Structural and Fatigue Analysis of a Type C Tank Vessel at Class Renewal No IV

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I, Kailas Cheriyan declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Structural and Fatigue Analysis of a Type C tank Vessel at Class Renewal No IV.

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Nomenclature

ADN	: European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways
BV	: Bureau Veritas
DNI	: Direction de la Navigation Intérieure (Inland Navigation Management)
FEA	: Finite Element Analysis
FEM	: Finite Element Method
GUI	: Graphical User Interface
SNAME	: Society of Naval Architects and Marine Engineers
UNECE	: United Nations Economic Commission for Europe

ABSTRACT

During the lifetime of a vessel, structural defects arise in the form of material wastage (corrosion), fractures, deformations leading to the deterioration of its condition. The impact of corrosion on vessels is one of the most indispensable point of interest in terms of safety and economics. In order to decide on actions to be taken for a proper maintenance of the vessel, surveys are to be performed in compliance with sound marine practice. Namely, regarding the hull condition, these surveys include visual examination of the hull, assessment of possible structural defects and, depending on the vessel age and maintenance condition, thickness measurements in order to determine the structure wastage. The vessel under consideration is a type C tank inland vessel at class renewal number IV (vessel age > 15 years). The scope and extent of thickness measurements at class renewal number IV are defined, together with acceptance criteria, in Bureau Veritas NR 597 requirements for thickness measurements applicable to inland vessels.

Taking into account the thickness measurements report, structural and fatigue analysis is carried out in the present thesis using BV Rules and direct engineering calculations (finite element method) to provide information regarding the strength of the vessel structure and to estimate the fatigue life of structural details. Fatigue damage and fatigue life of critical structural details have been evaluated in accordance with a deterministic/simplified approach proposed by BV.

Keywords; *Structural Analysis, FEM, Fatigue, Hot spots, Stress Range*

1 INTRODUCTION

1.1 Vessel Structural Defects

1.1.1 *General*

During its life, the vessel is affected by structural defects leading to deterioration of its condition. Structural defects may take form of material wastage, fractures or deformations, origin of which may be traced to: [1]

- In service stage: environment, collision, weather, loading / unloading operations, etc,
- Building stage: structural detail, material, misalignment, welding defects, etc.

1.1.2 *Coating Failure*

Coating failure can take the form of coating cracking, flaking and blistering. Coating cracking may result from, [1]

- over thickness of paint,
- plastic structure deformations exceeding the elongation properties of paint film,
- localized fatigue stress.

Coating flaking is defined as the lifting of the paint from the underlying surface in the form of flakes or scales. The causes of a loss of adhesion may be the following:[1]

- unsatisfactory surface preparation,
- incompatibility with under layer,
- contamination between layers,
- excessive curing time between layers.

Coating blistering appears as a bubble formation scattered on the surface of a paint film with a diameter ranging from 3-4 mm to 20-30 mm. Blisters contain liquid, vapor or gas. Blistering is a localized loss of adhesion and lifting of the film, coming generally from osmosis due to one of the following causes: [1]

- solvent retention,
- improper coating application,
- soluble salt contamination under the paint film due to insufficient cleaning of the surface.

1.1.3 *Corrosion Wastage*

Corrosion is the result of a chemical reaction between metal and the environment. The various types of corrosion which can occur in seawater or river water environment are general corrosion, galvanic corrosion, pitting corrosion, crevice corrosion, stress corrosion, erosion, etc. General corrosion, the most common form of corrosion, spreads uniformly over the surface of the metal. Galvanic corrosion can occur when two dissimilar metals are electrically coupled in the presence of an electrolyte such as seawater or river water. Pitting is caused by the action of a localized corrosion cell on a steel surface due to the breaking of the coating (if present), to the presence of contaminants or impurities on the steel (e.g. mill scale) or to impurities present in the steel. For coated surfaces, the attack produces deep and relatively small diameter pits that can lead to hull penetration. Crevice corrosion is also a localized corrosion that appears as pitting. The most common case occurs in cracks and generally on steel surfaces covered by scales and deposits. Typical examples are vessel welding seams, pipe supports and bolts. Stress corrosion is a form of local deterioration resulting from the combined action of static stress and corrosion which leads to the cracking of metal.[1]

Ship structural items affected by corrosion are shown in Figure 1.

Figure 1: Corrosion Affected Areas

Source; *http://www.amteccorrosion.co.uk/coatingbreakdown.html* [Accessed July 2017]

1.1.4 *Erosion*

Erosion is caused by the effect of liquid and abrasion due to mechanical effect.[1]

1.1.5 *Cracking*

Cracks will normally initiate at notches, stress concentrations or weld defects. In most cases fractures are found at locations where stress concentrations occur. These points of stress concentrations could be due to:[1]

- Discontinuity: cuts in highly stressed areas, abrupt changes in continuity,
- Fabrication problems: faulty welding, rough plate edges, misalignment of structure.

Weld defects, flaws, and areas where lifting fittings used during the construction of the vessel are not properly removed are often recognized as areas of stress concentration when cracks may be found. If cracks have occurred under repeated stresses which are below the yielding stress, the fractures are called fatigue fractures. Cracks may also be initiated by undercutting the weld in way of stress concentrations. [1]

1.1.6 *Deformations*

Deformation of structure is caused by in-plane load, out-of-plane load or combined loads. Such deformation is often identified as local deformation, such as deformation of panel including stiffener, or global deformation, such as deformation of structure including plating, beam, frame, girder, floor, etc. If in the process of the deformation, large deformation is caused due to small increase of the load, the process is called buckling. Deformations are often caused by impact loads/contact and inadvertent overloading. Permanent buckling may arise as a result of overloading, overall reduction in thickness due to corrosion, or contact damage. Elastic buckling will not be directly obvious but may be detected by coating damage, stress lines or shedding of scale. [1]

In Short,

Aging of vessel structures is a deterioration of the vessel structure resulting from operating conditions. Structural deterioration may take form of material wastage, fractures or deformations. Measures are to be taken: [1]

- at the design and building stages to minimize repairs during vessel life,
- during operation in order to monitor the vessel condition and ensure its proper maintenance.

Only corrosion wastage is covered by this study.

1.2 Hull Condition Assessment

Surveys based on sound marine practice have to be carried out periodically to ensure proper condition of the vessel and to avoid failure. Vessel surveys carried out within the scope of class hull condition assessment include finding anomalies relative to structural defects as described in section 1.1. These surveys are carried out in compliance with the classification societies Rules according to given instructions schedule. The recording of the surveyor's findings is usually textual and in some cases quantified as good, fair or poor[26].

Condition Assessment Programme for inland vessels (CAP Inland) is a service provided by Bureau Veritas as a supplement to class and designed to be complementary. CAP Inland may be requested by a client at any period of the vessels life in order to identify the actual quality standard of the vessel with respect to class Rules. This service is a very useful tool for all marine industry players, applicable to classed vessels or to vessels not classed at all, allowing [26] :

- More inspection criteria for assessing the hull structure,
- More quantifiable parameters for the reporting on the extent of the condition or damage found, namely, quality ratings are set in order to easily identify the condition, reliability and maintenance standard associated with the vessel or sub-system being assessed,
- More documented reporting of the condition found.

The requirements dealing with services provided by CAP Inland are set down in the guidance note NI575.

1.3 Thickness Measurements

Thickness measurement is one of the major part of surveys as it is required not only to maintain the class but also to determine the extent of repairs and renewals of vessel's structural components. Measurements of different parts of the structure are taken to ensure that the overall and local strength of the vessel are within the acceptable limits defined by the class. The extent of thickness measurements are defined based on the vessels type and age. Several means of thickness measurements include ultrasonic thickness (UT) gauging techniques, other NDT techniques (DP,X-ray etc).

Ultrasonic thickness gauge (refer figure 2) is a measuring instrument that evaluates the thickness of a component using ultrasonic waves by measuring the time it takes to travel from the transducer to the back end of the material and the reflection back to the transducer. The thickness is measured using the velocity of the sound through the material (standard frequency used is 5Hz).

UT measurement readings ensure whether the local strength/global strength of the ship is retained or not. Also, the specific areas which are more prone to corrosion can be identified and taken care of.

Figure 2: UT Gauging

Source; *http://carina-ind.com/utgauging.php.htm* [Accessed July 2017]

The diminution of thickness should be checked whether it is within the acceptable range. The acceptance criteria is defined in the following Rule note,

- Bureau Veritas NR 597 DNI R01 E: Requirements for thickness measurements applicable to Inland Navigation Vessels.

