

CLASSIFICATION NOTES

No. 34.2

PLUS - EXTENDED FATIGUE ANALYSIS OF SHIP DETAILS

JUNE 2010

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FOREWORD

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

Main changes

This issue of CN 34.2 replaces the April 2009 issue.

- the CSR correction factor for corrosive environment should be used for CSR vessels with **PLUS** notation
- a screening procedure for fatigue assessment of all frame positions, is also included
- scope of low cycle fatigue is elaborated. (2.7.1).

More detailed guidance given for:

- shell plating (2.3.1)
- deck details (2.5.1)
- stringer heels (2.4.1)
- ship specific details (2.6.1)
- load calculation (3.4.1)
- global model (5.2.1)
- screening procedure (2.2.1 and 5.7)
- shape of semi-nominal element mesh (8.5: new Table 8.7).

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1. Introduction

1.1 Objective

1.1.1

This Classification Note provides guidance on how to perform and document analyses required for compliance with the class notation **PLUS** as described in the DNV Rules Pt.3 Sec.1 Ch.15 E. The class notation provides enhanced scope for fatigue strength and ensures that specific critical structural details are adequately designed to meet specified fatigue requirements.

1.2 General

1.2.1

The PLUS notation is an optional class notation mainly intended for vessels operating in harsh areas and includes extended scope of fatigue strength verification for hull structural details. The scope of **PLUS** notation require additional calculations to those specified in the **NAUTICUS (Newbuilding)** and **CSR**.

This Classification Note covers a description of the following:

- scope
- procedures for
- modelling
- structural analysis
- stress read out
- fatigue analysis
- stress concentration factors
- example calculations
- documentation of the analysis.

Calculations documenting compliance with requirements in this section shall be submitted for verification.

The **PLUS** notation is primarily intended for tankers, gas carriers and container carriers of conventional design, but can also be applied to other types of vessel. Generally the vessels shall comply with: class notation **CSR** or **NAUTICUS (Newbuilding)**.

The fatigue strength evaluation shall be carried out based on the target fatigue life and service area specified by the **CSR** or **NAUTICUS (Newbuilding)** notation.

The following details in the cargo area are to be considered in the fatigue strength assessment in addition to those required for other class notations:

- longitudinal stiffener-frame connections located in the bottom, inner bottom, side and inner side including connected web stiffener, cut-out and collar plate. (See illustration in Fig. 2-2)
- deck plating including stress concentrations from openings, scallops, pipe penetrations and attachments
- bottom and side shell plating connection to frames and stiffeners.
- stringer heels and toes.
- specified ship specific details as specified in section 2.6.

The effect of low cycle fatigue is to be considered for details subjected to large stress variations during loading and unloading. Low cycle fatigue analysis shall be performed according to procedure given in Classification Note 30.7/1/.

1.3 Symbols and abbreviations

1.3.1

The following general symbols are used in this Classification Note:

AP	Aft perpendicular
BL	Base line
CL	Centreline
CSR	IACS Common Structural Rules for Bulk Carriers and Oil Tankers
HS	Hotspot
GM	Metacentre height
K_r	Roll radius of gyration
$D_{full\ load}$	Fatigue damage in fully loaded condition
$D_{ballast}$	Fatigue damage in ballast condition
$D_{non-corr}$	Fatigue damage in non-corrosive environment
D_{corr}	Fatigue damage in corrosive environment
SCF	Stress concentration factor
K_G	Geometric stress concentration factor
L	Rule length of ship in m, see Rules Pt.3 Ch.1 Sec.1.
T_d	Design fatigue life
T_C	Effective coating life
T	Fatigue life
T_{full}	Draught in full load condition
T_{ball}	Draught in ballast condition
$t/2$	Stress read out position at distance half plate thickness from hotspot
f_e	Environmental reduction factor
f_m	Mean stress reduction factor
h	Weibull shape parameter
h_o	Basic Weibull shape parameter
h_a	Additional shape factor depending on motion response period
$\log(\)$	10th logarithm
m	S-N fatigue parameter
\bar{a}	S-N fatigue parameter
q	Weibull scale parameter
v_o	Long-term average zero up-crossing frequency
σ_e	Stress amplitude due to external pressure
σ_i	Stress amplitude due to internal pressure
σ_t	Tensional stress for mean stress reduction
σ_c	Compressive stress for mean stress reduction
$\sigma_{semi-nom}$	Semi-nominal stress amplitude, e.g. stress derived from 50×50 mm model
$\Delta\sigma_0$	Combined local hotspot stress range before mean stress correction
$\Delta\sigma_1$	Combined local hotspot stress range
P_1	First principal stress direction
P_2	Second principal stress
σ_m	Membrane stress
σ_B	Bending stress
σ_{HS}	Principal hotspot stress amplitude
$\sigma_{t/2}$	Principal stress amplitude at t/2 position
$\Gamma(\)$	Gamma function [-]
$\gamma(\)$	Incomplete gamma function [-]
S_1	Stress range for which change in SN slope occurs

2. Scope of Class Notation PLUS

2.1 General

2.1.1

An overview of the different additional class notations used to document structural compliance is illustrated in Fig.2-1.

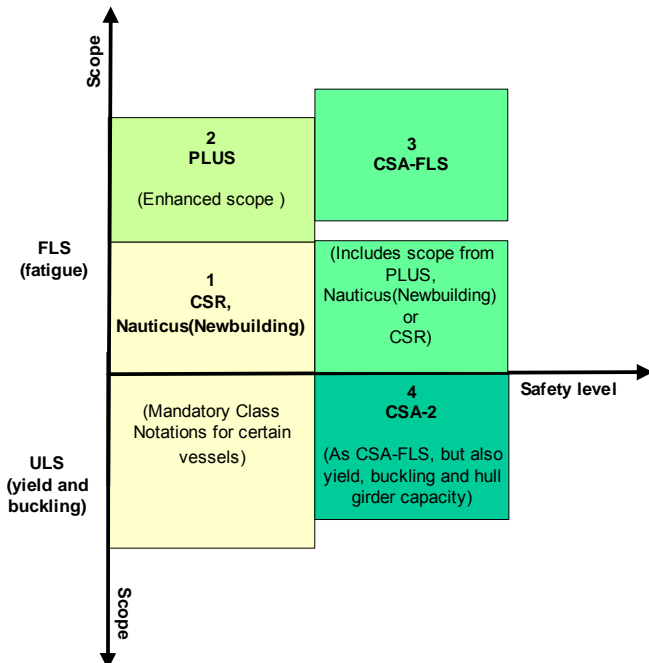


Figure 2-1
Class notation overview

The **PLUS** notation require compliance with **NAUTICUS (Newbuilding)** or **CSR** notation.

For the class notations **NAUTICUS (Newbuilding)** and **CSR** this implies that all requirements are to be complied with and documented independent of **PLUS**.

Only calculations for stiffener-frame connections and low cycle fatigue needs to be performed if the vessel is to comply with both **PLUS**-notation and **CSA-FLS** or **CSA-2** notation. Other requirements of the **PLUS** notation need not to be performed if compliance with the **CSA** notation is documented and confirmed.

2.2 Longitudinal stiffener-frame connections

2.2.1

In general the fatigue analysis should be conducted for all stiffener-frame connections in the midship-, forward-, and aft-tank. The connections in bottom, inner bottom, side, inner side and hopper tank should be assessed with finite element analysis according to section 5. Fig.2-2 illustrates the typical hotspots at a stiffener-frame connection. The hotspots include locations on the web-frame, stiffener lug and the web stiffener. The analyses should cover the entire cargo area of the selected vessel. See Fig.2-3 for an overview.

The work scope should minimum include the following:

All types of stiffener-frame connections found in the cargo tank area should be covered by the analysis. Every connection in double side and bottom at one web-frame in the middle of the forward-, amidship- and aft-tank should be analysed according to the procedure described in this Classification Note. If any stiffener-frame connections at other web-frames differ from the connections in the target web-frame then also these connections should be modelled into the target frame. The objective is that all the different types of stiffener-frame connections are covered by the analysis. See Fig.2-4.

The fatigue calculations should be performed for the mid-frame of:

- a) Amidship cargo tank
- b) Aft cargo tank
- c) Forward cargo tank.

A screening analysis should be performed in order to assess the fatigue capacity of the all the other frames in the forward-, amidship- and aft cargo tank. The screening procedure is described in section 5.7.

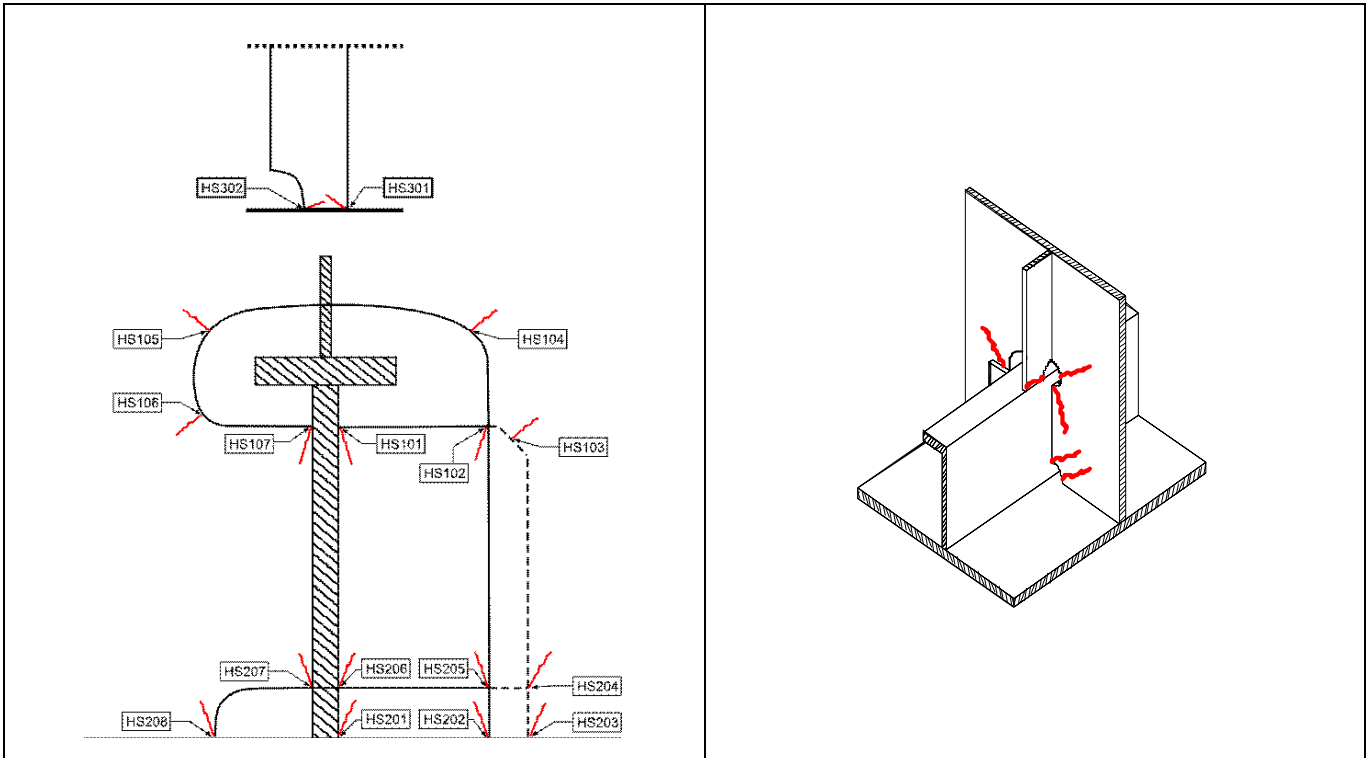


Figure 2-2
Hot spots at stiffener-frame connections

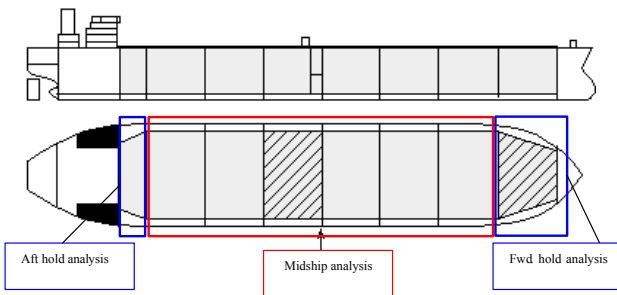


Figure 2-3
View of ship and location of details in ship

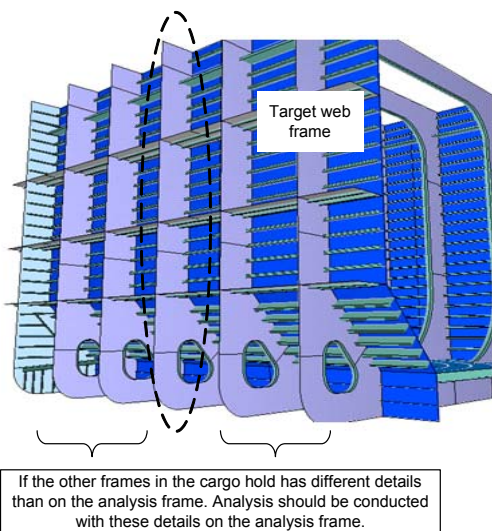


Figure 2-4
Frames in cargo tank

2.3 Bottom and side shell plating

2.3.1

The fatigue capacity of the bottom and side shell plating between two web-frame positions in midship-, forward- and aft-tank should be assessed using a simplified fatigue analysis. Both the transverse stress at stiffener mid-length and the longitudinal stress at the plate-transverse frame intersection should be assessed. It is sufficient to use simplified stress formulas for plate bending due to lateral pressure given in Classification Note 30.7 /1/.

The plate field should be subjected to internal and external rule pressure loads as given in Classification Note 30.7 /1/. The fatigue analysis should be based on relevant combination of stress components and stress concentration factors according to procedures of Classification Note 30.7 /1/.

2.4 Stringer heel and toe details

2.4.1

Fatigue calculations should be carried out for the stringers in the midship area, forward and aft hold. The heel and toe of the stringers are normally the critical locations to be assessed. This is illustrated in Fig.2-5. The fatigue calculations should be performed using a fine mesh finite element model with appropriate txt mesh in order to capture the hotspot stress. The procedures for modelling and stress read-out from fine mesh finite element models are described in Classification Note 30.7 /1/. The analysis is typically performed using a cargo hold model and a local fine mesh model together with the sub-modelling technique. The stringer model should be subjected to both lateral pressure loads and global vertical and horizontal bending moments. The global moments may be applied to the cargo hold model as unit moments. The resulting hotspot stress should be scaled such that the applied moment equal the global rule moments.

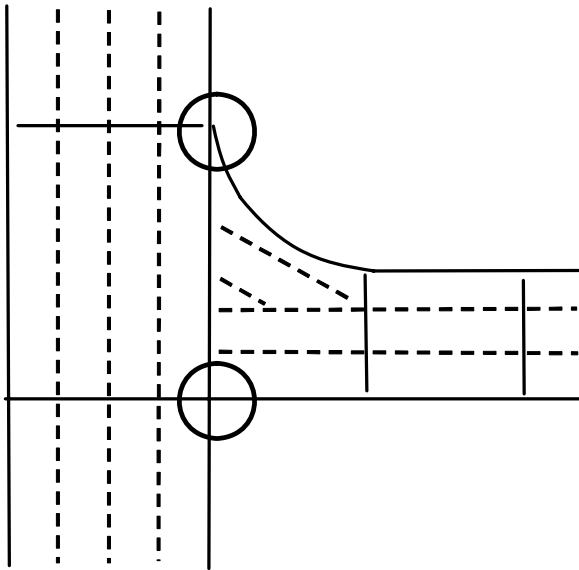


Figure 2-5
Critical locations on stringers

2.5 Deck openings and deck details

2.5.1

Deck openings and deck details in the cargo area should be analysed with respect to fatigue. Normally it is sufficient to use stress concentration factors for deck details as given in Classification Note 30.7. The details that should be included are:

- openings
- pipe penetrations
- attachments
- scallops.

The fatigue requirements for the deck plating will normally be satisfied provided that the target fatigue life is obtained with a stress concentration factor $K_G = 3.0$. Stress concentration model should be made if K_G of the target detail is not found in Classification Note 30.7.

The fatigue calculation is performed using the nominal stress due to hull girder bending together with relevant stress concentration factor to obtain the hotspot stress. The nominal stress level may be established using simplified formulas given in Classification Note 30.7 /1/.

The control of the deck openings and deck details may have direct impact on the hull girder cross section, ref. Pt.3 Ch.1 Sec.5 C305.

2.6 Ship specific details

2.6.1

For different ship types there are characteristic fatigue prone areas. Critical areas of attention should be included in the fatigue analysis for **PLUS** notation. Since these details may vary from vessel type to vessel type these ship specific details should be discussed at an early stage for clarification. Details that require fatigue analysis are:

LPG carriers:

- lower and upper side brackets
- dome opening and coaming.

LNG membrane carriers:

- upper hopper knuckle
- longitudinal girders at transverse bulkheads
- upper and lower chamfer knuckles
- dome opening and coaming.

In general a finite element analysis is required to verify the fatigue strength of these details. The procedures for modelling and stress read-out are described in Classification Note 30.7 /1/.

2.7 Low cycle fatigue

2.7.1

Low cycle fatigue strength of highly stressed locations under repeated cyclic static loads, mainly due to cargo loading and unloading, should be considered as significant yielding can cause cracks at hotspots even though the dynamic stress from wave loading is low.

A procedure for calculating the combined damage due to low cycle and high cycle fatigue is described in Classification Note 30.7 /1/. The low cycle stress range due to loading and unloading is based on the use of a pseudo-elastic hot spot stress range derived by use of a plasticity correction factor on the elastic stress range. The method enables use of standard hotspot SN-curve.

