IACS Common Structural Rules for Double Hull Oil Tankers, January 2006

Background Document

APPENDIX B – STRUCTURAL STRENGTH ASSESSMENT

NOTE:

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TABLE OF CONTENTS:

1 GENERAL

1.1 Application

1.1.1 General

1.1.1.a The scope of the finite element strength assessment covers the following:

- Assessment of strength of all hull girder, transverse bulkhead and primary supporting structural members in the midship cargo region (mandatory),
- Assessment of strengthening in way of transverse bulkheads against hull girder shear load in the forward and aft cargo region (mandatory),
- Assessment of strengthening in way of individual transverse bulkheads (optional, and the assessment procedure does not apply to forward collision bulkhead, engine room and slop tank bulkheads),
- Assessment of local strength of structural details in midship cargo region (mandatory), and
- Assessment of fatigue strength of lower hopper knuckle joint in midship cargo region (mandatory).

1.1.1.b For the purpose of defining which tanks are to be considered for the midship region strength assessment, tanks in the midship cargo region are defined as tanks with their longitudinal centre of gravity position at or forward of 0.3L from AP and at or aft of 0.7*L* from AP. This follows the logic that if a tank with over 50% of its length is within the traditional definition of the midship region (i.e. $0.3L < x < 0.7L$), then this tank should be considered for the midship region strength assessment. In practise, for design with 5 cargo tanks along its length, this would normally mean that nos. 3 and 4 tanks (no.1 tank is the forward most tank) will be considered for the midship assessment. For design with 6 cargo tanks along its length, it would normally mean that nos. 3, 4 and 5 tanks (no.1 tank is the forward tank) will be considered for the midship strength assessment.

1.1.1.c For the assessment of the tanks in the midship region, maximum permissible vertical still water and wave bending moments, calculated at 0.5*L* from AP, is used.

1.1.1.d As the rule wave shear force increases from 0.6*L* to a maximum at 0.7*L* from AP, and the still water shear force is usually increased in the forward region, therefore the combined shear force is usually at its maximum at or around 0.7*L*. For this reason, it is considered unreasonable that the strength assessment of the tanks in the midship region is based on this most onerous shear force, which could lead to overly conservative requirements of the midship region scantlings.

1.1.1.e Instead the shear force used in the midship strength assessment is based on the maximum shear force within the region, $0.3L < x < 0.65L$, and including the shear force at the forward transverse bulkhead of the aftmost cargo tank. The intention of including the aftmost bulkhead position in the selection of maximum shear force is to avoid the need to carry out a separate analysis to assess the strengthening requirement against shear load should this bulkhead be located at a position aft of 0.3L from AP. It is to be noted that, in practise, the forward transverse bulkhead of the aftmost cargo tank is usually close to 0.3L from AP.

1.1.1.f In accordance with the rule procedure for the selection of hull girder shear force, for a design with 5 cargo tanks along its length, this would normally mean that the bulkheads between tank nos. 2 & 3, 3 & 4 and 4 & 5 (no.1 tank is the forward-most tank) will be included in the midship strength assessment. For a design with 6 cargo tanks along its length, this would normally mean that the bulkheads between tank nos. 3 & 4, 4 & 5 and 5 & 6 (no.1 tank is the forward-most tank) will be included, and the bulkhead between nos. 2 & 3 tanks (usually located at about 0.7*L* from AP) is to be assessed as part of the strengthening assessment against hull girder shear load for the forward cargo region.

1.1.1.g The assessment of strengthening in way of transverse bulkheads against hull girder shear load in the forward cargo region is mandatory to cover transverse bulkheads that are not included in the midship strength assessment. As a minimum requirement, a single assessment may be carried out to cover all transverse bulkheads forward of 0.65L from AP (but not including the forward collision bulkhead, which is not covered by the FE analysis), based on the maximum shear force in the region.

1.1.1.h Uniform strengthening may be applied in way of all transverse bulkheads in the midship cargo region (i.e. between the forward bulkhead of the aftmost cargo tank and $x < 0.65L$) and the forward cargo region (i.e. $x > 0.65L$) based on the result of the midship strength assessment and the forward hull girder shear strength assessment described above. Alternatively, if considered desirable, an optional assessment may be carried out to determine the strengthening requirement against hull girder shear load in way of each individual transverse bulkhead.

1.2 Symbols, Units and Definitions

1.2.1 General

1.2.1.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

1.2.2 Finite element types

1.2.2.a Linear finite element analysis is a standard assessment method used by Classification Societies and the shipbuilding industry for verifying the strength of ship structure. The finite element analysis is based on a three-dimensional finite element model constructed using linear plate and line elements.

1.2.2.b Two node line elements and three or four node plate/shell elements are sufficient for the representation of the hull structure and are most commonly used by Classification Societies, shipbuilders and designers for carrying out the finite element analysis. These elements are recommended to be used for the construction of the FE models.

1.2.2.c If higher order elements, e.g. eight node plate/shell elements, are used, the stresses are evaluated at the element centroid and assessed against the criteria given. For ship type structure with only pressure and nodal forces applied to the elements (i.e. no edge shear) the results from higher order shell elements should be reasonably close to that from four node shell elements at the element centroid.

1.2.2.d The reason for using membrane (or in-plane) stresses of plate elements as acceptance criteria for FE strength assessment is given in the background of *Section 9/2.2.5 of the Rules*. The reason for using surface stresses of plate elements for the calculation of fatigue stress range is explained in the background of *Appendix C/2.4.2 of the Rules*.

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2 CARGO TANK STRUCTURAL STRENGTH ANALYSIS

2.1 Assessment

2.1.1 General

2.1.1.a The finite element assessment procedure is applicable to double hull tankers of conventional arrangement. For definition of novel designs and equivalence assessment procedure, see *Section 3/4 of the Rules*.

2.2 Structural Modelling

2.2.1 General

2.2.1.a Boundary conditions applied at the ends of the cargo tank model in general will introduce abnormal stress responses in way of the constrained areas due to the constraint of model displacements. The area in the model where the stress responses are to be assessed must be adequately remote from the model boundary so that the constraint applied will not have significant effect on the stress responses.

2.2.1.b A three-tank length finite element (FE) model is used for the following reasons:

(1) A three-tank length FE model is used to ascertain that the area in the model where the stress responses are assessed are adequately remote from the model boundary so that the constraint applied will not affect the stress result. It is to be noted that the area in the model for assessing against the acceptance criteria covers structure within the longitudinal extent from the termination of the transverse bulkhead stringer/buttress aft of middle tank to the termination of the bulkhead stringer/buttress forward of the middle tank. A three-tank length FE model is considered more appropriate than a ½ +1 + ½ tank length model in this case, especially with correction bending moment applied to the model ends, otherwise, the effect of the end constraints may be significant as the ends of the model could be only two web frame spaces from the areas that are required to be assessed.

(2) With the presence of the transverse bulkheads at both ends of the three-tank length model, the three tank model ascertains that the middle tank of the model has similar deformation as the one for the whole vessel.

(3) A three-tank length model is used in conjunction with the procedure of applying adjustment forces and bending moments to obtain the correct bending moment and shear force distributions along the model length. The required distributions are difficult to achieve with a ½ + 1 + ½ model. The required distributions of hull girder shear force and bending moment are described in *Appendix B/2.4.5 of the Rules*. The importance of applying all simultaneously acting hull girder and local loads directly to the FE model is explained in *Section 9/2.2.4.a*.

2.2.1.c Where asymmetrical loads are applied, if the structure is symmetrical about the ship's centreline, the analysis could theoretically be carried out using a half breadth FE model by combining the stress responses obtained from the analysis of a number of symmetrical and anti-symmetrical load cases with appropriate boundary conditions imposed at the centre line plane. The procedure is complicated and increases risk in introducing user errors in the analysis. The requirement of a full breadth FE model is to simplify the analysis of asymmetrical loading conditions and hence reduce the probability of introducing errors in the analysis process.

2.2.1.d With today's computer technology, the issue of additional processing power and storage capability required for carrying out analysis of a full breadth three-tank length FE model is no longer considered to be a limitation.

2.2.1.e The choice of modelling thickness is in accordance with the Rule net thickness philosophy described in *Section 6/6.3.3.1 of the Rules*.

2.2.1.f The cargo tank FE model is to represent the overall corroded state of the hull. It is not realistic to assume that the whole hull structure is corroded by the maximum corrosion addition thickness for each individual member. In the assessment of the overall strength of the hull, it is assumed that all plates of the structure are corroded by 50% of the corrosion addition thickness. This is consistent with the assessment of global hull girder properties as well as consistent with the in-service global hull girder gauging requirements to be followed throughout the life of the vessel. See *12/1.2.3* and *12/1.5*.