1.4 Aim and Research Methodology

The aim of this thesis work is to carry out structural and fatigue analysis of an in-service vessel (age > 15 years) using both classification society rules and direct engineering calculations (FEM), taking into account the corrosion wastage.

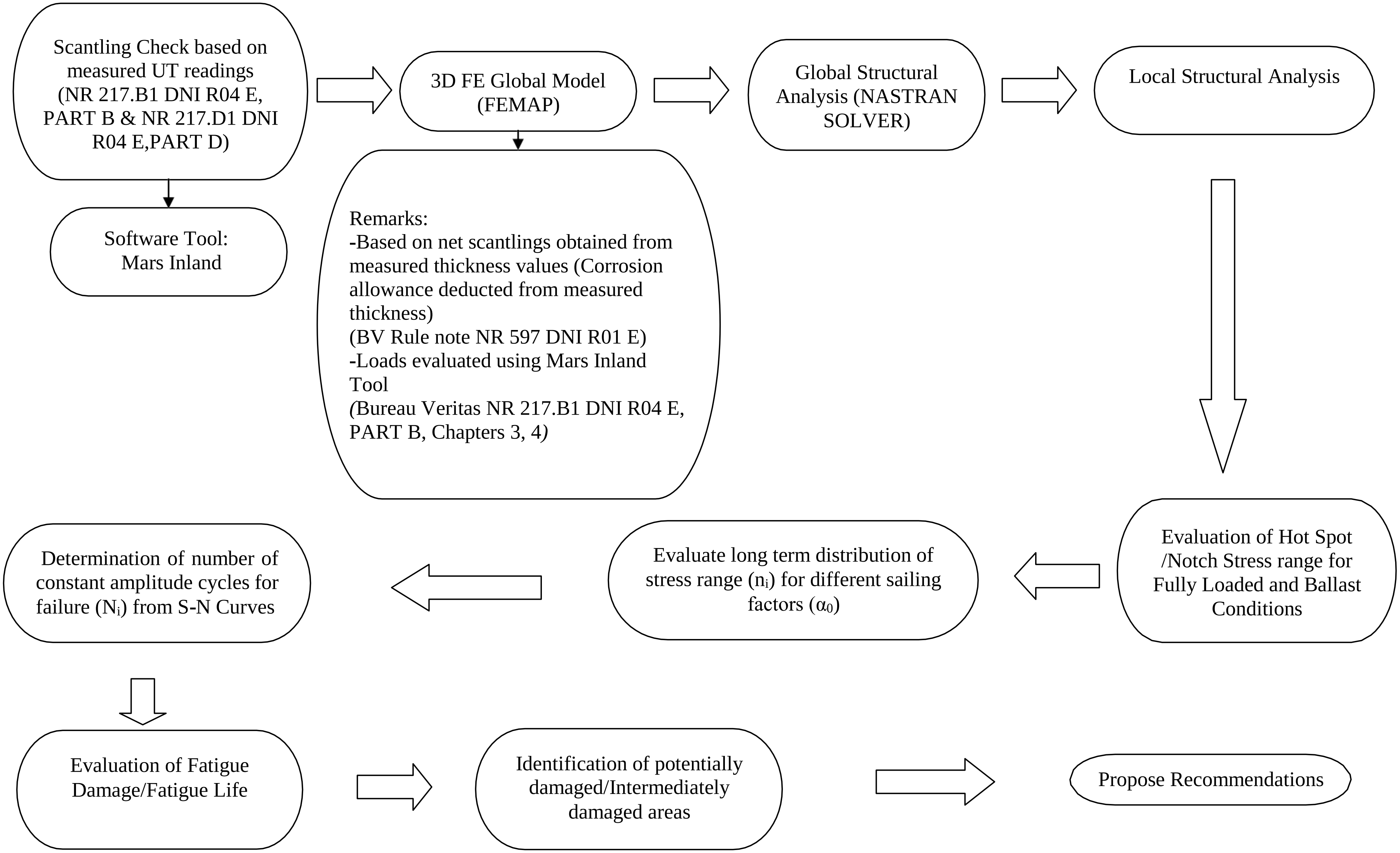
Initially, the UT measurements of the vessel will be checked with the acceptance criteria proposed by BV. Scantling check will be carried out based on rule formulations followed by a FEM analysis. The results obtained from both cases (BV rules and FEM) will be compared. Highly stressed areas (Hot-spots) can be identified by implementing a global FE analysis. Evaluation of fatigue damage will be carried out on these hot-spot areas and on the critical areas recommended by the classification society. In this thesis, stress based approach with deterministic method proposed by BV has been implemented for the evaluation of cumulative fatigue damage.

Following steps have been fulfilled to complete the study,

- Estimation of design loads based on BV rules (NR 217),
- Checking the compliance of measured thickness readings (from UT report) with the acceptance criteria (NR 597),
- Evaluating net scantlings by deducting the corrosion allowance values from the measured thickness (NR 597),
- Carryout scantling check to ensure compliance with the BV rules (NR 217.B1 and NR 217.D1),
- Developing a 3D model of the vessel based on the net scantlings using FEMAP and carry out structural analysis using NX-NASTRAN solver,
- Identifying critical locations prone to fatigue (Hot-spot areas),
- Evaluating Hot spot and Notch stresses by imposing appropriate stress concentration factors on the Nominal stresses,
- Evaluating Fatigue Damage/Fatigue Life using Deterministic/Simplified Method (NI 575) for fully-loaded and ballast conditions (based on Weibull distribution),
- Evaluating cumulative Fatigue damage/Fatigue life,
- Based on the results, propose recommendations on structural areas to be repaired/replaced and those areas to be monitored.

Flowchart 1 represents the methodology adopted for this master thesis. Each step has been explained explicitly in subsequent chapters of this report.

THESIS METHODOLGY



FLOW CHART 1

Fatigue analysis has been carried out based on the following BV guidance document,

NI 575, Appendix 4, Guide for Fatigue Analysis adapted to inland navigation conditions (Derived from NR 467, Part B, Chapter 7, Section 4, Fatigue check of structural details for sea-going vessels).

For secondary structural members (ordinary longitudinal stiffeners) stresses have been calculated using BV rules.

For primary supporting members (Longitudinal Girders) and other hotspot areas, stress values for different load cases are taken directly from the FEMAP model and the fatigue damage is calculated using the above mentioned rules.

2 VESSEL UNDER INVESTIGATION

In this thesis work, the vessel under investigation is a type C Inland tanker at class renewal number IV operated on Belgium Inland water way between the Ports of HEMIKSEM and ANTWERP.

The vessel has been navigating for about 30 years. The maximum significant wave height it encounters is 1.2m. The class renewal survey report dated 12.11.2015 has been taken into account for the study. All the measured thickness readings and the areas which need repairs or renewals based on the acceptance criteria by BV has been clearly mentioned in the report. Also, those locations under substantial corrosion were also specified.

According to ADN[6], Type C tank vessel applies to a tanker built and equipped for the carriage of dangerous liquids in bulk. As per the A.D.N regulations this type of vessel has to be flush deck (continuous from stem to stern)/double hull type with double bottom. The cargo tanks may be independent tanks installed in the hold spaces or may be formed by the inner structure. Refer figures 3 and 4 for General Arrangement and Midship drawings. Table 1 gives the main particulars of the vessel.

