STRENGTH ANALYSIS OF HULL STRUCTURE IN ROLL ON/ROLL OFF SHIPS AND CAR CARRIERS

APRIL 2011
FOREWORD

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The Society reserves the exclusive right to interpret, decide equivalence or make exemptions to this Classification Note.

Motives:

Based on experience with the April 2006 version of the Classification Note, relevant modifications and clarifications are incorporated.

This document supersedes Classification Note 31.2, April 2006.

Main Changes:

— New balancing procedure for the global FEM racking LC1a and LC5.
— Clarification of the racking analysis procedure including screening process for LC5.
— LC9, docking, is removed from required FEM loadcases.
— Based on new two slope SN-curve, fatigue calculation example in appendix A is changed.
— Structure of the CN changed and aligned with the new CN 31.7 for Container Ships.
— New required FLS scope for Level 2 analysis.

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1. Introduction

1.1 General
The “Rules for Classification of Ships” (hereafter referred to as “the Rules”) Pt.5 Ch.2 Sec.4 and Sec.7 give several requirements for structural analyses including loads and acceptance criteria to be applied for the hull structures of General Cargo Carriers, Ro/Ro and Car Carriers.

For girders being part of a complex 2-dimensional or 3-dimensional structural system, the Rules require a complete structural analysis to be carried out. It should be shown that the stresses are within acceptable limits when loaded in accordance with described design load cases.

This Classification Note describes the scope and methods required for such structural analyses including the load cases and the acceptable stress level. In case there are differences between the Rules and this Classification Note, the current Rules prevail.

Any recognized calculation method or computer program for structural response may be applied, provided the effects of bending, shear and axial deformations are considered when relevant.

If the wave loads are calculated from a direct wave load analysis, it is required to use recognised software. As recognised software is considered all accepted wave load programs that can show results to the satisfaction of the Class Society.

Strength analysis carried out in accordance with the procedure outlined in this Classification Note will normally be accepted as basis for class approval.

1.2 Objectives
The objective of this Classification Note is:
— to give a guidance for the design and assessment of hull structures in Ro/Ro and Car Carriers in accordance with the Rules
— to give a general description on how to carry out the required calculations and analyses
— to provide information on alternative methods for determining the racking response and fatigue damage of critical details
— to promote reliable designs through encouraging rational design and analysis procedures.

1.3 Vessel categorisation

1.3.1 Ro/Ro
Ro/Ro is a common abbreviation for a ship specially arranged for roll-on and roll-off cargo handling.

General Cargo Carrier Ro/Ro vessels are cargo handling vessels with a limited number of decks, all intended for heavier cargo. By cargo is meant cars, trucks, dumpers, containers, road trailers and MAFI trailers. The vessel is loaded either by use of the cargo’s own engine power or by use of special loading and un-loading vehicles.

Structural wise, the General Cargo Carrier Ro/Ro vessels have deep transverse deck girders that may carry the deck load without pillar support. The racking moment of each transverse frame is normally carried by the frame alone. This means that a simplified structural analysis approach can be followed for the racking assessment of General Cargo Carrier Ro/Ro vessels.

The loading capacity of such ships is often given as lane metres.

1.3.2 Ro/Ro /Container
Several Ro/Ro ships are specially arranged also for transportation of containers. Such arrangement includes special fittings/lashing arrangement, and may also include special cargo handling vehicles onboard the ship.

1.3.3 Car Carriers
Car Carriers are specially made for transportation of cars or other vehicles. Arrangement-wise, the vessel has one or two side ramps in addition to the stern ramp (quarter ramp).

Structural-wise, a Car Carrier is similar as a General Cargo Carrier Ro/Ro vessel but has more decks (i.e. ‘Multiple decks Ro/Ro carrier’). A Car Carrier has different load carrying capacity for the different decks. The upper most decks are designed for a low uniform deck load corresponding to private cars, down to 150 kg/m² while some of the lower decks are designed for a higher load and are intended for busses, trucks, trailers or other heavier vehicles. Movable decks may in many cases be located above the decks with high specified load. Movable decks are either liftable, meaning free panels lifted by scissor lift on board the vessel, or hoistable, meaning that the panels are equipped with internal jigger winch and wires for lifting. The load capacity of the movable deck is similar as for the upper decks. The decks may be supported by pillars and longitudinal girders.
are then usually connecting the pillars.

Due attention is to be paid to the racking response of the hull structure:

— for the smaller car carriers, the racking moment on each frame may be carried by the frame alone.
— smaller Car Carriers may also be designed assuming that the racking moment over a broader area (i.e. several web frame spacings) of the cargo space should be carried by the same broad area.
— for larger Car Carriers, the structure may be designed so that the racking moment for each frame section is not fully carried by the frame itself. Thus, the racking moment is transferred through the decks to stronger racking constraining structure. Examples of such racking constraining structure are bow, stern, engine casings, partial bulkheads, engine bulkhead, deep webs and strengthened ventilation trunks.

The load capacity of Car Carriers is normally given as number of cars, or free deck area (m²). Car Carriers are normally limited to the Panama Canal requirements (32.26 m).

Car Carriers are normally denoted as PCTC or PCC.

PCTC/ LCTC: Pure/ Large Car and Truck Carriers are arranged for transportation of cars and vehicles including trucks, dumpers, containers, road trailers and MAFI trailers. One or several decks are specially strengthened to carry the heavier cargo.

PCC: Pure Car Carriers are arranged for transportation of light and heavier cars including SUV (Sport Utility Vehicles) and Land Cruisers. PCCs are normally designed for smaller draft compared to PCTCs.

1.4 Car Carrier design concepts

1.4.1 Design concepts

There exist two different structural concepts for Car Carriers. These are the conventional rigid deck design and the hinged deck design. The hinged deck design is often referred to as the ‘flexible’ design. In this classification note, the term hinged deck design will be used.

1.4.2 Conventional design

A conventional Car Carrier design means that the vertical side webs are in line with the deck transverses (see Figure 1-1). This means that transverse forces on the decks will induce bending of the deck transverses. Consequently, the frame section (vertical side and transverse deck girder) is rigid when exposed to transverse forces, compared to the hinged deck design. A considerable fraction of the racking moment created above the bulkhead deck (freeboard deck) is then mainly to be carried by the frame section itself.

![Figure 1-1](image-url)

Typical deck plan for conventional (rigid deck design) car carrier
1.4.3 Hinged design
A hinged deck Car Carrier design means that the vertical side frame is not in line with the deck transverse girder (see Figure 1-2). This means that no bending moment is induced in the transverse deck girder when the deck is exposed to transverse forces. The vertical side frame will then deform as a cantilever beam supported at the freeboard deck and is only able to carry a reduced portion of the racking force on the transverse frame. The bow region and the stern are then activated and contribute as racking constraining structure together with other main structure such as engine- and stair casings, deep racking web(s) and strengthened ventilation trunks.

An elastic hinge arrangement between the vertical web and the deck girders increases the ability of the ordinary side web frames to sustain transverse racking deformations of the upper hull. In consequence, the side webs are then normally more slender than for a conventional design. However, the main transverse racking constraining members have to be increased in strength to carry the racking moment.

With reference to Figure 1-2, the longitudinal flexible hinge should have low torsional stiffness (i.e. flat bar is preferred) and the distance between the flexible hinge and the face plate of the side girder should be made as small as possible. Further, the flexible hinge is supported and will transfer the shear load to the side girders through short beams with sufficient web height considering local bending.

The total capacity of the racking constraining structures has, however, to be the same for a conventional (rigid deck) design as for a hinged deck design.

1.5 Operational considerations
Modern Ro/Ro vessels are normally operated in regular routes between designated ports. Most of the charters are relatively long term. The weather and sea conditions may vary a lot depending on where the ship is trading. Change in loading will also affect the behaviour of the ship at sea, that may change the actual long term loads on the hull structure.

This Classification Note will focus on typical loading conditions and load cases to ensure structural integrity during regular trade around the world. Ship owners/operators having specific knowledge about possible loading conditions/trading routes/intended GM-values during operation etc. should give such information to the designer/yard as early as possible when planning a new project. By providing such information, the amount of assumptions made during the construction phase may be reduced, giving increased confidence to the design calculations.

1.6 Critical items and areas
1.6.1 Wheel loaded decks
In addition to the effect of longitudinal hull girder forces, the deck structures are subject to local loads from wheel print/axle loads and from container post loads where such arrangement is used. The Rules have specific requirements for wheel loaded decks, with separate requirements depending on the direction of traffic relative
to direction of deck plate stiffeners. Areas where the traffic direction is perpendicular to the direction of deck plate stiffeners are more prone to local plate deformation. For areas where cargo handling vehicles are frequently operated, the effect of driving perpendicular to the stiffener direction should be specially considered (relevant formulas are described in the Rules Pt.5 Ch.2 Sec.4).

1.6.2 Deflections in way of ramps
Deflections in way of ramps should always be addressed. Satisfactory functionality and safe operation of ramps and movable decks depend on limited deflections of adjacent structure. Ramp openings may be closed by watertight ramps/ramp covers/doors or gas tight doors, and the designer should take into account possible deflections of loaded deck girders above ramp opening, allowing for realistic deflections during normal operation.

1.6.3 Transverse racking
Ro/Ro ships have normally few racking constraining structural members that are effective with respect to support of transverse racking forces. The fatigue effect of racking forces due to the rolling of the ship in combination with vertical dynamic acceleration should be addressed at an early stage of the design process. The operators will always prefer a design with a limited number of transverse bulkheads in the cargo area to reduce the loading/unloading time and the frequency of cargo damage by the cargo operation.

1.6.4 Racking constraining structures
Racking constraining structures are the structure that will constrain deflections in transverse direction. Such structures are in many cases unstressed when the ship is in upright condition. Hence the racking induced stresses may be mainly dynamic, which implies that fatigue will be a primary design criterion. The local details, the thickness of plates and dimensioning of welds are of great importance for the fatigue performance.
In case of door openings in such structure it is of outmost importance that proper radius, preferably elliptical, are ensured and that rectangular door frames without radius are not welded directly to the bulkhead plate. Recommended solution is to introduce a recess structure in order to avoid unnecessary stress concentrations.
Typical examples of racking constraining structures are engine room bulkheads, collision bulkhead, engine- and stairway casings and partial racking bulkheads/deep vertical web structure. For strength assessment it is also important to include boundary members of the main racking constraining structures (i.e. side shell, decks, tank top).

1.6.5 Pillar structure
Pillars connecting two decks have to be designed to withstand the transverse relative deflection between the decks. Such connections may in particular be demanding when the deflections between the decks are high (for example as for the hinged deck car carrier design).

1.6.6 Fixed ramps
Fixed ramps between two decks have to be designed to withstand the transverse relative deflection between the decks. In particular this is important for decks above freeboard deck for the hinged deck car carrier design, where fixed ramps must be split in two parts or disconnected to one of the decks.