For compliance with the PLUS-notation the following locations should be verified with respect to low cycle fatigue:

- Web stiffener on top of inner bottom longitudinal and hopper slope longitudinals when wide frame space is employed.
- Web-frame hotspots at the stiffener-frame connections in areas of high girder shear stress or where web stiffener is not fitted on top of longitudinal flange.
- Heel and toe of horizontal stringer of transverse bulkhead for frequent alternate loading anticipated.
- Inner bottom connection to transverse bulkhead for frequent alternate loading anticipated.
- Lower stool connection to inner bottom for a loading condition with one side tank empty and the other tank full.

3. PLUS Analysis Procedure

3.1 PLUS analysis flowchart

3.1.1

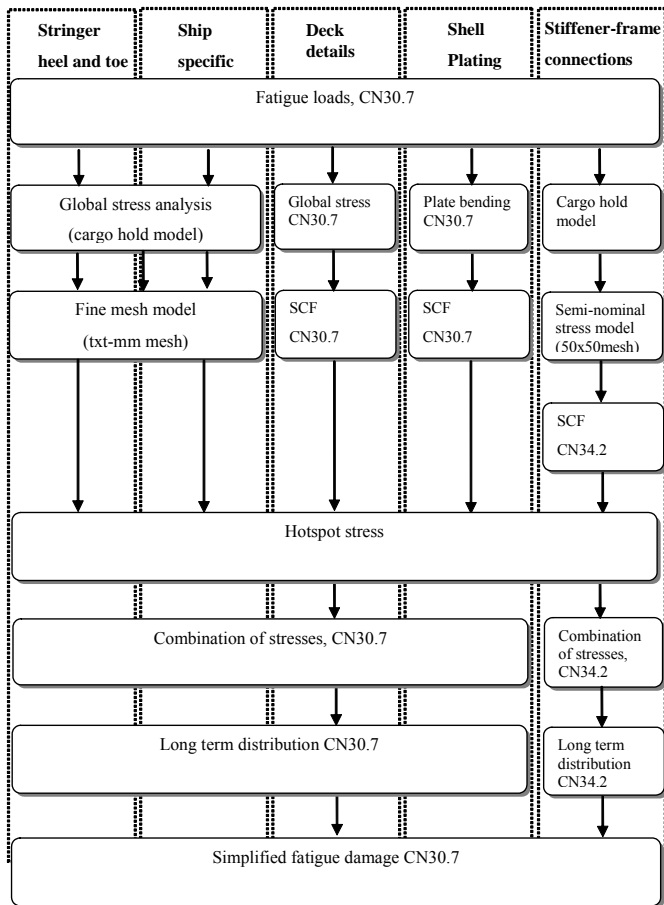


Figure 3-1
PLUS Analysis flowchart

3.2 Fatigue analysis

3.2.1

The fatigue life of details covered by the scope of **PLUS** notation as described in section 2 is to be calculated according to the procedure given in Classification Note 30.7. Fig.3-1 shows the analysis flow of all details included in the **PLUS** notation.

In order to obtain the class notation **PLUS** all structural details described in the scope should comply with a fatigue damage ratio equal or below 1.0 for the specified design fatigue life.

3.3 Stress analysis

3.3.1

The long term stress ranges for fatigue calculations of **PLUS** details are in general to be calculated according to the procedure given in Classification Note 30.7 except for the stiffener-frame connections. The stress analysis procedure for the longitudinal stiffener-frame connections is described in section 3.8.

3.4 Load calculation

3.4.1

The procedure for calculation of loads is given in Classification Note 30.7 /1/.

The following loads should be considered:

Location	Loads
Stiffener-frame connection	Pressure
Stringer	Pressure + global moments
Deck openings and details	Global moments
Shell plating	Pressure + global moments
Hopper/chamfer knuckle	Pressure
Web-frame brackets	Pressure
Dome openings	Global moments
Inner bottom – bulkhead connection	Pressure + global moments

3.5 Finite element analysis

3.5.1

Finite element models and analysis for all details included in the scope of **PLUS** notation except the stiffener-frame connections should be according to Classification Note 30.7 /1/. The procedure for modelling of longitudinal stiffener-frame connections is given in section 5.

3.6 Corrosion additions

3.6.1

Net scantlings as defined by **NAUTICUS (Newbuilding)** or **CSR**-notation, whichever is relevant, shall be used.

3.7 Effect of corrosive environment

3.7.1

Joints that are located in combined corrosive and non-corrosive environment should be analysed according to procedures give in Classification Note 30.7 /1/. For vessels with **CSR**-notation the effect of corrosive environment could be accounted for by use of the stress correction factor $f_{sn} = 1.06$.

3.8 Longitudinal stiffener-frame connections

3.8.1

The analysis of the longitudinal stiffener-frame connections follows a different procedure than the other details included in the **PLUS** notation. The flowchart in Fig.3-2 illustrates the different steps of the procedure for stiffener-frame connections.

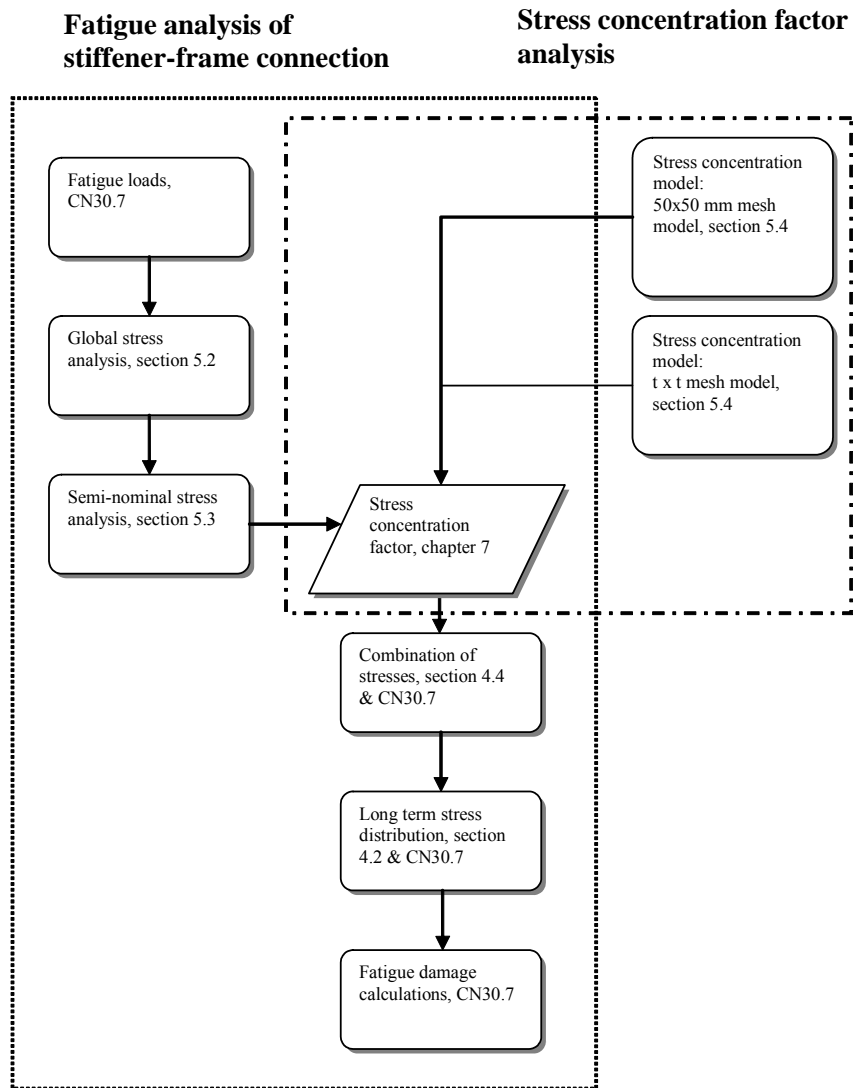


Figure 3-2
Analysis flowchart for stiffener-frame connections

4. Stress Analysis of Stiffener-Frame Connections

4.1 General

4.1.1

The stress analysis differs slightly from Classification Note 30.7 on two items. The first item is the combination of stresses from external and internal loads which has been revised into a simpler format. Secondly only one Weibull shape parameter in the long term distribution of stresses is used. The rest of the stress analysis procedure uses the same principles as Classification Note 30.7. The items which differ are presented below.

4.2 Long term distribution of stresses

4.2.1

The Weibull shape parameter shall for all longitudinal stiffener-frame connections be taken as:

$$h = h_o + h_a \quad \text{For all longitudinals}$$

where:

$$\begin{aligned} h_o &= \text{basic shape parameter} \\ &= 2.21 - 0.54 \log_{10}(L) \\ h_a &= 0.05 \end{aligned}$$

4.3 Stresses to be considered

4.3.1

The local dynamic stress range is the only stress to consider for fatigue calculation of longitudinal stiffener-frame connections. Global dynamic stress components are considered small and can be neglected. Static stress ranges are used for calculation of the mean stress reduction factor.

4.4 Combination of stresses

4.4.1

For each loading condition is a combined stress range of simultaneous internal and external stress components to be calculated. The combined local stress range is taken as a linear combination given as:

$$\Delta\sigma_l = 2 * f_e f_m * \max \left\{ \begin{array}{l} |\sigma_e + 0.6\sigma_i| \\ |0.6\sigma_e + \sigma_i| \end{array} \right.$$

Where

f_e = Reduction factor on derived combined stress range ac-

counting for the long- term sailing routes of the ship considering the average wave climate the vessel will be exposed to during the lifetime. Assuming world wide operation the factor may be taken as 0.8. For shuttle tankers and vessels that frequently operates in the North Atlantic or in other harsh environments, $f_e = 1.0$ should be used. The choice of the environmental value should be based on the service area specified by the class notation **NAUTICUS (Newbuilding)** or **CSR**

f_m = Reduction factor on derived combined stress range accounting for the effect of mean stresses, see CN30.7
 σ_e = total local stress amplitude due to the dynamic sea pressure loads (tension = positive)
 σ_i = total local stress amplitude due to internal pressure loads (tension = positive).

4.5 Calculation of stress components

4.5.1

The calculation of the stress range is performed by finite element analysis of a semi-nominal 50×50 mm mesh size model. Hotspot stress range for fatigue calculations is found by multiplying the semi-nominal stress with stress concentration factors. Chapter 5 describes the procedure for finite element analysis.

4.6 Load calculation

4.6.1

For calculation of longitudinal stiffener-frame connections is only external and internal pressure loads considered. The formulas for calculating the pressure loads are defined by Classification Note 30.7.

4.6.2

Fatigue analyses should be carried out for representative loading conditions. The following two loading conditions are normally sufficient for documentation for analysis of oil tankers, container vessels and gas carriers.

- normal full load departure condition, T_{full}
- normal ballast arrival condition, T_{ball} .

Some vessels may require other representative loading conditions in addition to these two conditions.

4.6.3

For vessels intended normal world wide trading, the fraction of design life in each loading condition is to be taken as the values in Table 4-1.

Table 4-1 Fraction of time in each loading condition

Vessel type	Oil Tankers	Gas Carriers	Bulk Carriers larger than Panamax	Bulk carriers Panamax	Container Vessel
Loaded condition	0.425	0.45	-	-	0.65
Ballast condition	0.425	0.40	0.35	0.35	0.20
Alternate condition	-	-	0.25	0	-
Homogenous condition	-	-	0.25	0.5	-

4.6.4

The six pressure load cases that should be analysed by finite element analysis are listed below:

1. External pressure Full load condition
2. Internal pressure Full load condition
3. External pressure Ballast condition
4. Internal pressure Ballast condition

5. Static pressure Full load condition
6. Static pressure Ballast condition

The loads are pressures given at 10^{-4} probability level. Global bending moments can be disregarded. The magnitude of the loads is given in Classification Note 30.7. See Fig.4-1 and Fig.4-2 for illustration.

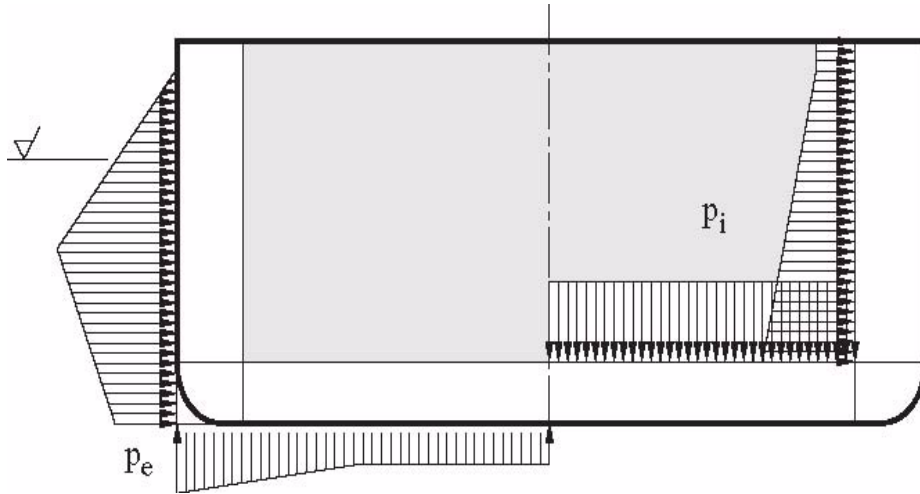


Figure 4-1
Distribution of pressure amplitudes for tankers in the fully loaded condition

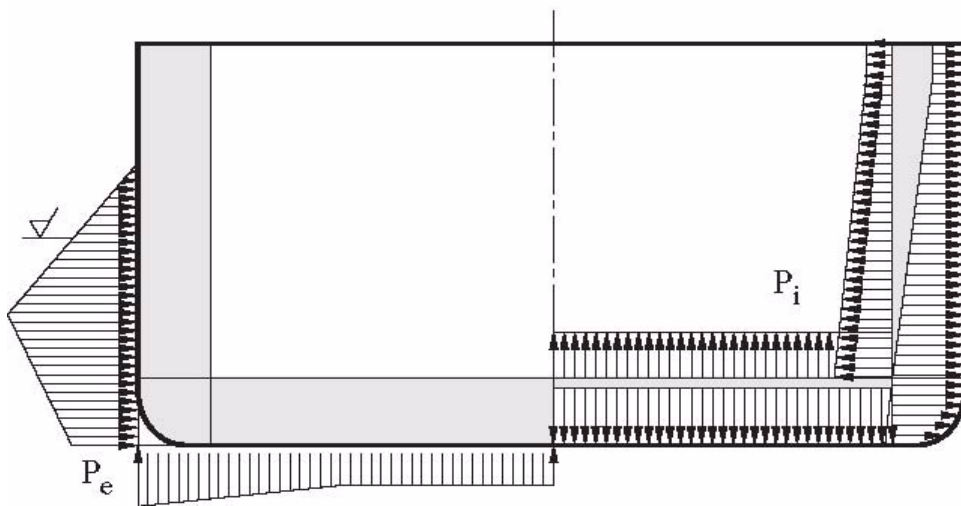


Figure 4-2
Distribution of pressure amplitudes for tankers in ballast condition

5. Finite Element Modelling of Stiffener-Frame Connections

5.1 General

5.1.1

This section applies to the longitudinal stiffener-frame connection details. A finite element analysis with a semi-nominal stress model (50×50 mm mesh) is required for stress calculations of the stiffener-frame connections. For all the other details reference is made to Classification Note 30.7 for guidance on the finite element modelling.

5.2 Global model

5.2.1

The purpose of the global model is to obtain a description of the global stress distribution in the hull. The cargo tank model should be modelled according to Classification Note 31.3 /2/.

Normally, a ½ + 1 + ½ cargo tank model is sufficient to represent the behaviour of the ship structure. Cargo tank models should be made for analysis of the forward-, amidship-, and aft-tank. The cargo tank models should take into account the change in hull shape at forward and aft part of the vessel. Fig.5-1 shows a typical amidship cargo tank model of a VLCC. The shell plating is not shown in the figure.

The cargo-tank model is equivalent with the model that is used for **NAUTICUS (Newbuilding)** or **CSR** notation. This implies that net scantlings are to be applied according to DNV rules or **CSR** rules respectively.

Element types to be used:

Quad elements:	4 or 8 node
Triangular elements:	3 or 6 node
Beam elements:	2 or 3 node.

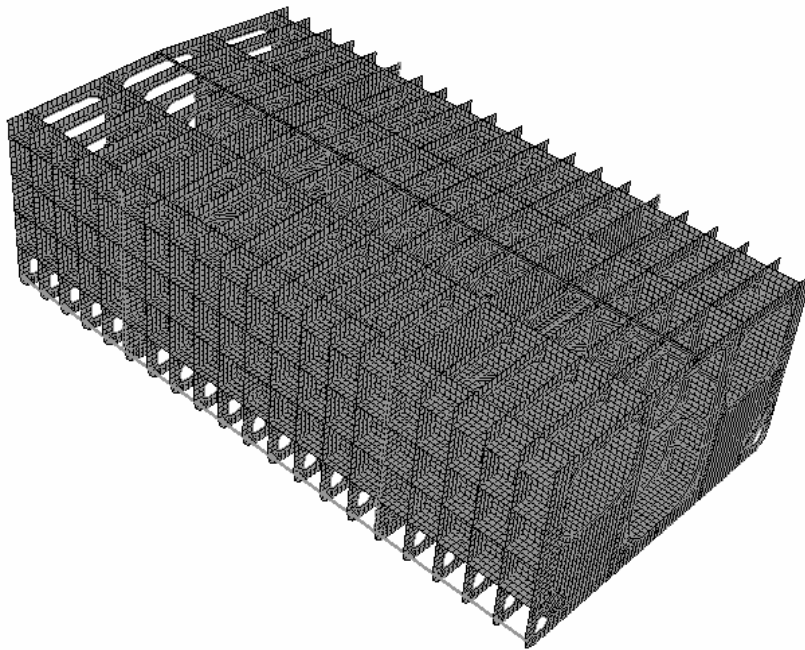


Figure 5-1
Cargo tank FE-Model

The cargo-hold model should be analysed using the load cases given in section 4.6.1. These loads are external and internal pressure loads which means that no inertia forces or global bending moments need to be analysed. The boundary conditions to be used are given in Classification Note 31.3.