2.2.1.g For the assessment of detailed stress at localised area using fine mesh finite element analysis, full corrosion additional thickness is deducted in way of the localised area. See *3.2*. This is consistent with the in-service plate and stiffener gauging requirements to be followed throughout the life of the vessel. See *12/1.2.2*, *12/1.5* and *12/1.6*.

2.2.1.h For buckling assessment of local plate and stiffened panels, full corrosion addition thickness is deducted over the entire panel, including stiffeners. See *2.7.3*. This is consistent with the in-service plate and stiffener gauging requirements to be followed throughout the life of the vessel. See *12/1.2.2*, *12/1.5* and *12/1.6*.

2.2.1.i Modelling the ship's plating and stiffener systems as closely as possible to the actual structure allows a more accurate structural response to be determined, and minimises the discrepancy in the result which helps to achieve common scantlings in the application of the Rules. In addition, modelling plate mesh that follows the stiffening system eliminates the need of approximating the property of group of stiffeners by a single line element at the edges of a plate element. This modelling procedure also makes the process of extracting stresses for buckling assessment of panels easier and more accurate. It should be noted that the aim of the cargo tank finite element analysis is to assess the overall strength of the structure and is not intended to determine the stresses at structural details and discontinuities, as the mesh size employed is too coarse to correctly represent their geometry. Instead, fine mesh finite element analysis is used to determine such stresses.

2.2.1.j For corrugated bulkheads, it is important to retain the correct geometrical shape of the corrugation. A difference in geometry alters the sectional inertia and cross sectional area of the corrugation which will result in incorrect stress response. Inaccurate modelling of corrugation shape is better to be avoided, however, where impossible, the stress response obtained is to be corrected using the procedure given in *Appendix B/2.7.2 of the Rules*, which is intended not to give lower stress than that obtained from the FE model.

2.2.1.k Stiffened panels under lateral pressure load should be modelled using a combination of beam elements (i.e. line elements with axial, torsional and bi-directional shear and bending stiffness) and shell elements (i.e. plate elements with in-plane stiffness and out-of-plane bending stiffness) to enable correct displacements and rotations due to local pressure to be determined at the nodal points and to avoid singularities due to incompatibility of degrees of freedom which may occur when using a combination of beam elements and membrane elements (i.e. plate elements with in-plane stiffness only). In areas where no lateral pressure is applied, a combination of rod and membrane elements may be used.

2.2.1.l Small sniped end stiffeners less than the edge of a plate element (e.g. 150mm) do not need to be modelled. Stiffeners, with one end or both ends sniped, which are longer than the edge of a plate element should be included. It is to be noted that it is not the intention to accurately represent the sniped termination of the stiffener but to get a more realistic representation of the stiffness of such stiffeners and their contribution to stress reduction in the primary support members. However, it should be noted that the correct dimensions of the panel according to the web stiffener arrangement are to be used in assessment of panel buckling strength. The modelling of the stiffeners allows clear identification of the dimensions, applied FE stresses and pressure load for each plate panel which helps enhancing the efficiency and consistency of the panel buckling assessment. Web stiffeners parallel and close to the face plate of stringer or web frame contribute to the section modulus of that structural member and hence reduce the stress. If sniped end stiffeners are not corrected in some way the stress in the face plate of the stringers/web frames will be underestimated

2.2.1.m On transverse web frames and bulkhead stringers, the arrangement of web stiffeners can become irregular. In order to avoid undesirable element mesh (such as introduction of triangular or highly skewed elements) in way, consideration may be given to slightly adjusting the end points of the web stiffener in line with the primary element mesh. In general, it is considered acceptable if the adjusted distance does not exceed 0.2 times the stiffener spacing. Provided that this tolerance is met the stresses and buckling capacity models may be taken from the FE model and do not need to be adjusted.

2.2.1.n The intention of introducing the thickness correction procedure in *Appendix B/Table B.2.2 of the Rules* for modelling web plating in way of an opening is to enable correct representation of the overall stiffness of the three cargo tanks FE model to allow correct load transfer within the structure without modelling of all openings. It is to be noted that the cargo tank analysis is only intended for assessing the overall strength of the structure. Local stresses in way of an opening is in addition assessed using fine mesh finite element analysis, as required by *Appendix B/3.1 of the Rules*, with accurate modelling of the opening geometry.

2.2.1.o For openings with height, h_o, greater or equal to length, l_o, the deflection across the opening is governed by shear deflection and the thickness correction is proportional to the loss of material in a given cross section.

2.2.1.p For longer openings the deflection is a result of combined shear and bending deflection. This effect of bending deflection is taken into account by applying the correction factor, g_o, to the pure shear deflection thickness.

2.2.1.q For large openings, i.e. with $h_o/h \geq 0.5$ or $g_o \geq 2.0$, it is considered necessary to include the geometry of the opening in the cargo tank model in order to obtain an acceptable result, see *Appendix B/Table B.2.2 of the Rules* for definitions of l_o, h_o and g_o. In this case, fine mesh finite element analysis is mandatory in order to determine the local stress in way of the opening. See *B/3.1.6.b.*

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2.2.1.r In all cases the geometry of an opening can be included in the cargo tank finite element model, even if its size is such that it is acceptable to represent its effect by means of reduced thickness in accordance with *Appendix B/Table B.2.2 of the Rules*. However, it should be noted that the screening formula, given in *Appendix B/3.1.6 of the Rules* for determining whether it is necessary to perform a fine mesh analysis of the opening, is only applicable for the cases where the geometry of an opening has not been included in the cargo tank model. If the geometry of an opening is included in the cargo tank model, fine mesh analysis is to be carried out to determine the local stress in way of the opening.

2.3 Loading Conditions

2.3.1 Finite element load cases

2.3.1.a A finite element load case is the combination of a loading pattern defined in *Table B.2.3* and *B.2.4 of the Rules* and a dynamic load case defined in *Table 7.6.2 of the Rules*. The corresponding dynamic load cases for each loading pattern are indicated under the column 'Dynamic Load Cases' in *Appendix B/Table B.2.3 and B.2.4 of the Rules*.

2.3.1.b The standard FE analysis considers loading patterns, ship draughts, hull girder still water bending moments and shear forces that are intended to provide an envelope of the typical loading conditions anticipated in operations. The operation envelope stipulates:

- A maximum ship draught equal to 90% of the ship's scantlings draught and a minimum ship draught equal to 60% of the ship's scantlings draught for seagoing partial load conditions.
- For tankers with two longitudinal bulkheads, a maximum ship draught equal to the ship's scantling draught and a minimum ship draught equal to 25% of the ship's scantlings draught for harbour and tank testing conditions
- For tankers with one centreline longitudinal bulkheads, a maximum ship draught equal to the ship's scantling draught and a minimum ship draught equal to 33.3% of the ship's scantlings draught for harbour and tank testing conditions.
- Seagoing and harbour hull girder still water bending moments and shear forces specified by the designer as included in the ship's loading manual

2.3.1.c The seagoing ship draughts considered are to provide adequate flexibility for partial load conditions in normal operations. Full scantling draught is normally not achieved when one or more cargo tanks are empty unless the master intentionally increases the draught by filling a number of ballast tanks. Hence, it is considered that partial loading conditions with full scantling draught, and one or more cargo tanks empty, are not necessary as a mandatory requirement for all designs. Instead, a maximum ship draught equal to 90% of the ship's scantlings draught is used. The minimum ship draught considered for seagoing partial load conditions is 60% of the ship's scantling draught.

2.3.1.d For harbour and tank testing load cases, shallow draught conditions could be critical for the double bottom structure. The minimum draught chosen for the analysis is based on the smallest draught that can be achieved with the loading pattern considered for a given tank arrangement (*see 2.3.1b*). Note that the minimum ship draught used in harbour/tank testing conditions is less than that for the seagoing conditions to allow additional flexibility during these operations. The strength of the hull structure under harbour permissible still water bending moment and still water shear force is also assessed for shallow and full scantling draught conditions.

