chapter 6 of Parts 6, and 7 of the Rules for Special Service Craft, respectively.

4.6 Additionally for sailing craft, rig loadings are to be considered (see Pt 4, Ch 3,1.2.1 of the Rules). This may include the induced torsional effects of rig loads and counteracting righting loads. Load cases to be considered are to be discussed with LR, prior to submitting the direct calculations report.

Other points to note:
- Dynamic bending moments and shear forces are to be considered as appropriate (see Pt 5, Ch 5, Section 5 of the Rules).
- Rig loadings are to be added to the still water conditions where applicable.
- Vehicle loadings are to be added to the still water conditions where applicable (see 4.7).

4.7 Where applicable, vehicle deck loads should be applied to the model. Vehicle loads are to be in accordance with Ch 3, Section 3 of LR's ShipRight Procedure - Structural Design Assessment Primary Structure of Ro-Ro Ships.

4.8 At the request of LR, a racking case may also need to be considered. This comprises of the self-weight of the structure and outfitting with the craft, fixed at an angle of heel of 30º. Where appropriate, e.g. for multihull vessels, alternative proposals for racking loadings in place of the 30º heel will be specially considered.

4.9 The induced stresses and factors against buckling arising from the following combined load cases are to be compared with the acceptance criteria in PART A, Section 6:
- Hogging bending moment case, the combination of:
  - Still water (hogging); and
  - Rule hogging design wave bending moment.
- Sagging bending moment case, the combination of:
  - Still water (sagging or minimum hogging); and
  - Rule sagging design wave bending moment.
- Hogging shear force case, the combination of:
  - Still water hogging; and
  - Rule hogging wave shear force.
- Sagging shear force case, the combination of:
  - Still water (sagging or minimum hogging); and
  - Rule sagging wave shear force.
- Racking case (see PART A, Section 4, 4.7)
- Multi-hull loads (see PART A, Section 4, 4.6).

4.10 In constructing the load cases referred to in PART A, Section 4, 4.9, the load components given in Table 1 are to be included.

4.11 For a half-breadth model, only the loads applicable to one half of the model are to be applied. These loads are to be derived in the same manner as that required for a full-breadth model.

4.12 Loading of the model may be achieved by application of gravity force on the modelled mass distribution, together with buoyancy pressures with reference to suitable surface definition, and factored if necessary; and/or by applying sets of distributed forces on the model; or by a combination of both.

4.13 Model loading may require factorisation, e.g. where there is a variation between the bending moment generated by the applied load distribution and the Rule bending moments. Guidance in stress factorisation and its applicability can be found in PART A, Ch 1, 6.1, 6.2.4, 6.3.3 and Appendix B of LR's ShipRight Procedure - Structural Design Assessment Primary Structure of Passenger Ships.
### Table 1 List of load components for full craft FE model