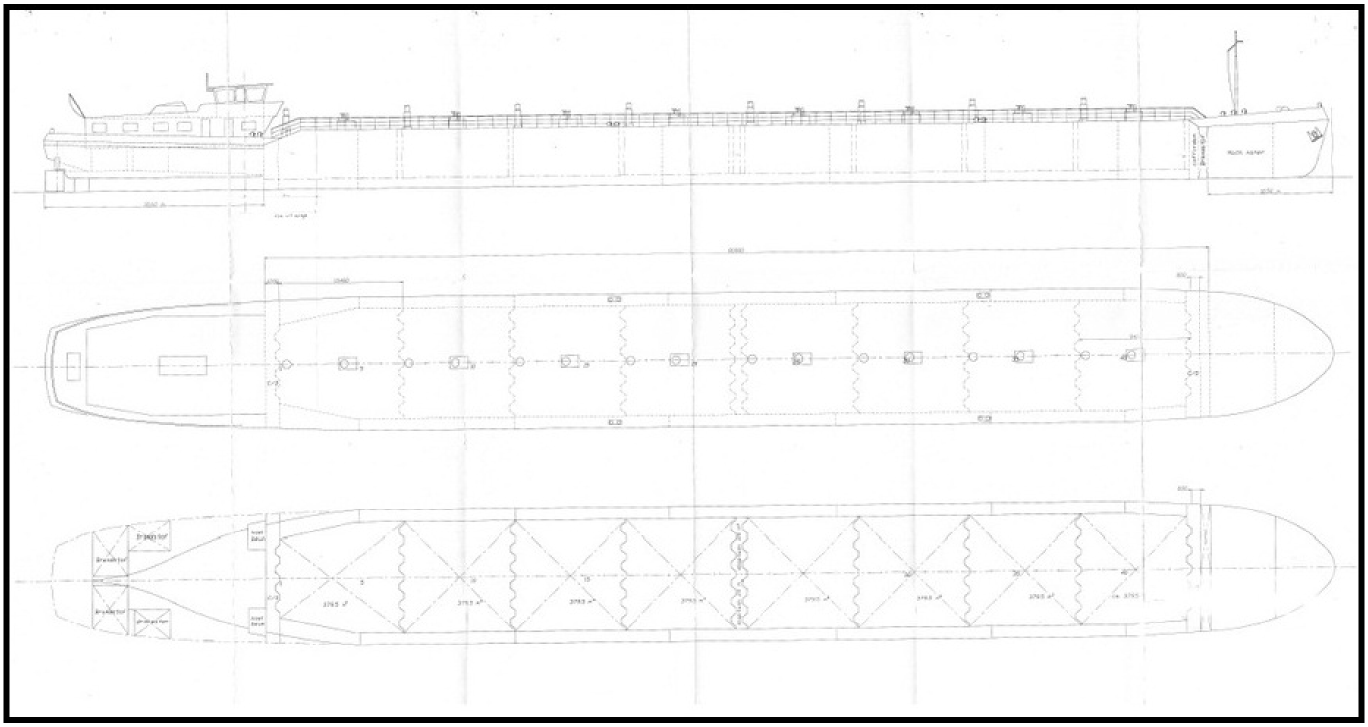


Figure 3: General Arrangement of the investigated Vessel (Type C tank Inland Tanker)

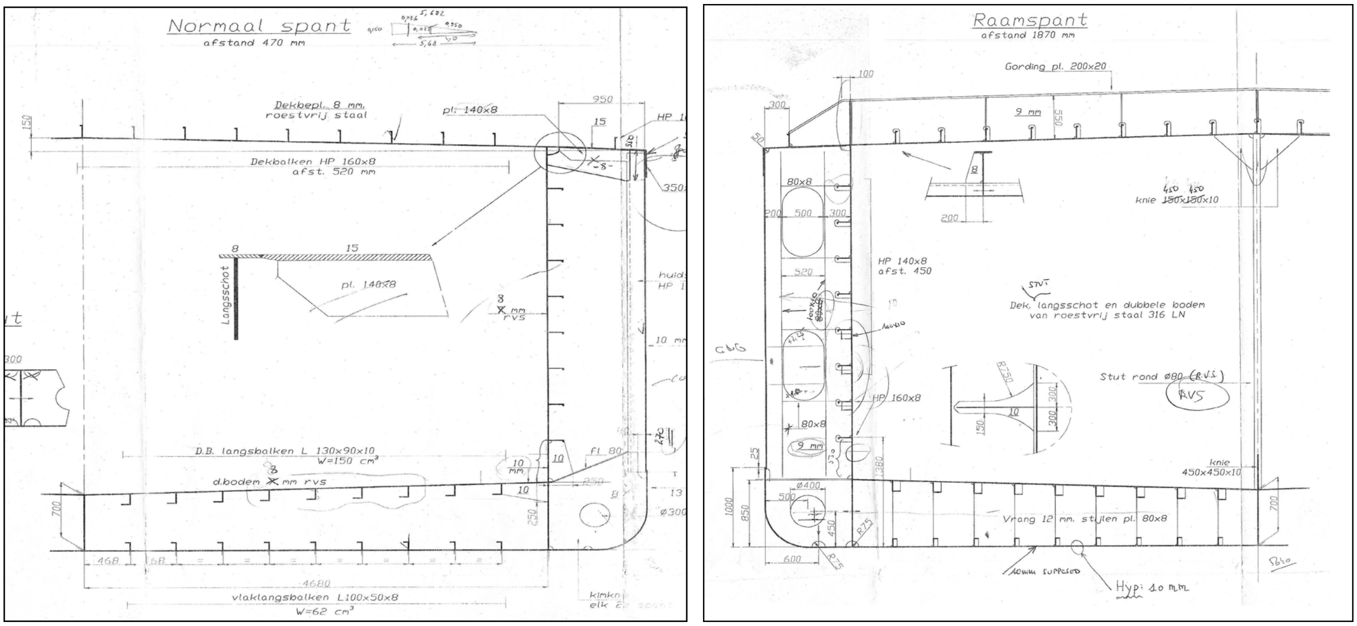


Figure 4: Typical Midship Section (Normal Frame) and Web Frame

Table 1: Main Particulars of the vessel (Type C)

Length Overall(m)	109.23
L.B.P(m)	106.5
Breadth(m)	11.4
Depth(m)	5.03
Draught(m)	3.22
Mass Displacement(t)	3370.54
Block Coefficient	0.86
Maximum Service Speed(km/hr)	10.37 (5.6 kn)
Range of Navigation	IN(1.2)
Significant Wave Height (m)	1.2
Loading sequence	2R(2 Runs)
Propulsion	Self Propelled
Date of Build	01 Oct 1984
Hull Material	Steel (S235JR/SS 316L)

2.1 Structural Configuration

The vessel has longitudinal framing system on deck, innerside shell, innerbottom and bottom shells. Transverse framing system is followed on the sideshell.

The maindeck, innerside plating and innerbottom plating are constructed out of stainless steel material (Grade:SS 316L). Whereas, the outerside and outerbottom plating are out of mild steel (Grade: S235JR).

There are eight cargo tanks separated transversely by corrugated bulkheads. There are no longitudinal bulkheads.

There are three normal frames arranged between two consecutive web frames.

The double bottom and side wing tanks allows the flow of ballast water through the openings on the side girders (DB and Side tanks together can be considered as a single compartment).

All stiffeners are oriented outward of the cargo area.

Innerside and Innerbottom stiffeners are oriented to the wing tank and double bottom tank respectively.

The deck stiffeners are oriented to the top (refer figure 4).

Stiffener spacing and other dimensional details are provided in Table 2.

The Gross/As-build scantlings of the main structural members of the vessel are provided in Table 3.

Table 2: Stiffener Spacing

Structural Members	**Spacing (mm)**
Deck Longitudinals(HP)	520
Innerside Longitudinals(HP)	450
Bottom and Innerbottom Longitudinals(L Section)	468
Side Transverse Stiffeners (HP)	470
Spacing between Web frames	1870
Spacing between Normal frames	470

Table 3: Gross Scantlings

Structural Elements	
Plating	**Gross Thickness (mm)**
Sheerstrake	25
Stringer Plate	15
Bilge Plate	13
Keel/Bottom Plate	10
Sideshell plate	10
Deck Plate	8
Inner Side	8
Inner Bottom	8
Bulkhead Plate(Corrugated)	8
CL Girder	8
Side Girder	8
Side Web Frame	9
Bottom Web Frame	12
Bottom Web Frame(below Bkhds)	8
Stiffeners (Numbers in each half section of the Vessel)	**Gross Scantlings (mm)**
Deck Longitudinals(HP) - 8 No’s	160x8
Innerside Longitudinals(HP) - 6 No’s	140X8
Innerside Longitudinals(HP) - 2 No’s	160X8
Innerbottom Longitudinals(L Section) - 9 No’s	130x90x10
Bottom Longitudinals(L Section) - 9 No’s	100x50x8
Side Transverse Stiffeners (HP)	180X8

3 HULL CONDITION ASSESSMENT/HULL SURVEY

3.1 General

Thickness measurements has been carried out according to Bureau Veritas Rule Note NR 597, Requirements for thickness measurements applicable to inland vessels. Structural and fatigue assessment has been done according to Bureau Veritas Guidance Note NI 575 Condition Assessment Programme for inland vessels.

3.2 Scope and Extent of Thickness Measurements

For vessels at class renewal number IV (age > 15 years), the scope and extent of thickness measurements have been provided in table 4. Figure 5 represents the typical locations for thickness measurements.