5.3 Semi-nominal stress model

5.3.1

For calculation of the stress level at the longitudinal stiffener-frame connections a semi-nominal stress finite element model should be made. The purpose of the semi-nominal model is to capture the local geometric stress flow and effect of cut-outs, web frame-toes and tripping brackets. The model also captures more accurately the shear stress distribution from longitudinal stiffeners to web frame.

The stress results are used together with stress concentration factors to obtain the hotspot stress range for use in fatigue calculation.

The model should have approximately 50 mm elements at the critical hotspots for each longitudinal stiffener-frame connection in side, inner side, bottom, inner bottom and hopper tank. The longitudinal extent of the model should be at least one frame spacing on each side of the target frame. Examples of

models are shown in Fig.5-2 and Fig.5-3.

The element types to be used are:

Quad elements:	8 node
Triangular elements:	6 node
Beam elements:	3 node.

The semi-nominal stress model should be included in the cargo tank model or sub-modelling should be used.

The slot geometry should be modelled as described in section 8.5 and Fig.5-4. It is important that the area around all hotspot locations is modelled with 50 mm size elements. In cases where it is impossible to create square 50 mm elements an aspect ratio of 4 should not be exceeded. If elements different from 50×50 mm size are needed these elements should preferably be placed away from the hotspots i.e. at mid-span of cut-out opening. Away from the hotspots the mesh can gradually become coarser. The rounded corners of the slot should be modelled as “square” elements.

Eccentric lugs are not to be modelled as eccentric but as in-plane shell elements, and the plate thickness should not be increased to account for the overlapping plates. The effect of eccentric lug induced bending stresses will be captured by the stress concentration factors. The cut-out should be modelled as

at is on drawings with correct width and height. As a consequence will the distance from the longitudinal top flange to cut-out edge increase with half the thickness of top flange. The stiffener is idealized with plate elements in the centre of the actual stiffener.

Guidance on meshing of the slot geometry is given for all connection types in section 8.5. It is important that the finite element mesh is similar in order to ensure correct hotspot stress.

The loads are to be the same pressure loads as applied to the cargo tank model specified in section 4.6. If a sub-modelling analysis is to be used, the applied loads will also include either prescribed displacements or prescribed forces/stresses.

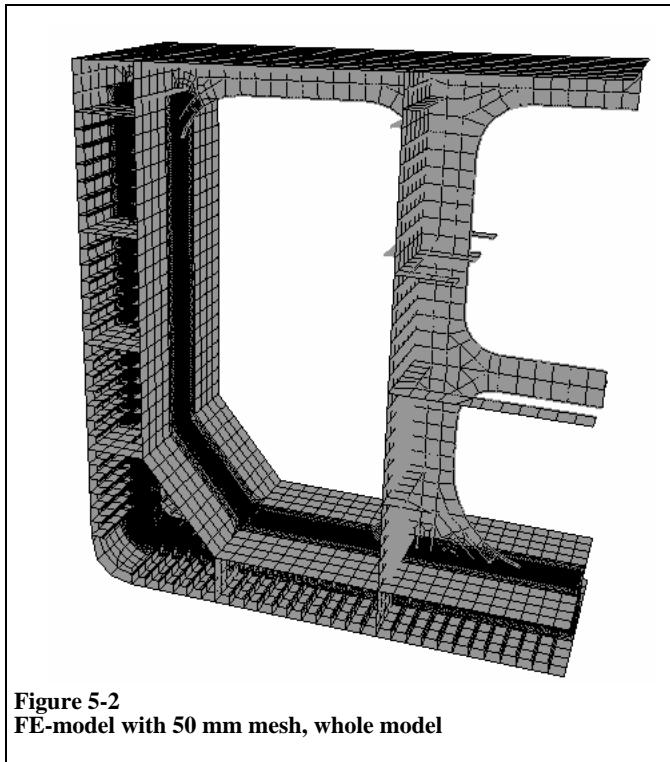


Figure 5-2
FE-model with 50 mm mesh, whole model

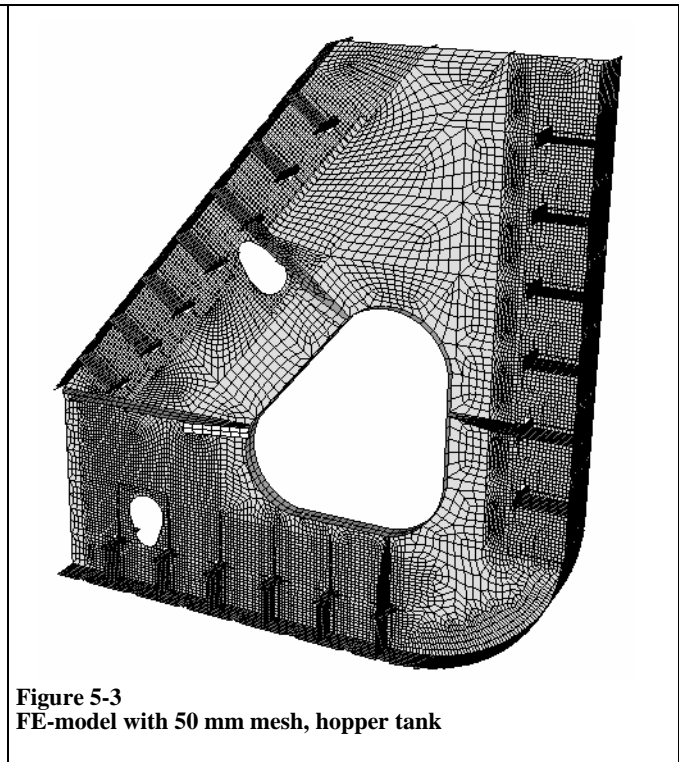


Figure 5-3
FE-model with 50 mm mesh, hopper tank

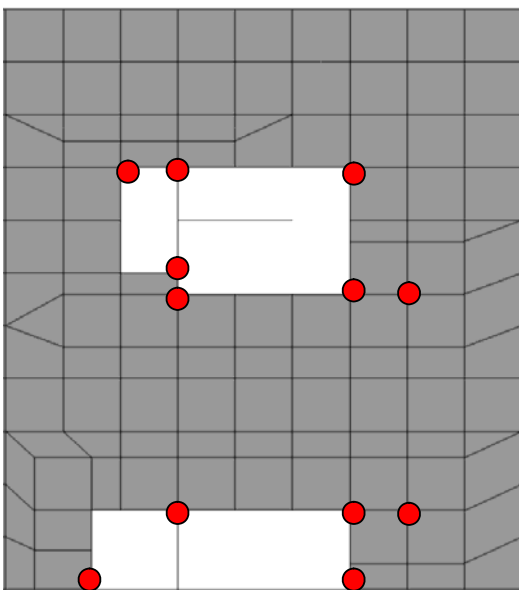


Figure 5-4
Slot geometry with stress read out points

5.3.2

All types of stiffener-frame connections in the cargo area should be analysed using semi-nominal models. If the mid-tank target web-frame does not include all types of connections then the remaining should be included in another model based on the mid-tank web-frame model. This should also be done for all connections in the forward and aft tank. Since a vessel does not have parallel body in the forward and aft tank area some simplification will be necessary. The remaining frames of the cargo tanks should be assessed based on a screening procedure described in section 5.7.

5.4 Stress concentration models

5.4.1

If the design of a longitudinal stiffener-frame connections is not found among the typical designs listed in section 8.4 a stress concentration model should be made in order to establish the stress concentration factor of that particular design. The stress concentration models should be modelled according to the procedure given in this section. Section 8.2 describes how the stress concentration factors are calculated while section 6.4 lists requirements to documentation.

5.4.2

Two models are needed if additional stress concentration factors are to be made:

- *50×50 mesh model*: This model shall be used to predict the semi-nominal stress.
- *t×t mesh model*: This model shall be used to predict the hotspot stress.

The stress concentration factor will be the stress ratio between the models. The models are made to simulate the behaviour of double side and double bottom. The models should have a vertical extent of 3 stiffeners, i.e. 4 stiffener spacing, and the longitudinal extent should be $\frac{1}{2}$ frame spacing in both forward and aft direction. Two typical models are shown in Fig.5-5 and Fig.5-6. No cut-outs for manholes should be included in the stress concentration models. Both models should include the typical hotspots for the target detail. Fig.2-2 shows typical

hotspots to be assessed.

The element types to be used are:

Quad elements: 8 node
 Triangular elements: 6 node
 Beam elements: 3 node.

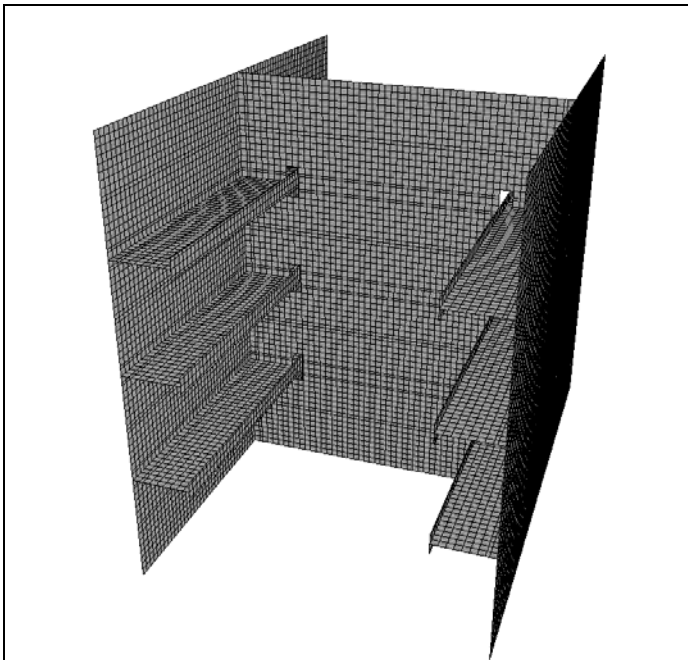


Figure 5-5
 FE-Model with 50 mm mesh, SCF analysis

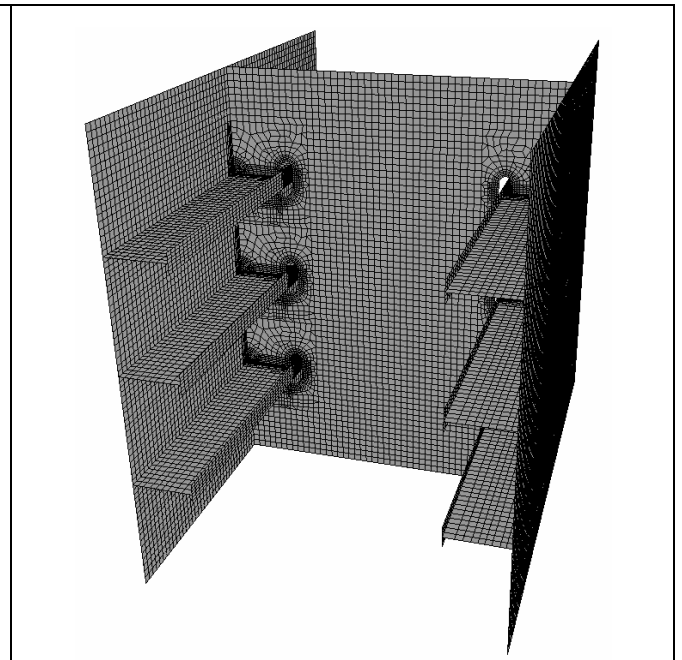


Figure 5-6
 FE-Model with $t \times t$ mesh, SCF analysis

For the 50×50 mm mesh model, the mesh density in the area of the web frame slots, including web stiffeners, is to be approximately 50×50 mm but adjusted to fit the slot geometry. Outside this area the mesh density may be increased to reduce the size of the model. The element aspect ratio should however not exceed 4. Smooth corners are to be modelled as sharp corners and the eccentricity of the stiffener lug is to be ignored. An example of a detail is shown in Fig.5-8.

For the $t \times t$ mesh model the mesh density in the area of the web

frame slots, including web stiffeners, is to be approximately the plate thickness size should extend at least four elements in all directions at all relevant hotspots. Outside this area the mesh density may be increased to reduce the size of the model. The element aspect ratio should however not exceed 4. The eccentricity of the stiffener lug is to be included in the model and modelled according to Fig.5-9. Fig.5-7 shows an example of a stiffener lug detail modelled with $t \times t$ mesh.

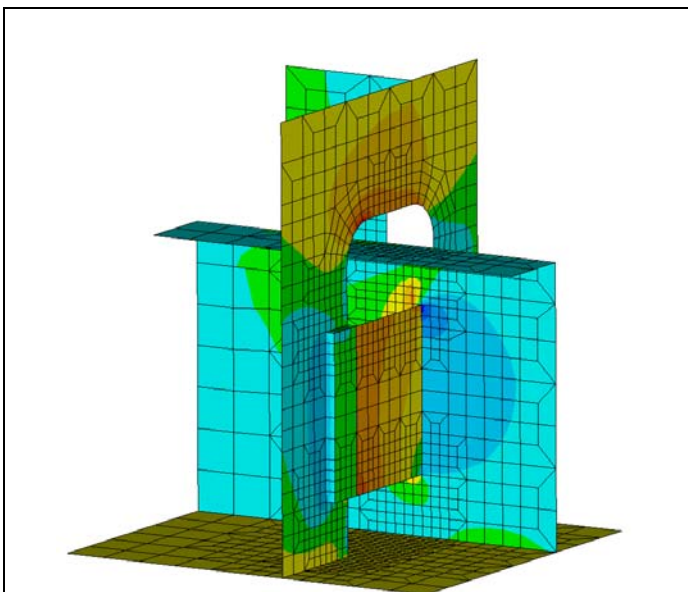


Figure 5-7
 Stiffener and lug details – with web stiffener on top, $t \times t$ mesh

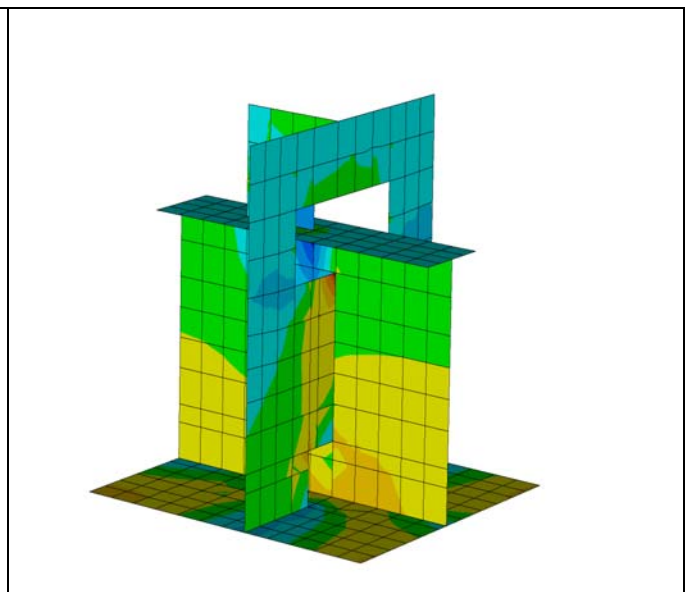


Figure 5-8
 Stiffener and lug details – with web stiffener on top, 50×50 mesh

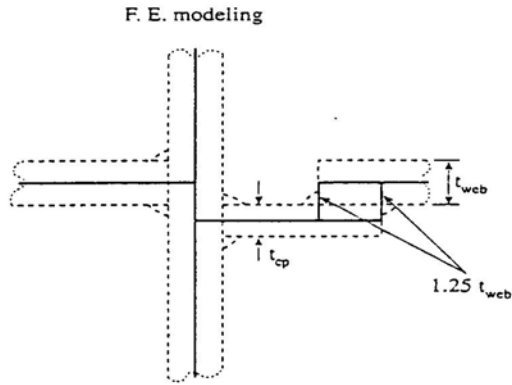


Figure 5-9
Modelling of eccentric collar plate

5.5 Loads

The procedure for calculation of loads given in Classification Note 30.7 /1/ should be used for both DNV NAUTICUS (New-building) and CSR classed vessels.

Three load effects are to be modelled in both models.

- LC1: External pressure
- LC2: Shear stress
- LC3: Axial load

Each load effect will result in a stress concentration factor. In order to combine the stress concentration factors into one stress concentration factor, weighting of the different load effects should be used. The weighting is to be conducted by scaling the applied load according to the following criteria:

- LC1: External pressure, nominal shear stress in the middle of the stiffener web of 100 MPa.
- LC2: Shear stress, nominal stress in the middle of the web frame of 100 MPa.
- LC3: Axial stress, nominal stress in the middle of the web frame of 100 MPa.

The applied pressure and prescribed displacements should be used to obtain the nominal stress criteria in the areas indicated in Fig.5-10.

The different load effects and boundary conditions are shown in Fig.5-11 through Fig.5-13. The forward and aft part of the finite element model should have symmetry condition describing the behaviour in a double side or double bottom.