2.3.1.e A deep draught condition with an empty cargo tank is critical for the bottom structure due to high upward acting static and wave pressure on the bottom shell and no counteracting tank pressure. When a wing cargo tank is empty in a deep draught condition, the side and transverse structures are also under critical condition in beam seas due to lack of counteracting tank pressure against the static and wave dynamic pressure on the ship side. Likewise, shallow draught with a full tank is also a critical loading condition for the bottom structure due to high downward acting static and dynamic tank pressure and little counteracting external sea pressure. When a wing tank is full with a shallow draught, the side and transverse structures are also under considerable load due to small counteracting pressure on the ship side. It is therefore extremely important to note that if the required operational draughts for partial load conditions are greater than the maximum draught and/or lesser than the minimum draught used in the standard FE analysis, the required draughts must be specified and included in the FE analysis.

2.3.1.f For tankers with two oil-tight longitudinal bulkheads and a cross tie arrangement in the centre cargo tanks, special asymmetrical loading patterns with one wing tank abreast full (i.e. seagoing condition A7 and harbour/tank testing condition A12) are analysed to verify the strength of the longitudinal bulkhead and support structure (in way of the empty wing tank) under the ‘punching’ load exerted by the cross tie in the middle tank as a result of the fluid pressure in the full wing tank. In the seagoing condition, this loading pattern is combined with the beam sea dynamic load case to obtain the maximum combined static and dynamic tank pressure acting on the longitudinal bulkhead in way of the full wing tank. Loading pattern A12 is mandatory and is to be analysed for the possibility of unequal filling level in paired wing cargo tanks in harbour or tank testing operation operations and to account for accidental non-symmetric filling of tanks. Loading pattern A7 is optional and is only required to be analysed if such loading pattern is included in the ship loading manual as a condition for seagoing operation. These asymmetrical loading patterns are not critical for the longitudinal bulkhead and supporting structure for ships with no cross-tie structure in the middle tank, and therefore these loading patterns do not need to be analysed for ships with no centre tank cross-tie structure.

2.3.1.g Fully loaded condition and normal ballast condition are not included in the FE loading patterns, as these conditions do not impose the most onerous loads on the main supporting structural members as the net load on the double hull structure is small in both cases, i.e. full cargo tank with deep draught and empty cargo tank with shallow draught. Fully loaded and normal ballast conditions are important for determination of hull girder bending strength, which is adequately checked by the longitudinal strength calculation described in *Section 8/1 of the Rules*.

2.3.1.h Where the designer requests an operation envelope that is not covered by the standard FE load cases, the additional loading conditions must be specified and included in the FE analysis.

2.3.1.i The loading patterns used in the finite element analysis were chosen such that the most severe static pressure loads, localised shear forces and bending moments are imposed on the primary supporting structure of the hull (i.e. frame and girder system). The loading patterns chosen consist of possible alternative tank partial load

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conditions, where adjacent tanks are in various configurations of fully loaded and empty condition in both longitudinal and transverse directions, to optimise the loads acting on the structure.

2.3.1.j For each of the loading pattern analysed, the distribution of cargo and ballast is only defined within the three-tank length FE model. The use of actual still water bending moment from the loads applied to the three-tank FE model may be non-conservative as this does not take into account the loads applied along the whole ship length outside the extent of the model. For this reason, the permissible seagoing and harbour still water hull girder bending moments are used in the seagoing and harbour/tank testing FE load cases respectively.

2.3.1.k The hull girder still water shear force is most critical for loading conditions with either all cargo tanks abreast empty (and all adjacent cargo tanks abreast full) or all cargo tanks abreast full (and all adjacent cargo tanks abreast empty), whilst the hull girder still water shear force resulting from other 'checker board' loading patterns is less critical. This “full or empty across” loading condition is analysed using FE loading patterns A3, A5, A11, A13, B3, B6, B8 and B11 in combination with the dynamic load cases with maximum wave shear force to assess the hull strength against hull girder shear loads. For these load case combinations, shear force correction procedure is to be applied, where necessary, to ensure that the required combined seagoing permissible still water and maximum wave shear force is achieved in the sea going FE load cases and harbour permissible still water shear force is achieved in the harbour/tank testing FE load cases. By carefully matching of the FE loading pattern with ship draught, only minor adjustment of shear forces are needed to obtain the required hull girder shear forces. Shear force correction procedure is not required to be applied to other 'checker board' FE loading patterns where the hull girder shear force is less critical. See *Appendix B/2.5 of the Rules* for description of the procedure for adjusting hull girder bending moments and shear forces.

2.3.1.l For tankers with two oil-tight longitudinal bulkheads (typical for VLCC designs), loading condition with all cargo tanks abreast empty (and all adjacent cargo tanks abreast full) is not typically adopted for all designs. This loading condition in combination with a deep draught will result in still water shear forces much higher than that of other loading conditions; and will require additional strengthening of side shell, inner hull, bottom girders, hopper plate and longitudinal bulkheads. For this design configuration, it is considered not necessary to include deep draught and shallow draught for this loading condition as a mandatory requirement. Instead, less demanding draught conditions are used in the FE loading patterns A3, A5, A11 and A13 given in *Table B.2.3 of the Rules* to assess the hull strength against the required hull girder shear loads. However, if all cargo tanks abreast empty (with all adjacent cargo tanks abreast full) loading conditions are required in operation for a particular vessel, where the maximum seagoing/harbour draughts specified in the ship's loading manual for these conditions are greater than the default draughts used in the FE loading patterns A3 and A13, then the specified maximum draughts should be used in the FE loading patterns to assess the hull strength against the required maximum negative hull girder shear forces at sea and in harbour. Similarly, the minimum seagoing/harbour draughts specified for the condition with all cargo tanks abreast full (and all adjacent cargo tanks abreast empty) in the ship's loading manual are to be used in the FE loading patterns A5 and A11 to assess the hull strength against the required maximum positive hull girder shear forces, should the minimum seagoing/harbour draughts specified for a particular vessel be smaller than the standard default draughts used in FE loading patterns A5 and A11.

2.3.1.m The dynamic load cases used in the finite element analysis are to simulate the most severe dynamic hull girder and local loads that can simultaneously occur in a seaway at the probability level considered, See *B/2.3.2.*

2.3.1.n The finite element load cases (i.e. combination of static and dynamic loads for seagoing conditions and static loads only for harbour/tank testing conditions) are to generate the most severe combination of global and local loads on the structure for the loading patterns considered.

2.3.1.o The following general considerations are given in combining a loading pattern with dynamic load cases:

(1) The hull girder loads are maximised by combining a static loading pattern with dynamic load cases that have hull girder bending moments/shear forces of the same sign.

(2) The net local load on primary supporting structural members is maximised by combining each static loading pattern with appropriate dynamic load cases, taking into account the net pressure load acting on the structural member and influence of loads acting on an adjacent structure. The general principle of maximizing the net local pressure loads is explained in *Table B.2.a.*

Table B.2.a
Principle of Maximising the Net Local Pressure Loads

	Loading pattern	**Ship draught**	**Dynamic loads**
Internal tight-bulkheads	Full tank/adjacent tank empty	NA	Maximise load due to accelerations in fully loaded tanks
Double bottom or Double side	Empty tank	Deep still water draught	Maximise external sea pressure (head sea wave crest condition or weather side beam/oblique sea condition)
Double bottom or double side	Full tank	Shallow still water draught	Maximise internal pressure due to accelerations. Minimise external sea pressure (head sea wave trough condition or lee side beam sea condition)

2.3.1.p The global hull girder loads and local loads are to be combined in such a way that the stresses due to net local pressure loads acting on the primary support members and hull girder loads are additive to maximise the stress in certain parts of the structure. For example, hull girder maximum sagging condition (i.e. dynamic load case 1, defined in *Section 7/Table 7.6.2 of the Rules*, with maximum wave sagging bending moment in a wave trough, and maximum sagging still water bending moment) is combined with a loading pattern with fully loaded tanks (middle tanks of FE model) and shallow draught to generate maximised tensile stress at the outer bottom.

2.3.1.q Similarly, hull girder maximum hogging condition (i.e. dynamic load case 2, defined in *Section 7/Table 7.6.2 of the Rules*, with maximum wave hogging bending moment in a wave crest, and maximum hogging still water bending moment) is combined with a loading pattern with empty tanks (middle tanks of FE model) and deep draught to maximise compressive stress at the outer bottom.

2.3.1.r For seagoing finite element load cases, several different dynamic load cases may require to be combined with one loading pattern in order that critical conditions for different structural members can be examined.

2.3.1.s For the harbour and tank testing FE load cases, only static loads are to be applied. The required still water bending moment and shear force for these FE load cases are based on harbour permissible still water bending moments and shear forces.

2.3.1.t A study was carried out for a number of designs of various configurations and sizes to further minimise the required number of combinations of loading pattern and dynamic load cases.