<table>
<thead>
<tr>
<th>Load cases</th>
<th>Load components</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still water (hogging)</td>
<td>Material weight</td>
<td>As generated from the modelled area, suitably factored to achieve the specified material weight including the position of the LCG. In this regard, it may be useful to divide the model longitudinally into a number of material zones, each having a separate factored value of material density.</td>
</tr>
<tr>
<td>Still water (sagging or minimum hogging)</td>
<td>Machinery and outfit</td>
<td>All major items to be applied as point loads or pressure loads at their correct locations (see Note 1). Minor or unknown items may be included in the steel weight.</td>
</tr>
<tr>
<td>Deadweight items</td>
<td>Applied as distributed pressure to relevant deck areas.</td>
<td></td>
</tr>
<tr>
<td>Buoyancy loads</td>
<td>To be applied as pressure loads, ( \rho gh ), to wetted shell elements, where ( h ) is the vertical distance from the waterline to the element centroid below the still waterline.</td>
<td></td>
</tr>
<tr>
<td>Tank loads</td>
<td>To be applied as pressure loads or nodal forces at the tank base or boundary, based on the actual liquid head. Any over-pressurisation of the tank is to be omitted.</td>
<td></td>
</tr>
<tr>
<td>Vehicle loads</td>
<td>Vehicle loads are to be applied, as specified in Pt 6, Ch 5.3 or Pt 7, Ch 5.3 of the Rules for Special Service Craft, respectively.</td>
<td></td>
</tr>
<tr>
<td>Rig loads</td>
<td>To be defined by the designer and applied as distributed pressure to relevant structure.</td>
<td></td>
</tr>
<tr>
<td>Rule hogging design vertical wave bending moment</td>
<td>Rule design vertical wave bending moment (see Note 5)</td>
<td>Incremental forces are to be applied to the shell nodes below the waterline at the bulkhead positions to represent the incremental shear force change. When integrated along the craft length, the incremental shear forces are to generate the Rule design vertical wave bending moment distribution. (See PART A, Section 4.4 and Note 2)</td>
</tr>
<tr>
<td>Rule sagging design vertical wave bending moment</td>
<td>Rule wave shear force</td>
<td>Incremental forces are to be applied along the length of the craft as forces acting in the plane of the bulkhead position in the craft. When integrated along the craft length, the incremental force values are to generate the Rule wave shear force distribution. (See Notes 2 and 4)</td>
</tr>
<tr>
<td>Rule hogging wave shear force</td>
<td>Lightweight and deadweight items</td>
<td>Applied to simulate a 30° static heel angle. (See Notes 2 and 3)</td>
</tr>
<tr>
<td>Rule sagging wave shear force</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTES**

1. Major items such as rudder, main generators, etc., are to be included.
2. No other load components are to be included.
3. Including tanks and swimming pool above the bulkhead deck only.
4. These conditions need not be run if the shear force distribution derived from the wave bending moment load cases represents the rule shear force distribution.
5. Guidance on the application of vertical wave bending moment can be found in PART A, Ch 1.4.6 of LR’s *ShipRight Procedure - Structural Design Assessment Primary Structure of Passenger Ships*. 

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**Rule hogging design vertical wave bending moment**

**Rule sagging design vertical wave bending moment**

**Rule hogging wave shear force**

**Rule sagging wave shear force**

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**Racking condition (see PART A, Section 4.4.8)**

**Lightweight and deadweight items**

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Section 5
Boundary conditions

5.1 The loading cases specified in PART A, Section 4, 4.9 require boundary conditions as given in Table 2 and Table 3 for mono-hulls and multi-hulls, respectively.

5.2 The boundary conditions specified in Table 4, combined with those in Table 2, are appropriate for a half-breadth model.

5.3 As an alternative to the requirements of Table 2 and Table 4, a suitable set of equivalent boundary conditions may be used, provided that there is no net imbalance of load in any of the six degrees of freedom. Proposals will be specially considered and should be discussed with LR.

Table 2 Boundary conditions for a mono-hull full craft (full-breadth) model

<table>
<thead>
<tr>
<th>Load cases</th>
<th>Boundary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still water cases</td>
<td>The model is to be free of imposed constraints, except for those necessary to prevent rigid body motion. Rigid body motions may be prevented by the use of free-body constraints (e.g. the Inertia Relief facility in NASTRAN FE software package). Alternatively, a suitable set of equivalent constraints may be used. (See Notes 1 and 3)</td>
</tr>
<tr>
<td>Wave bending moment cases</td>
<td></td>
</tr>
<tr>
<td>Wave shear force cases</td>
<td></td>
</tr>
<tr>
<td>Racking</td>
<td>The boundary conditions for model nodes at the intersection of the racking structure with the uppermost hull weather deck (as applicable) will be arrangement specific, but are generally to be constrained against translation. (See Note 2)</td>
</tr>
</tbody>
</table>