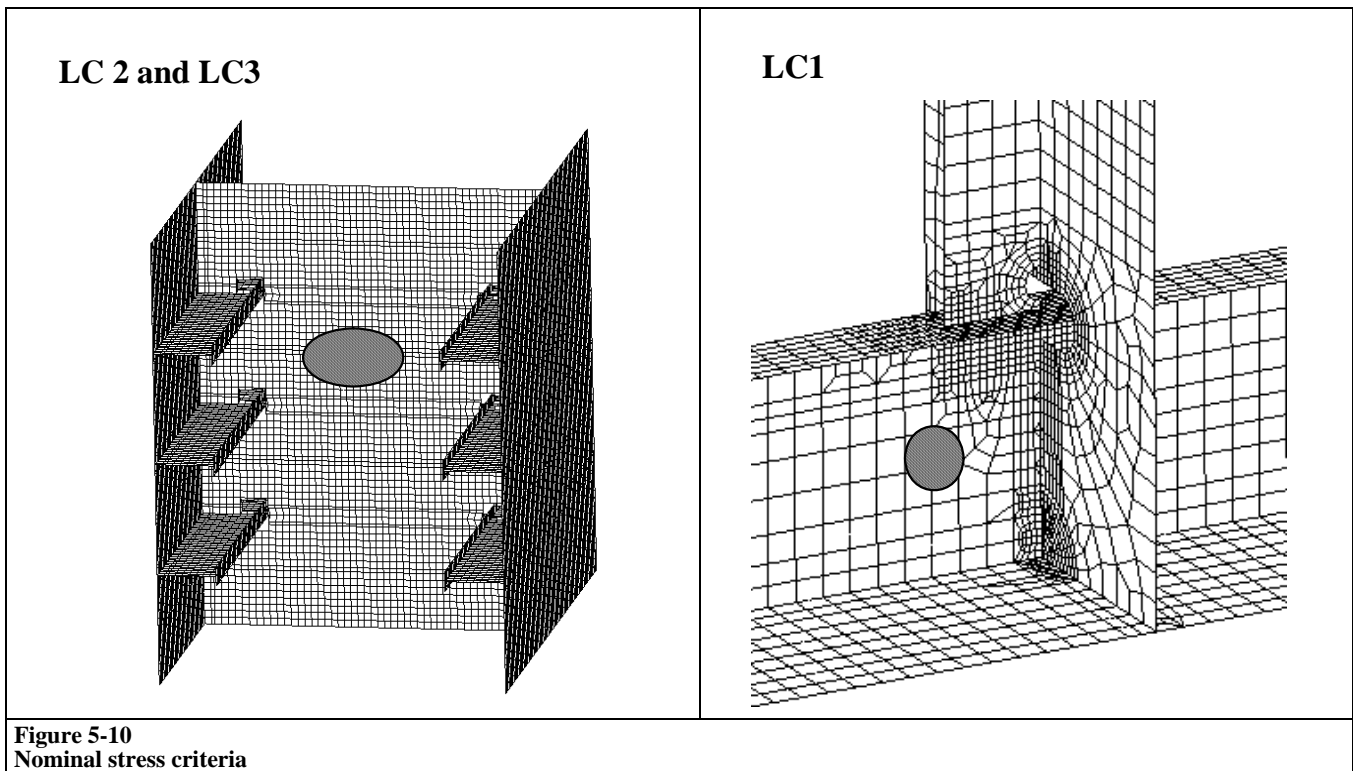


Figure 5-10
Nominal stress criteria

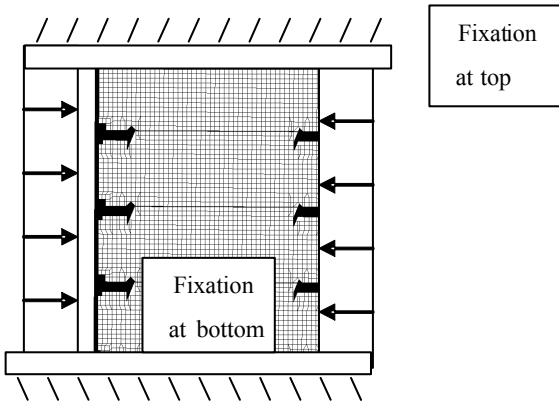


Figure 5-11
Load application and boundary conditions for LC1, external pressure

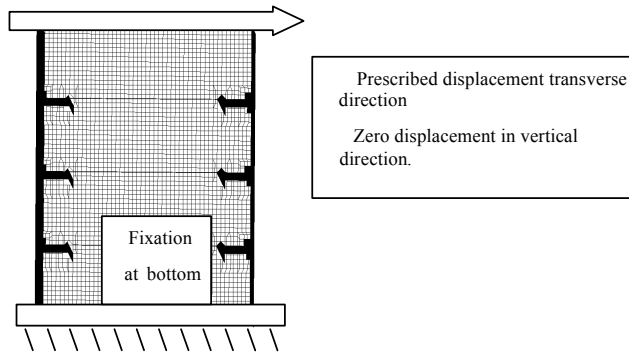


Figure 5-12
Load application and boundary conditions for LC2, shear stress

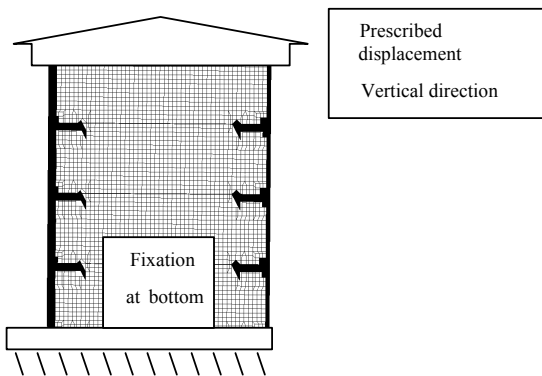


Figure 5-13
Load application and boundary conditions for LC3, axial stress

5.6 Stress read out from FE models

5.6.1

The maximum principal element stress within $\pm 45^\circ$ of the normal to the weld should be used for the analysis. As a conservative approach the absolute maximum principal stress could be used regardless of direction to the weld.

5.6.2

The semi-nominal stress should be the maximum principal

membrane stress at the considered hotspot location.

The stress read point on the semi-nominal model is to be at the hotspot node location. Among all the elements that have a result at the considered hotspot node it is the element result with maximum principal stress value that should be used for damage calculation. No averaging of nodal stresses is allowed. See Fig.5-4, Fig.5-14 and Fig.5-15 for illustration. If necessary the membrane stress should be calculated using the surface stresses at upper and lower surfaces.

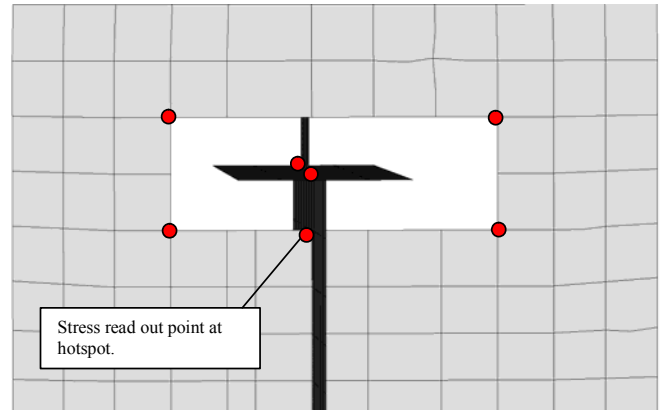


Figure 5-14
Example of stress read out point from 50x50 mm mesh model

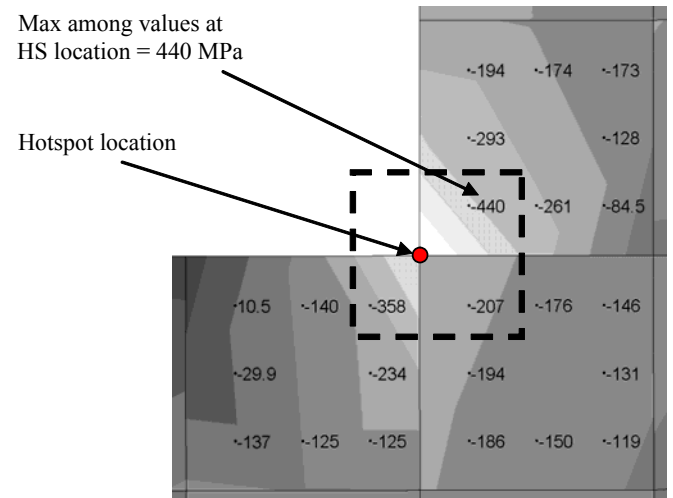


Figure 5-15
Example of maximum principal membrane stress value among adjacent elements

5.6.3

The maximum semi-nominal stress value for a certain hotspot node may be found at different elements among the various load conditions. The semi-nominal stress values should not necessarily be taken from the same element in all load conditions. For a certain hotspot the result values should be found at the same node position but they might result from various elements connected to that node.

5.6.4

The stress read out points in the stress concentration model is to be at a distance $t/2$ from the hotspot. The principal element stresses at $t/2$ should be multiplied with a factor 1.12 to calculate the hotspot stress. This is one of the two stress extrapolation procedures given in Classification Note 30.7. See Fig.5-16 and Fig.5-17 for illustration.

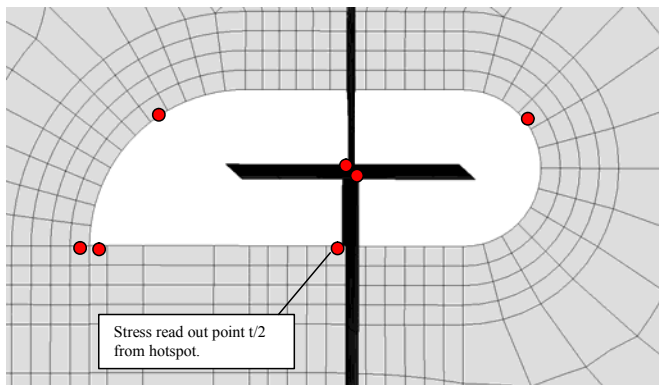


Figure 5-16
Example of stress read out point from $t \times t$ mesh model

5.6.5

When extracting stress results from the stress concentration model there could for a given hotspot be many possible $t/2$ -nodes. The maximum principal stress value at position $t/2$ away from the hotspot location should be used as the relevant hotspot stress. All $t/2$ -positions will have to be assessed with regard to stress level in combination with principal stress direction in order to locate the maximum relevant stress value. See Fig.5-17 for illustration.

5.6.6

The maximum principal stress value at $t/2$ -position may occur at different positions for the three considered load cases. Despite possibly different location of maximum stress location the stress read out node in the stress concentration model should for a given hotspot remain the same for all three load cases: axial, shear and pressure load. The node position giving the absolute maximum value among all three load cases should be used when extracting stress for all three load cases. Note that both upper and lower element surface should be checked in order to find the maximum principal stress.

5.6.7

At the stress read out node the finite element model will report a result for both upper and lower surface and also principal stress in two directions. The principal stress direction that is within 45 degrees to the weld normal should be used as relevant hotspot stress. If both principal stresses are both at 45 degrees to the weld normal one should choose the maximum of the two directions. Both upper and lower surface stress should be reported for all three load cases. The surface resulting in the largest total stress when summing up the contributions from the load cases should be used as basis for calculation of stress concentration factor.

5.6.8

For a specific hotspot location the stress read out procedure for the stress concentration model can be summarized as follows:

- Locate all possible $t/2$ -nodes with principal stress direction within 45 degrees to weld normal ($t/2$ nodes: nodes with a distance of $t/2$ from the hotspot)
- Find the $t/2$ -node with the largest principal surface stress among all load cases

- Perform stress read out of both first and second principal stress on upper and lower surface at the same node for all three load cases.
- For a certain load case locate the largest principal stress among the two principal directions (P1 or P2) for both upper and lower surface.
- To decide on which surface to use calculate the sum of the three load cases for both upper and lower surface. The surface with the largest total stress should be used for calculation of the SCF.
- The SCF is calculated according to the expression in section 8.2.2.

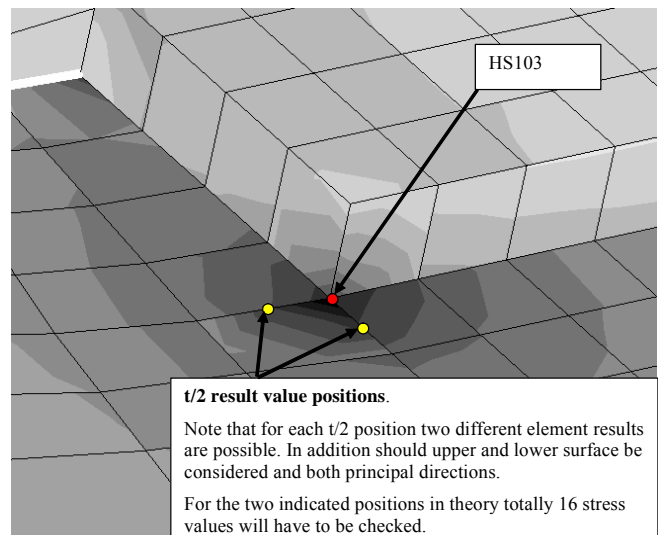


Figure 5-17
Possible stress read out nodes at $t/2$ position

5.6.9

In the stress concentration model is the collar plate modelled with eccentricity. In the area with overlapping collar plate and web plate is the stress normally reduced due to the increase effective plate thickness. Some hotspots are located on the boundary between web plate and collar plate. For these hotspot the stress results in the overlapping area are not be considered. These stress values are assumed not to give rise to fatigue crack growth. Fig.5-18 illustrates the overlapping area.

5.6.10

Example of relevant elements to consider for identification of possibly maximum principal stress values at $t/2$ position are shown in Fig.5-18 for the hotspots of detail type T201. For the hotspots #101, #107, #202, #206, #207 and #208 is the marked element the only relevant to consider regarding $t/2$ -stress values. For hotspot #104, #105 and #106 which are located at the slit opening edge, several element along the edge needs to be considered marked with arrows on Fig.5-18.

Hotspot #102, #103, #204 and #205 are located adjacent to the area where the lug plate and the web-plate are overlapping each other. Elements that are inside this overlapping area will not be necessary to consider when locating the relevant $t/2$ -stress result. Normally these elements will have smaller stress values and stresses in this area will not contribute to crack growth in real structures.

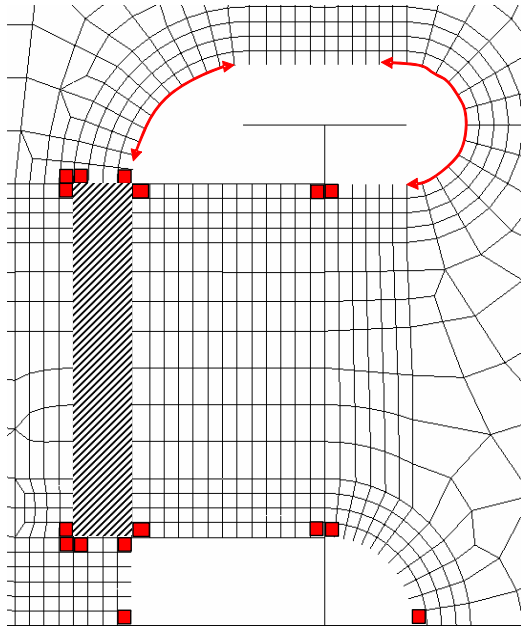


Figure 5-18
Elements to consider in stress read out

5.6.11

The hotspots on the edge of the slit opening i.e. hotspot #104, #105 and #106 are located in base material. Stress read out on hotspots in base material should be performed at the hotspot. No extrapolation using $t/2$ stress values should be performed and stress results on the opening edge should be used.

The use of dummy beam elements at slit opening edge is not allowed. It is found that significant bending may occur at the slit opening hotspots. Since the dummy beam element does not capture bending stress across the plate thickness they are not allowed to use.

Note that the maximum stress position along the slit opening most likely will vary for the various load cases. The position with the largest value among the load cases should be used for stress read out for all three load cases.

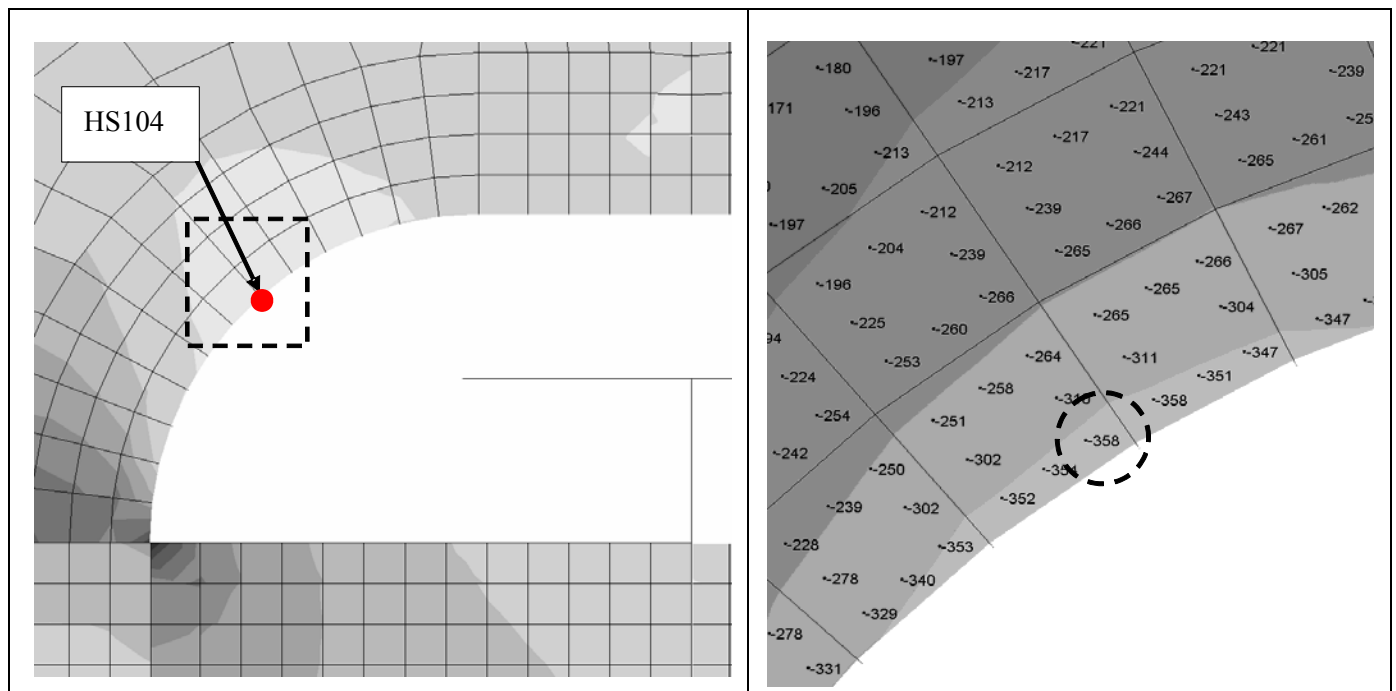


Figure 5-19
Possible stress read out nodes at slit opening edge

5.7 Screening procedure

The below screening procedure should be used to assess the fatigue capacity of the web-frames that are not modelled using a 50×50 mm element mesh. The screening should be based on the nominal stress level of the cargo hold model. The screening analysis should follow the following steps:

- 1) Establish a scaling factor for each stiffener-frame connection in each load case. The scaling factors should be based on maximum element average principal stress from the cargo hold model at the reference connection and at the target connection. The web-frame that has been modelled with 50×50 mm element mesh is defined as the reference web-frame. The scaling factor, f_{ss} , is defined as the ratio between the average value of the absolute principal stress level of four neighbouring elements at the relevant

stiffener-frame connection in the target frame and the reference frame, figure 5-20:

$$f_s = \frac{\left[\frac{(|\sigma_{p1}| + |\sigma_{p2}| + |\sigma_{p3}| + |\sigma_{p4}|)}{4} \right]_{TARGET_CONNECTION}}{\left[\frac{(|\sigma_{p1}| + |\sigma_{p2}| + |\sigma_{p3}| + |\sigma_{p4}|)}{4} \right]_{REFERENCE_CONNECTION}}$$

- 2) Establish hotspot stress at target stiffener-frame connection by multiplying the scaling factor with the hotspot stress of the relevant hotspot location at the reference stiffener-frame connection. The reference hotspot stress is established by use of the semi-nominal model and stress concentration factors according to section 5.3 and 8.4.
- 3) Fatigue damage is calculated for the relevant hotspot location at the target stiffener-frame connection.
- 4) The above procedure is repeated for all hotspots at all stiffener-frame connections in all web-frames in the forward-, aft- and amidship cargo-hold models.

frame. Since the 50×50 mm mesh is similar for many different connections it will be possible to use the screening procedure for a number of different connections even if the two connections in the target and the reference web-frame are somewhat different.