2.3.2 Dynamic load cases

2.3.2.a The dynamic load cases used in the finite element analysis are derived based on maximising certain load component at 10^{-8} probability level. The following dynamic load cases are considered for the finite element strength assessment:

Table B.2.b
Dynamic Load Cases for Finite Element Strength Assessment

Dynamic load case	**Wave direction**	**Maximised load component**	**Application**
Case 1	Head seas	sagging vertical wave bending moment (and positive wave shear force)	midship and aft cargo region
Case 2	Head seas	hogging vertical wave bending moment (and negative wave shear force)	midship and aft cargo region
Case 3	Head seas	positive vertical wave shear force	forward cargo region
Case 4	Head seas	negative vertical wave shear force	forward cargo region
Cases 5a, 5b	Beam seas	vertical acceleration (and dynamic wave pressure)	midship cargo region
Cases 6a, 6b	Oblique Seas	wave horizontal bending moment	midship cargo region

2.3.2.b These load cases represent the most severe dynamic loads in a seaway at the required probability level. The load components specified in each FE load case are obtained by applying dynamic load combination factors to the rule envelope loads and represent dynamic loads that occur simultaneously in a seaway. The derivation of the dynamic load cases and dynamic load combination factors for the finite element strength analysis is explained in the background of *Section 7/6.*

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2.4 Application of Loads

2.4.1 General

2.4.1.a Further information to *Table B.2.6 of the Rules* is given in *Table B.2.c* below.

<table>
<tr><th colspan="5">Table B.2.c
Further Information to *Table B.2.6* of the Rules
Locations for the Determination of Loads and Accelerations</th></tr>
<tr><th></th><th>Strength assessment</th><th colspan="3">Hull girder shear strength</th></tr>
<tr><th></th><th>Midship cargo region</th><th>Forward cargo region</th><th>Midship cargo region</th><th>Aft cargo region</th></tr>
<tr><td colspan="5">**Design load combinations S + D (Sea-going load cases)**</td></tr>
<tr><td rowspan="2">**Dynamic wave pressure and green sea load**</td><td>Dynamic wave pressure distribution calculated at 0.5L from AP
Green sea load distribution on deck calculated at 0.5L from AP</td><td>Dynamic wave pressure distribution calculated at 0.75L from AP
Green sea load distribution on deck calculated at 0.75L from AP</td><td>Dynamic wave pressure distribution calculated at 0.5L from AP
Green sea load distribution on deck calculated at 0.5L from AP</td><td>Dynamic wave pressure distribution calculated at 0.25L from AP
Green sea load distribution on deck calculated at 0.25L from AP</td></tr>
<tr><td colspan="4">*Note:*
• *Dynamic wave pressure is to be calculated in accordance with Section 7/6.3.5.1 and 6.3.5.3 of the Rules.*
• *Green sea load on deck is to be calculated in accordance with Section 7/6.3.6.1 of the Rules.*
• *Dynamic wave pressure distribution and deck green sea load distribution calculated at the specified section is to be applied to the full length of the FE model*</td></tr>
<tr><td rowspan="2">**Overpressure in ballast tanks**</td><td colspan="4">In connection with the optional gale/emergency ballast condition, the maximum overpressure (for seagoing load cases) of all wing ballast tanks in the cargo region is to be applied.</td></tr>
<tr><td colspan="4">*Note:*
• *For calculation of overpressure in ballast tanks, see background of Section B/2.4.7 of the Rules.*
• *All ballast tanks include ballast tanks ulitising sequential method and ballast tanks ulitising flow through ballast water exchange method.*
• *For seagoing load cases, no overpressure is to be applied to cargo tanks, including cargo tank(s) used for ballast.*</td></tr>
<tr><td rowspan="2">**Acceleration a_v, a_t, a_{lng}**</td><td>at CG position of midship tanks (a midship tank is defined as a tank where 0.5*L* from AP is within the tank boundary)</td><td>at CG position of forward tanks (a forward tank is defined as a tank where 0.75*L* from AP is within the tank boundary)</td><td>at CG position of midship tanks (a midship tank is defined as a tank where 0.5*L* from AP is within the tank boundary)</td><td>at CG position of aft tanks (an aft tank is defined as a tank where. 0.25L from AP is within the tank boundary)</td></tr>
<tr><td colspan="4">*Note:*
• *Vertical, longitudinal and transverse accelerations are to be calculated at the specified centre of gravity position of each abreast cargo and/or ballast tank. The calculated accelerations are to be applied to all three corresponding cargo or ballast tank along the length of the FE model, such that, for example, all port wing cargo tanks are subjected to the same accelerations.*
• *In the calculation of vertical acceleration, the acceleration component due to roll is taken as zero for head sea load cases, and the acceleration component due to pitch is taken as zero for beam sea load cases, see Appendix B/2.4.7.2 of the Rules.*
• *Dynamic tank pressure is to be calculated in accordance with Section 7/6.3.7.1 of the Rules.*</td></tr>
</table>

VWBM and SWBM (SWBM is to be based on seagoing permissible values)	VWBM calculated at 0.5L from AP Seagoing permissible SWBM at 0.5L (i.e. midship)	VWBM calculated at 0.75L from AP seagoing permissible SWBM at 0.75L, may be taken as 0.7875 SWBM amidships, in accordance with the SWBM distribution given in *Section 7/Figure 7.2.1 of the Rules.*	VWBM calculated at 0.5L from AP Midship seagoing permissible SWBM	VWBM calculated at 0.25L from AP seagoing permissible SWBM at 0.25L, may be taken as 0.7875 SWBM amidships, in accordance with the SWBM distribution given in *Section 7/Figure 7.2.1 of the Rules.*
	Note: • *VWBM is to be calculated in accordance with Section 7/6.3.2.1 of the Rules.*			
HWBM	HWBM calculated at 0.5L from AP See *Section 7/3.4.2* of the Rules for rule formula	No need, as beam sea and oblique sea dynamic load cases are not used for assessment of shear strength	No need, as beam sea and oblique sea dynamic load cases are not used for assessment of shear strength	No need, as beam sea and oblique sea dynamic load cases are not used for assessment of shear strength
	Note: • *HWBM calculated in accordance with Section 7/6.3.3.1 of the Rules.*			
VWSF and SWSF	The selection of shear force is based on the maximum of all combined seagoing permissible SWSF and envelope VWSF for all cargo tank transverse bulkheads in the region x $\le$ 0.65L, i.e. including the forward bulkhead of the aft most cargo tank. See *Appendix B/1.1.1.5 of the Rules*	The selection of shear force is based on the maximum of all combined seagoing permissible SWSF and envelope VWSF for all cargo tank transverse bulkheads in the region x > 0.65L, if common strengthening is applied in way of all transverse bulkheads in the region. See *also Appendix B/1.1.1.6 of the Rules.* Combined seagoing permissible SWSF and VWSF at each individual bulkhead if strengthening requirement is to be determined at each transverse bulkhead position separately, see *Appendix B/1.1.1.8 of the Rules*	No further assessment is required if common strengthening is applied in way of all transverse bulkheads in the region based on results from the midship cargo tank strength assessment, see *Appendix B/1.1.1.7 of the Rules* Combined seagoing permissible SWSF and VWSF at each individual bulkhead if strengthening requirement is to be determined at each transverse bulkhead position separately, see *Appendix B/1.1.1.8 of the Rules.*	