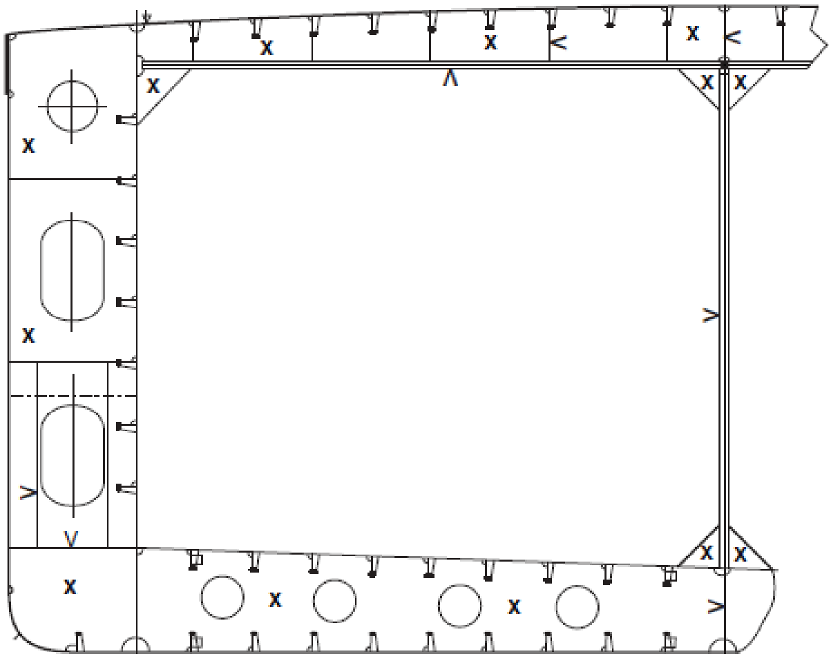


Figure 5: Locations of thickness measurements on web frame

Source(Table 4 and Figure 5); *Bureau Veritas Guidance Note NI 575 Condition Assessment Programme for inland vessels, Appx 1*

Table 4: Scope and extent of thickness measurements - Tank vessels with 15 years age and more

Tank vessels with 15 years age and more	
SYSTEMATIC MEASUREMENTS	Substantial corrosion and suspect areas For additional thickness measurements in way of substantial corrosion and suspect areas.
	Within the cargo length area: Each deck plate Four transverse sections in three different tanks (1) Each bottom / inner bottom plate Each side shell plate At least three points on each plate of transverse and longitudinal cargo tank bulkheads (2) , to be taken either at each 1/4 extremity of plate or at representative areas of average corrosion At least three points on each hatch cover and coaming plate to be taken either at each 1/4 extremity of plate or at representative areas of average corrosion (2)
	Outside the cargo length area: Each deck plate Each side shell plate Each bottom plate
	At least 65% of transverse and longitudinal bulkheads outside cargo length area (2) (3)
	In engine room (3): River chests River water manifold Duct keel or pipe tunnel plating and internals
	At least 30% within the cargo area and 15% outside the cargo area of internal structure such as ballast tanks, floors and longitudinals, transverse frames, web frames, deck beams, girders, etc. Measurements may be increased if the Surveyor deems it necessary
CLOSE-UP SURVEYS	Within the cargo length area: All web frames (complete transverse web frames ring including adjacent structural members) in all cargo and ballast tanks All transverse bulkheads (transverse bulkhead complete, including girder system and adjacent structural members) in all cargo and ballast tanks
(1) The number of transverse sections may be reduced at the Surveyors discretion for vessels of length under 40 m.	
(2) Including plates and stiffeners.	
(3) Measurements may be waived or reduced after satisfactory visual examination, when such bulkheads form the boundaries of dry void spaces or river chests, etc. are found in good condition.	

3.3 Acceptance Criteria

The corrosion and wear tolerances stipulate limits of wastage which are to be taken into account for reinforcements, repairs or renewals of hull structure. They are classified and determined by the Society, depending on the local conditions of the structural elements into, [20]

- criteria on global and buckling strength,
- criteria on local strength and pitting.

Each measured structural item is to be checked against these criteria, as far as applicable. When the criteria are not met, reinforcements, repairs or renewals are to be carried out as appropriate.

For each structural item, thicknesses are measured at several points and the average value of these thicknesses is to satisfy the acceptance criteria for the relevant item. These criteria are to considered for all structural items which contribute to the hull girder longitudinal strength. If the criteria are fulfilled but substantial corrosion is observed, it will be provided in the report.

Acceptance criteria for isolated areas

The thickness diminution of isolated areas of items should not be greater than 1,25 t_C, where t_C is the value of corrosion addition.

Acceptance criteria for items

The thickness diminution of isolated items should not be greater than the value of corrosion addition defined.

Acceptance criteria for zones

The sectional area diminution of a zone should not to be greater than 10% of the original sectional area. Otherwise, necessary actions will be taken. Refer Table 5, (Source; *Bureau Veritas Guidance Note NR 597*) for zone definitions for flush deck vessels.

The criterion applicable to the zones are based on the general rule that the current hull girder section modulus is not to be less than 90% of the original section modulus within 0,5L amidships.

Table 5: Zone definition - Flush deck vessels

Group of items	**Zone structural items**	**Remarks**
	DECK ZONE	
1	Deck plating Deck longitudinals Deck girders	Including stringer plate
2	Sheerstrake Sheerstrake longitudinals	The height of a sheerstrake having the same thickness as the adjacent side shell is to be taken equal to 0,08D
3	Inner side upper strake Inner side upper strake longitudinals	The height of the inner side upper strake is to be taken equal to that of the sheerstrake
4	Longitudinal bulkhead upper strake Longitudinal bulkhead upper strake longitudinals	The height of the longitudinal bulkhead upper strake is to be taken equal to that of the sheerstrake
	NEUTRAL AXIS ZONE	
5	Side and inner side shell plating	
6	Side and inner side shell longitudinals	
7	Side and inner side shell stringers	
8	Longitudinal bulkhead plating	
9	Longitudinal bulkhead longitudinals	
10	Longitudinal bulkhead stringers	
	BOTTOM ZONE	
11	Bottom plating Bottom longitudinals Bottom girders	Including keel plate
12	Bilge plating Bilge longitudinals	
13	Inner bottom plating Inner bottom longitudinals Inner bottom girders	
14	Inner side lower strake Inner side lower strake longitudinals	The height of the inner side lower strake is to be taken equal to: height of the bilge, for single bottom vessels height of the double bottom
15	Longitudinal bulkhead lower strake Longitudinal bulkhead lower strake longitudinals	The height of the longitudinal bulkhead lower strakee is to be taken equal to: height of the bilge, for single bottom vessels height of the double bottom

3.4 Structural and Fatigue Analysis according to CAP Inland

CAP Inland Structural and Fatigue Analysis (SFA) is carried out using BVs calculation programs. These programs use direct engineering calculations and 2D/3D modelling to provide information regarding the strength of the vessel structure (hull girder, secondary stiffeners, plating, primary supporting members) and to estimate eventually the design fatigue life of structural details.

3.5 UTM Report of Investigated Vessel

The UT measurement report of the vessel has been provided for this study. However, the thickness measurement values of all the structural members were not available in the report. Therefore, for those structural members with unavailable UT measurements, the thickness values have been generated by considering the thickness reductions of structural elements in the same compartment (close vicinity).

Table 6 gives the available measured thickness values of structural elements on tank no.4 (Midship Section-SB, Frame no's 17-22) and table 7 gives the generated values of measured thickness for the other elements,

As a conservative approach, the minimum values of thickness measured have been taken into account.

For instance, the forward and aft measurements of sideshell plating (item no.5 in table no 6) are given as 8.4mm and 9.1mm respectively. Out of the two values, the minimum thickness (8.4mm) is taken into consideration.

Also, there are three values provided for innerside longitudinals (item no's 6,7,8 in table no 6), out of those values the minimum value (7.5mm) has been taken.