NOTES
1. Care is to be taken to ensure that, within practicable limits, there is no net imbalance of load or moments in any of the six degrees of freedom.
2. Where a half-craft model is employed, the racking analysis loadings will require to be subdivided into symmetric and anti-symmetric components with appropriate boundary conditions (see also Note 3).
3. Care is to be taken to ensure that the FE model is not over-constrained.
Table 3  Boundary conditions for a multi-hull full craft (full-breadth) model

<table>
<thead>
<tr>
<th>Load cases</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still water cases (including rig loads where applicable)</td>
<td>Global constraints should be avoided by the use of free body supports, which are to be arranged as required to provide the necessary reference points for 'Inertia Relief' type constraint. This type of constraint uses the accelerations caused by imbalanced loading, and applies a set of internal forces distributed throughout the model in order to obtain equilibrium.</td>
</tr>
<tr>
<td>Wave bending moment cases</td>
<td>(See also Note 1)</td>
</tr>
<tr>
<td>Wave shear force cases</td>
<td>(See also PART A, Section 4, 4.8)</td>
</tr>
<tr>
<td>Racking</td>
<td>The boundary conditions for model nodes at the intersection of the racking structure with the uppermost hull weather deck (as applicable) will be arrangement specific, but are generally to be constrained against translation.</td>
</tr>
</tbody>
</table>

NOTES
1. Care is to be taken to ensure that, within practicable limits, there is no net imbalance of load or moments in any of the six degrees of freedom.

Table 4  Additional boundary conditions for a full craft half-breadth model (Not suitable for multi-hull models)

<table>
<thead>
<tr>
<th>Load cases</th>
<th>Boundary conditions, centre line plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still water cases</td>
<td>Symmetry constraints: ( \delta_y = \theta_x = \theta_z = 0 )</td>
</tr>
<tr>
<td>Wave bending moment cases</td>
<td>Anti-symmetry constraints: ( \delta_x = \delta_z = \theta_y = 0 )</td>
</tr>
<tr>
<td>Wave shear force cases</td>
<td>Anti-symmetry constraints: ( \delta_x = \delta_z = \theta_y = 0 )</td>
</tr>
</tbody>
</table>

NOTES
1. These boundary conditions are additional to those given in Table 2, and take precedence over the requirements therein.
2. The transverse constraints in Table 2 need not to be included in the half-breadth model.
3. Care is to be taken to ensure that the FE model is not over-constrained and that there are no conflicting constraints.

Section 6
Acceptance criteria

6.1 The stresses resulting from the application of the assessment load cases specified in PART A, Section 4, 4.9 are not to exceed the membrane stress criteria given in Table 5. Where plate elements with bending properties are used, the membrane stress can be obtained as the stress evaluated at mid-plane.

6.2 The structural analysis recommended in this part of the procedure uses a relatively coarse mesh model, and the permissible stress criteria in Table 5 are based on this. Fine mesh models or fine mesh regions of the model will usually indicate higher stresses, and should be assessed in accordance with the criteria given in PART B.
6.3 The column stability of pillars, and vertical webs acting as pillars, is to comply with the requirements of Table 5. Provided that the wall or plate thickness of the pillar complies with the requirements specified in the Rules, local wall buckling of the pillar is considered satisfactory. The buckling requirements are to be met using the net scantlings, hence any additional thickness for corrosion margin or Owners extra is not to be included in scantlings used to assess the buckling performance.

6.4 The value of $\sigma_o$ is to be taken and the yield or 0.2 per cent proof stress of the subject material as appropriate. Further, this value may be based on welded or un-welded material properties, depending on the location of the material. See also 2.1 of the INTRODUCTION.

6.5 The critical buckling stress of plate panels is to be derived in accordance with Section 4, Chapter 7 of Part 6 or Part 7 of the Rules for Special Service Craft, respectively.

6.6 The structure is to maintain minimum factors against buckling (utilising the critical buckling stresses calculated in accordance with 6.5 above), in accordance with Table 6.