	Note: • *Percentage of permissible SWSF to be applied to each FE load case is to be in accordance with loading patterns specified in Appendix B/Tables B.2.3 and B.2.4 of the Rules.* • *VWSF to be applied to each FE load case is to be multiplied by corresponding dynamic load combination factor, calculated in accordance with Section 7/6.3.4.1 of the Rules.* • *Envelope VWSF means VWSF calculated in accordance with Section 7/3.4.3 of the Rules, without application of dynamic load combination factor* • *Engine room, slop tank and forward collision bulkhead are not to be included for determining the vertical shear force and evaluation of strength* • *When calculating combined shear forces, positive SWSF should be combined with positive VWSF and negative SWSF should be combined with negative VWSF*			
Design load combination S (Harbour and tank testing load cases)				
Overpressure in cargo tanks	The maximum overpressure (for harbour/tank testing load cases) of all cargo tanks in the cargo region is to be applied.			
	Note: • *For calculation of overpressure in cargo tanks, see background of B/2.4.7.*			
Overpressure in ballast tanks	Ballast tanks not filled in harbour/ tank testing load cases.			
SWBM (SWBM is to be based on harbour permissible values)	Harbour permissible SWBM at 0.5L from AP	Harbour permissible SWBM at 0.75L from AP, may be taken as 0.7875 harbour permissible SWBM amidships, in accordance with the SWBM distribution given in *Section 7/Figure 7.2.1 of the Rules.*	Harbour permissible SWBM at 0.5*L* from AP	Harbour permissible SWBM at 0.25*L* from AP, may be taken as 0.7875 harbour permissible SWBM amidships, in accordance with the SWBM distribution given in *Section 7/Figure 7.2.1 of the Rules.*
SWSF	Maximum of all harbour permissible SWSF at cargo tank transverse bulkheads within the region $x \le 0.65L$, i.e. including the forward bulkhead of the aft most cargo tank See also *Appendix B/1.1.1.5 of the Rules*	Maximum of all harbour permissible SWSF at cargo tank transverse bulkheads in the region $x > 0.65L$ if common strengthening is applied in way of all transverse bulkheads in the region, see *Appendix B/1.1.1.6 of the Rules.* Harbour permissible SWSF at each individual bulkhead if strengthening requirement is to be determined at each transverse bulkhead position separately, see *Appendix B/1.1.1.8 of the Rules.*	No further assessment is required if common strengthening is applied in way of all transverse bulkheads in the region based on results from the midship cargo tank strength assessment, see *Appendix B/1.1.1.7 of the Rules* Harbour permissible SWSF at each individual bulkhead if strengthening requirement is to be determined at each transverse bulkhead position separately, see *Appendix B/1.1.1.8 of the Rules.*	

	Note: • *Percentage of permissible SWSF to be applied to each FE load case is to be in accordance with loading patterns specified in Appendix B/Tables B.2.3 and B.2.4 of the Rules.* • *Engine room, slop tank and forward collision bulkhead not included for determining the vertical shear force and evaluation of strength*

2.4.2 Structural weight, cargo and ballast density

2.4.2.a It is important to include the static effect of structural steel weight of the ship in the analysis as this weight represents a significant proportion of total weight carried by the ship. For example, for a typical VLCC, the lightship weight is equal to 12 to16% of the total weight of the cargo carried for a typical full load condition (cargo density of 0.85 tonnes/m^3) and 40 to 50% of the total weight of the ballast carried based on typical normal ballast condition.

2.4.3 Static sea pressure

2.4.3.a A constant draught is applied along the model length to simplify the load application process.

2.4.3.b It is to be noted that the static sea pressure due to immersed draught for the ship in an upright condition is to be applied for all finite element load cases. The static sea pressure change due to rolling of the ship in beam and oblique seas load cases is included in the dynamic wave pressure formulation.

2.4.4 Dynamic wave pressure

2.4.4.a A green sea load and dynamic wave pressure profile is applied uniformly over the full length of the FE model draught to simplify the load application process.

2.4.4.b Green sea load is to be applied to the weather deck where the calculated dynamic wave pressure at deck side is greater than zero. For FE load cases which consist of the beam sea dynamic load case 5a or 5b and where the ship draught is greater or equal to 90% of the scantling draught, a minimum green sea pressure of 34.3 kN/m^2 is to be applied at the deck side of the weather side. The green sea load on the weather deck is to be obtained by linear interpolation between the pressure at the deck sides.

2.4.5 Hull girder vertical bending moment and vertical shear force

2.4.5.a As the three-tanks FE model is only representing part of the ship simply supported by ground springs at both ends, when the required local loads (i.e. static and dynamic tank pressure, static sea and dynamic wave pressure and structural weight) are applied to the model, the global hull girder bending moment and shear force generated may not necessarily reach the required values (i.e. combined still water and wave vertical shear force and bending moment specified for each FE load case in *Appendix B/Table B.2.3 and B.2.4 of the Rules*).

2.4.5.b The hull girder bending moment and shear force is adjusted to the required values using the procedure described in *Appendix B/2.5 of the Rules*. The required hull girder bending moment is to be reached within the length of the middle tank of the cargo tank FE model. In practice, this position is either at the mid-position or at the ends of the middle tank of the cargo tank finite element model at which it is considered to give the most onerous combination with stress due to local loads. The reason why the maximum within the length of the hold is selected and not the mid hold position is to avoid a situation where the bending moment in the model will be greater than the permissible at locations close to the transverse bulkhead.

2.4.5.c Hull girder shear stress is considered to give the most onerous combination with stress due to local loads close to transverse bulkheads. The hull girder shear force is adjusted to reach the required maximum value at the fore transverse bulkhead of the middle tank of the FE model.

2.4.5.d In-between the transverse bulkhead position and the mid-tank position, the hull girder load is a combination effect of shear force and bending moment below their required maximum values. The requirement of hull girder shear strength in the area close to the mid-tank is covered by the prescriptive requirements for longitudinal strength described in *Section 8/1 of the Rules*.

2.4.6 Hull girder horizontal wave bending moment

2.4.6.a Following the same argument given in *2.4.5.a,* the global hull girder horizontal bending moment may not necessary reach the specified value for the beam sea and oblique sea dynamic load cases. The hull girder horizontal bending moment is adjusted by applying a horizontal bending moment to the model ends to obtain the specified value at the mid-position of the middle tank. The procedure for adjusting the horizontal bending moment is described in *Appendix B/2.5 of the Rules*.

2.4.7 Pressure in cargo and ballast tanks

2.4.7.a The combined static and dynamic tank pressure used in the seagoing finite element load cases are based on 10^{-8} probability level for dynamic loads (i.e. 25 years design life) taking into account the variation of cargo densities in the ship's life. To account for the variation of cargo density, a factor for the joint probability of occurrence of cargo density and maximum sea state is introduced. The basis for this factor is the consideration that most tankers, for the major part of their life, will operate with cargo of a density below 0.9 tonnes/m^3. The introduction of this factor implies that the actual pressure load at 10^{-8} probability level is lower in comparison with that derived based on the assumption in which the ship is operated with a cargo of density 1.025 tonnes/m^3 throughout the whole of the ship's life.

2.4.7.b Where the ship's loading manual specifies a cargo density greater than 0.9 tonnes/m^3 associated with full tank, the specified density is to be used for calculating the required joint probability factor. Vessels that have loading manual with conditions incorporating full cargo tanks with higher densities are expected to operate with such cargo densities. The increase in scantling requirement will be reflected through the application of joint probability factor which will lead to increased dynamic and static pressures in the analysis.

2.4.7.c In general, the FE analysis in existing classification rules/procedures is based on a cargo density of 1.025 tonnes/m^3 but with only static loads or combined static and dynamic loads at higher probability level (typically 10^{-4} to 10^{-6} versus 10^{-8} as used in these Rules) in conjunction with gross or semi-net scantlings calculated using a corrosion reduction which is less than that actually allowed in operation (i.e. corrosion reduction used in the existing classification rules for scantling calculation is less than that specified in these Rules which is the same as the corrosion allowance in operation). The approach adopted in the Common Structural Rules is considered to be conservative compared with the existing classification rules as the analysis is based on maximum allowable wear down in form of corrosion, maximum local and global dynamic loads (i.e. tank pressure calculated based on maximum accelerations) in conjunction with partial loaded loading patterns in the analysis (i.e. assumption of the ship operates in most onerous loading patterns through the ship's life).

2.4.7.d The approach based on a cargo density of 1.025 tonnes/m^3, in combination with maximum loads and maximum allowable corrosion, has been proven to be over conservative, which results in unwarranted and substantial increases in scantling of transverse bulkhead structure found from the FE analysis when compared to existing designs. It is to be noted that the adopted approach in these Rules, incorporating the joint probability factor, does not result in reduced scantling of the transverse bulkhead but a scantling which is in general ,above that required by existing classification rules and in existing designs.

2.4.7.e For harbour/tank testing load cases, the static tank pressure is calculated based on a cargo density of 1.025 tonnes/m^3.

2.4.7.f The additional static pressure to be added to the static pressure due to the fluid filled to the highest point of a tank is summarised in *Table B.2.d*.