The available and generated readings for Tank No.4 (PS) are provided in table 8 and table 9 respectively,

Table 6: Available UT Readings (SB)

RESULTS OF UT MEASUREMENTS - AMIDSHIPS (STARBOARD SIDE)					
TANK NO 4 ; Frame No's 17-22					
SL NO	**Item**	**As-build/Gross thickness(mm)**	**frwd (mm)**	**aft (mm)**	**Minimum thickness(mm)**
1	Sheerstrake	25	24.9	-	**24.9**
2	Stringer Plate	15	14.9	-	**14.9**
3	Bilge Plate	13	10.6	12.4	**10.6**
4	Keel/Bottom Plate	10	9.5	10	**9.5**
5	Sideshell plate	10	8.4	9.1	**8.4**
6	Innerside Longitudinals	8	7.7		7.7
7	Innerside Longitudinals	8	7.5		7.5
8	Innerside Longitudinals	8	8		8.0
9	Innerside Longitudinals (Min Thickness)	8			**7.5**
10	Inner bottom Longitudinals	10			8.9
11	Inner bottom Longitudinals	10			8.8
12	Inner bottom Longitudinals (Min Thickness)	10			**8.8**
13	Bottom Longitudinals	8			**7.8**

Table 7: Generated UT Readings (SB)

RESULTS OF UT MEASUREMENTS - AMIDSHIPS (SB)			
TANK NO 4 ; Frame No's 17-22			
SL NO	**Item**	**As-build/Gross thickness(mm)**	**Thickness(Generated Values in mm)**
1	CL Girder	8	**7.8**
2	Side Girders	8	**7.8**
3	Deck Longitudinls	8	**8.0**
4	Bottom Vertical Stringer	8	**7.0**
5	Web Frames sides	9	**8.4**
6	Web Frames bottom	12	**10.6**
7	Web Frames bottom(Bkhds)	8	**7.0**
8	Side Vertical Stringer	10	**9.4**
9	Side Horizontal Stringers	8	**7.5**
10	Side Transverse Stiffeners	8	**7.5**
11	Deck Vertical Plates	9	**9.0**
12	Deck Gording Flanges	20	**20.0**
13	Pillar Top brackets	10	**10.0**
14	Midsection Bilge Plate	8	**7.0**
15	Midsection Bilge Plate Flange	8	**7.0**
16	Intermediate bilge plate	10	**8.8**
17	Intermediate Bilge Plate Flange	8	**7.0**
18	Gording Plate on Bulkhead (Bottom)	10	**8.8**
19	Watertight Web frame Stringer	10	**9.4**

Table 8: Available UT Readings (PS)

RESULTS OF UT MEASUREMENTS - AMIDSHIPS (PORT SIDE)					
TANK NO 4 ; Frame No's 17-22					
SL NO	**Item**	**As-build/Gross thickness(mm)**	**frwd (mm)**	**aft (mm)**	**Thickness (mm)**
1	Sheerstrake	25	24.8	-	**24.8**
2	Stringer Plate	15	15	-	**15**
3	Bilge Plate	13	11.6	11.8	**11.6**
4	Keel/Bottom Plate	10	8	8.2	**8**
5	Sideshell plate	10	8.4	8.5	**8.4**
6	Innerside Longitudinals	8			7.5
7	Innerside Longitudinals	8			7.6
8	Innerside Longitudinals	8			7.7
9	Innerside Longitudinals (Min Thickness)	8			**7.5**
10	Inner bottom Longitudinals	10	9	9	**9**
11	Bottom Longitudinals	8			7.8
12	Bottom Longitudinals	8			8.2
13	Bottom Longitudinals	8			8
14	Bottom Longitudinals (Min Thickness)	8			**7.8**

Table 9: Generated UT Readings (PS)

RESULTS OF UT MEASUREMENTS - AMIDSHIPS (PS)			
TANK NO 4 ; Frame No's 17-22			
SL NO	**Item**	**As-build/Gross thickness(mm)**	**Thickness(Generated Values in mm)**
1	CL Girder	8	**7.8**
2	Side Girders	8	**7.8**
3	Deck Longitudinal	8	**8.0**
4	Bottom Vertical Stringer	8	**7.2**
5	Web Frames sides	9	**8.4**
6	Web Frames bottom	12	**10.8**
7	Web Frames bottom(Bkhds)	8	**7.2**
8	Side vertical Stringer	10	**9.4**
9	Side Horizontal Stringers	8	**7.5**
10	Side Transverse Stiffeners	8	**7.5**
11	Deck Vertical Plates	9	**9.0**
12	Deck gording Flanges	20	**20.0**
13	Pillar Top brackets	10	**10.0**
14	Midsection Bilge Plate	8	**7.2**
15	Midsection Bilge Plate Flange	8	**7.2**
16	Intermediate bilge plate	10	**9.0**
17	Intermediate Bilge Plate Flange	8	**7.2**
18	Gording Plate on Bulkhead (Bottom)	10	**9.0**
19	Watertight Web frame Stringer	10	**9.4**

The UT measurement report and assessments of items, zones based on acceptance criteria (NR 597) has been provided in APPENDIX A.

Various structural items and also the bottom zone does not meet the acceptance criteria proposed by BV. However, an investigation has been carried out using FEM tools to check if the situation is the same if direct calculation is performed.

4 SHIP STRENGTH AND FATIGUE; THEORETICAL ASPECTS

4.1 Historical Background

Strength of Ships

For hundreds of years softwood and timber from oaks has been used as the material for ship building. Strength assessment was purely based on the practical knowledge and experience of the builders. The strength of Iron ships has been estimated first by William Fairbairn in 1860. His method was based on ultimate load concept.[21]

After two years John Macquorn Rankin proposed the correct formulation for longitudinal bending moment of the whole hull structure including wave effects. After several research works, Schnadel(1929) found a proper explanation by taking the post buckling behavior of the thin deck plating under consideration.

It took almost a century to consider the probabilistic nature of seaway into the design formulations to evaluate the longitudinal strength of ships. Currently structural strength has been evaluated based on classical theory of elasticity following the classification society rules.

Since the end of the last century, direct calculation techniques like Finite Element Method has been used for structural analysis and optimization.

Fatigue

Poncelet (France - 1788-1867) introduced the term fatigue- progressive fracture is more descriptive. Minute crack at critical area of high local stress (flaws, pre-existing cracks), the crack gradually enlarges (creating bench marks) and final fracture when the section is sufficiently weekened. [7]

Wohler (1819-1914) The basis of stress-life method is the Wohler S-N diagram which plots nominal stress amplitude S versus cycle to failure N (usually represented in log-log plot). There are numerous testing procedure to generate the required data for a proper S-N diagram. [8]

Gerber (1874), Goodman (1899) Proposed empirical models to compensate for the tensile normal mean stress effect on high-cycle fatigue strength. This can be plotted as constant life diagrams. Gerber has proposed a parabolic representation on Wohlers fatigue limit data. [9]

Twentieth century -From Fatigue damage process to fracture mechanisms;

Palmgren (1924) -Miner (1945)-Linear cumulative damage. Based on the assumption that the fatigue damage accumulation is a linear phenomenon. States that the total fatigue damage caused by different stress ranges is the cumulative linear sum of individual fatigue damage at constant stress range ”S” as given by the S-N curves. [2]

Manson- Coffin (1945) Plastic strain method. Most of the designs are based on the fact that the stress is within the elastic range. But in certain cases due to stress concentration effects, plastic strains can develop at the vicinity of the notches. The notch tip is strain controlled since it is plastically deformed. The assumption in this case is that the fatigue damage accumulation and the fatigue life to crack initiation at the notch tip are the same as in smooth material specimen if the stress/strain states in the notch and the specimen are the same.[10]

From the geometry and the loads imposed on the notched components, the local stress-strain histories on the notches has to be estimated by any convenient methods (Neuber or ESED). Fatigue damage should be calculated for each stress-strain cycle history.

Inglis (1913), Griffith (1921) (Energy Methods) - Fracture mechanics is the study of mechanical behavior of cracked material subjected to the applied load. It deals with the irreversible process of rupture due to nucleation and growth of cracks. The imperfections in the micro structure can act as fracture nuclei under unfavorable conditions. For instance, brittle fracture is a low-energy process which causes serious damage since the velocity of crack propagation is generally high. On the other hand, ductile fracture is a high energy process since it involves large energy dissipation with large plastic deformation. [11]

The linear-elastic fracture mechanics was developed by the work on glass by Griffith. His theory considers the energy changes associated with the incremental crack growth. An energy balanced approach was utilized to predict the fracture stress of glass. When a stressed elastic material which contains crack, the potential energy per unit thickness decreases and surface energy per unit thickness increases during the crack growth. Then, the total potential energy of the stressed solid body is related to the release of stored energy and the work done by the external loads. The surface energy arises from a non equilibrium configuration of the nearest neighbor atoms at any surface in a solid.