Note that when different connections having similar 50×50 mm mesh are compared it is important to account for the correct SCF giving the relevant reference hotspot stress.

If the connections in the target and reference web-frame would have different 50×50 mm mesh the screening procedure should be used with care. In such case, the 50×50 mm element mesh for the reference connection may be modified to reflect the geometry of the target connection.

The above screening procedure is only applicable when comparing similar connections in the target and the reference web-

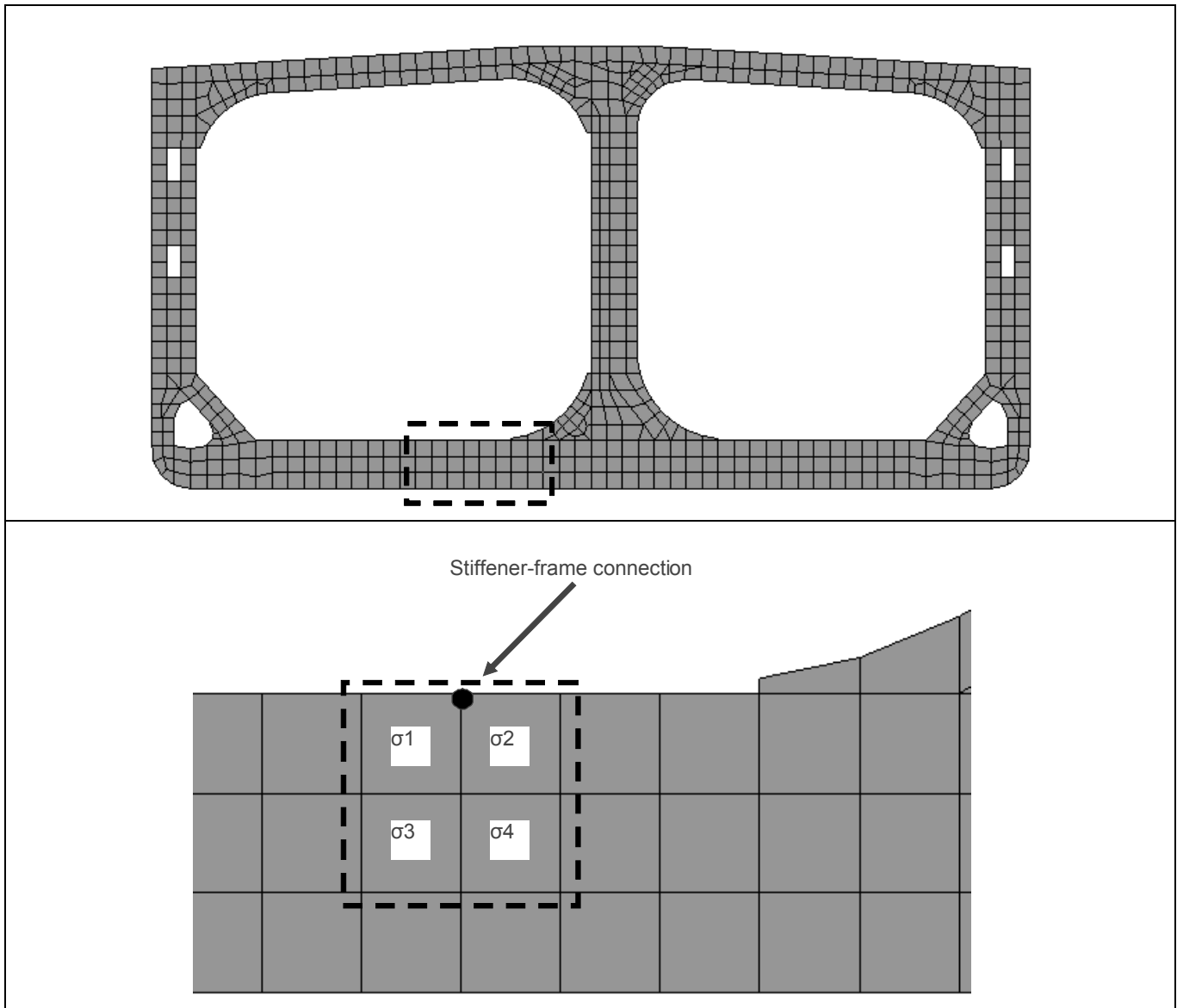


Figure 5-20
Neighbouring elements for screening average stress

6. Documentation of PLUS Analysis

6.1 FE-Models

6.1.1

All finite element models should be documented with plots clearly showing the mesh at the various details. The model extension and a thorough description of the applied loads and boundary conditions should be documented. Element types should be reported. A description of the analysis flowchart should be included as documentation for to understand the analysis flow.

6.2 Stresses

6.2.1

The semi-nominal stress in the web frame should be documented with stress plots showing clearly the stress distribution at all stiffeners. For validation of the predicted fatigue damages all stress values for all locations should be reported in table formats.

6.3 Fatigue calculations

6.3.1

The fatigue calculations should be reported including the following items:

- choice of SN-Curves
- fraction of time in each loading condition
- fraction of time in non-corrosive/corrosive environment
- Weibull shape factor used in the calculations
- number of stress cycles
- mean stress correction factors
- fatigue damages for each loading condition in non-corrosive/corrosive environment
- total fatigue damage or fatigue life prediction
- stress concentration factors.

6.4 Stress concentration factor analysis

6.4.1

Analysis of additional stress concentration factors should be thoroughly documented. A detailed description of the longitudinal stiffener-frame connection geometry is to be provided together with a description and plots of both the txt-model and the 50×50 mesh finite element models. The applied loads and boundary condition should also be documented, and plots clearly showing the element mesh around the stiffener-frame connection should be provided. The nominal stress level and the hotspot stress should be documented with plots for all load-cases in both models. The stresses used in calculation of the stress concentration factor are to be reported together with the resulting stress concentration factor.

7. References

- 1) Det Norske Veritas, Classification Note no. 30.7 *Fatigue assessment of ship structures*, Høvik, October 2008
- 2) Det Norske Veritas, Classification Note no. 31.3 *Strength analysis of hull structures in tankers*, Høvik, January 1999
- 3) Det Norske Veritas, Rules for classification of ships Part 8 Chapter 1, *Common structural rules for double hull oil tankers with length 150 meters and above*, Høvik, January 2006.
- 4) Det Norske Veritas, *Finite element analysis of large scale fatigue test of stiffener web frame connections*, DNV Report No. 2007-19-09, T. Lindemark, November 2007
- 5) Lotsberg, Inge (et.al) *Fatigue Capacity of Stiffener to Web Frame Connections*, OMAE2009-79061, Honolulu, Hawaii, USA, 31 May-5 June 2009.

8. Appendix A - Stress Concentration Factors

8.1 General

8.1.1

This section describes the procedure of how to establish stress concentration factors for longitudinal stiffener-frame connection details. Section 8.4 lists stress concentration factors for the critical hotspots of typical stiffener-frame connections. If a particular detail is not listed among the typical ones in section 8.4 then the user should follow the procedure in section 8.2 for calculating the stress concentration factors.

8.2 Establish stress concentration factors

8.2.1

In order to calculate the stress concentration factor a semi-nominal model with 50x50mm mesh and a stress concentration model with txt-mesh should be made. The finite element modelling and analysis should be performed according to the procedure described in section 5.

8.2.2

When extracting stress results the maximum element principal stresses should be used and not the node averaged stresses. The stress read out points should be located:

- At t/2 from the intersection line in the t×t-mesh model, see Fig.5-17.
- At the node at hotspot in the 50x50mm mesh model, see Fig.5-14.

Note that the stress at t/2 should be multiplied with an extrapolation factor of 1.12 to find the hotspot stress. See Classification Note 30.7 /1/ for details on extrapolation procedures.

The maximum principal stress within ±45° of the normal to the weld should be used for the analysis. This requirement will in most cases decide whether first or second principal stress should be used.

For some hotspots the position of maximum element principal stress could vary among the three load cases. Note that the stress read out position for a given hotspot should be the same for all load cases. The position giving the maximum stress value among all load cases should be used for stress read out in all load cases.

The SCFs are calculated as the ratio of the principal stresses between the semi-nominal model and the fine mesh model. The sum of absolute principal stresses at read out position is to be used for both models as described in the formula:

$$K_G = \frac{\max \left(\begin{array}{l} \sum_{LC1}^{LC3} \max |\sigma_1^{HS} \text{ or } \sigma_2^{HS}|^{txt-mesh} \text{ Upper} \\ \sum_{LC1}^{LC3} \max |\sigma_1^{HS} \text{ or } \sigma_2^{HS}|^{txt-mesh} \text{ Lower} \end{array} \right)}{\sum_{LC1}^{LC3} \max |\sigma_{m,1} \text{ or } \sigma_{m,2}|^{50x50-mesh}}$$

$$\sigma_1^{HS} = \sigma_1^{t/2} \cdot 1.12 = \text{hotspot stress in first principal direction}$$

$$\sigma_2^{HS} = \sigma_2^{t/2} \cdot 1.12 = \text{hotspot stress in second principal direction}$$

$$\sigma_1^{t/2} = \text{maximum first principal element stress at t/2 position}$$

$$\sigma_2^{t/2} = \text{maximum second principal element stress at t/2 position}$$

$$\sigma_{m,1} = \text{semi-nominal principal membrane element stress at hotspot node}$$

$$\sigma_{m,2} = \text{semi-nominal principal membrane element stress at hotspot node}$$

The checked hotspots should normally include the hotspots marked in Fig.5-4.

8.2.3

The stress concentration factor for hotspot #102 and #103 see Fig.2-2, should be based on effective hotspot stress according to the expression below:

$$K_G = \frac{\max \left(\begin{array}{l} \sum_{LC1}^{LC3} \max |\sigma_{Effective,1}^{HS} \text{ or } \sigma_{Effective,2}^{HS}|^{txt-mesh} \text{ Upper} \\ \sum_{LC1}^{LC3} \max |\sigma_{Effective,1}^{HS} \text{ or } \sigma_{Effective,2}^{HS}|^{txt-mesh} \text{ Lower} \end{array} \right)}{\sum_{LC1}^{LC3} \max |\sigma_{m,1} \text{ or } \sigma_{m,2}|^{50x50-mesh}}$$

The effective hotspot stress reduces the bending component of the surface stress with a factor of 0.6. Effective stress is calculated according the following expression:

$$\sigma_{Effective_HS} = \sigma_{m,HS} + 0.60 \sigma_{B,HS}$$

$$\begin{array}{l} \sigma_{m,HS} = \text{membrane stress} \\ \sigma_{B,HS} = \text{bending stress} \end{array}$$

8.3 Example of establishing stress concentration factors

8.3.1

This example illustrates how to establish stress concentration factors for a T-shaped longitudinal through a slot with lug connection. The example is based on finite element analysis as described in section 5.4 and shows how to weight the different load cases and stresses, and how to establish the stress concentration factors.

The stresses from the finite element analysis are found in Table 8-1. The magnitude of the sum of the stresses in the t×t-mesh model is used to predict the criticality of the hotspots. The critical hotspots will vary from detail to detail dependent on the different detailed design.

The weighted stress concentration factors are shown in Table 8-1. The weighted stress concentration factors are established based on the columns marked with “sum”, which is basically the sum of the different load cases as illustrated in the formula above. The weighted stress concentration factors should be used in the fatigue calculations.

8.3.2 Flowchart

The below flowchart shows the main steps of the procedure to be followed when establishing a stress concentration factor, reference is given to the indicated sections for detailed guidance.

8.4 Stress concentration factors for typical longitudinal end connection details

8.4.1

The stress concentration factors listed below covers typical stiffener-frame connections found in ship structures. Fig.8-3 shows possible hotspot locations and the numbering system. Table 8-2 shows the dimensions of the details used in calcula-

tion of the tabulated SCFs. Stress concentration factors for details without web stiffener, with web stiffener, and with backing bracket and soft toe are listed in Table 8-4. Stress concentration factors for hotspots on the web stiffener are listed in Table 8-5.

If the detail to be checked differs significantly from the typical details in Table 8-2 separate analysis should be conducted according to section 8.2.