Table B.2.d Static Overpressure in Tanks

	Ballast Tanks (Ballast Exchange by Sequential Method)	**Ballast Tanks** (Ballast Exchange by Flow Through Method)	**Cargo Tanks**
Seagoing load cases (design combinations S + D)	None	Sum of: Maximum vertical height of air/overflow pipe of all ballast tanks (minimum 2.4m above top of tank) and Maximum pressure drop due to sustained liquid flow through air/overflow pipe (minimum 25 kN/ m^2)	None
Harbour/tank testing load cases (design combination S)	Not filled in FE load cases	Not filled in FE load cases	Greater of: Maximum setting of pressure relief valve in all cargo tank (minimum 25kN/m^2) and Maximum height of air/overflow pipe (minimum 2.4m above top of tank)

2.4.7.g For ballast tanks which are designed for ballast water exchange by flow-through method, the reference point for calculating the dynamic tank pressure due to vertical acceleration is to be taken at the top of the air pipe/overflow of the tank.

2.4.7.h The additional overpressure applied to a cargo tank in harbour/tank testing load cases provides the internal load for assessing the deck head structure, without the counteracting external green sea load on deck and wave pressure on deck side applied in the seagoing load cases. The harbour/tank testing and seagoing load cases compliment each other and target different areas of the tank structure. In combination, these load cases define the envelope of the internal pressure on the boundaries of the cargo tank.

2.4.7.i The rule formula for vertical acceleration given in *Section 7/3.3.3 of the Rules* is for the determination of the envelope vertical acceleration. The formula is modified for use by the finite element analysis. For head sea condition, zero roll motion is considered and the vertical acceleration due to roll is set to zero. For beam sea condition, zero pitch motion is considered and the vertical acceleration due to pitch is set to zero.

2.5 Procedure to Adjust Hull Girder Shear Forces and Bending Moments

2.5.1 General

2.5.1.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

2.5.2 Shear force and bending moment due to local loads

2.5.2.a The method used to calculate the hull girder bending moment and shear force along the length of the cargo-tank finite element model should be consistent with that used in the longitudinal strength calculation and ship's loading computer, which is used for calculating the still water bending moment and shear force of the ship in operation.

2.5.2.b The hull girder bending moment and shear force due to local loads may be calculated based on a simple beam model. If the hull girder bending moment is calculated using the longitudinal stresses at a cross section of the FE model with respect to the corresponding neutral axis, the hull girder bending moment is equal to the sum of bending moments produced by the longitudinal stress acting on each individual element over the entire cross section (i.e. both port and starboard sides). If the hull girder shear force is calculated by considering the shear stresses at a cross section of the FE model, the shear force is equal to the sum of the vertical forces produced by the shear stress of each individual element over the entire cross section (i.e. both port and starboard sides).

2.5.2.c It should be noted that a ship's loading computer calculates the bending moments and shear forces based on a simple beam and does not take into account abreast distribution of cargo/ballast in tanks. When a ship is loaded unevenly abreast, due to the effect of local loads, the longitudinal stress and shear stress will be increased in some parts of the hull girder more than that of an evenly loaded condition for the same amount of hull girder bending moment and shear force. The stress increase due to local loads resulting from uneven abreast tank loading distribution is checked by the finite element analysis to ensure adequate hull strength when the ship is subjected to the maximum permissible still water bending moment and shear force in uneven abreast tank loaded conditions.

2.5.3 Procedure to adjust vertical shear force distribution

2.5.3.a It is important to distribute the vertical force only to the vertical shear carrying members in correct proportion in order to obtain the correct stress response from the FE analysis. The vertical force is distributed to the vertical part of the side shell, inner skin longitudinal bulkhead, hopper slope plate, side girders and cargo tank longitudinal bulkheads (including double bottom girder in way) as shown in *Appendix B/Figure B.2.1.2* of the Rules.

2.5.3.b The proportion of vertical force to be distributed to each of the above structural members is ideally to be determined by a shear flow calculation.

2.5.3.c In lieu of a shear flow calculation, the shear force distribution factors provided can be applied. The same set of shear force distribution factors is applied in the prescriptive longitudinal strength requirement. Note that in the calculation of the shear distribution factors, the shear areas of the hopper plate and side girders are taken into account.

2.5.4 Procedure to adjust vertical and horizontal bending moments

2.5.4.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

2.6 Boundary Conditions

2.6.1 General

2.6.1.a Ground springs are applied at the ends of the cargo tank model to provide constraint of the model (except constraint in δ_x which is provided by constraint at grid point) and support of the unbalanced forces.

2.6.1.b In practice, it is sufficient to consider only the vertical shear forces acting on the side shell, inner skin and cargo tank longitudinal bulkheads, and only the lateral shear forces acting on the deck, inner bottom and bottom shell. In other words, it is only necessary to apply ground spring supports at these locations. The effects of shear forces on side longitudinal girders or horizontal stringers are considered negligible in the cargo tank analysis.

2.6.1.c Ground spring constraint has the advantage over point constraint of distributing the loads in accordance with the stiffness of the springs applied. This enables a more correct distribution of loads and reduces the localised stress increase at the supports.

2.6.1.d The spring stiffness of each structural member is calculated based on shear area of the members as described in *Appendix B/2.6.2 of the Rules*, which is considered adequate at the model ends.

2.6.2 Calculation of spring stiffness

2.6.2.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

2.7 Result Evaluation

2.7.1 General

2.7.1.a See *Section 9/2.2.5.a* for an explanation of the background on selecting the region for assessment against acceptance criteria.

2.7.2 Stress assessment

2.7.2.a The stress acceptance criteria are set against a particular mesh size. These criteria should not be used in conjunction with stress obtained from a model with mesh size larger than that intended as this will lead to a non-conservative scantling requirement.

2.7.2.b The stress criteria are based on Von Mises stress calculated based on membrane stress at the element centroid. See *Section 9/2.2.5.b, 2.2.5.c and 2.2.5.d.*

2.7.2.c Where shell elements are used, the stresses are to be taken at the mid-plane of the element to eliminate the bending effect due to local pressure load.

2.7.2.d Most finite element analysis programs will have output for stress evaluated at the element centroid. Where element centroid stress is not available, it can be calculated using the stresses at the Gauss points based on the shape function of the element. The calculation method is described in most finite element text books and software manuals. An example is given in *Figure B.2.a* to demonstrate the process using a simple four node element with four interior Gauss points. It is important to note that the shape functions vary by element type and element order. The shape functions shown in this example are not necessarily the same as those used in a particular element formulation and in a particular FE packages; they are to illustrate the interpolation method only. However, if the shape functions for a linear four node element are not available, the shape functions shown in this example may be used as an approximation.

2.7.2.e Also see background for *Section 9/2.2.5* of the Rules.

2.7.3 Buckling assessment

2.7.3.a For assessing the buckling capability of a localised panel, the panel and associated stiffeners are assumed to be corroded by the full corrosion addition thickness representing the worst corrosion state as allowed by the Rules.

2.7.3.b The combined interaction of biaxial compressive stresses, shear stress and lateral pressure loads are to be considered in the buckling calculation.

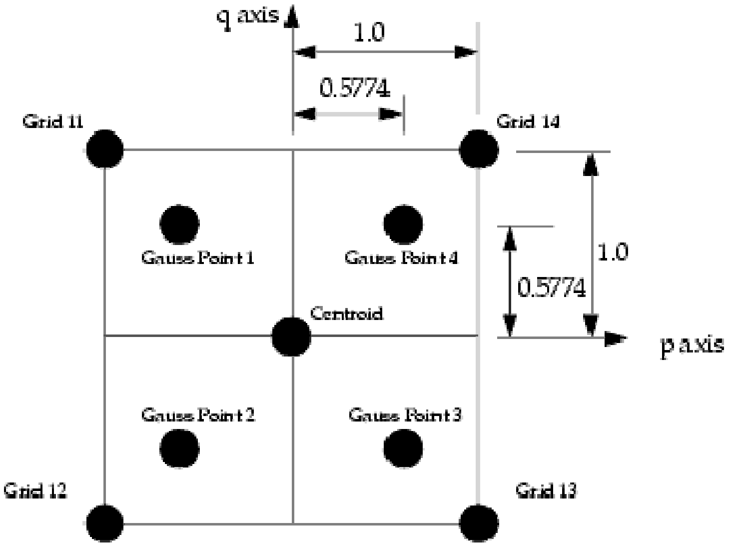
2.7.3.c The membrane stress of a plate element obtained from the finite element analysis is to be used for buckling assessment. The effect of localised pressure is accounted for separately in the panel buckling assessment. The pressure value is to be taken as the corresponding pressure in the finite element analysis.