The Liberty ship series built at the United states during WWII has serious issues with the generation of cracks due to brittle fracture. More than 1000 damages and accidents were reported and more than 200 Liberty ships were sunk or damaged (refer figure 6). The shipyards have used inexperienced welders and new welding techniques for construction. Also, the riveted ships did not had the same issue. The ships was used in the areas where the temperature was well below the critical point (for steel) which changes from ductile to brittle which facilitates the crack inception easily. [15]

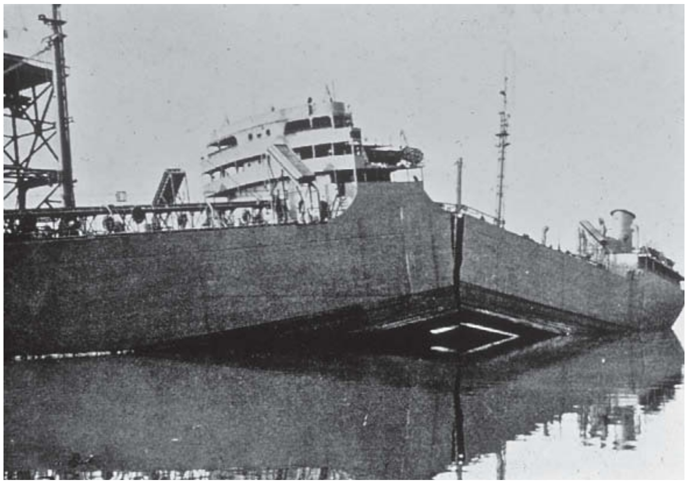


Figure 6: Liberty Ship Damage

Source; *https://metallurgyandmaterials.wordpress.com/2015/12/25/liberty-ship-failures*

The first rule for fatigue verification was introduced in offshore (1987) and in steel ships on 1988 (BV guidance notes) [15]

4.2 Strength of Ship Structures

Adequate strength at reasonable cost is the major concern as far as the owner or the designer is concerned. Classification societies have been providing the necessary standards to ensure adequate strength satisfying the required demands using simple formulations derived from their past experience of good ships. From around 1970, the allowable stress from simple mechanics principle were derived but there were so many uncertainties and assumptions involved so that it cannot be standardized. Recent developments in the field of structural analysis and hydrodynamics provide reliable tools for structural optimization.

Ship responses in a particular sea state can be studied by sea keeping model test experiments. But, there are some practical difficulties because of setting up the arrangement and the cost involved in carrying out the experiments are high. With the advent of recent theories in structural analysis and hydrodynamics, also with the aid of computer programming/software, numerical simulations can be used to obtain accurate and reliable solutions.

Direct Strength Analysis has been used nowadays which takes into account the effects of bending, shear, torsional effects independently and their combinations. This is very useful for larger ships with complex structural arrangements with complex loading conditions.

Following are the major steps involved in the structural analysis,

- Creation of FE structural model,
- Definition of boundary conditions,
- Estimation of loads and transferring to the structural elements,
- FE analysis,
- Extraction of results/report.

4.3 Fatigue

Fatigue damage is one of the major concern in vessels and offshore structures, which are induced by cyclic loading excited by hydrostatic and inertial pressure induced by internal liquids and external sea water, inertial loads resulting from fixed weights subjected to accelerations induced by ship motions, hull girder still water loads and wave induced loads. Major contributing factor is the wave induced loads which is capable of initiating the cracks on specific/detail areas which are not very well designed, constructed and maintained.

The cost for repair and inspection are too high for the crack affected areas. So, fatigue design should be addressed at the initial design stages itself.

The most important parameter is the fluctuating component of stress, known as stress range (refer figure 7), [13]

Mainly there are two different types of fatigue, [13]

- Low cycle fatigue: Occurs due to lesser number of cycles ($< 5 * 10^3$, will be in the range of plastic deformations (beyond the elastic limit),
- High cycle fatigue: Occurs due to larger number of cycles which is within the elastic regime (Generally observed in ship structures).

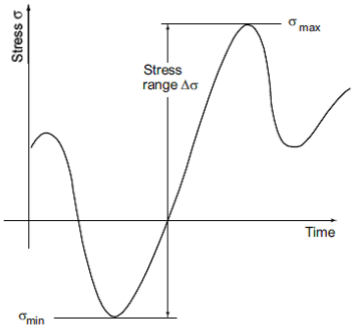


Figure 7: Cyclic Stress Time History

Source; *FATIGUE OF SHIP STRUCTURAL DETAILS, Dr. Dominique Beghin, SNAME, New Jersey*

The fatigue process involves the following three phases for welded structures, [13]

1. Initiation of macro cracks: Cumulative plastic strains will be developed at the tip of micro cracks and which changes the material micro structure results in the growth and coalescence of weld defects and finally induces the formation of macro cracks,
2. Crack growth or propagation: The macro crack grows normal to the direction of the largest principal stress with an average propagation rate of about 10^{-6} to 10^{-3} mm per cycle,
3. Final Failure: Occurs either by Brittle fracture/ Ductile fracture/ Plastic collapse.

4.3.1 *Stresses to be Used*

Fatigue strength assessment of structural details can be addressed based on different kinds of stresses (refer figure 8). Depending upon the type of problem and required level of refinement, following stresses are taken into consideration for the study.

Nominal Stress: The general stress in the structural component, calculated using beam theory based on the applied loads/moments and sectional properties of the member disregarding the structural discontinuities and the presence of welds. Nominal stress can be calculated either using structural mechanics or by coarse mesh FEM analysis.

For stiffener sections the nominal stress is defined as,

$$\sigma_n = \frac{P}{A} + \frac{My}{I} = \sigma_a + \sigma_b \tag{1}$$

σ_a : axial stress (e.g., from hull girder bending)
σ_b : local bending stress

Hotspot Stress: The stress at the hotspot considering the geometric discontinuities excluding the stress concentration induced by the associated welds.

$$\sigma_G = K_G\,\sigma_n \tag{2}$$

σ_G : Hot spot stress
σ_n : Nominal stress
K_G : Stress concentration factor due to geometric discontinuity

Finite element 3D fine mesh is used for the evaluation the hot spot stresses. The nodal displacements/forces obtained from the 3D coarse mesh are applied to the fine mesh model as the boundary conditions.

Notch Stress: Total stress at a notch (weld root), takes into account the geometric discontinuities and presence of welds. Notch stress can be expressed as follows,

$$\sigma_{loc} = K_w \, \sigma_G = K_w \, K_G \, \sigma_n = K_t \, \sigma_n \tag{3}$$

σ_{loc} : Notch Stress

K_t : Total Stress concentration factor considering both geometric discontinuity and weld effects

K_w : Stress concentration factor considering the presence of welds.

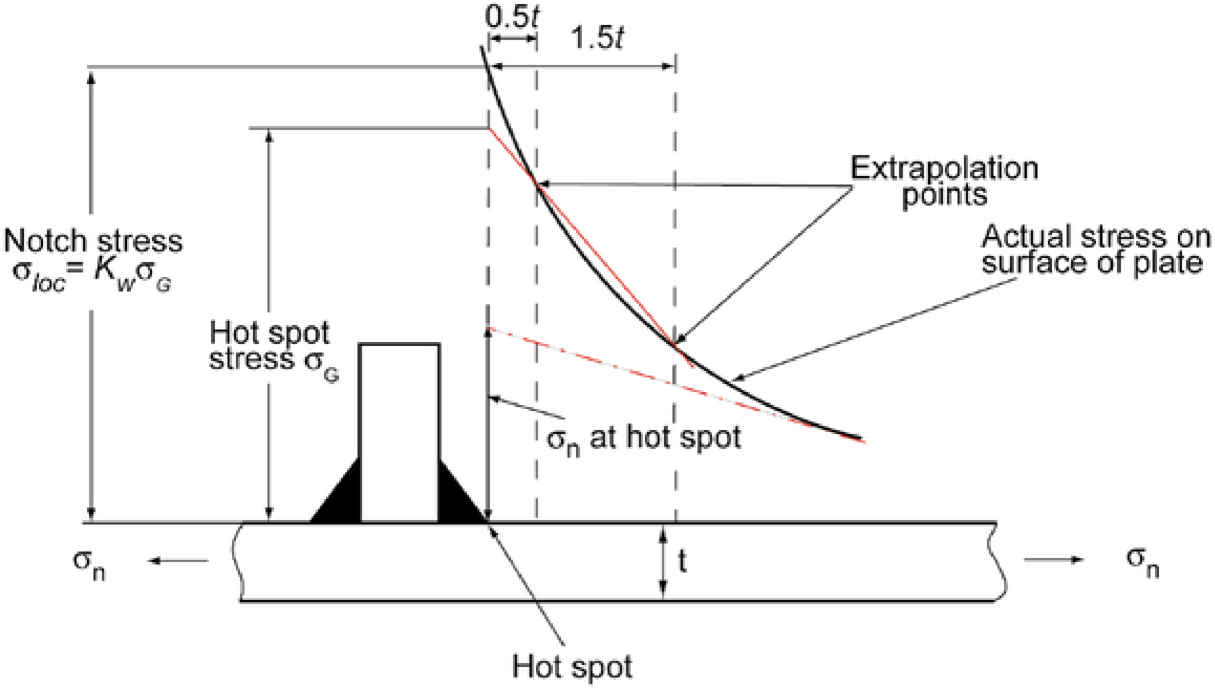
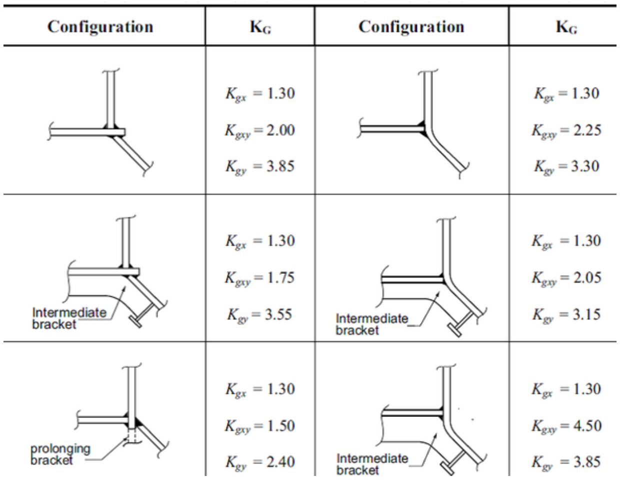