6.7 Structures in way of high stress gradients, such as major openings or discontinuities, are to be subject to further investigation as indicated in PART B of this guidance.

6.8 Where it is noted that a course mesh is demonstrating that an area of structure is reaching 0.8 or more of the allowable stress, that area is to be further investigated, as indicated in PART B of this guidance.

6.9 Strain and elongation criteria may additionally be imposed by outfitting requirements (glazing, shell doors, house bulkhead doors, etc.). Such additional acceptance criteria are to be discussed and agreed with LR, and clearly indicated in the supplied report (see also Section 2 of the INTRODUCTION).

### Table 5 Maximum permissible membrane stresses for structure

<table>
<thead>
<tr>
<th>Structural item</th>
<th>Acceptance criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Von Mises stress</td>
</tr>
<tr>
<td>All longitudinally effective material</td>
<td>0.94 $\sigma_o$ (see Note 3)</td>
</tr>
<tr>
<td>All transverse material</td>
<td>0.70 $\sigma_o$</td>
</tr>
<tr>
<td>Pillars in tension</td>
<td>-</td>
</tr>
<tr>
<td>Pillars in compression</td>
<td>-</td>
</tr>
</tbody>
</table>

Where

$$\sigma_{\text{crit}} = \frac{\sigma_o \left(1 + \frac{L_o}{E \cdot \pi \cdot r} \right)^2}{1 + \frac{\sigma_o \cdot L_o}{E \cdot \pi \cdot r}}$$

$L_o = \text{effective length of pillar, in mm, and is taken as 0.8 overall length of pillar}$

$r = \text{least radius of gyration of pillar cross-section, in mm}$

### NOTES

1. Special attention, in modelling and analysis, is to be paid to the weld attachments of the heads and heels of tensile pillars.
2. For pillars, stresses to be calculated at the extreme fibre of the pillar section; if line elements are used to represent pillars, then bending properties, including relevant stress recovery points, are to be specified. If two-dimensional (2-D) elements are used to represent non-circular pillars, then stress is to be obtained for the node points at the extreme fibres of the pillar cross-section. If accurate nodal stresses are not available, the stresses are to be obtained from a line element of nominal area located at the extreme fibre of the pillar cross-section.
3. For areas constructed of high tensile steel, the value of $\sigma_o$ may be replaced by $\frac{235}{k_L}$. 


Table 6  Minimum factors against buckling

<table>
<thead>
<tr>
<th>Structural item</th>
<th>Buckling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>All longitudinally effective material</td>
<td>1.0</td>
</tr>
<tr>
<td>All transverse material</td>
<td>1.2</td>
</tr>
</tbody>
</table>
PART B – Analysis of Local Details

Section 1
Application

1.1 For the application of PART B, see Paragraphs 1.1 and 1.12 of the INTRODUCTION.

Section 2
Objectives

2.1 The objective of PART B of this guidance is to verify that the stress levels are within acceptable limits for highly stressed, structural components; novel or unusual features; or structural components exposed to direct loading, that are not covered by the Rules for Special Service Craft, e.g. a crane foundation loaded by an overturning moment, due to rescue boat launching.

2.2 Areas applicable to PART B may include, but are not limited to:
• Ends of superstructure.
• Window, shell, deck and bulkhead openings.
• Transverse steps/knuckles in upper decks.
• Any feature which is expected to present a structural discontinuity or stress concentration.
• Structure in way of high stress gradient or areas exceeding the stress criteria specified in PART A of this guidance.
• Foundations of deck fittings e.g. cranes, capstans or tie down points.
• Chain plates.
• Keel foundation structure.
• Mast step foundation structure.
• Cross-deck structure for multi-hulled craft.