1.6.7 Ventilation ducts
Ventilation ducts connecting several decks with high relative deflection between the decks have to be designed with sufficient flexibility in order to avoid stress concentration.

1.6.8 Garage
The connection between the garage and the upper deck has to be designed with sufficient flexibility to avoid stress concentration. The racking strength of the garage itself needs special attention.

1.6.9 Transverse bulkheads
For vessels with a reduced number of effective transverse bulkheads or transverse bulkheads with reduced vertical shear capacity due to openings or ramp penetrations, the effective vertical shear capacity is to be specially considered.

1.6.10 Bottom girders
Bottom longitudinal girders in the cargo area may be subject to large shear forces in way of their end supports. This typically applies in way of the engine room bulkhead, cargo space front bulkhead and connection to partial longitudinal bulkhead in way of internal ramps.

1.6.11 Floors
In cases where a rigid lower side structure provides end support of the bottom without allowing rotation, special
attention should be paid to cut-outs in tank top since this will reduce the top plate flange. Local buckling in combination with the direction of stiffening has to be considered in way of support of the double bottom.

1.6.12 The fore ship
Car carriers normally have a large flare and speed, meaning that bow impact is highly important item for the bow structure. Reference it made to Pt.3 Ch.1 Sec.7.

1.6.13 Flat stern slamming
Large horizontal parts of the bottom in the aft ship may be exposed to large stern slamming pressures. If relevant according to Pt.3 Ch.1 Sec.7 E201, webs, stringers, frames and plating must be dimensioned according to Pt.3 Ch.1 Sec.7.

1.6.14 Internal ramps, stern- (quarter) and side ramps
Internal ramps, stern- (quarter) and side ramps are all subject to loads during cargo operations and from lashed vehicles. Deck plating and stiffeners subject to wheel loads must be dimensioned accordingly. Ramps forming part of the external side shell must also be dimensioned for relevant sea pressure. Stern ramps extending above upper deck are in addition subject to loads from seas on upper deck. Ramps should also be carefully assessed with respect to supporting and securing arrangement taking into account the actual inertia loads that apply. The flexibility of the surrounding structure to the ramp should be addressed.

1.7 Definitions

1.7.1 Units
The units (SI-units) as shown in Table 1-1 are used in this Classification Note.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Tons</td>
<td>(t)</td>
</tr>
<tr>
<td>Length</td>
<td>Millimetre</td>
<td>(mm)</td>
</tr>
<tr>
<td>Time</td>
<td>Second</td>
<td>(s)</td>
</tr>
<tr>
<td>Force</td>
<td>Newton</td>
<td>(kN)</td>
</tr>
</tbody>
</table>

1.7.2 Symbols
Symbols not mentioned in the following list are given in connection with relevant formulae. The general symbols may be repeated when additional definition is found necessary in connection with specific formulae.

L = Rule length in m
B = Rule breadth in m
D = Rule depth in m
T = Rule draught in m
TA = draught in m for considered loading condition
CB = Rule block coefficient
CW = wave coefficient
V = maximum service speed in knots on draught T
E = modulus of elasticity $2.1 \times 10^5$ N/mm$^2$ for steel
G = shear modulus $0.7 \times 10^5$ N/mm$^2$ for steel
av = combined dynamic vertical acceleration in m/s$^2$
go = acceleration of gravity = 9.81 m/s$^2$
hdb = height of double bottom in m
ϕ = rolling angle
θ = pitching angle
ms = self weight (t/m$^2$) of deck or double bottom
b = frame spacing, m.

1) For details, see the Rules Pt.3 Ch.1 Sec.1.
2) For details, see the Rules Pt.3 Ch.1 Sec.4 B.
1.7.3 Abbreviations
The following abbreviations are used in this Classification Note:

FLS = Fatigue Limit State
ULS = Ultimate Limits State
RAO = Response Amplitude Operator. Response per unit regular wave height.

2. Strength Assessment Levels

2.1 General
This section describes different ways to carry out a load, strength and fatigue assessment of Ro/Ro and Car Carriers. There may be different ways to assess the structure, both with respect to complexity and application. For this purpose three different analysis levels are defined.

2.1.1 Level 1
Level 1 analysis is sufficient for documentation of compliance with the strength requirements in the Rules for the class notations for 1A1 General Cargo Carrier Ro/Ro and 1A1 Car Carrier. Level 1 assesses global and local scantling including the racking response.

2.1.2 Level 2
Level 2 analysis is based on a Level 1 analysis and involves a more detailed approach with respect to the structural response and extended fatigue analyses. Level 2 scope fulfil the requirement for class notation Nauticus (Newbuilding).

2.1.3 Level 3
Level 3 is based on Level 2 and involves additional load cases were the loads are also based on a direct wave load analyses. These loads are used for fatigue and racking analyses. Level 3 scope fulfil the requirement for class notation CSA-2 (Rules Pt.3 Ch.1 Sec.15 E).

2.3 Level 1 analysis

3.1 Application
A Level 1 analysis is intended for documentation of compliance with the Rules for class notations Ro/Ro and Car Carrier.

3.2 Longitudinal strength and local Rule Scantling

3.2.1 Local scantling
A section scantlings analysis (i.e. all local Rule requirements including buckling) shall normally be calculated for the cross sections where the structural arrangement or the scantlings of longitudinal members are changed. Special attention should be made when doing cross section analysis at positions with large openings in the side or decks. These openings should be included in the analysis. Openings in the upper part of the side may cause interruption of the global stress transfer to the upper decks and the upper part of the side.

3.2.2 Wave bending moment
Ro/Ro and Car Carriers have moderate speed and large flare. Thus, the wave sagging moment according to the Rules should be adjusted for the speed effect ($C_{AV}$) and the flare effect ($C_{AF}$) for buckling check of upper decks.
and ship side, see Rules Pt.3 Ch.1 Sec.5 B200.

A similar correction should be made to the hogging moment and the corrected hogging moment is only to be used for buckling checks. The distance from summer load waterline to the deck line used to determine the factor \( C_{AF} \), should be taken to the lowermost deck where water can be entrapped and give raise to an increased hogging moment. For designs with open mooring deck forward, the distance should be taken up to the mooring deck.

### 3.2.3 Limits for still water bending moment

#### 3.2.3.1 Loading conditions
The longitudinal strength should be checked for loading conditions as described in Rules Pt.3 Ch.1 Sec.5 with due attention to non-homogenous loading conditions.

#### 3.2.3.2 Stillwater hogging moment
The actual still water hogging moment is usually much higher than the minimum design still water hogging moment according to the Rules.

#### 3.2.3.3 Stillwater bending moment limits
The still water bending moment limits should be based on non-homogenous loading condition. For the hogging conditions, an increased load density is to be assumed in the aft ship and fore ship area. After determining the amidships hogging moment, then the longitudinal distribution for the still water hogging moments can be taken according to the Rules.

Sagging still water bending moment limit may be accepted below the Rule value provided this can be documented. A negative still water sagging limit (i.e. minimum hogging) may be accepted provided that it can be demonstrated that the vessel will not experience static sagging, taking into account an extreme but realistic still water sagging condition with increased load density within 0.4 L and decreased load density outside 0.4 L.

**Guidance note:**
Based on a loading condition on scantling draught (for car carriers, the extreme sagging condition should include maximum load on lower decks including inner bottom), load density within 0.4 L should be increased with 25% without exceeding the maximum specified uniformed deck load (UDL) for the heavy RO/RO decks. Load density outside 0.4 L should then be reduced by totally 25% (12.5% Fwd and Aft). Scantling draught is not to be exceeded.

---end---of---Guidance---note---

#### 3.2.4 Global shear strength

#### 3.2.4.1 General
Usually, Ro/Ro and Car Carriers have sufficient global shear strength. However, for designs with thin plates in the ship side and vessels with large side openings, the shear stress should be specially considered.

#### 3.2.4.2 Global sear stress calculation
The global hull girder shear stress can be calculated according to the Rules Pt.3 Ch.1 Sec.5 D. Alternatively, the shear stress distribution due to a global hull girder shear force at a given cross section can be determined using a shear flow analysis. The shear stress is determined as:

\[
\tau = \frac{(Q_s + Q_w) \cdot SF \cdot 1000}{t} \quad (N/mm^2)
\]

where

- \( SF \) = shear flow (N/mm/N) per unit vertical load (i.e. \( F_z = 1 \) N)
- \( t \) = shell thickness (mm) at the position corresponding to the shear flow SF
- \( Q_s \) = static hull girder shear force in kN
- \( Q_w \) = dynamic hull girder shear force in kN

The shear force \( Q_s \) can be taken according to the actual loading conditions. The actual stress should be below the allowable stress \( \tau_{all} \) according to the Rules Pt.3 Ch.1 Sec.5 D.

#### 3.2.4.3 Ship side openings
Shear stress in way of large openings in the ship side should be specially considered. One way to analyse the shear stress is to determine the part of the total shear force which will distribute above and below the side opening based on the relative stiffness of the ship side above and below the opening. The shear stress can then be determined using a similar procedure as described in the Rules Pt.3 Ch.1 Sec.5 D but replacing the depth \( D \) with the local depth above and below the side opening.
3.3 Web frame and girder analysis
The primary structural members such as deck girders and side web frames are to be determined by use of beam- or FE cargo hold model as described in 6.6.

3.4 Racking analysis

3.4.1 Transverse strength of Ro/Ro vessels
For ships with a limited hull depth (e.g. Ro/Ro), the necessary racking strength is generally obtained by the transverse girder structures of bottom, sides and decks. This implies that the racking moment on a transverse frame is carried by the frame itself.

The transverse racking strength may be evaluated by a cargo hold analysis using beams or an FE model (Ref. 6.6) and should cover the hull structure over a representative length. As representative length is considered 1/2+1+1/2 pillar spacing for designs with pillars and longitudinal girders.

For designs without pillars, a two-dimensional transverse frame analysis covering one web spacing is then sufficient. It will then be conservative to apply the resulting transverse deformation as forced deformation to the stiffer racking constraining structure (e.g. engine/stairway casing).

3.4.2 Transverse strength of Car Carriers with uniformly distributed racking constraining structure.
The transverse strength of Car Carriers with uniformly distributed racking constraining structure may be analysed similarly as for a Ro/Ro described in 3.4.1 above. Uniformly distributed racking constraining structure means that the frames are self supporting or that heavy racking frames are uniformly distributed in the cargo area.

3.4.3 Transverse strength of Car Carriers with non-uniformly distributed racking constraining structure.
Car Carrier designs may however have the racking constraining structure non-uniformly distributed in the longitudinal direction. This means that the racking strength is limited to dedicated racking constraining structure such as bow structure including collision bulkhead, engine/stairway casings in the aft ship, partial bulkheads and deep racking webs throughout the cargo hold area. This may be the case for modern conventional Car Carrier designs with L > 120 m and is the case for all hinged deck designs (Ref. 1.4.3).