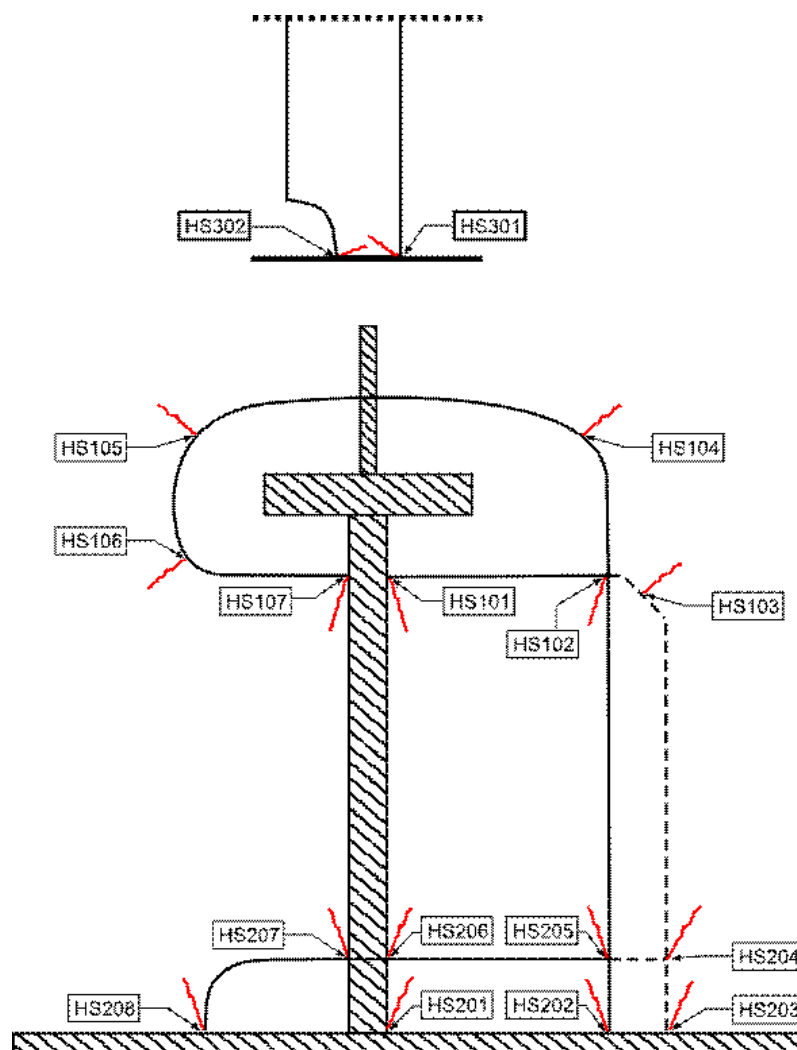


Figure 8-3
Numbering of possible hotspots

8.4.2

Table 8-2 Dimensions of calculated stiffener-frame connections

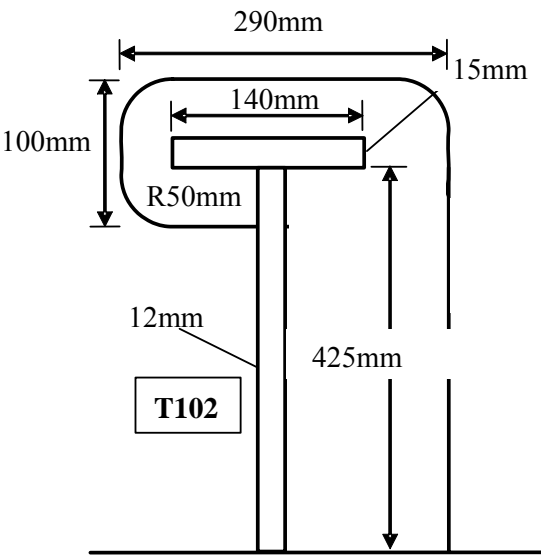
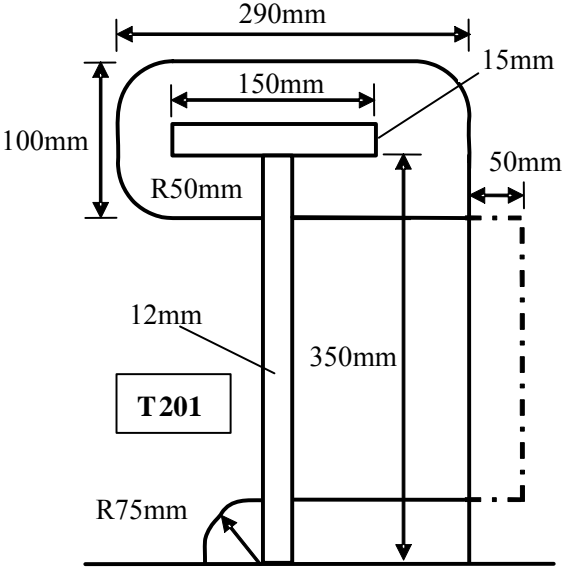
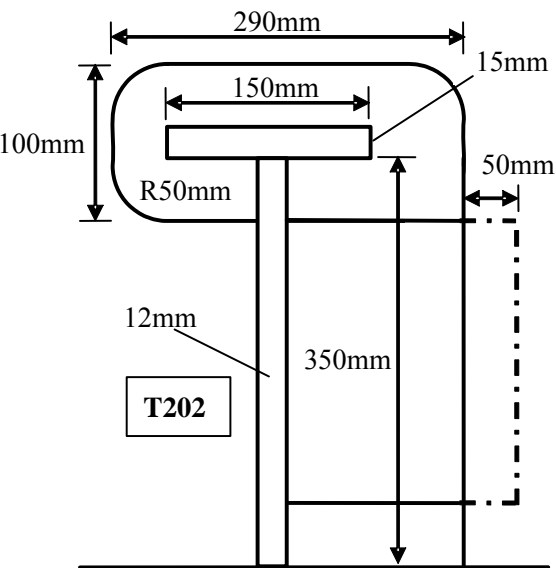
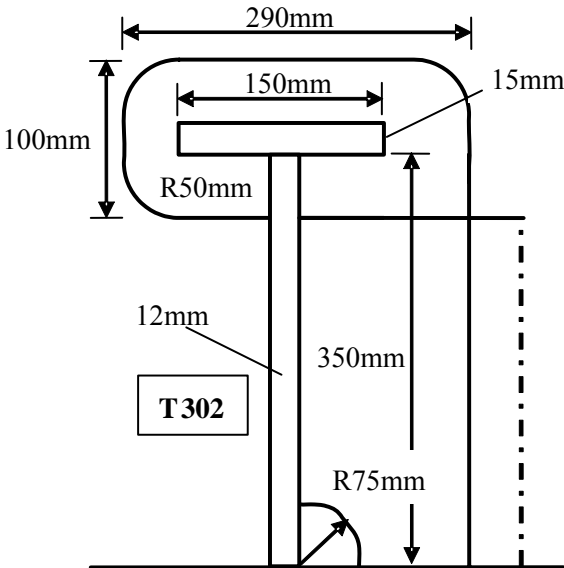
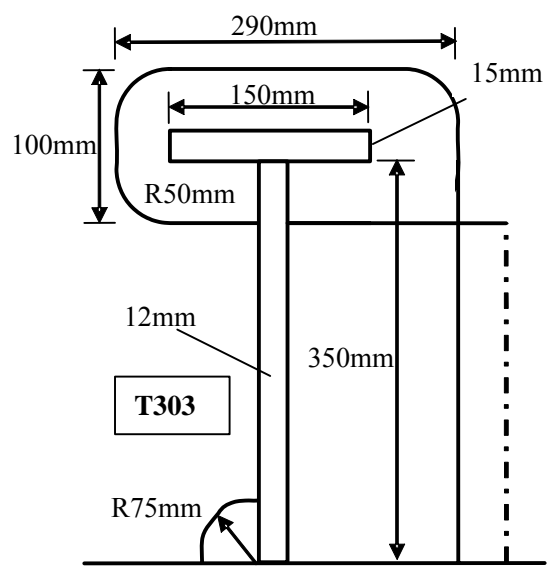
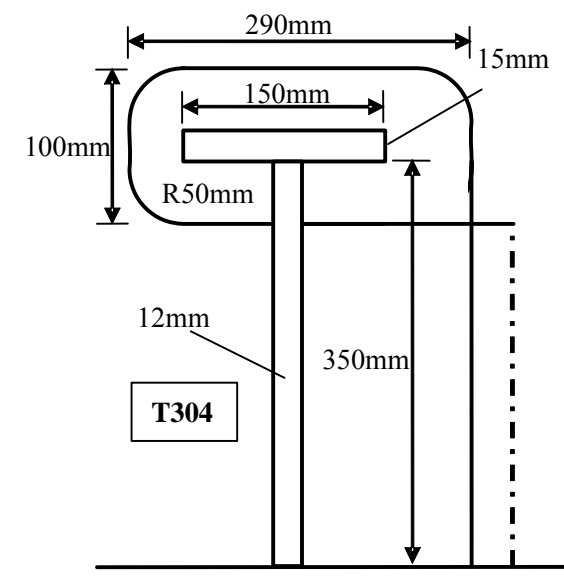
 <p>T102</p>	 <p>T201</p>
 <p>T202</p>	 <p>T302</p>
 <p>T303</p>	 <p>T304</p>

Table 8-2 Dimensions of calculated stiffener-frame connections (Continued)

<p>Diagram T305 shows a stiffener-frame connection. The top flange has a total width of 290mm and a thickness of 15mm. The inner stiffener has a width of 150mm. The connection height is 100mm, with a fillet radius of R50mm. The stiffener stem has a diameter of 12mm and a height of 350mm. A dashed line indicates the continuation of the frame.</p>	<p>Diagram T306 shows a stiffener-frame connection. The top flange has a total width of 290mm and a thickness of 15mm. The inner stiffener has a width of 150mm. The connection height is 100mm, with a fillet radius of R50mm. The stiffener stem has a diameter of 12mm and a height of 350mm. A dashed line indicates the continuation of the frame.</p>
<p>Diagram T403 shows a stiffener-frame connection. The top flange has a total width of 250mm and a thickness of 15mm. The inner stiffener has a width of 150mm. The connection height is 100mm, with a fillet radius of R50mm. The stiffener stem has a diameter of 12mm and a height of 350mm. A fillet radius of R75mm is shown at the base of the stem.</p>	<p>Diagram T404 shows a stiffener-frame connection. The top flange has a total width of 250mm and a thickness of 15mm. The inner stiffener has a width of 150mm. The connection height is 100mm, with a fillet radius of R50mm. The stiffener stem has a diameter of 12mm and a height of 350mm.</p>
<p>Diagram T406 shows a stiffener-frame connection. The top flange has a total width of 250mm and a thickness of 15mm. The inner stiffener has a width of 150mm. The connection height is 100mm, with a fillet radius of R50mm. The stiffener stem has a diameter of 12mm and a height of 350mm.</p>	<p>Diagram T504 shows a stiffener-frame connection. The top flange has a total width of 290mm and a thickness of 15mm. The inner stiffener has a width of 150mm. The connection height is 100mm, with a fillet radius of R50mm. The stiffener stem has a diameter of 12mm and a height of 350mm.</p>

Table 8-2 Dimensions of calculated stiffener-frame connections (Continued)

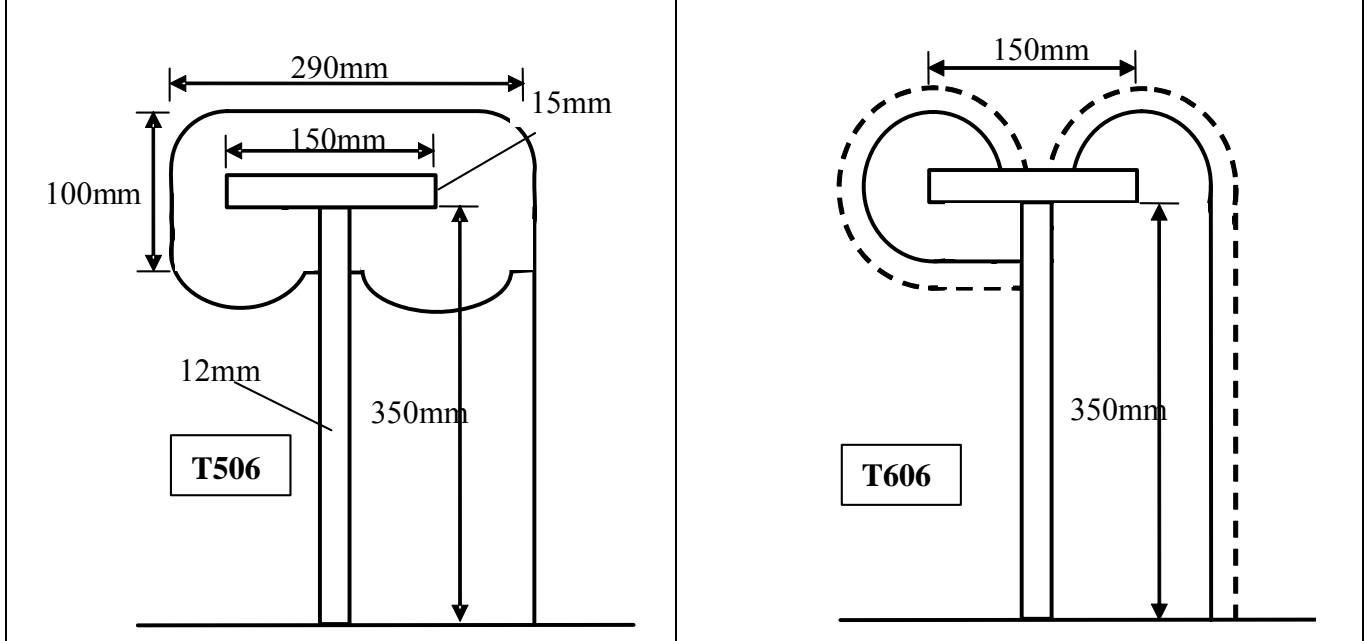


Table 8-3 Dimensions of top stiffener connections

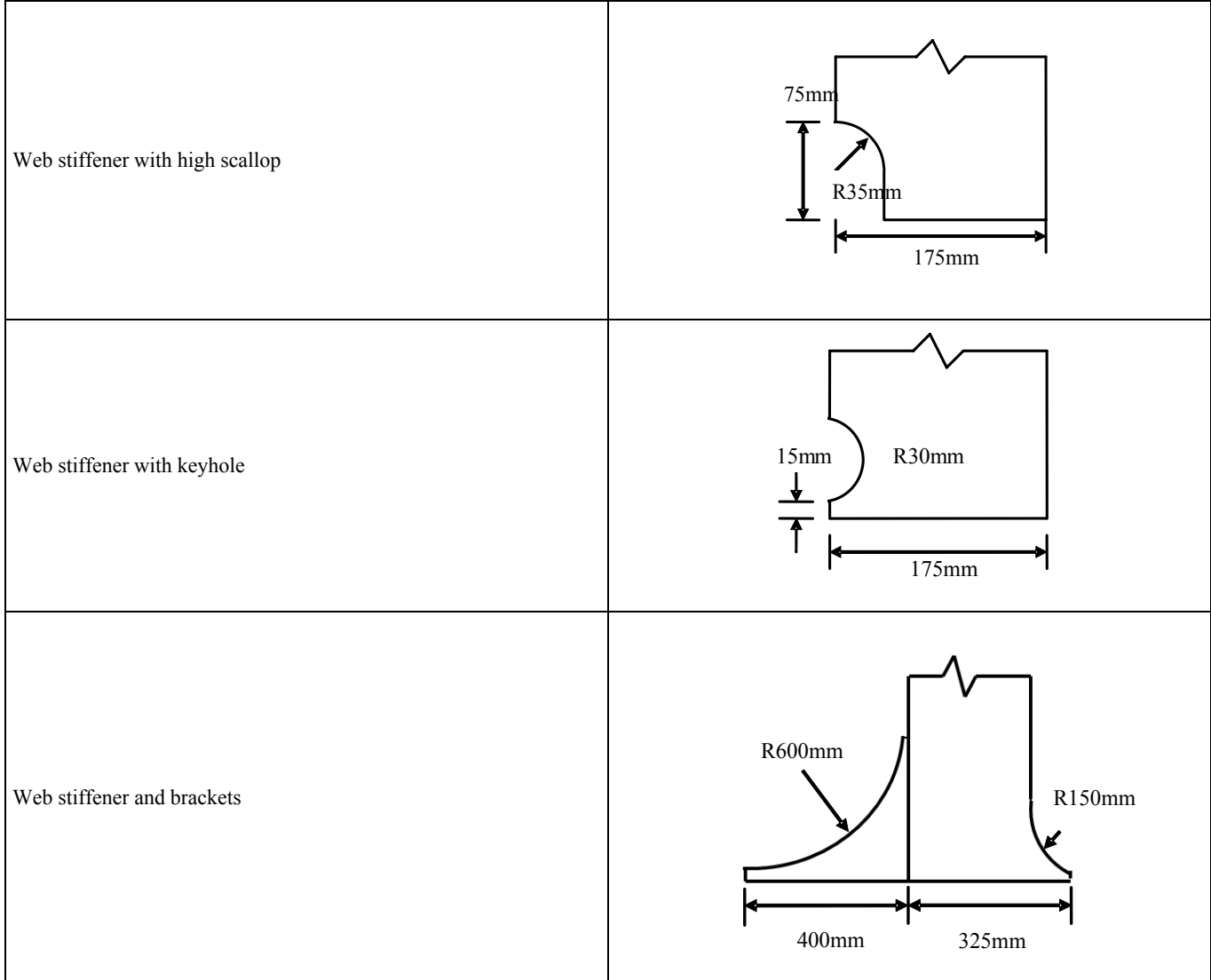


Table 8-4 Stress concentration factors for stiffener-frame connections

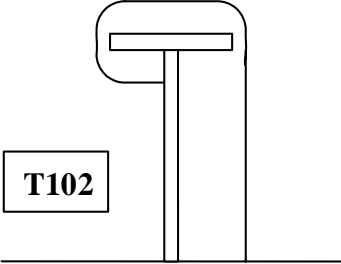
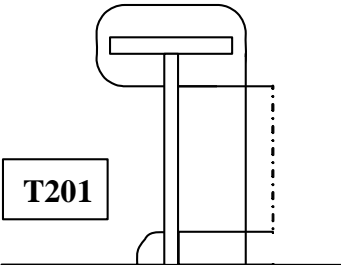
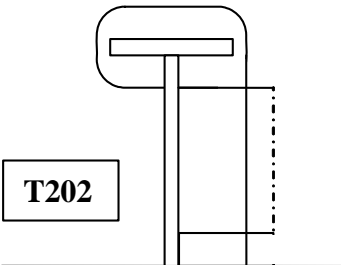
Geometry	Hotspot	<i>K-factor with web stiffener and high scallop</i>	<i>K-factor with soft toe and bracket</i>	<i>K-factor without web stiffener</i>
		<i>K-factor</i>	<i>K-factor</i>	<i>K-factor</i>
	101	-	-	-
	102	-	-	-
	103	-	-	-
	104	0.61	0.64	0.59
	105	0.82	0.84	0.94
	106	-	0.85	1.00
	107	1.05	1.37	1.10
	201	-	-	-
	202	1.38	1.35	1.43
	203	-	-	-
	204	-	-	-
	205	-	-	-
	206	-	-	-
	207	1.12	1.12	1.13
	208	-	-	-
	101	1.68	-	-
	102	0.87*	-	-
	103	2.26*	-	-
	104	0.78	-	-
	105	0.92	-	-
	106	-	-	-
	107	1.49	-	-
	201	-	-	-
	202	2.08	-	-
	203	-	-	-
	204	2.83	-	-
	205	1.06	-	-
	206	1.46	-	-
	207	1.47	-	-
	208	1.52	-	-
	101	1.60	-	-
	102	0.88*	-	-
	103	2.28*	-	-
	104	0.78	-	-
	105	0.87	-	-
	106	-	-	-
	107	1.49	-	-
	201	-	-	-
	202	1.72	-	-
	203	-	-	-
	204	3.16	-	-
	205	1.34	-	-
	206	1.35	-	-
	207	-	-	-
	208	-	-	-

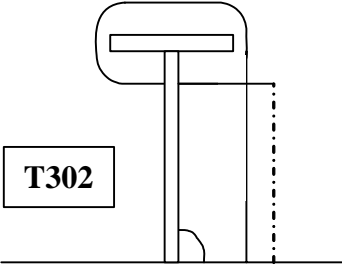
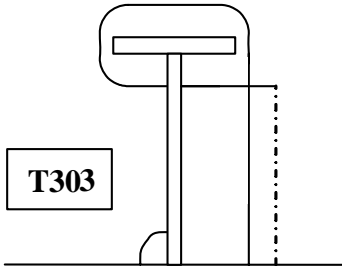
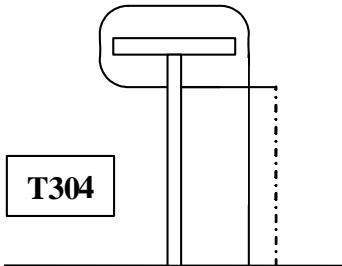
Table 8-4 Stress concentration factors for stiffener-frame connections (Continued)				
<i>Geometry</i>	<i>Hotspot</i>	<i>K-factor with web stiffener and high scallop</i>	<i>K-factor with soft toe and bracket</i>	<i>K-factor without web stiffener</i>
		<i>K-factor</i>	<i>K-factor</i>	<i>K-factor</i>
	101	1.74	2.01	1.83
	102	0.94	0.73	0.85
	103	2.33	2.18	2.17
	104	0.77	0.86	0.71
	105	0.93	0.95	1.02
	106	-	0.92	-
	107	1.30	1.32	1.95
	201	1.28	1.22	1.34
	202	1.41	1.36	1.34
	203	1.33	1.04	0.89
	204	-	-	-
	205	-	-	-
	206	1.16	1.19	1.17
	207	-	-	-
208	-	-	-	
	101	1.74	2.07	1.89
	102	0.94*	0.75*	0.88*
	103	2.33*	2.23*	2.21*
	104	0.77	0.86	0.73
	105	0.93	0.96	1.06
	106	0.89	0.94	0.86
	107	1.30	1.32	1.87
	201	1.33	1.22	1.30
	202	-	-	-
	203	1.33	0.88	1.05
	204	-	-	-
	205	-	-	-
	206	-	-	-
	207	1.22	1.24	1.25
208	1.40	1.39	1.46	
	101	1.74	2.08	1.90
	102	0.95*	0.77*	0.88*
	103	2.33*	2.24*	2.21*
	104	0.78	0.86	0.73
	105	0.93	0.95	1.06
	106	0.86	0.87	0.87
	107	1.09	1.34	1.92
	201	1.32	1.36	1.32
	202	-	-	-
	203	1.32	1.11	1.01
	204	-	-	-
	205	-	-	-
	206	-	-	-
	207	-	-	-
208	1.36	1.31	1.36	