Section 3
Structural modelling

3.1 Model extents are to be in accordance with Section 3 of the INTRODUCTION.

3.2 Separate detailed fine mesh FEA models covering the structural components noted in PART B, Section 2, 2.2 are to be prepared and loaded with displacements obtained from the full craft global analysis, or direct loads, where the latter is more appropriate. Alternatively, where computing power, run time, model file size, and clarity of display and reporting allow, these areas may be modelled in fine mesh and incorporated into the global FE model.

3.3 Structural geometry and material properties are to be accurately represented throughout the fine mesh model. The level of refinement is to be such as to enable stress concentrations to be identified, whilst not inducing artefacts.

3.4 The plating and supporting primary structure are to be represented by plate elements having both membrane and bending capability.

3.5 Secondary stiffening in way of the detail being considered is also to be represented by plate elements having both membrane and bending capability. However, outside the areas of interest, secondary stiffening may be represented by line elements having appropriate bending and axial geometric properties.

3.6 Where the model is to be loaded with enforced displacements, the fine mesh is to be such that suitable element nodes and boundaries are coincident with those of the coarse mesh model, allowing direct application of previously calculated displacements.

3.7 The element mesh size used in way of large radii should be that required to achieve a minimum of 15 elements in a 90° arc of the free edge of the plate.

3.8 Mesh size between closely spaced openings is to be such that a minimum of 10 elements should be arranged between concurrent openings.

3.9 In way of areas of interest other than those indicated in PART B, Section 3, 3.7 and 3.8, a mesh size of $t \times t$, $t$ being the thickness of the thinnest plate in way of area of interest, should be arranged. This mesh should extend at least 10 elements in all directions from the point of interest. A smooth transition of mesh density is to be maintained.

3.10 Elsewhere, the element size is not to be greater than the lesser value of 15$t$ $\times$ 15$t$ and 150 mm $\times$ 150 mm. A smaller mesh may be required to adequately represent the geometry of the detailed being considered.

3.11 Mesh size need not be less than $t \times t$, unless this is necessary to adequately represent the geometry of detail being considered.
3.12 Where FE analysis programs do not supply accurate nodal stresses, a line (or rod) element of nominal area is to be incorporated at the plating free edge, to obtain the peak edge stresses.

3.13 Where a connection is made by a non-continuous weld or slot weld procedure, the connection is to be modelled by considering the material in way of welds as continuous and outside of the weld zone, as not attached. However, it should be noted that, generally, non-continuous welds are not permitted in highly stressed areas.

3.14 Figures 3 and 4 illustrate example fine mesh models.

![Figure 3 Example fine mesh detail around a window opening](image)

![Figure 4 Example fine mesh detail of opening in a bulkhead](image)

### Section 4

**Loading and boundary conditions**

4.1 When investigating the case of local detail response under global loading, load cases detailed in PART A, Section 4, 4.10 (see also Table 1), are to be investigated. For each case, the fine mesh models are to be loaded with:
- The structural self-weight.
- The outfit and equipment loading within the model boundaries.
- Enforced displacements at the model boundary, obtained from the results of PART A.

4.2 When investigating a local detail response to a directly imposed load, finite mesh models are to be loaded with:
- The structural self-weight applied.
- Outfit and equipment loadings (taking note of shipboard accelerations, directly applied to nodes or elements). Model boundary conditions may be fixed, pinned, free, or symmetric, as best represents the ‘real world’ situation. In cases where partial fixity is required, a free and fixed case should be investigated, and both cases supplied to LR for consideration.

4.3 When a 2-D follow-up fine mesh model is developed to investigate in-plane responses, then the out-of-plane degrees of freedom may be constrained.
Section 5

Acceptance criteria

5.1 The stresses resulting from the application of the assessment load cases specified in PART B, Section 4, 4.1 and/or 4.2, are not to exceed the membrane stress criteria given in Table 7. Where plate elements with bending properties are used, the membrane stress can be obtained as the stress evaluated at the mid-plane of the plate.