For such vessels, a global FE model of the hull structure, as described in 6.3, will be required for the racking analysis (Ref. 3.5.2.2). Required fatigue scope is defined in 3.8.2.

3.5 Loadcases

3.5.1 General
This section describes Rule loads to be applied to a global FE model of the structure and/or local FE model and/or beam models. Additional load cases may be required for cases were a direct wave load analysis according to Section 6 is carried out.

3.5.2 Description of loadcases

3.5.2.1 Overview of loadcases
Table 3-1 describes typical Rule load cases and is indicating its critical areas.

LC1a and LC5 are load cases for heeled condition while the remaining load cases are for the upright condition.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Description</th>
<th>Examples of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC 1</td>
<td>FLS Combined dynamic heeled (LC1a) and vertical (LC1b) load case for fatigue analysis of transverse members, $10^{-4}$ probability level (daily)</td>
<td>— All racking constraining structure — Fore and aft ship structure — Partial bulkhead, deep webs and typical webs structures — Engine/stairway casings and ventilation trunks effective for racking</td>
</tr>
<tr>
<td>LC 2</td>
<td>Maximum cargo on lower decks</td>
<td>— Lower cargo deck structures — Pillar structure</td>
</tr>
<tr>
<td>LC 3</td>
<td>Maximum cargo on upper decks</td>
<td>— Upper cargo decks — Bottom structures — Pillar structure</td>
</tr>
<tr>
<td>LC 4</td>
<td>Ballast condition</td>
<td>— Bottom structures</td>
</tr>
</tbody>
</table>
3.5.2.2 Racking conditions
The heeled racking load cases LC1 and LC5 will be applied on a global FE model of the ship or a beam model, depending on the design and required scope (Ref. 3.4).

3.5.2.3 Upright conditions
The load cases LC2-LC9 (except LC5) may be applied to a cargo hold FE model or to beam models (Ref. 6.6) as found relevant (Ref. 3.3).

3.5.3 Combined fatigue load case (LC1)

3.5.3.1 Scope
This combined load case is intended for the assessment of fatigue of transverse structural elements at a 10⁻⁴ probability level. The load case is used for fatigue check of critical areas based on stresses under combined transverse and vertical dynamic loading, and hence divided in two separate load cases, LC1a and LC1b, as shown in Figure 3-1 and Figure 3-2.

For hinged designs LC1b will give a negligible contribution and may hence be disregarded for ordinary web frames due to no bending moment transfer from the deck girders.

3.5.3.2 Loads
As LC1a and LC1b are fatigue load cases, all static loads may be disregarded.

A realistic maximum value for deck cargo is to be assumed for the uppermost cargo decks. The loading condition (i.e. mass distribution) should in general be different from LC5 and represent an average- or most frequently used loading condition taken from the vessels trim and stability booklet.

Actual GM value for loading condition chosen for LC1 FLS analysis should be applied, but not taken less than 0.035 B. It should be noted that using a lower GM value means that the predicted fatigue life will be more optimistic. The GM value representative for the departure condition should therefore be used as basis for the fatigue analysis.

Transverse acceleration loads are to be determined using the above GM values.

The deck load may generally be applied as distributed transverse loads as given in 3.6.4 for the relevant deck areas. Self-mass of the upper thin car decks including accommodation- and garage decks must be included. Movable car decks must be included as point loads in way of actual support positions.

The vertical acceleration (dynamic part only) for LC1b can be taken as the acceleration amidships.

If the structural arrangement is not symmetric about the centre line, both racking port- and starboard must be considered in order to find the correct stress range.

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**Table 3-1 Load cases (Continued)**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Description</th>
<th>Examples of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC 5</td>
<td>ULS Racking condition for transverse strength, 10⁻⁸ probability level (20 years). Maximum cargo on upper decks</td>
<td>— Upper cargo decks — Side structures — Bottom structures</td>
</tr>
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<td>LC 7</td>
<td>Longitudinally unsymmetrical deck loads</td>
<td>— Longitudinal deck girders</td>
</tr>
<tr>
<td>LC 8</td>
<td>Damage flooding condition</td>
<td>— Watertight deck structure</td>
</tr>
</tbody>
</table>
3.5.4 Maximum cargo on lower part of section in upright condition (LC2)

3.5.4.1 Scope
This symmetric load case with maximum cargo on lower decks is shown in Figure 3-3. The load case may be decisive for the lower decks and pillars.

Note that the higher decks are also loaded, although not to its maximum load capacity, in order to achieve vertical balance at scantling draught.

3.5.4.2 Loads
The deck pressure $P_v$, due to cargo and steel self weight are to be taken as given in 3.6.2. For accommodation decks, the total mass ($\rho H + m_o$) may be taken according to Table C1 in Rules Pt.3 Ch.1 Sec.4 C400, but is not to be less than what is given in the trim and stability booklet. For exposed weather decks, only self weight to be applied.

The sea pressure, $p_e$, is to be taken according to Section 3.5.
3.5.5 Maximum cargo on upper part of section in upright condition (LC3)

3.5.5.1 Scope
This symmetric load case with maximum cargo on upper decks is shown in Figure 3-4. The load case may be decisive for the double bottom, higher decks, pillars and longitudinal girders in the double bottom. If maximum pillar force significantly exceeds the one corresponding to the sea load, the maximum pillar force supported by double bottom may be estimated by direct calculation (LC2 and LC3) with due consideration given to uneven distribution of deck cargoes in longitudinal direction and additional support effect adjacent to solid bulkhead structures. In such case, permissible usage factor should be reduced to 0.6 for sea load.

All cargo spaces, except the tank top, are normally to be considered loaded to maximum values.

3.5.5.2 Loads
The deck pressures $P_v$, due to cargo and self weight are to be taken as given in 3.6.2. For accommodation decks, the total mass $(\rho H + m_s)$ may be taken according to Table C1 in Rules Pt.3 Ch.1 Sec.4 C400, but is not to be less than what is given in the trim and stability booklet. For exposed weather decks, only self weight to be applied, if no design load is given.

The sea pressure, $p_e$, is to be taken according to Section 3.5.
3.5.6 Ballast condition (LC4)

3.5.6.1 Scope
This symmetric load case is shown in Figure 3-5. The load case may be decisive for the double bottom.

3.5.6.2 Loads
The vertical load from the decks should be steel weight multiplied by \( g_0 \) only, i.e. no dynamic accelerations. Double bottom bunker tanks are to be considered empty. Ballast in double bottom tanks may be included as counteracting forces to the external pressure. The counteracting force corresponds to the gravity effect of the mass of water in the ballast tanks.

In case the ballast tanks are assumed empty special stress acceptance criteria apply (3.7.1.2).

The sea pressure, \( p_e \), is to be taken according to 3.6.5.4 with the draught \( T \) equal to the maximum relevant ballast draught \( T_B \).

3.5.7 Racking induced extreme load case (LC5)

3.5.7.1 Scope
This load case describes a heeled condition with maximum load on upper part of the section in order to maximise the racking moment and is shown in Figure 3-6. The load on the accommodation deck should be
included in the analysis. An average distributed load equal to 200 kg/m² in addition to the self weight may be used as guidance. For un-loaded weather decks, it is sufficient to include the load corresponding to the steel weight as long as no design load is specified.

This load case is mainly for assessing the strength of the racking constraining structure such as the fore ship, transom, engine/ stairway casings, deep webs, typical webs, racking effective ventilation trunks, racking bulkheads etc. Special care should be shown with respect to the accuracy of the results in case the load case results in high stresses in the double bottom or other structure directly exposed to the sea pressure. This is because the sea pressure usually needs to be scaled in order to achieve balance of the FE model (Ref. 6.4).

3.5.7.2 Loads

It is important to establish a realistic extreme loading condition (mass distribution) for the racking analysis having the load located at the upper decks (similar as LC3).

In the process of selecting the most relevant loading conditions, an assessment of the racking moment with respect to the bulkhead deck (main deck or deck 5 on PCTCs) shall be carried out. The bulkhead deck is the deck level at which the vertical side webs may be considered effectively supported with respect to the transverse forces. Usually, this coincides with the freeboard deck level. The racking moment is calculated using both cargo weight and the self weight. The transverse force on each deck level is obtained as the mass times the transverse acceleration. Thus, the racking moment $M_R$ may be estimated as:

$$M_R = \sum_i (M_i + m_{s,i}) \cdot a_{t,i} \cdot (z_i - z_{\text{main}})$$

where

- $M_i =$ mass on deck number $i$.
- $m_{s,i} =$ self weight of deck number $i$.
- $a_{t,i} =$ transverse acceleration at deck number $i$.
- $z_i =$ vertical distance above base line for deck number $i$.
- $z_{\text{main}} =$ vertical position above base line for bulkhead deck.

A high racking moment is achieved if the load is located on the upper decks. However this results in lower GM values and thus also lower transverse accelerations which will reduce the racking moment. Usually, several loading conditions for racking analysis should be reviewed using the simplified racking moment calculation described in this paragraph. The loading condition resulting in the highest transverse racking moment should normally be selected as basis for the fatigue analysis.

If the maximum allowable cargo mass has been assumed for the heavy cargo decks, movable cargo decks as installed directly above such decks should be assumed empty, and in the stowed position.

Lower decks are to be assumed loaded until the design draught is reached.

Actual GM value for loading condition chosen for LC5 ULS analysis should be applied, but not taken less than 0.05 B. It should be noted that using a lower GM value means that the predicted fatigue life will be more optimistic. The GM value representative for the departure condition should therefore be used.

The vertical and transverse deck loads $P_v$ and $P_t$, due to cargo are to be taken as given in 3.6.3 and 3.6.4.2. The sea pressures, $p_o$, are to be calculated according to 3.6.5.3.

If the structural arrangement is not symmetric about the centre line, both racking towards starboard and racking towards portside must be considered.
3.5.8 Transversely unsymmetrical deck load (LC6)

3.5.8.1 Scope
This load case is shown in Figure 3-7 and is applicable only for deck grillages including pillars. This load case may be dimensioning for the transverse deck girders.

For two-pillar system, the load between the pillars and the load outside the pillars need to be studied separately.

3.5.8.2 Loads
The maximum deck load to be determined as given for LC2 and LC3 for the lower and upper decks; respectively.

3.5.9 Longitudinally unsymmetrical deck load (LC7)

3.5.9.1 Scope
The load case is shown in Figure 3-8 and is applicable only for deck grillages including pillars. The load case may be dimensioning for the longitudinal deck girders.
3.5.9.2 Loads
Maximum deck load is to be determined as given for LC2 or LC3 for lower and upper decks respectively.

Figure 3-8
Load case LC7

3.5.10 Damage flooding condition (LC8)

3.5.10.1 Scope
The damage flooding condition were the ship is floating on a watertight deck is in general subject to special assessment with respect to the strength of the watertight deck in the final damage condition.