Table 8-4 Stress concentration factors for stiffener-frame connections (Continued)

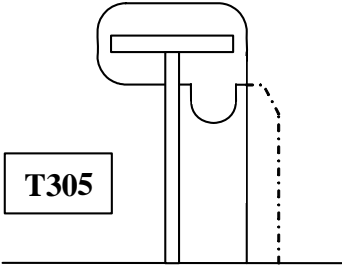
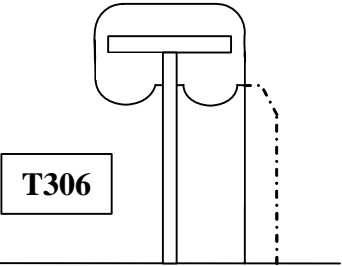
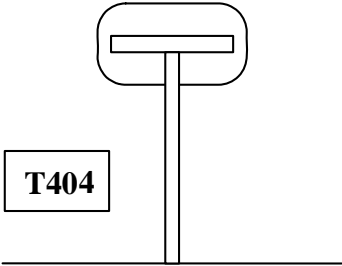
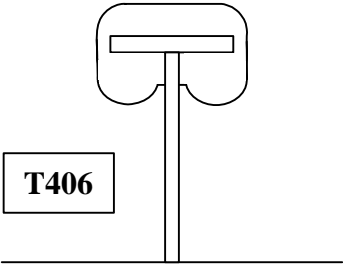
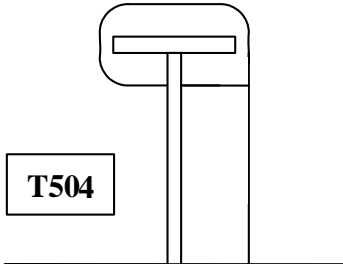
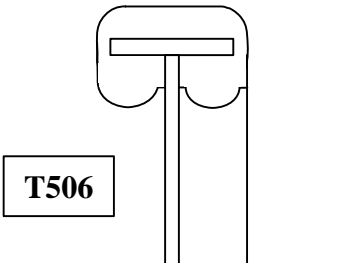
Geometry	Hotspot	<i>K-factor with web stiffener and high scallop</i>	<i>K-factor with soft toe and bracket</i>	<i>K-factor without web stiffener</i>
		<i>K-factor</i>	<i>K-factor</i>	<i>K-factor</i>
 <p>T305</p>	101	2.06	2.57	
	102	1.80*	1.70*	
	103	2.85*	2.94*	
	104	0.78	0.84	
	105	0.87	0.87	
	106	0.86	0.86	
	107	1.86	1.96	
	201	1.30	1.35	
	202	-	-	
	203	0.76	1.15	
	204	-	-	
	205	-	-	
	206	-	-	
	207	-	-	
208	1.26	1.19		
 <p>T306</p>	101	1.55		1.39
	102	1.15*		0.99*
	103	2.84*		0.81*
	104	0.76		0.74
	105	0.77		0.84
	106	0.70		0.80
	107	1.08		1.07
	201	1.22		1.21
	202	-		-
	203	1.17		1.18
	204	-		-
	205	-		-
	206	-		-
	207	-		-
208	1.25		1.29	
 <p>T404</p>	101	-		-
	102	0.69		0.85
	103	-		-
	104	1.00		0.90
	105	1.00		0.90
	106	0.69		0.85
	107	1.19		1.18
	201	1.14		1.55
	202	-		-
	203	-		-
	204	-		-
	205	-		-
	206	-		-
	207	-		-
208	-		-	

Table 8-4 Stress concentration factors for stiffener-frame connections (Continued)				
<i>Geometry</i>	<i>Hotspot</i>	<i>K-factor with web stiffener and high scallop</i>	<i>K-factor with soft toe and bracket</i>	<i>K-factor without web stiffener</i>
		<i>K-factor</i>	<i>K-factor</i>	<i>K-factor</i>
	101			-
	102			0.82
	103			-
	104			0.73
	105			0.73
	106			0.82
	107			0.50
	201			-
	202			-
	203			-
	204			-
	205			-
	206			-
	207			-
	208			-
	101		1.29	
	102		1.06	
	103		-	
	104		0.71	
	105		0.85	
	106		0.89	
	107		1.19	
	201		1.14	
	202		-	
	203		-	
	204		-	
	205		-	
	206		-	
	207		-	
	208		1.10	
	101			0.81
	102			1.10
	103			-
	104			0.69
	105			0.74
	106			0.68
	107			0.81
	201			1.15
	202			-
	203			-
	204			-
	205			-
	206			-
	207			-
	208			1.13

* based on effective stress

Table 8-5 Stress concentration factors for top stiffener connections to longitudinal

<i>Geometry</i>	<i>Hotspot</i>	<i>K_G-factor with web stiffener for high scallop</i>	<i>K_G-factor with web stiffener for keyhole</i>	<i>K_G-factor with web stiffener and brackets</i>
		<i>K_G-factor</i>	<i>K_G-factor</i>	<i>K_G-factor</i>
T102	302	1.31	-	0.50
	301	1.71	-	0.42
T302	302	1.43	0.91	0.50
	301	1.26	1.09	0.42
T303	302	1.40	0.92	0.51
	301	1.24	1.07	0.43
T304	302	1.42	0.91	0.51
	301	1.26	1.08	0.59
T305	302	-	-	0.50
	301	-	-	0.42
T306	302	1.53	0.90	-
	301	1.33	1.12	-
T404	302	1.28	0.85	-
	301	1.13	0.98	-
T606	302	0.98	-	-
	301	1.63	-	-

8.5 Semi-nominal finite element mesh of stiffener-frame connections

Table 8-6 shows the semi-nominal element mesh that is used to calculate the stress concentration factors in Table 8-4 and

Table 8-5. It is important that a similar element mesh configuration is used for the respective stiffener-frame connections in the semi-nominal web-frame model.

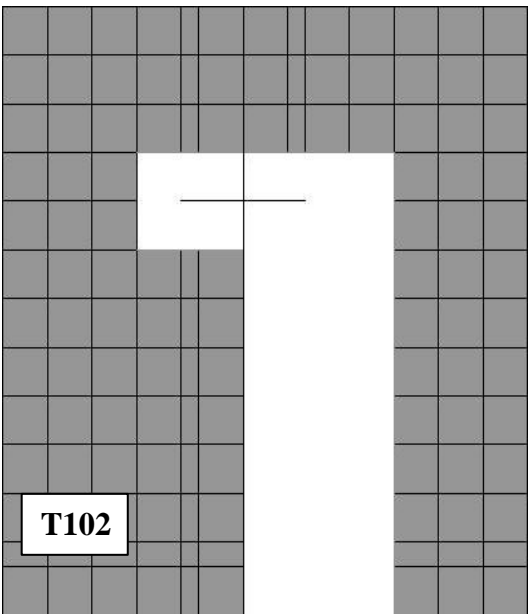
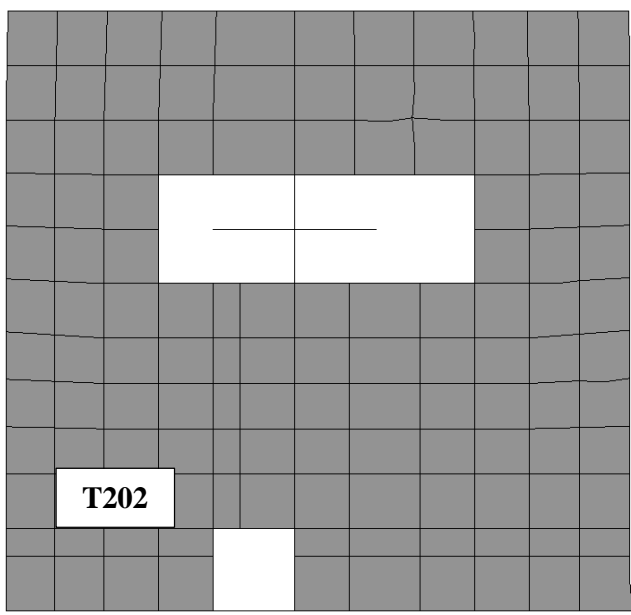
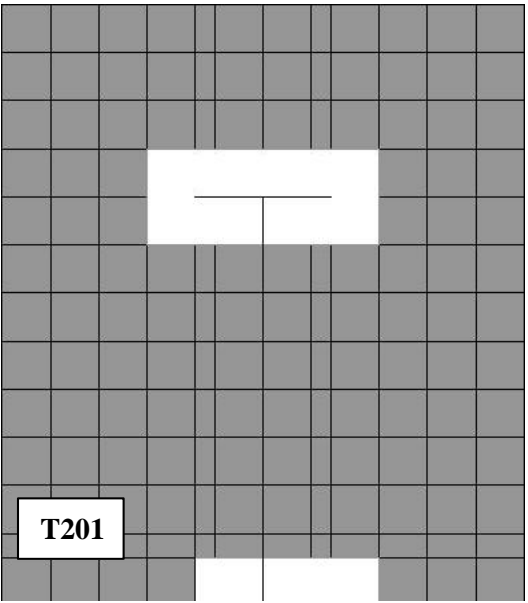
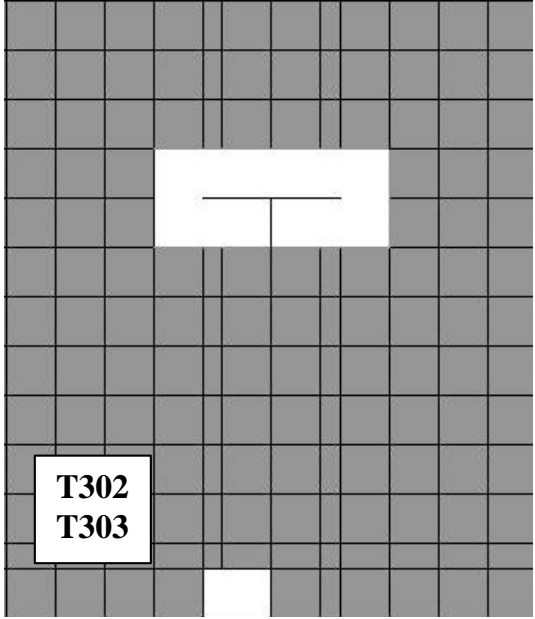
Table 8-6 Semi-nominal element mesh	
 <p>T102</p>	 <p>T202</p>
 <p>T201</p>	 <p>T302 T303</p>

Table 8-6 Semi-nominal element mesh (Continued)

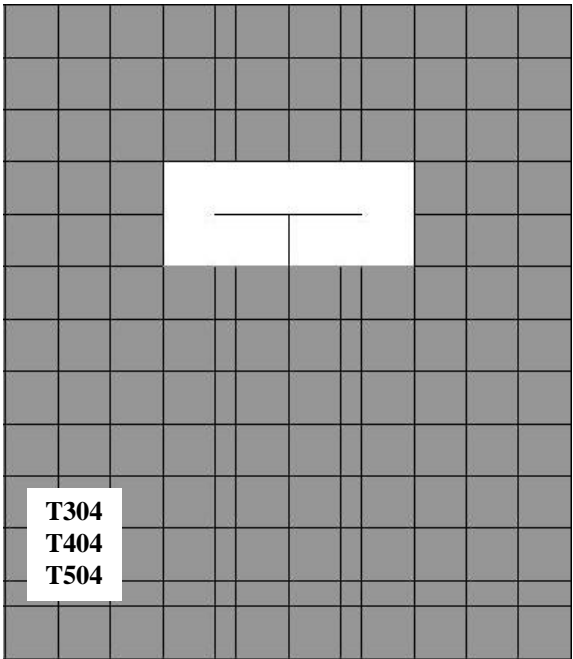
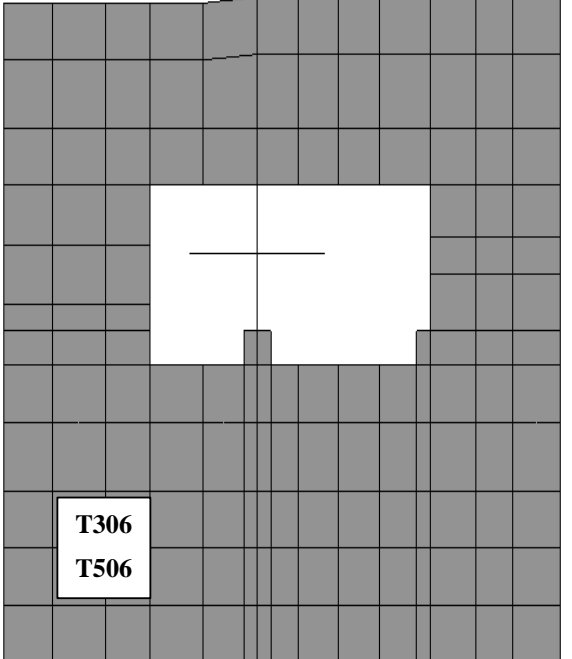
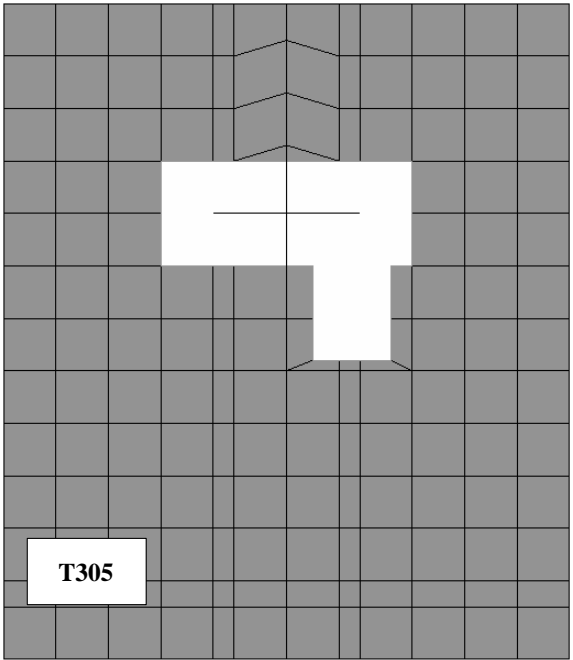
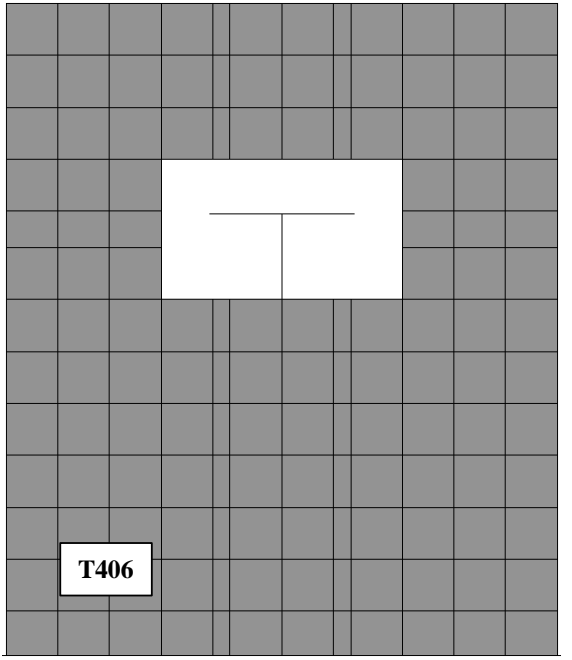
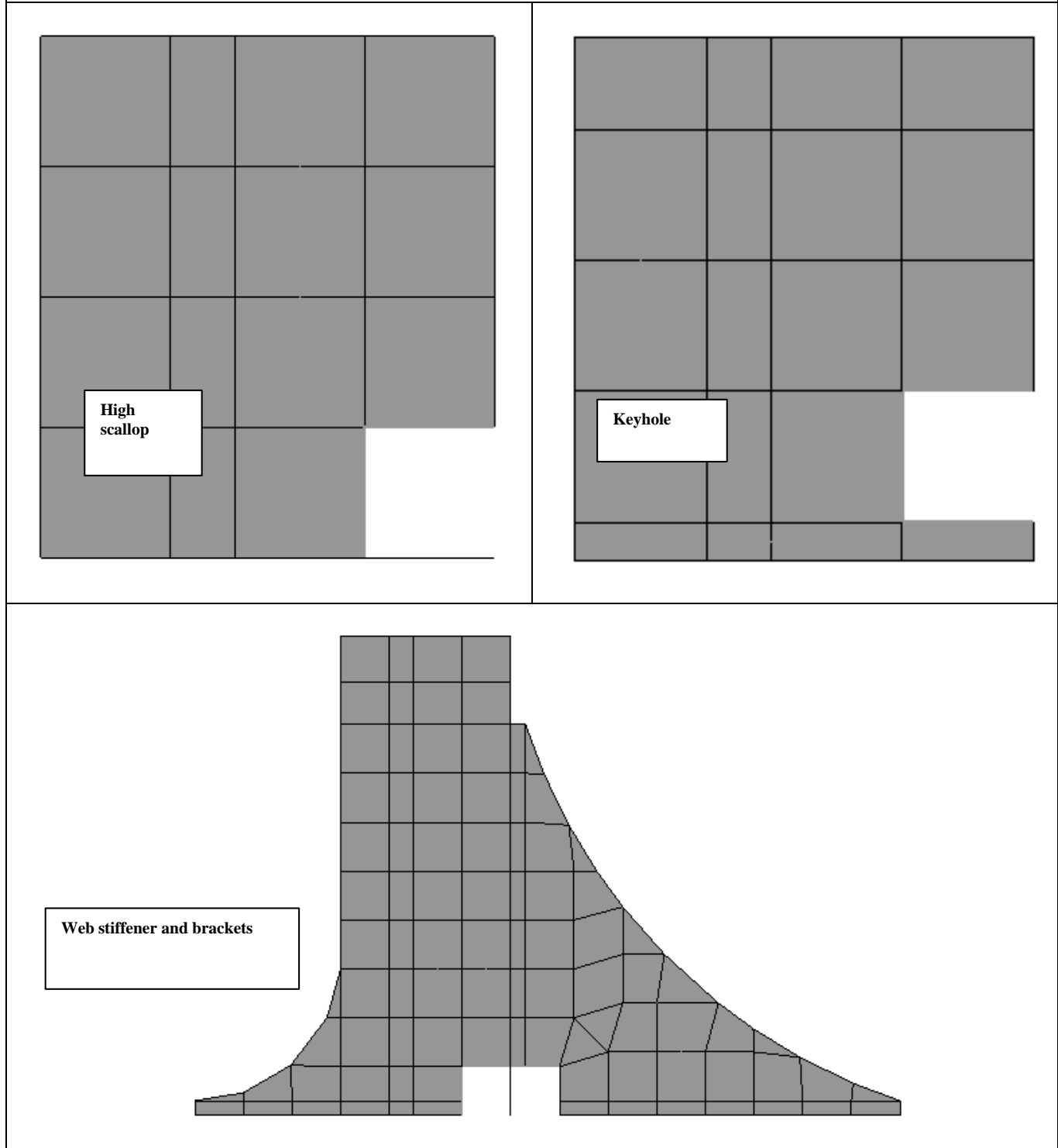
 <p data-bbox="209 712 300 808">T304 T404 T504</p>	 <p data-bbox="911 725 1002 808">T306 T506</p>
 <p data-bbox="209 1458 300 1503">T305</p>	 <p data-bbox="911 1464 1002 1503">T406</p>

Table 8-7 Semi-nominal element mesh at web stiffener



9. Appendix B - Calculation Example: Longitudinal Stiffener Frame Connection of an Oil Tanker

9.1 Introduction

The following calculation example follows the flowchart of Fig.3-2.