5.2 The value of $\sigma_0$ is to be taken and the yield or 0.2 per cent proof stress of the subject material as appropriate. Further, this value may be based on welded or un-welded material properties, depending on the location of the material. See also 2.1 of the INTRODUCTION.

5.3 The column stability of pillars and vertical webs acting as pillars is to comply with the requirements of Table 5. Provided that the wall or plate thickness of the pillar complies with the requirements specified in the Rules, local wall buckling of the pillar is considered satisfactory. The buckling requirements are to be met using the net scantlings, hence any additional thickness for corrosion margin or Owners extra is not to be included in scantlings used to assess the buckling performance.

5.4 The critical buckling stress of plate panels is to be derived in accordance with Section 4, Chapter 7 of Part 6 or Part 7 of the Rules for Special Service Craft, respectively.

5.5 The structure is to maintain minimum factors against buckling (utilising the critical buckling stresses calculated in accordance with PART B, Section 5, 5.3), in accordance with Table 6.
# Table 7  Stress criteria for fine mesh investigations

<table>
<thead>
<tr>
<th>Structure</th>
<th>Stress criterion</th>
<th>Allowable stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundations, major openings, sweep brackets and side screens</td>
<td>Average von Mises stress</td>
<td>$0.85 \sigma_0$</td>
</tr>
<tr>
<td></td>
<td>Peak stress in free edge radius (e.g. of openings or brackets)</td>
<td>$1.005 \sigma_0$</td>
</tr>
<tr>
<td></td>
<td>Peak stress $t \times t$ mesh, other than in way of free edge radius plate.</td>
<td>$1.275 \sigma_0$</td>
</tr>
<tr>
<td>Minor openings, such as windows, doors, etc.</td>
<td>Average direct stress between openings</td>
<td>$0.8 \sigma_0$ (see Notes 2 and 3)</td>
</tr>
<tr>
<td></td>
<td>Average shear stress between openings</td>
<td>$0.47 \sigma_0$ (see Notes 2 and 4)</td>
</tr>
<tr>
<td></td>
<td>Average von Mises stress between openings</td>
<td>$0.94 \sigma_0$ (see Note 3)</td>
</tr>
<tr>
<td></td>
<td>Peak stress in radius</td>
<td>$1.5 \sigma_0$ (see Note 1)</td>
</tr>
<tr>
<td></td>
<td>Single element peak stress in $t \times t$ meshed areas other than corner plating and plating between openings</td>
<td>$1.5 \sigma_0$</td>
</tr>
<tr>
<td></td>
<td>Average von Mises stress in $t \times t$ meshed areas other than corner plating and plating between openings</td>
<td>$\sigma_0$ (see Note 5)</td>
</tr>
<tr>
<td>Primary transverse or girder web plating under local loading</td>
<td>Maximum shear stress</td>
<td>$0.35 \sigma_0$</td>
</tr>
<tr>
<td></td>
<td>Maximum von Mises stress</td>
<td>$0.75 \sigma_0$</td>
</tr>
<tr>
<td>Primary transverse or girder face plate under local loading</td>
<td>Maximum direct stress</td>
<td>$0.52 \sigma_0$</td>
</tr>
<tr>
<td>Primary girders or transverses under combined global and local loading</td>
<td>Maximum direct stress</td>
<td>$0.85 \sigma_0$</td>
</tr>
<tr>
<td></td>
<td>Maximum von Mises stress</td>
<td>$0.94 \sigma_0$</td>
</tr>
</tbody>
</table>

**NOTES**

1. This is a theoretical peak stress obtained from a linear elastic finite element analysis.
2. Average stress is to be calculated independently of the sign of the individual stress levels.
3. No single element stress in the corner plating is to exceed $\sigma_0$.
4. No single element stress in the corner plating is to exceed $0.58 \sigma_0$.
5. To be averaged over an area equivalent to $15t \times 15t$ with the element containing the peak stress. Averaging not to be taken across abutting structural boundaries or members.