2.7.3.d If the panel buckling assessment software used is unable to correctly model changes in pressure, axial or shear stress over a panel, then average stresses and pressure may be used for the buckling assessment. If a panel contains more than one finite plate element, then the element area weighted average stresses and pressure of the elements within the panel are used. Uniform pressure and stresses may be assumed over the panel. Procedure for calculating average stresses and pressure is described in *Appendix D/6.3 of the Rules.*

2.7.3.e Assessment of local buckling of unit corrugation flanges assumes local buckling failure mode under uniaxial compressive loads parallel to corrugation knuckles. Other buckling modes are not considered critical due to the insignificant magnitude of other stress components as compared to the corresponding buckling capacity.

Figure B.2.a
Example of Calculation of Element Centroid Stress by Interpolation of Element Gauss Point Stresses for 4-node Element

Coordinates of Gauss points and element centroid



The Gauss points are located in the *p*/*q* parametric space at +/- $(3)^{-1/2}$. The element centroid is at coordinate (0,0)

The following set of linear shape functions of the element apply:

$$N_1 = -(p-1)(q+1)$$

$$N_2 = (p-1)(q-1)$$

$$N_3 = -(p+1)(q-1)$$

$$N_4 = (p+1)(q+1)$$

the stress at any point in the element is given by the following formula:

$$\sigma(p,q) = \frac{1}{4}\sum_{i=1}^{4} N_i(p,q) * \sigma_i$$

Where

$\sigma(p,q)$	Stress at coordinate (*p*, *q*) in *p*/*q* parametric space
σ_i	Stress at Gauss point *i*

Note:
For simple 4-node element, the centroid stress is equal to the average of the stresses at the four Gauss points

2.7.3.f For an area near to the connection of the corrugation to the stool, where localised high stress and steep stress gradient occurs, it is considered not relevant to carry out buckling assessment of the panel based on this localised stress. For the part of the corrugated plate flange from the lower bulkhead stool top to a level of *s*/2 above, where *s* is the breadth of the flange, it is considered appropriate to base the buckling assessment on the stress obtained at a vertical distance *s*/2 above the stool top.

Where the stress at this position cannot be obtained directly from a plate element, it is acceptable to obtain the stress based on linear interpolation of centroid stress from neighbour elements.

2.7.3.g Elsewhere on the corrugation flange, stresses obtained directly from the finite element analysis are appropriate to be used for the buckling assessment.

2.7.3.h Also see background for *Section 9/2.2.5*.

3 LOCAL FINE MESH STRUCTURAL STRENGTH ANALYSIS

3.1 General

3.1.1 Application

3.1.1.a Evaluation of detailed stresses requires the use of refined finite element mesh in way of areas of high stress. This localised stress cannot be obtained from the cargo tank FE model due to the limited accuracy in representation of a structural detail and modelling simplifications owing to the coarser mesh size used. The objective of the local fine mesh analysis is to verify that detailed stress at critical locations, including the effects due to local structural geometry, is within the acceptable limit.

3.1.1.b The structural members and critical areas that require finite element fine mesh analysis are selected based on service experience and previous finite element studies.

3.1.1.c In view of the large number of locations that need to be investigated, a mathematical formula based screening procedure, based on the stresses obtained from the 'coarse mesh' cargo tank FE analysis, has been developed to identify the critical locations that need to be assessed using finite element fine mesh analysis to avoid unnecessary and repetitive analysis. The screening procedure applies to common structural details including openings, bracket toes and heels of primary support members. Fine mesh analysis is not required for structural details that comply with the screening criteria. Also see background for *Section 9/2.3.1* and *B/3.1.6*.

3.1.1.d As there are many openings in the web of primary support members, a further screening procedure is introduced to identify openings in non-critical areas that need not be checked (using the screening formula or fine mesh analysis). The deciding criterion is based on the size of the opening and its location.

3.1.2 Transverse web frame and wash bulkhead

3.1.2.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

3.1.3 Transverse bulkhead stringers, buttress and adjacent web frame

3.1.3.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

3.1.4 Deck, double bottom longitudinal and adjoining transverse bulkhead vertical stiffeners

3.1.4.a The objective of the fine mesh analysis of end connections of longitudinal stiffeners at deck and double bottom is to investigate the increased stresses caused by the relative deflection between the stiffener supports, which may cause localised structural and/or paint cracks. Selection of the stiffeners for analysis is based on maximum relative deflection between primary supports and transverse bulkheads. Also see *Section 9/2.3.1b*.

3.1.4.b Longitudinally, maximum relative defection of deck, inner and outer bottom longitudinal stiffeners usually occurs in way of transverse watertight bulkheads and transverse swash bulkhead. Transversely, maximum deflection usually occurs in way of the mid-tank position between longitudinal bulkheads.

3.1.5 Corrugated bulkheads

3.1.5.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

3.1.6 Screening criteria for Fine Mesh Analysis

3.1.6.a The screening criteria apply to the following common structural details:

- openings in primary supporting members (where the geometry of the model is not included in the cargo tank FE model)
- bracket toes of primary supporting members
- bracket heels in way of transverse bulkhead horizontal stringers and adjoining side horizontal girders

3.1.6.b Fine mesh analysis is mandatory for the following structural details:

- Upper hopper knuckle on typical transverse web frame
- Connection of corrugated parts of transverse and longitudinal bulkheads to bottom stools
- End connections and attached web stiffeners of typical deck and double bottom longitudinal stiffeners and adjoining vertical stiffener of transverse bulkhead
- Openings where their geometry is represented in the cargo tank finite element model (see also *B/2.2.1.r*)

3.1.6.c Fine mesh finite element analysis is to be carried out if the structural details under assessment do not comply with the screening criteria. The compliance with these criteria is to be verified for all finite element load cases.

3.1.6.d It is to be noted that the screening formulae given are intended to provide a conservative estimation of the localised stress in way of the structural details, based on the stresses obtained from the cargo tank FE analysis, for the purpose of identifying the necessity for carrying out a further fine mesh analysis. These formulae will not necessarily give accurate prediction of the stress level.

3.1.6.e The screening criteria were developed based on correlation studies of the stresses obtained from the 'coarse mesh' cargo tank FE analysis and the fine mesh FE analysis. Unless the requirements specified in *Appendix B/2.2.1 of the Rules* for the construction of the cargo tank finite element model are followed, any screening assessment carried out is not valid.

3.1.6.f The screening formula for openings in primary supporting structural members given in *Appendix B/Table B.3.1 of the Rules* is intended to predict the maximum stress at the corners of an opening in a web plate. The intention of each term in the formula is given below:

- The term $\left|\sigma_x + \sigma_y\right|$ in the formula is to account for the contribution from element axial stresses in both x direction and y direction.

- The term of $\left(2+\left(\frac{l_0}{2r}\right)^{0.74}+\left(\frac{h_0}{2r}\right)^{0.74}\right)|\tau_{xy}|$ in the formula is to account for the contribution from element shear stress.
- The term of C_h is to account for the effect of limited height of a web. For an opening in the web of main bracket or buttress, this effect is ignored and the value of C_h is set to 1.0.
- The coefficient of 0.85 is a factor derived from correlation of the stresses obtained from the 'coarse mesh' cargo tank FE analysis and fine mesh FE analysis

3.1.6.g The screening formula for bracket toes of primary support members given in *Appendix B/Table B.3.2 of the Rules* is intended to predict the maximum stress at the bracket toe in way of the termination of the bracket flange. The intention of each term in the formula is given below:

- The term $\left(\frac{b_2}{b_1}\right)^{0.5}|\sigma_{vm}|$ in the formula is to account for the stress contribution from the plate element in way of bracket toe, where the ratio $\left(\frac{b_2}{b_1}\right)^{0.5}$ accounts for the effect of steepness (angle) of bracket toe.
- The term of $\left(\frac{A_{bar-net50}}{b_1 t_{net50}}\right)^{0.5}|\sigma_{bar}|$ is to account for the stress contribution from the flange of the bracket, where the term $\left(\frac{A_{bar-net50}}{b_1 t_{net50}}\right)^{0.5}$ represents the effect of flange size.
- The term of C_a is a correction factor to account for the geometry of the bracket toe (i.e. toe angle and length), which is not included in the cargo tank FE model
- The coefficients 0.75 and 0.55 to the above terms are derived from correlation of the stresses obtained from the 'coarse mesh' cargo tank FE analysis and fine mesh FE analysis

3.1.6.h Localised stress at the heel of side horizontal girder and transverse bulkhead horizontal stringer was found to be proportional to the Von Mises stress of the element in way of the heel in the cargo tank FE model (see screening formula given in *Appendix B/Table B.3.3 of the Rules*). A stress concentration factor of 3.0 was derived from correlation between stress result from cargo tank and fine mesh analysis.