3.5.10.2 Loads
The actual loads on the watertight deck (acting from below and upwards) will depend on the actual final damaged water line position. Only hydrostatic pressure need to be considered. Special acceptance criteria apply according to 3.7.1.1.

3.6 Design loads

3.6.1 General
Design pressure loads due to external pressure, liquids in tanks and cargo should be according to the Rules Pt.3 Ch.1 Sec.12. In some cases, Section 3.2 - 3.6 in this note shows alternative simplified loads that can be applied.

3.6.2 Vertical pressure loads from deck cargo - upright condition.

3.6.2.1 Deck loads
The vertical pressure loads on cargo decks based on the uniform design load (UDL) are not to be taken less than:

\[ P_v = (\rho H + m_s)(g_0 + 0.5 a_v) \quad (\text{kN/m}^2) \]

where

\( \rho H \) = specified allowable uniform cargo load (t/m²)
\( a_v \) = dynamic vertical acceleration according to Rules, Pt.3 Ch.1 Sec.4 B
\( m_s \) = self-mass of deck in (t/m²). In particular, the self weight is important for decks with low specified design load. In lieu of more detailed data, the self weight of the lighter decks can be taken as 0.1 t/m². The term \( m_s \) can be neglected when it is less than 5% of the specified deck load \( \rho H \) (Rules Pt.3 Ch.1 Sec.12 B300). Additionally, \( \rho H + m_s \) should not be taken less than 0.25 t/m² (Rules Pt.5 Ch.2 Sec.7 C200). Additional mass items such as self-mass of accommodation and garage decks on the upper deck and movable decks should be taken into account.

3.6.2.2 Point loads from vehicles
To determine the load on a single girder exposed to axle load, the width of a road trailer can be taken as 2.5 m with 0.5 m clearance between the trailers, if not specified.
3.6.3 Vertical pressure loads from deck cargo - heeled condition LC5
The vertical pressure load for cargo decks in heeled condition is not to be taken less than:

\[ P_v = g_o (\rho H + m_s) \quad (\text{kN/m}^2) \]

\[ \rho H = \text{as given in 3.2} \]
\[ m_s = \text{as given in 3.2} \]

3.6.4 Transverse load from deck cargo - heeled conditions LC1a and LC5

3.6.4.1 Heeled condition LC1a
The transverse load for cargo decks is not to be taken less than:

\[ P_t = (\rho H + m_s) 0.5^{1/h} a_t \quad (\text{kN/m}^2) \]

\[ \rho H = \text{as given in 3.6.4.1} \]
\[ m_s = \text{as given in 3.6.4.1} \]
\[ h = \text{Weibull shape parameter (see paragraph)} \]
\[ a_t = \text{as given in the Rules, Pt.3 Ch.1 Sec.4 with } R_R \text{ taken with a negative sign for positions below the centre of rolling.} \]

3.6.4.2 Heeled condition LC5
The transverse load for cargo decks is not to be taken less than:

\[ P_t = (\rho H + m_s) a_t \quad (\text{kN/m}^2) \]

3.6.5 Sea pressure

3.6.5.1 Heeled condition LC1a
The dynamic sea pressure \( p_e \), of the heeled condition LC1a (see Section 5.2) acting over the side and bottom shell is to be taken as:

\[ p_e = 10 y \tan(\phi/2) \quad (\text{kN/m}^2) \]

\[ y = \text{transverse distance in m from centre line to considered position. Starboard and port side should have opposite signs.} \]

3.6.5.2 Upright condition LC1b
Sea pressure (dynamic part only) for the upright condition LC1b is to be taken as:

\[ p_e = p_l - 1.2(T - z) \]

where \( p_l \) is to be taken according to the Rules Pt.3 Ch.1 Sec.4 C201.

3.6.5.3 Heeled condition LC5
For the heeled condition LC5 (see Section 5.6), the sea pressure should be taken as:

\[ p_e = 10 (T - z) + 10 y \tan(\phi) \quad (\text{kN/m}^2) \]
for \( z < T \)

for the submerged side and

\[ = 10 (T - z) - 10 y \tan(\phi) \quad (\text{kN/m}^2) \]
for \( z < T \)
for the emerged side. The pressure should not be taken as less than zero. For the submerged side, the pressure above \( z = T \) can be reduced linearly to \( p_e = 0 \) at \( z = 0.5 B \tan(\phi) \)

3.6.5.4 Upright conditions
The sea pressure is in general to be taken according to the Rules. However, sea pressure in an upright condition and for the analysis of the double bottom structure can be taken as:

\[ p_e = 10h_b + p_l - 1.2(T - z) \]

where

\[ h_b = \text{vertical distance from waterline at draught } T \text{ to the load point (m)} \]
\[ p_l = \text{to be taken according to the Rules Pt.3 Ch.1 Sec.4 C200.} \]
\[ T = \text{draught (m).} \]

The minimum pressure does not have to be used for the ship side if the intention with the analysis is to analyse the deck girder system.

The sea pressure when analysing exposed weather decks should be according to the Rules.
3.6.6 Pressure due to liquid in tanks

3.6.6.1 Heeled condition LC1a
The tank pressure for the heeled condition LC1a should be taken as:

\[ p = g_0 \cdot \rho \left( 0.5 \cdot \varphi \cdot b - 0.1 \cdot \sqrt{\varphi \cdot H \cdot b_t} \right) \]

where
\[ \rho = \text{liquid density} \ \text{t/m}^3 \]
\[ b = \text{athwart-ships distance in m with the vessel on even keel from load point to the point which represents the top of the tank when the ship is heeled to an angle of 0.5} \ \varphi \]
\[ H = \text{height of tank in m with the vessel on even keel} \]
\[ b_t = \text{breadth of top of tank in m with the vessel on even keel} \]

The tank pressure can be neglected when \( b_t < 0.56 \ B \) (\( B = \text{vessel width} \)).

3.6.6.2 Heeled condition LC5
The tank pressure for the heeled condition LC5 is to be taken as:

\[ p = g_0 \cdot \rho \left( h_i + \varphi \cdot b - 0.1 \cdot \sqrt{\varphi \cdot H \cdot b_t} \right) \]

For tanks with breadth less than 0.56 \( B \) (\( B = \text{vessel width} \)), then the tank pressure can be replaced by the hydrostatic pressure.

3.6.6.3 Upright condition
The tank pressure for the upright conditions is to be taken according to Rules Pt.3 Ch.1 Sec.4 C300. The highest of acceleration pressure [1], over pumping pressure [4] or tank test pressure [5] should be used.

3.7 Acceptance Criteria

3.7.1 Allowable stresses

3.7.1.1 General
Allowable girder stresses for load cases described in 3.5 to be taken as given in the Rules Pt.3 Ch.1 Sec.12 B400, except for separate limits given in 3.1.7.2 and 3.7.1.3.

3.7.1.2 Shear in double bottom
Allowable shear stresses for the double bottom when the double bottom is empty (LC3/LC4) can be taken as 110 \( f_1 \) N/mm\(^2\).

3.7.1.3 Racking structure, ULS LC5
The nominal membrane stress in racking constraining structure is for LC5 generally not to exceed the limit:

\[ \sigma_b = 200 \ \text{N/mm}^2 \ \text{in way of dry areas} \]
\[ = 200xf_1 \ \text{N/mm}^2 \ \text{in way of dry areas provided FLS, LC1, assessment is carried out according to 3.8.1.1.} \]
\[ = 170 \ \text{N/mm}^2 \ \text{in way of coated ballast tanks} \]
\[ = 170xf_1 \ \text{N/mm}^2 \ \text{in way of dry areas provided FLS, LC1, assessment is carried out according to 3.8.1.1.} \]
\[ \tau = 120 \ f_1 \ \text{N/mm}^2 \]

In addition the above stress limits, the nominal Von Mises stress should not exceed the following limits:

\[ \sigma_{vm} = 0.95 \times \sigma_{yield} \]

Assuming 20 year North Atlantic operation, the allowable local peak stresses (equivalent stress) in critical racking constraining details may be taken as:

\[ \sigma_e = 400 \ f_1 \ \text{(N/mm}^2) \]

The peak stress is found from a FE model with mesh size similar as for the stress concentration model, see 6.3.3. In way of stress concentration areas, it is assumed that special (soft) brackets, edge reinforcement (gussets) or inserts with increased plating thickness are introduced in order to keep notch effect and stress concentration at an acceptable level.

It is assumed that the dynamic normal stresses are controlled to be within the allowable limits given above in areas with significant dynamic shear stresses combined with structural discontinuities (holes and openings etc.).
3.7.2 Buckling
Except for special items mentioned in this chapter, plate buckling requirements according to Rules Pt.3 Ch.1 Sec.13 B applies in general.

3.7.2.1 Bi-axial buckling of double bottom
Except for special items mentioned in this chapter, plate buckling requirements according to Rules Pt.3 Ch.1 Sec.13 B applies in general. The bi-axial buckling need to satisfy $\eta_{XY} < 1.0$, with the longitudinal stress $\sigma_X$ and the transverse stress $\sigma_Y$ defined as:

$$
\sigma_X = \sigma_{MS} + \sigma_{MW} + \sigma_{DBl}
$$

$$
\sigma_Y = \sigma_{DBt}
$$

where

- $\sigma_X$ = compressive stress in longitudinal direction
- $\sigma_Y$ = compressive stress in transverse direction
- $\sigma_{MS}$ = hull girder stress at bottom due to design still water hogging bending moment
- $\sigma_{MW}$ = hull girder stress at bottom due to wave hogging bending moment
- $\sigma_{DBl}$ = double bottom stress in longitudinal direction
- $\sigma_{DBt}$ = double bottom stress in transverse direction
- $\sigma_c$ = critical buckling stress, to be calculated with DNV software PULS or equivalent recognised software.

The double bottom stresses from above can be calculated by an FE model or a beam model of the bottom. If the double bottom stresses are extracted from an FE analysis of LC4, then the axial stress component can be deducted when checking bi-axial buckling only.

3.7.2.2 Deck plating intended for cargo

Transverse buckling:
The usage factor for plating acting as transverse girder flange of cargo decks is to comply with Rules Pt.5 Ch.2 Sec.7 C209:

$$
\eta = \frac{\sigma_t}{\sigma_c} \leq 0.87
$$

$\sigma_t$ = actual transverse compressive stress on a probability level of $10^{-4}$.

Longitudinal buckling, ULS:
The usage factor for plating acting as longitudinal girder flange of cargo decks is to comply with:

$$
\eta = \frac{\sigma_{uc} + \sigma_{uw} + \sigma_l}{\sigma_c} \leq 1.0
$$

$\sigma_c$ = critical buckling stress for the deck panel calculated with DNV software PULS or equivalent recognised software.

$\sigma_l$ = local longitudinal stress in deck for upright condition from FE- or beam cargo hold model.

The above $\sigma_c$ calculated with PULS will for some car carriers, especially single pillar designs, reflect the elastic buckling capacity for the transverse girder.