Figure 8: Definition of Stresses (BV)

Source; *FATIGUE OF SHIP STRUCTURAL DETAILS, Dr. Dominique Beghin, SNAME, New Jersey*

4.3.2 *Parametric Formulas*

The stress concentration factors K_G of typical structures details are given by the parametric formulas provided by the classification societies (ex.for knuckle joints, connections b/w secondary stiffeners to web frames etc..)



Configuration	K_G	Configuration	K_G
	$K_{gx} = 1.30$ $K_{gxy} = 2.00$ $K_{gy} = 3.85$		$K_{gx} = 1.30$ $K_{gxy} = 2.25$ $K_{gy} = 3.30$
Intermediate bracket	$K_{gx} = 1.30$ $K_{gxy} = 1.75$ $K_{gy} = 3.55$	Intermediate bracket	$K_{gx} = 1.30$ $K_{gxy} = 2.05$ $K_{gy} = 3.15$
prolonging bracket	$K_{gx} = 1.30$ $K_{gxy} = 1.50$ $K_{gy} = 2.40$	Intermediate bracket	$K_{gx} = 1.30$ $K_{gxy} = 4.50$ $K_{gy} = 3.85$

Figure 9: Geometric SCF

Source; *FATIGUE OF SHIP STRUCTURAL DETAILS, Dr. Dominique Beghin, SNAME, New Jersey*

The above table from Bureau Veritas (1998) gives the geometric stress concentration factor (K_G) longitudinal and transverse directions for two basic designs of the double bottom structure in way of hopper tanks.

4.3.3 *Fatigue Damage Models*

For a welded ship, fatigue strength assessment can be evaluated using below approaches,

Stress-based approach: The cyclic stresses considering the stress concentration factor are assumed to be below the yield strength of the material. [14]

Strain-based approach: Plastic deformations are considered in some localized areas where the stresses are beyond the yield strength of the material where the probability of fatigue crack initiation is maximum. [14]

Fracture Mechanics: The fatigue strength of welded joints is expressed in the terms of the relationship between the stress intensity factor and the rate of crack growth, [14]

$$\frac{da}{dN} = C(\Delta K)^m \tag{4}$$

da/dN : crack growth rate
ΔK : stress intensity range
C, m : crack growth parameters.

In this thesis work, cumulative fatigue damage evaluation has been carried out based on stress-based approach.

4.3.4 *Generalized Procedure for the Assessment of Fatigue Strength*

Procedures for the assessment of fatigue strength is different for each classification societies, but the below common steps were followed,

- Calculation and application of loads,
- Evaluation of Stress Range for different loading conditions (predominantly for Fully-loaded and Ballast conditions),
- Determination of fatigue damage of welded joints,
- Calculation of Fatigue life.

For the assessment of fatigue damage, the stress variation for a long span of time has to be determined which is dictated by the long term load history. Most significant loads are enumerated as follows, [13]

- Still water loads (for example, cargo loads that vary from voyage to voyage),
- Transient loads such as thermal stresses,
- Wave-induced loads, directly generated by the action of waves,
- Vibratory loads resulting from main engine or propeller induced vibratory forces,
- Impact loads such as bottom slamming, bow flare impact (whipping), sloshing, and shipping of green seas,

- Residual stresses.

In this thesis work, fatigue damage evaluation is carried out for the stress range corresponding to maximum and minimum bending moments in Fully-Loaded (Sagging) and Ballast (Hogging) conditions.

4.3.5 *Different Methods for the Evaluation of Long-term Distribution of Stress Range*

The most contributing load which affects the fatigue strength of welded structural joints in a ship is the wave-induced load which induces alternative sagging and hogging moments thereby developing repetitive tensile and compressive stresses on critical areas and welded joints resulting in the fatigue damage and final fracture/deformation of structural elements.

Generally, following methods have been employed to estimate the long term distribution of stress range to evaluate the cumulative fatigue damage [13],[16],[17]

- Spectral Method,
- Equivalent Design Wave method (EDW),
- Simplified Method.

In this thesis work, the simplified approach (Deterministic method) has been adopted to carryout the study. Detailed explanation about the application of this method has been presented later in the report. However, a concise description has been provided about the first two methods in subsequent headings.

4.3.6 *Spectral Fatigue Analysis*

Direct evaluation of long term distribution of stresses by conducting direct ship motion and load analysis using hydrodynamic tools. Following steps have to be carried out. [13]

- Determination of transfer function (load RAOs) for regular wave of unit amplitude for a range of wave period, heading angle and vessel speed (Encounter Spectra),

- Determination of response spectra from each encounter spectra,

  The wave spectrum is represented by two parameters Hs (Significant wave height) and Tp (Peak time period),

- Determination of short term structural response for different sea states,heading angles and speeds,

- Construction of Long-term distribution of stress range giving the probability $P(S_0)$ of the stress range exceeding a specified value S_0.

The probability density function can be represented by Rayleigh distribution,

$$P(S) = \frac{S}{4\mu^2} e^{-\frac{S^2}{8\mu^2}} \tag{5}$$

The loads/stress evaluation are conventionally limited to fully loaded and ballast loading conditions.

4.3.7 *Equivalent Regular Wave Concept*

Equivalent Design Wave (EDW) is a design wave which represents the long-term response of the load parameter. In this method, a rule based formula is used to calculate the wave induced load effects from an equivalent to design waves (EDW) effect. The main load wave induced load effects contributing to the fatigue damage are,

1. Vertical wave bending moment,
2. Horizontal wave bending moment,
3. Wave torsional moment, where applicable,
4. External sea pressures, especially near the waterline,
5. Internal pressures.

For each of these affects an equivalent regular wave, defined by its wave height, wave length, heading angle and position along the ship length, is determined so that the maximum response for the selected load effect be equal to its value given by the rules for the probability of exceedance considered. The amplitude of the other effects is obtained from a ship motion analysis assuming the ship to be positioned on the equivalent regular wave.

4.3.8 *Simplified Method for Fatigue Analysis (Deterministic Method)*

Classification societies have developed a simplified procedure for the calculation of loads/stresses and corresponding stress range. Severe dynamic effects are considered for the evaluation of stress cycles which makes the simplified method conservative and also as the name suggests, it is easy to implement.

Simplified/Deterministic method proposed by Bureau Veritas has been implemented to carryout the thesis work,

As the scope of this work includes the fatigue life evaluation for vessel navigating in inland waters, the amplitude of wave she encounters is considerably smaller when compared to the sea-going vessels.

Following load components has been considered for the study,

- Hull girder loads (Rule still water/wave bending moments),
- External sea pressures (Hydrostatic and Wave induced Loads),
- Internal inertial and fluctuating loads (Cargo/Ballast Loads).