3.1.6.i Localised stress at the heel of longitudinal bulkhead horizontal stringer and transverse bulkhead horizontal stringer was found to be proportional to the longitudinal axial stress of the element in way of the heel in the cargo tank FE model (see screening formula given in *Appendix B/Table B.3.3 of the Rules*). A stress concentration factor of 5.2 was derived from correlation between result from cargo tank and fine mesh analysis.

3.2 Structural Modelling

3.2.1 General

3.2.1.a A maximum mesh size of 50mm x 50mm is chosen on the basis that this mesh size is required for representing the actual geometry of structural details, such as toes of brackets and corners of openings. Local stress is sensitive to the localised geometry of the structure and actual modelling of the geometry is necessary to determine the stress level in different detailed designs. Also see background to *Section 9/2.3.5 of the Rules*.

3.2.1.b Areas of localised high stress are assumed to be corroded fully to the minimum thickness (i.e. deduction of full corrosion addition thickness from the gross thickness). Areas outside the localised high stress zone are assumed to have average corrosion represented by deduction of half of the corrosion addition thickness from the gross thickness, which is the same reduction as used in the global cargo tank FE model.

3.2.1.c For bracket toes, bracket heels and crucified joints, the extent of the fine mesh zone is to be taken at least 500mm (i.e. 10 elements) in all directions from the area under investigation. Any parts of stiffeners, including web and flange, inside the fine mesh zone are to be modelled using shell elements. The extension of these stiffeners outside of fine mesh zones may be modelled as shell or beam elements. Stiffeners outside the fine mesh zones may be modelled using line elements. All plate areas, including web and flange of stiffeners, within the fine mesh zone are assumed to be corroded fully to the minimum allowable thickness.

3.2.1.d For openings, the minimum extent of the fine mesh zone is to be taken at least 100mm (two layers of elements) from the opening edge. The area within the fine mesh zone is assumed to be corroded fully to the minimum allowance thickness.

3.2.1.e Edge stiffener of opening, i.e. flat bar stiffener welded directly to the edge of the opening, is to be modelled with plate elements. Web stiffener which is welded to the web plating but not directly to the edge of the opening can be modelled using line elements (e.g. beam or rod elements). If the web stiffener is located less than 50mm from the edge of the opening (i.e. less than the width of one element in the fine mesh zone of mesh size 50mm x 50mm) then it can be represented by line elements along the nearest plate element’s boundary inboard of the opening edge. These line elements are not to be located on the edge of the opening

3.2.2 Transverse web frames

3.2.2.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

3.2.3 Transverse bulkhead stringers, buttress and adjacent web frame

3.2.3.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

3.2.4 Deck, double bottom longitudinal and adjoining transverse bulkhead vertical stiffeners

3.2.4.a For the assessment of detailed stress at connections of longitudinal stiffeners, the entire longitudinal stiffener under investigation, including web, face plate and associated brackets, is assumed to be corroded fully to the minimum allowable thickness (i.e. modelling thickness equals to gross thickness minus full corrosion addition thickness). This assumption is consistent with the prescriptive rule for determination of the scantlings of local stiffeners.

3.2.5 Corrugated bulkheads

3.2.5.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

3.3 Loading Conditions

3.3.1 Stress analysis

3.3.1.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

3.4 Application of Loads and Boundary Conditions

3.4.1 General

3.4.1.a The most common method used is to apply the nodal displacements as prescribed boundary condition to the sub-model. Where the sub-model has additional grid points between the common nodal points, multi-point constraint equations can be used to define the displacements at the additional grid points. Linear multi-point constraint equation is considered to be sufficient.

3.4.1.b It is to be noted that multi-point constraint equations can appear in different forms in different finite element software. However, as long as the displacements at the nodes on the primary support members (such as girders and floors) are defined, the exact choice of multi-point constraint equations should not have significant effect on the stresses at the area of interest, which should be located at adequate distance from the boundary of the model.

3.4.1.c Where nodal forces are applied, it is common to hold the model at certain point(s) on its boundary to prevent rigid body motion. As the system is itself in equilibrium, the net force at the fixed point(s) should be negligibly small.

3.4.1.d In practice, prescribed nodal displacements will usually be applied, as most finite element software caters for this method.

3.5 Result Evaluation and Acceptance Criteria

3.5.1 Stress assessment

3.5.1.a Please see background for *Section 9/2.3.5 of the Rules.*

4 EVALUATION OF HOT SPOT STRESS FOR FATIGUE ANALYSIS

4.1 Application

4.1.1 General

4.1.1.a This section describes the procedure to perform a finite element analysis using very fine mesh for the evaluation of geometric hot spot stresses for use in the determination of fatigue damage ratio in accordance with *Section 9/3.4.2* and *Appendix C/2 of the Rules*.

4.2 Structural Modelling

4.2.1 General

4.2.1.a The thickness used for finite element fatigue assessment is in accordance with *Section 6/3.3.7 of the Rules*. As fatigue is an accumulative process throughout the life of a ship, the scantlings used in the FE model for the assessment of fatigue strength are to represent the average corroded state (i.e. anticipated corroded state at half design life of the ship), instead of the worst corrosion state, of the structure. For areas that are close to the fatigue hot spot position, the structure is assumed to be corroded by half of the corrosion addition thickness. The extent of this localised corrosion zone is taken as at least 500mm in all directions leading up to the fatigue hot spot position. The extent of the localised corrosion zone is consistent with that used in fine mesh strength analysis, see *3.2.1.c*. Structure outside the localised corrosion zone is assumed to be corroded by a quarter of the corrosion addition thickness.

4.2.1.b For fatigue assessment, ideally the cargo tank model is to be based on a thickness obtained by deduction of a quarter of the corrosion addition thickness from the gross thickness. However, this will require a cargo tank FE model different from that used for strength assessment to be built.

4.2.1.c Alternatively, the analysis may be based on the same cargo tank finite element model used for strength assessment (i.e. based on deduction of half of the corrosion addition thickness from the gross thickness) in conjunction with a modelling correction factor, see *Appendix C/2.4.2.7 of the Rules*. Note that if the cargo tank finite element model for strength assessment is used, all structural parts, inside or outside of the localised corrosion zone, are to be modelled using a thickness obtained by deducting half corrosion addition from the gross thickness.

4.2.2 Hopper knuckle connection

4.2.2.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

4.3 Loading Conditions

4.3.1 General

4.3.1.a As fatigue is an accumulative process throughout the life of a ship, the density of the cargo used in the fatigue assessment should represent the cargo carried in regular trade. The cargo density to be used for the fatigue assessment is to be taken as the greater of the cargo density specified for the homogeneous scantling draught condition and 0.9 t/m^3, *see B/4.3.1.2 of the Rules*.

4.3.2 Finite element load cases for hopper knuckle connection

4.3.2.a In accordance with *Appendix C/2.3.1 of the Rules*, only dynamic external pressure and internal pressure are required to be applied for the evaluation of hot spot stress for assessing the fatigue strength of hopper knuckle joint. Vertical and horizontal hull girder bending moments are not to be applied.

4.3.2.b Vertical and horizontal hull girder bending moments are induced when external pressure and internal pressures are applied to the cargo tank FE model. The procedure described in *Appendix B/4.5.2 of the Rules* is used to eliminate the stress induced by the vertical and horizontal bending of the hull girder. Effect of hull girder shear force is not corrected.

4.3.2.c Where only dynamic loads are applied to the FE model in the evaluation of fatigue stress range, the effect of mean stress due to static loads can be accounted for by applying scaling factors given in *Appendix C/2.4.2.8 of the Rules*. Alternatively, the reduction in stress ranges due to mean stress effect may be derived based on *C/1.4.5.11 of the Rules* and the static stresses obtained from the cargo tank FE model for the full load and ballast conditions, with the effect of vertical and horizontal hull girder bending moments removed.

4.4 Boundary Conditions

4.4.1 Cargo tank model

4.4.1.a The boundary conditions applied to the ends of the cargo tank finite element model are the same as those used for the strength assessment. See *Appendix B/2.6 of the Rules*.

4.4.2 Local finite element models

4.4.2.a The boundary conditions applied to the boundary of finite element sub-model are the same as those used for fine mesh finite element strength assessment. See *Appendix B/3.4 of the Rules*.

4.5 Result Evaluation

4.5.1 General

4.5.1.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.

4.5.2 Hopper knuckle connection

4.5.2.a It is considered that for this topic, no information in addition to that shown in the Rules, is necessary to explain the background.