3.7.2.3 Racking constraining structure
The buckling usage factor $\eta$ for LC5 is in racking constraining structure to be less or equal to 1.0.

3.7.2.4 Elastic buckling
For thin deck plating, elastic buckling as given in the Rules Pt.3 Ch.1 Sec.13 B207 may be considered. In such case the design load shall be based at an extreme load level on a $10^{-8}$ probability level (i.e. 20 year return period). This means that the vertical accelerations for loaded decks is to be taken as $(g_0 + a_v)$ m/s².

3.7.2.5 Deck longitudinals
In longitudinally stiffened decks, the deck longitudinals will act as support for the plate flange of the transverse deck girders. In such cases, the moment of inertia of the deck longitudinals shall be considered with respect to stiffener buckling according to the Rules Pt.3 Ch.1 Sec.13 C501.

3.7.2.6 Transverse deck girders
The minimum moment of inertia for the transverse deck girders (acting as support for the deck longitudinals) shall be considered according to the Rules Pt.3 Ch.1 Sec.13 C502.
The transverse girders will in addition be checked according to required longitudinal ULS buckling check stated in 3.7.2.2, taking the deck panel into account.

3.7.2.7 Pillars
The usage factor $\eta$ for pillars in open spaces is generally to be taken in accordance with Rules Pt.3 Ch.1 Sec.13 C203 with $k = 0.7$ and $k = 0.6$ when the sea pressure is applied.

3.8 Fatigue Assessment

3.8.1 General
Structure designed with complex details and abrupt connections are prone to crack when subject to repeated dynamic loads. Careful design of details and weld connections in combination with good workmanship and final weld toe grinding for the welds will increase the predicted fatigue life (Ref. Classification Note 30.7 Ch.11).

In case a fatigue analysis should be carried out or required according to 3.4, this section shows applicable methods and procedures.

3.8.1.1 Scope and Critical areas
For Car Carriers where a limited number of transverse bulkheads are supporting the racking (transverse) moment, fatigue assessment may be required for the following structural details based on screening process for LC5 in the global FEM:

— transverse bulkheads and deep web structure with small radii openings (including bow and stern).
— connection of engine room-/stairway casing bulkheads to bulkhead deck (normally main deck).
— connection of other racking constraining structure such as racking boxes in cargo area to lower decks.
— connections between transverse deck girders and vertical girders (cruciform joints) for standard section and pillar section
— connection between transverse deck girders and racking constraining structure such as casings and/or racking boxes
— connections of vertical girders to bulkhead deck (or where vertical girder are to be considered fixed to rigid body)
— pillar connection to transverse deck girders and inner bottom
— transverse girder connection to webframe in way of weather deck
— pillar connection to topdeck girder.

3.8.1.2 Self-supporting frames
For Ro/Ro and smaller Car Carrier designs were each frame is self supporting when exposed to racking loads, the following items could be investigated for fatigue:

— connections between transverse deck girder and vertical web frames in ship side
— connections of vertical girders to freeboard deck (or where vertical girder are to be considered fixed to rigid body).

3.8.1.3 Net scantlings
The fatigue analysis is to be based on the net thickness.

3.8.2 Fatigue scope
For vessels with uniformly distributed racking constraining structure or with length $L < 120$ m, the fatigue performance of transverse members is controlled by comparing stresses with the allowable stresses for load case LC5, ULS. Special attention must anyhow be paid to detail design for critical areas where dynamic loads are dominating ($>50\%$) with respect to fatigue performance. Typical reinforcement will then be to introduce local inserts with soft radius and ensure grinding of critical areas.

For vessels of length $L \geq 120$ m, with non-uniformly distributed racking constraining structure as described in 3.4.3, the fatigue performance of transverse members is to be carried out based on the combined load case LC1 defined in 3.5.3. Based on a screening process of all critical areas in global FEM for LC5 (ULS) with respect to acceptance criteria given in 3.7.1.3, position and number of required fine mesh stress concentration models (Ref. 6.5) for FLS LC1 check, will be established. For critical areas where dynamic loads are dominating ($>50\%$) and local details are considered poor with respect to fatigue performance, FEA and FLS LC1 may be required even if nominal stress for LC5 (ULS) is within the acceptance criteria. The fine mesh model may be run separately through a sub modelling technique or be inserted into the higher level FE model. If a sub-modelling technique is used, due attention should be paid to ensure consistency between the node forces and the node deformation of the sub-model and the global FE model. As an alternative to carrying out local FEA for typical racking constraining structure, the structure may be reinforced locally based on a conservative
approach taking into account known stress concentration factors for the specific detail.

**3.8.3 Fatigue assessment issues**

For further reference regarding fatigue damage calculations, references are made to CN 30.7 Ch.2.

### 3.8.3.1 Stress range

The stress range may normally be taken as two times the stress amplitude. However, with reference to 3.5.3.2, actual stress range should be applied were the structure is un-symmetric about the centre line.

### 3.8.3.2 Operational life

The operational life of Ro/Ro and Car Carriers is usually more than 20 years. It is recommended that the target fatigue life is selected same as the operational life.

### 3.8.3.3 Fraction at sea

The fraction at sea should not be taken less than 85%.

### 3.8.3.4 Nominal stress

Definition of the nominal stress is important in case stress concentration factors are used. In general, the nominal stress should be taken from a beam model at the position corresponding to the hotspot. Special care should be shown if the nominal stress is extracted from an FE model.

### 3.8.3.5 Mean stress effect

With reference to CN 30.7, a mean stress factor, f_m, of 0.85 for welded details and 0.8 for the base material may be applied for structural details where the static stress is zero in racking condition. The calculated dynamic stresses are reduced accordingly by multiplication with f_m. Examples of such structure with negligible static stresses are a partial racking bulkheads and engine/stairway casing bulkheads.

For structural details where the total stress is a combined effect due to roll and vertical accelerations, the static stress will not be zero. Typical examples of such structure are transverse deck girders, pillar structure and vertical web frame structure. The corresponding stress range can be reduced by a factor varying from 0.7 (0.6 for base material) to 1.0 for respectively compression/tension over the whole stress cycle as described in CN 30.7.

### 3.8.3.6 Thickness effect

The thickness effect on stresses for plates exceeding 25mm should be included according to the procedure in CN 30.7. The thickness effect can be represented as an additional stress concentration factor K_t:

\[
K_t = \left( \frac{t}{25} \right)^{0.25}
\]

\(t\) = net plate thickness mm.

### 3.8.3.7 Areas of operation

The loads used in CN 30.7 and the fatigue loadcase, LC1, for FLS represent operation in the North Atlantic. For World Wide trade the stress can be reduced with a factor \(f_e = 0.8\). This corresponds to a nominal life time approximately twice to that of North Atlantic.

For ships that operate World Wide but which frequently (more than 5% of total time) are operated in special routes with rough sea conditions normally occur, a stress reduction as for the World Wide operation might underestimate the actual fatigue damage.

### 3.8.3.8 Stress concentration factors

A general reference is given to Appendix A in CN 30.7 for Stress Concentration Factors

The notch stress \(\sigma_{\text{notch}}\) relates to the nominal stress \(\sigma_{\text{nominal}}\) through several stress concentration factors (SCF):

\[
\sigma_{\text{notch}} = K \sigma_{\text{nominal}} = K_g K_t K_{\text{other}} \sigma_{\text{nominal}}
\]

\(K_g\) is the stress concentration due to the gross geometry (hot spot).

For complex structural details, where the stress concentration factors are not available, the geometrical stress concentration may be determined based on a stress concentration FE model (Ref. 6.7). For further procedure how to determine the geometrical stress from a fine mesh FE model, references are made to of CN 30.7. Resulting geometrical stress, following the described procedure, will then be:

\[
\sigma_{\text{g}} = K_g \sigma_{\text{nominal}}
\]
Other relevant stress concentration factors have to be added as appropriate to derive the notch stress.

### 3.8.3.9 Combination of stresses

The transverse local stresses from load cases LC1a and LC1b need not to be combined with global stresses. The stresses as found from the load case LC1a and LC1b are single amplitude stresses at 10^-4 probability level and are to be combined as follow:

\[
\Delta \sigma_0 = \sqrt{(\sigma_{LC1a})^2 + (\sigma_{LC1b})^2 + 2 \cdot \rho \cdot \sigma_{LC1a} \cdot \sigma_{LC1b}}
\]

where \( \rho \) is the correlation that depends on GM as:

<table>
<thead>
<tr>
<th>GM (m)</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>1.75</td>
<td>0.4</td>
</tr>
<tr>
<td>3.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Linear interpolation can be taken between the specified GM values.

### 3.8.3.10 Weibull shape parameter

For general reference to the long term stress distribution references are made to Section 4.3 of CN 30.7

The Weibull parameter as suggested in CN 30.7 can be used for fatigue analysis of longitudinals and for the upright load case LC1b.

The Weibull parameter \( h \) for the transverse load case (i.e. LC1a) can be taken as:

<table>
<thead>
<tr>
<th>GM (m)</th>
<th>( h ) (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.75</td>
</tr>
<tr>
<td>2.3</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Linear interpolation can be taken for values in between.

If a direct wave load analysis is carried out, the Weibull parameter for the racking response and the longitudinal stresses can be taken from that analysis.

### 3.8.3.11 S-N Curves

Relevant S-N curves should be used as basis for the fatigue analysis. The selection of S-N curve should be based on the design and the location of the subject detail (e.g. base material/welded joint/air/ballast) according to Section 2.4 in CN 30.7.

### 3.8.3.12 Number of stress cycles

The formula for the zero crossing frequency of the response according to the CN 30.7 Section 4.7 can be used for the longitudinal stresses (i.e. longitudinals).

The zero crossing frequency \( \nu_{0,r} \) for the racking response, i.e. LC1a in Section 5.2 can be taken as:

\[
\nu_{0,r} = \frac{\sqrt{GM}}{2.3k_r}
\]

GM = meta centric height m

\( k_r \) = roll radii of gyration (can be taken as 0.40 B)

\[
\nu_{0,r} = \frac{1}{4 \cdot \text{Log}(L)}
\]

The combined zero crossing frequency for the racking response and the vertical dynamic response can be calculated as:

\[
\nu_0 = \sqrt{\left(\nu_{0,r}\right)^2 + \left(\nu_{0,a}\right)^2}
\]

The zero crossing frequency should in any case not be taken below \( \nu_0 = 0.1 \text{ s}^{-1} \).
4. Level 2 analysis

4.1 Application
The Level 2 analysis is an add-on of the Level 1 analysis. This means that all Level 1 requirements should be complied with.
Level 2 analysis is in addition intended for documentation of the compliance with the Rules for the class notation **NAUTICUS(Newbuilding)**, Ref. Pt.3 Ch.1 Sec.15.

4.2 Longitudinal strength and local Rule Scantling
Same as Level 1 approach. See 3.2.

4.3 Web frame and girder analysis
The primary structural members such as deck girders and side web frames are to be determined based on a FE cargo hold analysis as described in Section 6.6. Additional frame and girder analysis for untypical area’s in way of ramp openings in deck and ship side.