The vessel in this calculation example is a very large crude oil carrier, VLCC built in accordance with the **NAUSICUS (New-building)** class notation with a target fatigue life of 30 years in worldwide conditions. The considered hotspot is HS102 of the detail T302, Fig.9-1. The longitudinal is located at the midspan of the hopper tank outer bottom.

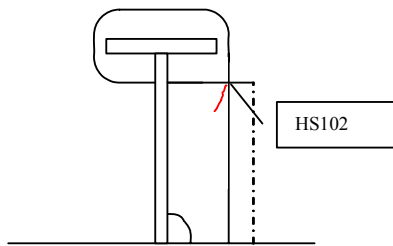


Figure 9-1
Example detail and hotspot location

Length O.A.	332.00 m
Length B.P.	320.00 m
Breadth moulded	58.00 m
Depth moulded	31.00 m
Draught design	20.80 m
Draught scantling	22.465 m

9.2 Fatigue loads

The load conditions to be considered will vary for specific ship types. For the considered tanker for oil it is expected to be 42.5% of its lifetime in Full Load condition, 42.5%. The remaining 15% are assumed to be spent in harbour/calm water.

Loading condition	Fraction
Full load	0.425
Ballast	0.425

For **PLUS** analysis of longitudinal stiffener-frame connections only external and internal pressure loads should be considered. The formulas for calculating the pressure values are according to Classification Note 30.7.

The following six load cases at 10^{-4} probability level are applied to the cargo tank model for global stress analysis and to the semi-nominal model for fatigue stress analysis:

- 1) External dynamic pressure, Full load
- 2) Internal dynamic pressure, Full load
- 3) External dynamic pressure, Ballast
- 4) Internal dynamic pressure, Ballast
- 5) Static pressure, Full load
- 6) Static pressure, Ballast

9.3 Global stress analysis

The deformation response of the primary members in the midship area is obtained by finite element analysis of a midship cargo tank model, see section 5.2. The cargo tank model is subjected to the six pressure load cases described in section 4.6. The displacement results of the cargo tank analysis are considered to be global results and transferred to the semi-nominal model by sub-modelling technique. Fig.9-2 shows the displacement results for the external pressure full load condition.

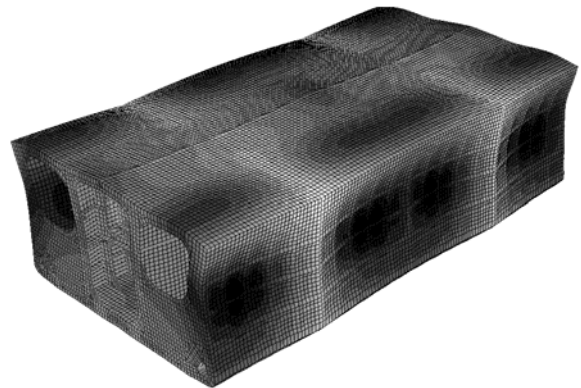


Figure 9-2
Global displacement analysis – full load external pressure

9.4 Semi-nominal stress analysis

A semi-nominal model is made to capture the local geometric stress flow and effect of cut-outs, web-frame toes and tripping brackets. The model requires finer mesh and the resulting stresses are used together with stress concentration factors to obtain the hotspot stress range for use in fatigue calculation. Section 5.3 describes the requirements for the semi-nominal model. The semi-nominal model is in addition to the six pressure load cases also subjected to displacements transferred from the cargo hold model. Fig.9-3 shows the stress flow in the hopper area of the semi-nominal model subjected to external pressure full load condition.

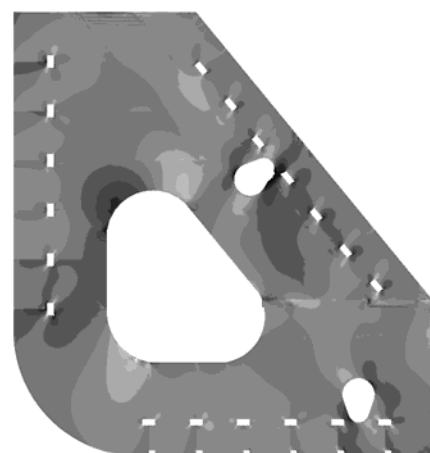


Figure 9-3
Semi-nominal stress analysis – full load external pressure

9.5 Read out of semi-nominal stress

The semi-nominal stress is read out at the hotspot node. Maximum element membrane principal stress at the hotspot should be used. Averaging is not allowed. Fig.9-4 shows the stress flow and the read out position for the considered hotspot HS102. Table 9-3 lists the semi-nominal stresses for the six load cases.

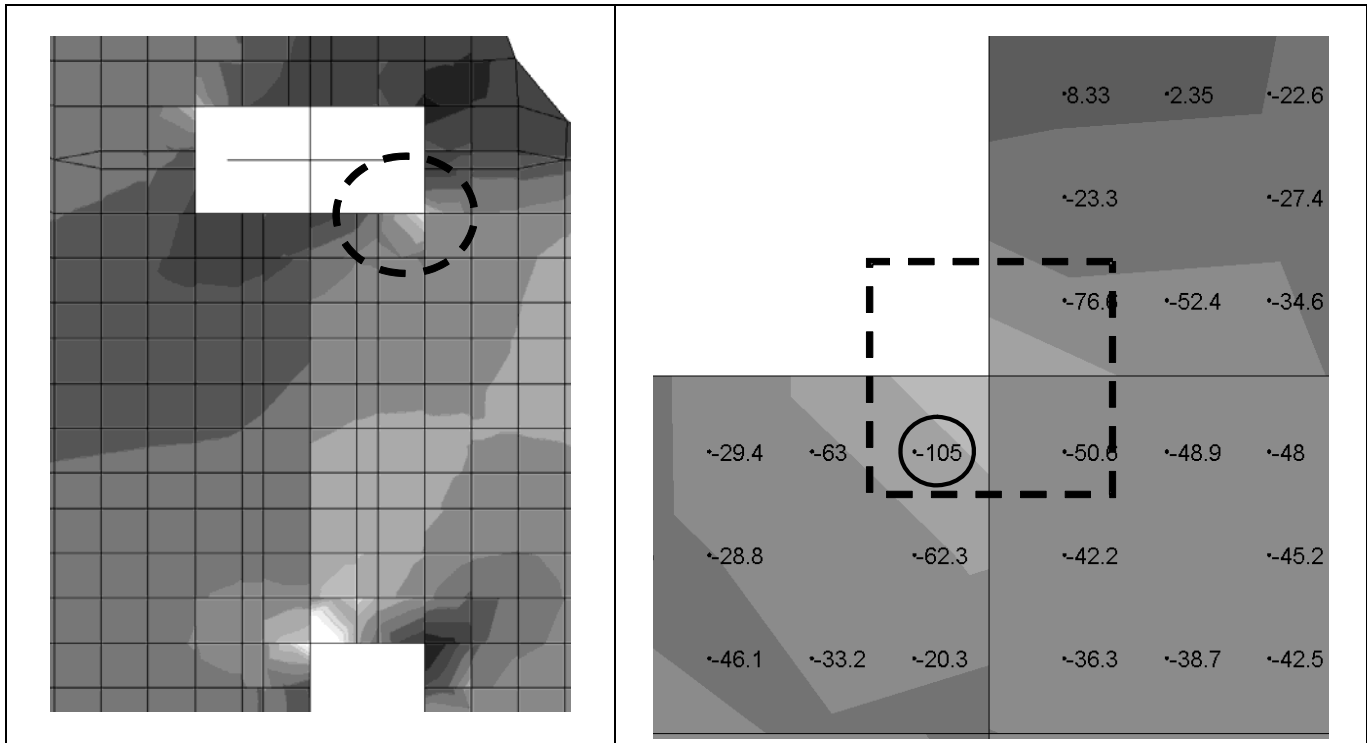


Figure 9-4
Stress read out at hotspot location – Full load external pressure

	Full load [MPa]	Ballast [MPa]
External	-105	-96
Internal	16	98
Static	-179	189

9.6 Stress concentration factor

In order to obtain the hotspot stress for use in fatigue calculation the semi-nominal stress result should be multiplied with stress concentration factors that accounts for the increase in stress due to local geometry and weld geometry. The geometry stress concentration factor K_G for the considered hotspot HS102 of detail type T302, at the considered detail is taken according to Table 8-4. Table 9-4 lists the hotspot stresses.

$$K_G \text{ (T302 - HS102)} = 0.94$$

$$\sigma_{\text{hotspot}} = \sigma_{\text{semi-nom}} \cdot K_G$$

	Full load [MPa]	Ballast [MPa]
External	-99	-90
Internal	15	92
Static	-168	178

9.7 Combination of stresses

The combined hotspot stress range is taken as a linear combination of external and internal pressure and corrected for mean stress level and trading route:

$$\Delta\sigma_i = f_m \cdot \Delta\sigma_0$$

$$\Delta\sigma_0 = 2f_e \cdot \max \left\{ \begin{array}{l} |\sigma_e + 0.6\sigma_i| \\ |0.6\sigma_e + \sigma_i| \end{array} \right.$$

according to CN30.7. In this example the environmental factor is based on worldwide environment, $f_e = 0.80$.

Full load condition:

$$\Delta\sigma_0 = 0.8 \cdot 2 \cdot \max \left\{ \begin{array}{l} |-99 + 0.6 \cdot 15| \\ |-99 \cdot 0.6 + 15| \end{array} \right. = 144$$

Ballast condition:

$$\Delta\sigma_0 = 0.8 \cdot 2 \cdot \max \left\{ \begin{array}{l} |-90 + 0.6 \cdot 92| \\ |-90 \cdot 0.6 + 92| \end{array} \right. = 60.8$$

Mean stress correction

The mean stress correction factor f_m is based on the static stresses. The static stresses are listed in Table 9-3.

The compression and tension stress and f_m factor is calculated according to CN30.7 /1/:

Full load condition:

$$\sigma_t = \max \left\{ \begin{array}{l} \sigma_{\text{static}} + \frac{\Delta\sigma}{2} = -179 + \frac{144}{2} = -107 \\ 0 \end{array} \right. = 0$$

$$\sigma_c = \min \left\{ \begin{array}{l} \sigma_{\text{static}} - \frac{\Delta\sigma}{2} = -179 - \frac{144}{2} = -251 \\ 0 \end{array} \right. = -251$$

$$f_m = \frac{\sigma_t + 0.7|\sigma_c|}{\sigma_t + |\sigma_c|} = \frac{0 + 0.7 \cdot 251}{0 + 251} = 0.7$$

For the mean stress and environmental factor the approach is *Ballast load condition*

$$\sigma_t = \max \left\{ \begin{array}{l} \sigma_{static} + \frac{\Delta\sigma}{2} = 189 + \frac{61}{2} = 219.5 \\ 0 \end{array} \right\} = 219.5$$

$$\sigma_c = \min \left\{ \begin{array}{l} \sigma_{static} - \frac{\Delta\sigma}{2} = 189 - \frac{61}{2} = 158.5 \\ 0 \end{array} \right\} = 0$$

$$f_m = \frac{\sigma_t + 0.7|\sigma_c|}{\sigma_t + |\sigma_c|} = \frac{219.5 + 0.7 \cdot 0}{219.5 + 0} = 1.0$$

Combined hotspot stress

Full load condition:

$$\Delta\sigma_l = 0.7 \cdot 144 = 100.8$$

Ballast condition:

$$\Delta\sigma_l = 1.0 \cdot 60.8 = 60.8$$

9.8 Long term stress distribution

The long term stress is assumed to be Weibull distributed. A common Weibull shape parameter is used for all details. The shape parameter is dependent on the ship length and is in this example:

$$h = h_0 + h_a = 2.21 - 0.54 \cdot \log_{10}(320) + 0.05 = 0.91$$

9.9 Fatigue damage calculation

The fatigue damage over a design life of 30 years is calculated based on the simplified approach using the stress range at 10⁻⁴ probability level according to CN 30.7 /1/:

Full load condition:

Non-corrosive environment:

$$D = v_0 T_d \left[\frac{q^{m_1}}{\bar{a}_1} \Gamma \left(1 + \frac{m_1}{h}; \left(\frac{S_1}{q} \right)^h \right) + \frac{q^{m_2}}{\bar{a}_2} \gamma \left(1 + \frac{m_2}{h}; \left(\frac{S_1}{q} \right)^h \right) \right]$$

where

$$v_0 T_d = \frac{30 \cdot 365 \cdot 24 \cdot 3600}{4 \text{Log}_{10}(320)} = 9.44135 \cdot 10^7 \quad (\text{the number of cycles during 30 years})$$

$$q = \frac{\Delta\sigma}{(\ln n_0)^{1/h}} = \frac{100.8}{(\ln 10^4)^{1/0.91}} = 8.79 \text{ N/mm}^2 \quad (\text{the Weibull scale parameter})$$

\bar{a}_1, m_1 = S-N parameters for N<10⁷ cycles

\bar{a}_2, m_2 = S-N parameters for N>10⁷ cycles

S₁ = Stress range for which change of slope occur

Corrosive environment:

The corrosive environment is based on the non-corrosive environment results (SN curve I) with a reduction factor of 2 on the fatigue life.

This gives the fatigue damage:

$$D_{\text{non-corrosive}} = 0.228$$

$$D_{\text{corrosive}} = 0.456$$

The vessel is assumed to be 30 - 5 = 25 years in non-corrosive environment and 5 years in corrosive environment. Non-corrosive environment applies for the first 25 years and corrosive environment applies for the remaining time.

This gives the following fatigue damage for the full load condition:

$$D_{\text{fullload}} = p_{\text{fullload}} \cdot \left(D_{\text{non-corrosive}} \cdot \frac{T_c}{T_d} + D_{\text{corrosive}} \cdot \frac{(T_d - T_c)}{T_d} \right)$$

Where

$$p_{\text{fullload}} = \text{part of design life in full load condition} = 0.425$$

$$T_c = \text{corrosion protection period} = 25 \text{ years.}$$

$$D_{\text{fullload}} = 0.425 \cdot \left(0.228 \cdot \frac{25}{30} + 0.456 \cdot \frac{30 - 25}{30} \right) = 0.113$$

Ballast condition:

$$D_{\text{ballast}} = 0.425 \cdot \left(0.026 \cdot \frac{25}{30} + 0.052 \cdot \frac{30 - 25}{30} \right) = 0.013$$

9.10 Total fatigue damage

The total fatigue damage in full load and ballast condition is:

$$D_{\text{total}} = D_{\text{fullload}} + D_{\text{Ballast}}$$

$$D_{\text{total}} = 0.113 + 0.013 = 0.126$$

Some fatigue parameters and fatigue damage for each load condition are shown in Table 9-5. The total fatigue damage of 0.126 is acceptable and corresponds to approximately 151 years fatigue life.

$$T = 25 + \left(\frac{30}{(0.228 \cdot 0.425 + 0.026 \cdot 0.425)} - 25 \right) \frac{(0.228 + 0.026)}{(0.456 + 0.052)} = 151.4$$

Table 9-5 Fatigue damage results

Load conditions	Part time in loading condition	Part time in non-corrosive/corrosive	Number of cycles	SN-Curve	Fatigue damage
Full load	0.425	0.83	3.53·10 ⁷	non-corrosive	0.081
		0.17	7.22·10 ⁶	corrosive	0.032
Ballast	0.425	0.83	3.13·10 ⁷	non-corrosive	0.009
		0.17	6.42·10 ⁶	corrosive	0.004
					0.126