4.4 Racking analysis
Same as Level 1 approach. See 3.4.

4.5 Load cases
Same as Level 1 approach. See 3.5.

4.6 Design loads
Same as Level 1 approach. See 3.6.

4.7 Acceptance criteria
Same as Level 1 approach. See 3.7.

4.8 Fatigue assessment
Same as level 1 scope for transverse structural members, ref. 3.8, but with the following minimum scope for car carriers:

1) Stairway- lift casing in the aft ship connection to bulkhead deck. Both sides if relevant
2) Connection between possible racking box and bulkhead deck
3) Corners in engine room bulkhead in way of ramps
4) Connection of web frame to racking box in upper part when racking box not extending to upper deck
5) Typical web frame connection to bulkhead deck and deck below if found applicable
6) Typical Pillar connection to deck girders in all decks
7) Connection between web frame and collision bulkhead.

The above items are in general referring to car carriers. For general cargo RO/RO vessels, applicable scope to be agreed case by case.

Additional fatigue scope according to simplified procedure:

1) Longitudinals below main deck *)
2) Transverse and/ or longitudinal block seam in upper deck if found critical
3) Most critical shear plate connection to web frame in ship side for hinge car carrier designs.

*) The loads can be taken as those described in CN 30.7 for longitudinals.

5. Level 3 analysis

5.1 Application
The Level 3 is an add-on of the Level 2 and Level 1 analyses. This means that all Level 2 and Level 1 requirements have to be complied with.
Level 3 analysis is sufficient for documentation of the compliance with the Rules for the class notation **CSA-2** as described in Pt.3 Ch.1 Sec.15E.

**NOTE:** Level 3 is not meant for standard designs operating in standard trade. Level 3 analysis is only meant for vessels with unusual high forward speed, vessels continuously operating in special harsh environment and
extraordinary designs. For such cases, a Level 3 analysis may be recommended by the Society.

5.2 Longitudinal strength and local Rule scantling
Same as Level 1 approach. See 3.4.

5.3 Web frame and girder analysis
Same as Level 2 approach. See 4.3.

5.4 Racking analysis
The racking analysis is to be based on a global FE model of the hull structure applying LC5 as described in 3.6.5.3.

5.5 Load cases
Same as Level 1 approach. See 3.5.

5.6 Design loads
Same as Level 1 approach see 3.6, except that the accelerations and applied sea pressure shall be based on a direct wave load analysis, see 5.9.

5.7 Acceptance criteria using direct wave loads
In general same as Level 1 approach, see 3.7. Special criteria’s for direct wave loads is specified in this section. The strength criteria described in this section is only intended for the structural assessment according to the Level 3 analysis when analysing the racking condition LC5 using direct calculated wave loads.

5.7.1 Nominal stress
Equivalent stress $\sigma_e$ (von-Mises) of longitudinal members should be below:

$$\sigma_e = 0.95 \sigma_f$$

$\sigma_f$ is the yield stress. Further, equivalent stress of transverse members should be below:

$$\sigma_e = 0.85 \sigma_f \text{ (N/mm}^2\text{)}$$

It has then been assumed that the wave loads are based on 20 years North-Atlantic operation.

5.7.2 Buckling
Buckling should be taken according to the Rules Pt.3 Ch.1 Sec.15 E600.

5.8 Fatigue assessment

5.8.1 Scope
Minimum scope according to level 2, ref. 4.8.

A fatigue analysis of the shell longitudinals below freeboard decks should be carried out in accordance with the requirements in Section 5.8.2. If the simplified fatigue procedure (App.A) results in a fatigue life more than twice the target fatigue life, no component stochastic fatigue analysis of the longitudinals has to be carried out.

In case of transverse stiffening of the shell plate, a similar procedure as described for the longitudinals can be followed. However, the global hull girder stress contribution can then be neglected.

A fatigue analysis of transverse racking constraining members is to be carried out as described in 5.8.3.

NOTE: Since all Level 1 and Level 2 requirement needs to be complied with, LC1 should also be carried out as described in Section 2.2.7.

5.8.2 Component stochastic fatigue assessment of outer shell longitudinals (level 3)
This section describes a component stochastic procedure for assessment of fatigue damage of outer shell longitudinals. The procedure accounts for the relative phase between the different local and global load components in different sea conditions (wave periods and wave headings).

The loads are to be based on a direct wave load analysis as described in 5.9.

The stress concentration in the hot spot can be calculated based on nominal stresses and tabulated values for the stress concentration factor $K$ as found appropriate. See also 3.8.3.8.
The component stochastic fatigue analysis assumes that the stress $\sigma$ for any regular wave period and wave direction can be written as a linear combination of the different local and global stress components acting on the member:

$$
\sigma = K_{\text{axial}} \left( \frac{VBM}{Z_h} + \frac{HBM}{Z_v} \right) + K_{\text{bending}} (C_1 \cdot p + C_2 \cdot p_i)
$$

- $VBM$ = vertical bending moment for the section in question
- $HBM$ = horizontal bending moment for the section in question
- $Z_h$ = global hull girder sectional modulus about horizontal axis for the position in question
- $Z_v$ = global hull girder sectional modulus about vertical axis for the position in question
- $p$ = sea pressure
- $p_i$ = internal pressure
- $C_1$ = coefficient relating sea pressure to the local nominal stress
- $C_2$ = coefficient relating internal pressure to the local nominal stress
- $K_{\text{axial}}$ = stress concentration due to axial stresses (geometrical stress and weld stress)
- $K_{\text{bending}}$ = stress concentration due to local bending (geometrical stress and weld stress)

The coefficient $C_1$ and $C_2$ includes local properties as stiffener span and spacing as well as local sectional modulus.

Other relevant stress concentration factors have to be added as appropriate to derive the notch stress.

### 5.8.3 Full stochastic fatigue assessment of transverse structure (level 3)

This section describes a full stochastic for assessment of fatigue of transverse structure. The procedure accounts for the relative phase between all local and global load components varying with the different sea conditions (wave periods and wave headings). For illustration of the procedure, references are made to Figure 5-1.

The loads are to be based on a direct wave load analysis as described in 5.9.

The geometrical stress concentration should be determined by a fine mesh stress concentration FE model or based on nominal stress together with tabulated values for the stress concentration factor $K_g$ as found appropriate. Other relevant stress concentration factors have to be added as appropriate to derive the notch stress.

A large amount of load cases are applied to the global FE model in the full stochastic fatigue analysis. A consistent load set (i.e. external sea pressure is in balance with the inertia forces) are applied to the structure for all relevant wave heading and wave period. The sea pressure and the accelerations are conveniently described as a complex number to account for the phasing effect.

Using 20 wave period and 12 headings (0 – 360 degrees with a step of 30 degrees) will result in 480 (=12·20·2) load cases for each loading condition (i.e. mass distribution).
5.9 Wave Load Analysis (CSA-2)

5.9.1 General
A direct wave load analysis has to be carried out in case of Level 3. The outcome of such wave load analyses is motion calculation, accelerations, hull girder loads and local pressures.

5.9.2 Objectives
The objectives of the wave load analysis are:
- to calculate the sea-keeping characteristics of the vessel including accelerations
- to calculate ULS load cases for global strength, buckling and yield checks
- to calculate FLS load cases for further fatigue assessment of critical details.

5.9.3 Numerical tools
The applied tools for the wave load analysis should be based on recognised software. As recognised software is considered all wave load programs that can show results to the satisfaction of the Class Society. Forward speed effects have to be properly taken care of. Additionally, non-linear effects have to be included in extreme sea conditions.

5.9.4 Type of analysis
Typically, two different types of wave load analyses can be carried out. These are:
- ULS (Ultimate Limit State) analysis intended to calculate hull girder loads, local sea pressure and motions in extreme environmental conditions
- FLS (Fatigue Limit State) analysis intended for calculation of dynamic loads used for fatigue assessment of critical details of the structure.

The scope of work and the calculation procedures will differ depending on what type of analysis that is carried out.
5.9.5 Linear versus non-linear analysis
Linear wave load analysis is usually sufficient for the fatigue assessment (FLS).
The ULS analysis should be based on a non-linear wave load approach. However, for extreme roll, the wave load analysis can be based on a linear procedure provided that the non-linear roll damping effects are properly taken care of.

5.9.6 Wave load analysis parameter

5.9.6.1 Wave period
The wave load analysis should be carried out for relevant wave periods. Due attention should be paid so that the natural period in roll is included as part of the range of period. Wave periods (s) ranging between 0.25 L^{1/2} and 2.6 L^{1/2} are usually sufficient. However, due attention should made in order to ensure that all relevant peaks and troughs of the transfer function is captured.

5.9.6.2 Wave direction
The analysis should cover all wave headings with step of no more than 30 degrees (i.e. 0, 30, 60, etc).

5.9.6.3 Ship speed
The wave load analysis should be carried out for speeds corresponding to 2/3 of the service speed for the racking case and for the fatigue analysis.

5.9.6.4 Short term analysis
The short term analysis should be carried out assuming a Pierson Moschowitz wave spectrum or equivalent. The wave spreading cos^2 should be used and the probability should be the same for all wave headings.

5.9.6.5 Long term analysis
The long term response analysis should be based on the short term analysis and a long term distribution of the waves (i.e. scatter diagram). The North-Atlantic wave scatter diagram is used for ULS analysis and World Wide trading scatter diagram should be used for the FLS analysis provided otherwise is not specified. The details of the scatter diagrams can be found in CN 30.7 “Fatigue assessment of ship structures”.
The long term analysis is based on standard linear wave load procedure utilising the principle of linear superposition.

5.9.6.6 Probability levels
The long term response for ULS analysis should be based on a 20 year return period.
The loads used as basis for the fatigue analysis (FLS) should be at 10^{-4} probability level.

5.9.7 Design sea state and design load cases

5.9.7.1 General
This section describes how the results from the direct wave load analysis could be transferred to design load cases for further analysis using a global FE model.

A design load case is defined as a consistent load set, i.e. the external sea pressure is in balance with the inertia loads on the global FE model. This ensures that the FE model is well balanced and that the reaction forces in boundary support are minimized.
The design load cases can be taken as snap shots (i.e. consistent load set) from a linear or non-linear (as appropriate) wave load analysis in a design sea state.

A design sea state is defined as a wave train consisting of one or several wave component and that represents the long term wave load at a specified time instant during the wave load simulation.

A design sea state consisting of one wave component only is denoted a regular design wave. The regular design wave is characterised by a wave direction, wave period and wave height.

5.9.7.2 Design sea state for racking
A single design sea state (i.e. regular design wave) based on the extreme roll motion can be used to represent the ULS racking moment on the hull structure, LC5 as described in 3.5.7.

A design sea state may be determined as follows:

— wave heading is selected as the wave heading were the roll transfer function (response to unit regular waves) is maximum
— wave period is selected as the wave period were the roll transfer function is maximum
— wave height is calculated as two times the linear long term response and divided by the transfer function value at the above wave period and wave direction
— wave steepness (wave height divided by wave length) should be checked and not be higher than 1/7. If so, a wave period slightly higher than the peak of the transfer function should be selected to ensure wave steepness below 1/7.

5.9.7.3 Design load case for racking
Non-linear wave load analyses are to be carried out for the racking design sea states.
Linear wave load analysis may be carried out if non-linear roll damping effects are properly taken care of.
The design load cases are extracted as snap shots from the time series of the roll motion.

5.9.7.4 Design load cases for fatigue
Design sea states need not to be defined in the case a fatigue analysis is to be carried out. However, an extensive amount of load cases using a unit wave amplitude need to be transferred to the FE model in case the scope involves a full stochastic fatigue analysis.

5.9.8 Load application
If the wave loads are directly applied to an FE model as sea pressure and inertia loads, special care has to be shown to ensure that the model is in balance with a minimum of forces in the boundary nodes.

6. Structural Modelling

6.1 General
This section describes how the structure can be modelled for a subsequent structural analysis.
Strength assessment of complex girder systems in deck and double bottom as well as bulkheads and racking constraining structure will normally require either beam models or FE models or a combination of those.
Depending on the complexity of the structure and the loads, the model may be 2- or 3 dimensional.

6.1.1 Beam- or FE analysis
The choice between beam models and FE models should be based on understanding of the load and response distribution and the purpose of the analysis. However, due attention should be paid to the fact that beam models will not automatically include the shear lag effect.

6.2 Reporting of structural analyses
The global transverse strength analysis of the vessel should be submitted to class for information. As guidance the following should as a minimum be included in the report:
— basic input (reference to drawings, loading manuals etc.)
— range of the model including eccentricity of beams, efficiency of curved flanges, assumptions, representations and simplifications
— units
— type of elements used in the model
— property applied to model (thickness)
— boundary conditions
— load description including load directions
— load balance
— computer program name and version
— result plots
— displacement/deformation plots
— plots of peak stresses
— numerical values for areas of high stress
— results presented for transverse member stresses, shear stresses, in plane stresses, equivalent stress (von-Mises), axial stresses (for free flanges). If flanges are modelled as beam elements, stress plots for the beam elements must be included together with property data.
— sum of loads and reactions
— result discussions and quality assurance.

6.3 Global finite element model
This section describes principle and guidelines for use in connection with a global FE modelling of the hull structure.
6.3.1 Extension
The global FE model should extend over the complete ship length, depth and breadth. All racking constraining structural members, i.e. external shell, decks, bulkheads, racking constraining girder structures, engine casing, deep webs, bow, stern bulkheads and partial bulkheads should be included in the model.

6.3.2 Loadcases
The racking load cases, LC1 and LC5, to be applied are described in 3.5.

6.3.3 Mesh size
The typical mesh size may be set equal to the vehicle deck spacing and to the transverse web frame spacing. The element size can be coarse as the global model is only intended to represent the overall stiffness and the deflection pattern for the global hull in a racking condition.

Typical global coarse mesh models of a PCTC are shown in Figure 6-2 and Figure 6-3.

When using element mesh size equal to the web distance then the effective flange will not be properly represented, and results must be used with care.

6.3.4 Structural representation
The deck panels including the deck stiffeners may be represented by isotropic plate elements and the girder structures by eccentric beam elements.

6.3.5 Element type
By preference 6/8 node elements should be used. The use of 3/4 -elements will require half mesh size. Due attention should be given to the element shapes, in particular in case 3/4 elements are used. Sharp corners, skewed elements and excessive use of triangle elements (3/6 nodes) may cause errors in the resulting deflection patterns in the model.

6.3.6 Boundary conditions
The boundary conditions should be specified only to prevent rigid body motions. An example of the boundary conditions is shown in Figure 6-1. The reaction forces in the boundary noted should be minimized.

![Figure 6-1](image)

**Figure 6-1**
Boundary conditions for global FE model
6.4 Balancing of global FE model

It is of outmost importance that the global FE model is in balance with minimum reaction forces. This section focus on such balancing for the unsymmetrical load case LC1 and LC5 only.

For cases were a direct wave load analysis is carried out and were these load are directly transferred to the FE model, the reaction forces will be small. For all other cases, the FE model will not automatically be in balance when the applied loads are those according to Section 3. No adjustment of the racking moment will be accepted to achieve force and moment balance of the FE model.

The dynamic sea pressure can be adjusted to ensure force and moment equilibrium of the global FE model. This is necessary in order to minimise the reaction forces in the boundary nodes. The following general principle for balancing may be followed:

1) Apply dynamic sea pressure as described herein. If sufficient balance is not possible when using the dynamic sea pressure, then a hydrostatic pressure will also be accepted.

2) Adjust the FE model vertically to achieve buoyancy force equal to the vertical loads (deck loads, self weight and tank content).

3) Rotate (roll) the model until balance of the transverse force is achieved or use the fraction of the sea pressure in heeled condition.
4) Re-check vertical force balance and adjust the pressure if necessary.
5) Re-check transverse force balance and adjust by rotation (roll) if necessary.
6) Balance the racking moment $M_{xx}$ by a force pair distribution (i.e. line load expressed in N/m) along the intersection line between the freeboard deck and the ship side. The racking moment $M_{xx}$ is then calculated about the axis defined as the intersection line between the freeboard deck and the centre line. The force pair distribution can either be constant or have a proper variation in the longitudinal direction. One option is to scale the force pair distribution with the height of the parallel ship side below the freeboard deck. Another option is to scale the force pair with the width of the hull in the waterline.

The following steps describe a possible balancing procedure more in detail, in line with the above principle:

1) Apply LC1a according to 4.2
2) Add a transverse horizontal unit load, $LC_{Fy}$, in bottom to cancel $F_y$ according to Figure 6-4
3) Add a vertical unit force couple, $LC_{Mxx}$, in order to cancel $M_{xx}$ according to Figure 6-4
4) Required unit loads for $LC_{Fy}$ and $LC_{Mxx}$ may then be calculated as follows:
   - Step 1) Final transverse horizontal load $F_y$ for $LC_{Fy} = F_y(LC1a) / F_y(LCFy)$
   - Step 2) $M_{xx}$ created by $LC_{Fy}$, $M_{xx}(LC1Fy) = M_{xx}(LC1a) * F_y(LCFy)/F_y(LC1a)$
   - Step 3) Final vertical force couple for $LC_{Mxx} = (M_{xx}(LC1a) - M_{xx}(LC1Fy)) / M_{xx}(LCMxx)$

![Figure 6-4](image)

**6.5 Finite element modelling of local structure**

Finite element modelling of local structures will be required for special structure with special focus on fatigue. For vessels with required FLS scope, required local FE models will depend on the nominal stress screening process for the ULS global FEA. Typical critical structures are the main transverse racking constraining members of the hull such as bow, stern, partial transverse bulkhead, the machinery bulkhead, engine casing front wall, shell, and deck structures in way of racking bulkheads and deep webs and typical pillar and web frame connections to lower decks.

**6.5.1 Model extent**

The extent of the local model must be sufficiently large in order to avoid influences from the applied boundary conditions. Recommended extent is one deck spacing above and below in the vertical direction between fixed decks.
6.5.2 Mesh size and element types
The mesh size should decrease gradually towards the area of particular interest. The mesh size should be fine
eough to describe the nominal stress increase for the subject details. Typical mesh size is one element between
the stiffeners.
References are made to 6.3.5 for element types and shapes.

6.5.3 Sub-modelling
The local FE model may be developed separately from the global FE model by using a sub-modelling
technique. Alternatively, the local model may be inserted into the global FE model. In case a sub-modelling
technique is used, the loads on the local FE model should be applied as forced deformation or nodal forces in
the boundary nodes.
The consistency between the global and the local model with respect to boundary forces and nodal
deformations has to be documented.

6.6 Cargo hold model
The objective of the cargo hold analysis is to determine the scantling of typical primary structural members
such as side girders, transverse and longitudinal deck girders and floors in the amidships cargo area. The
benefits with a FE cargo hold model compared to a beam model is that the interaction between the different
structural members is better accounted for.

6.6.1 FE Cargo hold model
6.6.1.1 General items
The loads should be according to load case LC2-LC8 (except LC5) described in 3.5. Normally, a cargo hold
model is only carried out amidships. The analysis model shall normally extend over two (2) pillar spacing
(1/2 + 1 + 1/2). The model shall cover the full breadth of the ship in order to account for unsymmetrical load
cases (LC6 and LC7). In principle the actual shape of outer shell may be modelled. However, a simplification
by assuming parallel body amidships will be accepted when due attention is paid to the stress analysis.
The extent of the recommended model is visualised in Figure 6-5. Only half the model is shown.

![Figure 6-5](image)
Model range of cargo hold analysis (port side shown)
6.6.1.2 Representation of geometry

Decks, shell, inner bottom and longitudinal bulkhead plates shall be modelled with shell elements in order to take lateral loads.

Transverse and longitudinal girders, floors and side girders may be of membrane elements.

Face plates of primary structures, e.g. vertical and transverse girders may be represented by either beam elements or truss elements.

All continuous longitudinals and stiffeners on shell elements shall be of beam element type in order to transfer the internal and external loads to the neighbouring primary structural members. Other ways of modelling the stiffeners will also be accepted provided the stiffness and the transition to surrounding structure are properly taken care of.

Non-continuous secondary structures such as web stiffeners on girders and floors may be included in the model as truss element when considered important, otherwise they may be ignored.

If non-continuous stiffeners are included in the model, then effective sectional area of such stiffeners may be calculated as follows:

- Snipped at both ends: 30% of actual area
- Snipped at one end: 70% of actual area
- Connected at both ends: 100% of actual area.

The structure shall, according to Rules, be modelled with net scantlings, i.e. corrosion addition according to the Rules shall be deducted from the actual scantlings.

Half thickness shall be applied on plates in symmetry plane at the boundaries of the model.

6.6.1.3 Element and mesh size

The stress and deformation results from the analysis are linked to the type-, shape- and aspect ratio of the elements, and mesh topology that are used. The following guidance on mesh size is based on 4-noded shell or membrane elements in combination with 2-noded beam or truss elements.

Higher order elements such as 8-noded or 6-noded elements with a coarser mesh than described below may be used provided the structure and the load distribution are properly described.

The element mesh should preferably represent the actual shape of the structures so that the stresses for the control of yield and buckling strength can be read and averaged from the results without interpolation or extrapolation. Some secondary stiffeners are therefore recommended to be modelled for mesh control.

The following is considered as guidance for the mesh arrangement:

- three elements over the web height of the girders (transverse and longitudinal), floors in double bottom structures
- one element between each longitudinal
- four elements between each floor
- access holes and larger openings in webs, girders and stringers can be considered in the analysis model in several alternatives, i.e. by including holes as-is in the model, by reduced web thickness or by due consideration in the stress evaluation stage.
6.6.1.4 Boundary conditions
Symmetry boundary conditions are in general to be applied at the ends of the model.
Vertically, the model should only be restricted along the intersection line between bulkhead deck (main deck on car carriers) and ship side.

6.6.2 Cargo Hold model, beams

6.6.2.1 General items
General guidance on modelling for direct calculations is given in the Rules Pt.3 Ch.1 Sec.12.
If a combination of 2- and 3-dimensional beam models is used, the correlation between them has to be proven satisfactory.
Local structures in way of openings for ramps and lifts may normally be analysed based on modified 2-dimensional beam models.

6.6.2.2 Model
Figure 6-7 shows a typical 3-dimensional beam model of a transverse frame structure covering 1/2 +1+1/2 pillar spacing. Fully clamped boundary conditions are applied in way of the inner bottom support and the side web support. The actual boundary condition has to be reviewed case by case based on the actual structure.
The figure also shows the frame system of a conventional rigid deck design. The misalignment between vertical side girders and transverse deck girders need to be accounted for in case of hinged deck design Car Carrier, see Figure 1-2.
In general the model should extend from the bottom to the deck and cover the entire width of the vessel.
The transverse web model shown in Figure 6-7 can be used to analyse all upright load cases.
The same figure also shows a beam model assuming parallel ship sides. In the fore and aft body this is not the case. Special models also taking in to account the reduced width may have to be developed for the fore and aft ship regions. Additionally, the increased vertical accelerations towards the ends of the vessel need to be included in the design of the decks.
If global racking calculations have been carried out for LC1 and LC5, the resulting transverse and vertical displacements of the decks side can be given as forced displacements on the beam model.
The effective breadths $b_e$ of the plate- and the free flanges of transverse deck girders and vertical side girders in way of deck- and side girder cross joints are not to be taken larger than:

$$b_e = 1.15 h_s + k h_d$$ for deck girders

$$= 1.15 h_d + k h_s$$ for side girders

\[ k = \begin{cases} 0.25 & \text{for plate flanges} \\ 0.0 & \text{for free flanges} \end{cases} \]

\[ b = \text{flange width (free flange of plate flange)} \]

### 6.6.3 Applicability

For designs where the racking moment at each transverse frame is fully carried by the frame itself, a beam model may be used to analyse racking. Then the bottom should be constrained in the transverse direction and the sides in the vertical direction as indicated in Figure 6-7.

For symmetrical load cases, zero transverse displacements may generally be assumed.

### 6.7 Stress concentration models

#### 6.7.1 General

The mesh size of local fine mesh FE-models for determination of stress concentration should be small enough to detect the geometrical stress increase in way of the hot spot area.

The aim of such FE analysis should not be to calculate directly the notch stress at the details, but rather to determine the geometric stress distribution in the region of the hot spot.

To achieve the local geometric stresses with sufficient accuracy, the mesh size should be gradually reduced to $t \times t$ ($t =$ plate thickness) at the region of particular interest. Shell elements should be used. As guidance, the area of the fine mesh zone should not be less than 10 elements in each direction.

References are made to CN 30.7 for further details regarding stress concentration models.

### 6.8 Flexible hinge member

The flexible hinge in the hinged deck design Car Carriers (see Figure 1-2) should preferably be of the flat bar type. If not of the flat bar type, the stresses in the flange can be estimated as:

$$\sigma = \frac{12 \cdot E \cdot b \cdot \delta \cdot h_d}{l^2 \cdot h_{th}}$$

\[ E = \text{module of elasticity} \]

\[ b = \text{flange width (mm)} \]
δ = relative transverse deflection between actual deck and the deck below (mm)
hd = web height of transverse deck web (mm)
l = web frame distance (mm)
h_{dk} = height between actual deck and deck below (mm).

The flexible hinge should have sufficient bending and shear strength against the vertical load.

6.9 Modelling and strength of cross joints

The flange discontinuity at cross joints of highly stressed girders may be compensated for by brackets. If the fitting of such brackets is not possible (e.g. between deck transverse and ship side vertical girders), high shear stresses in the web area that combines the girders may be the consequence. This is illustrated in Figure 6-9.

The shear stress may be taken as the mean value of:

\[ \tau = \frac{P_{F1} - 0.5F_{S1}}{1.2d_1 \cdot t_w} \quad \text{and} \quad \tau = \frac{P_{F2} - 0.5F_{S2}}{1.2d_2 \cdot t_w} \quad \text{(N/mm}\^2) \]

**Note:** For racking conditions, shear force, \( F_{S1/2} \), might give a positive contribution to the total shear force, hence – to be replaced by + if applicable.

\( F_{S1} = \) shear force in girder, N
\( P_{F1} = \) flange force in girder, N
\( D_i = \) web height of girder, mm
\( t_w = \) thickness of web plate of cross joint mm.

For evaluation of T-joint, the flange force \( P_F \) is to be taken as the sum of the flange forces of adjoining girders. Similarly, the shear force \( F_S \) is to be taken as the sum of the shear forces (absolute value) of the adjoining girder webs. This means that (Ref. Figure 6-9):

\[ P_{F1} = P_{F1a} + P_{F1b} \]
\[ F_{S1} = |F_{S1a}| + |F_{S1b}| \]

In case the shear stresses are taken from a finite element analysis, the average shear stress of the elements within the cross joint may be applied and compared against allowable stresses. The allowable shear stress of the web plate is to be taken in accordance with the Rules Pt.3 Ch.1 Sec.12 B400 (= 100 \( f_1 \) N/mm\(^2\)). The welding of the web plate of cross joints is to be based on the Rules Pt.3 Ch.1 Sec.11 C300.

The flange thicknesses of non-bracketed cross joints is generally not to be less than half of the required web plating thickness of the cross joint.

The shear flexibility of the web plates within girder cross joints gives rise to rotational deformation of the transverse deck girders relative to the vertical girders of the ship side. This flexibility may in the beam model be represented as a rotational spring between the deck girder element and the vertical web frame (see Figure 6-9). The spring stiffness \( K_{RC} \) may be determined as:

\[ K_{RC} = G \ d_1 \ d_2 \ t_w \quad \text{(Nmm/rad)} \]

where
\( d_1, d_2, t_w \) = as given in Figure 6-10 (unit is mm)
\( G \) = shear modulus, \( 0.7 \times 10^5 \) N/mm\(^2\) (steel)

---

**Figure 6-8**
Geometry of cross joint

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Figure 6-9
Analysis of cross joint

Figure 6-10
Spring representation of deck and side girder cross join
6.10 Bottom structures
A separate analysis of the double bottom strength could be carried out. Such analysis should account for the longitudinal variation of the double bottom width and the floor height in way of the supports. A typical beam model of the double bottom is shown in Figure 6-11. For designs were the bottom plating is not horizontal (i.e. rise of keel), a FE model should be considered as it will better represent the stresses of the double bottom. For designs with pillar arrangement, the counteracting pillar force on the double bottom due to the decks weights (ballast condition) and due to the deck cargo (loaded condition) should be taken into account.

Figure 6-11
Double bottom beam model

7. References
1) Det Norske Veritas, Rules for Classification of Ships, Høvik, Latest Version
2) Det Norske Veritas, Classification Note 30.7 Fatigue Assessment of Ship Structure
Appendix A

Example of simplified fatigue assessment of transverse structure

A.1 General
This section describes a simplified procedure for assessment of fatigue of main racking constraining structure with dynamic stresses due to transverse racking response, applicable for analysis level 1 and 2. The procedure can be used at the initial design stage and is usually not sufficient as basis for the documentation of vessel’s fatigue strength.

The simplified procedure is presented through an example of its application and shows a method how to determine the acceptable nominal stress range at $10^{-4}$ probability level in order to have sufficient fatigue life. For more information regarding the procedure applied, references are made to Classification Note 30.7 appendix C.

A.2 Calculation example

Input data:
S-N Curve I for welded joint for air

\[
\begin{align*}
L &= 200 \text{ m} \\
B &= 32.26 \text{ m} \\
\text{GM} &= 1.75 \\
\Delta \sigma_{LC1a} &= 220 \text{ MPa} \\
\Delta \sigma_{LC1b} &= 80 \text{ MPa}
\end{align*}
\]

The total damage $D$ should not exceed 1.0 which is expressed as:

\[
D = \nu_0 T_d \left[ q_1 \left( 1 + \frac{m_1}{h} \left( \frac{S}{q} \right)^h \right) + \frac{m_2}{h} \left( 1 + \frac{m_2}{h} \left( \frac{S}{q} \right)^h \right) \right] \leq 1.0
\]

\[
T_d = 20 \cdot 365 \cdot 24 \cdot 3600 \cdot 0.85 = 5.36 \cdot 10^8 \text{ for 20 years operation}
\]

\[
\nu_0 = \sqrt{(\nu_{0,r})^2 + (\nu_{0,\mu})^2}
\]

\[
\nu_{0,r} = \frac{\sqrt{\text{GM}}}{2.3k_r}
\]

$k_r =$ roll radii of gyration (can be taken as 0.40 B)

\[
\nu_{0,\mu} = \frac{1}{4 \cdot \text{Log}(L)}
\]

The combined zero crossing frequency should in any case not be taken below $\nu_0 = 0.1 \text{ s}^{-1}$.

\[
\Rightarrow \nu_0 = 0.117 \text{ s}^{-1}.
\]

\[
q = \frac{\Delta \sigma_0}{(\ln n_0)^{\frac{1}{h}}}
\]

Weibull shape parameter, $h = 0.813$ ref. 3.8.3.10.

\[
\Delta \sigma_0 = \sqrt{(\Delta \sigma_{LC1a})^2 + (\Delta \sigma_{LC1b})^2 + 2 \cdot \rho \cdot \Delta \sigma_{LC1a} \cdot \Delta \sigma_{LC1b} \cdot f_m \cdot 0.8}
\]

0.8 $=\text{Correction North Atlantic to World wide trade}$

$f_m = 0.85$ (Mean static stress is zero)

$\rho = 0.4$ ref. 3.8.3.9

\[
\Rightarrow \Delta \sigma = 178.5 \text{ MPa} \Rightarrow q = 11.63
\]

\[
\Delta a_0 = 10^{12.164} = 1.459 \cdot 10^{12} \text{ S-N parameters for N} < 10^7
\]

\[
\Delta a_2 = 10^{15.606} = 4.036 \cdot 10^{15} \text{ S-N parameters for N} > 10^7
\]
m_1 = 3
m_2 = 5

\[ S_i = 10^{\frac{\log_{10}^{\text{log}(-\log^{12.164-7}/m)} \cdot 3}{5}} = 10^{\frac{(12.164-7)}{3}} = 52.642 MPa \]

The above results in fatigue damage:

\[ D = 0.872 \text{ meaning } 22.9 \text{ years fatigue life} \]