The resultant long-term distribution of stresses are based on (hull-girder+local bending stresses) are based on a two parameter Weibull distribution.

For this distribution, the probability density function is mathematically defined as follows, [13]

$$P_s(S) = \frac{\xi}{w}\left(\frac{S}{w}\right)^{(\xi-1)} e^{-\left(\frac{S}{w}\right)^{\xi}} \tag{6}$$

S : Stress Range

$P_s(S)$: Probability Density Function

ξ : Weibull shape parameter

w : Characteristic value of the distribution

The above probability density function is graphically represented for different shape factors as follows,

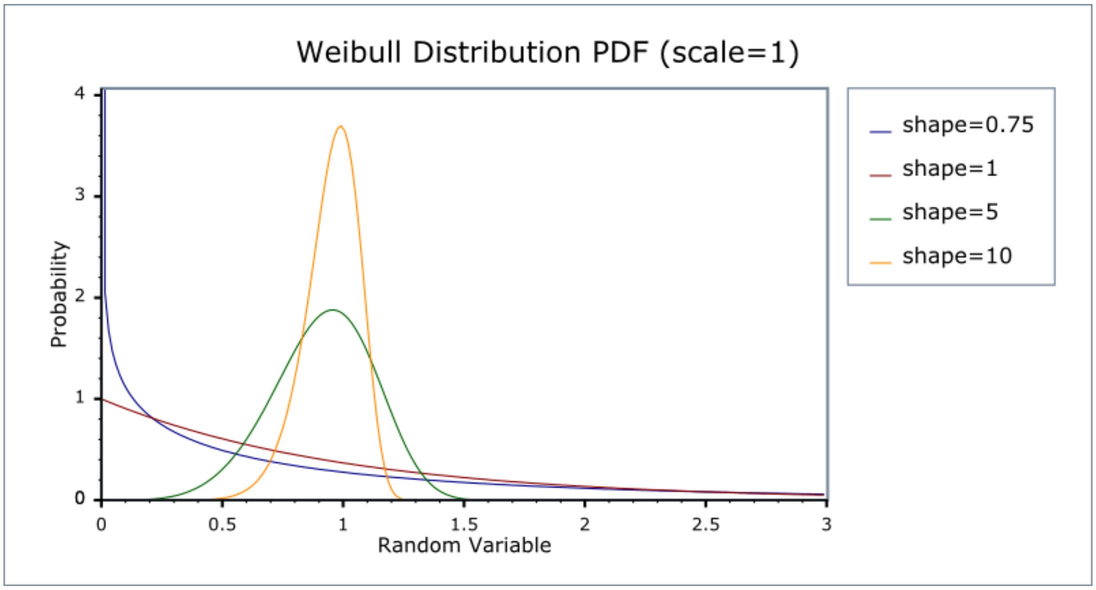


Figure 10: Weibull PDF

Source; *http://www.itl.nist.gov/div898/handbook/eda/section3/eda3668.htm*

Integrating equation 6 gives the cumulative distribution function derived as follows,

$$P(S) = \int_{0}^{S} P_s(S)\, ds = 1 - e^{-\left(\frac{S}{w}\right)^{\xi}} \tag{7}$$

where P(S) gives the probability that a stress range of magnitude S will not be exceeded. Now, the probability of exceedance of a given stress range S_0 is given by,

$$P(S > S_0) = 1 - P(S_0) = e^{-\left(\frac{S_0}{w}\right)^{\xi}} \tag{8}$$

Structural analysis is carried out for a given probability of exceedance, if S_0 is the maximum value of stress occurring once in a life time of N_0 wave encounters (Stress reversals), equation 8 becomes,

$$P(S > S_0) = e^{-\left(\frac{S_0}{w}\right)^{\xi}} = \frac{1}{N_0} \tag{9}$$

Extracting w from above equation,

$$w = S_0(lnN_0)^{-\left(\frac{1}{\xi}\right)} \tag{10}$$

Substituting equation 10 on equation 7, the expression of cumulative distribution function becomes,

$$P(S) = 1 - e^{-\left(\frac{S}{w}\right)^{\xi}} = 1 - e^{-lnN_0\left(\frac{S}{S_0}\right)^{\xi}} \tag{11}$$

4.3.9 *Fatigue Strength Calculation Based on S-N curve*

S-N curve is one of the way to determine the fatigue capacity of welded structural joints. S-N curves gives the relationship between the stress range and number of constant amplitude load cycles to failure (Fatigue Life). [13]

S-N curves are given for welded joints and flame-cut edges. [13]

Most of the S-N curves are determined in laboratories where specimens are subjected to constant amplitude cyclic loadings until failure (refer figure 11). The main parameters that influence the fatigue life of specimens are,

- The stress range $S = \sigma_{max} - \sigma_{min}$,
- The stress ratio $R = \frac{\sigma_{max}}{\sigma_{min}}$, Fatigue tests are generally performed at a constant stress ratio R lying between 0 and 0.1. The mean stress is given by,

$$\sigma_{mean} = \frac{1+R}{1-R}\frac{S}{2} \tag{12}$$

- The geometric and weld stress concentrations,
- The direction of fluctuating stresses,
- The residual stresses and welding procedures.

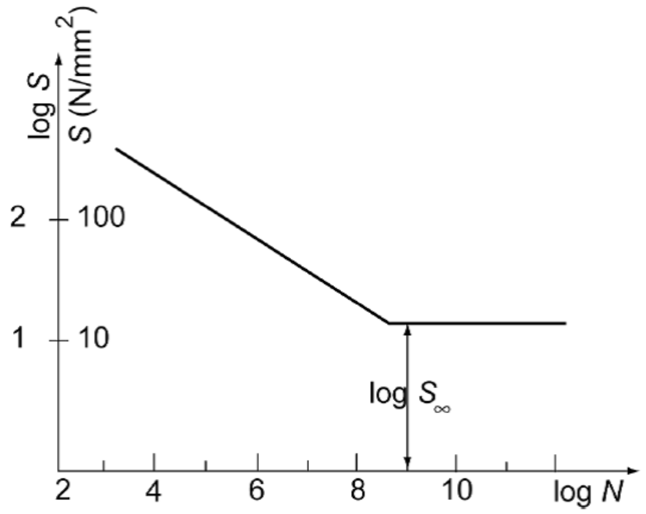


Figure 11: S-N Curve(Typical)

Source; *FATIGUE OF SHIP STRUCTURAL DETAILS, Dr. Dominique Beghin, SNAME, New Jersey*

If the stress range is below the threshold level S_∞, the fatigue life is infinite. But, for randomly loaded structures, the fatigue limit does not exist. S-N curves vary with respect to the location of detail, weld geometry etc..

4.3.10 *Palmgren and Miner Rule*

The fatigue strength is expressed in term of the cumulative damage ratio ”D” by Palmgren and Miner rule. [17]

According to this rule, the total fatigue damage can be evaluated by the following expression, [17]

$$D = \sum_{i}^{J} \frac{n_i}{N_i} \tag{13}$$

j : Number of different stress levels

N_i : Average number of cycle to failure (for a particular stress range S_i)

n_i : Number of cycles at stress range S_i

The structure is considered to be failed if the damage ratio is greater than unity (also, close to unity). The maximum allowable damage ratio should be below unity, [17]

Considering the partial safety factor γ,

$$D = \sum_{i}^{J} \frac{n_i}{N_i} \leq \frac{1}{\gamma} \tag{14}$$

Though there are different loading conditions which the vessel encounters, mainly full load and ballast conditions are only considered during the evaluation of fatigue damage/strength.

Taking into consideration both the loading conditions, the total fatigue damage is given by, [17]

$$D = \alpha D_f + \beta D'_f \tag{15}$$

D_f : cumulative damage ratio in full load condition

D'_f : cumulative damage ratio in ballast condition

α : ships life in full load condition

β : ships life in ballast condition

The number of cycle to failure (N: Fatigue life) can be obtained by the S-N curve which is discussed in the previous section.

There are various S-N curves published by many institutions such as IIW, HSE UK, AWS. But mainly IIW S-N curves, HSE S-N curves (refer figure 12) have been used by the classification societies,

Using the miners rule and S-N curve data, fatigue life of a structural location can be evaluated. Following gives the relation between the stress range and number of cycles to failure(N). [13]

$$m \log S + \log N = \log K \tag{16}$$

S : Nominal Stress Range

N : Number of cycles to failure

K, m : Constants depending upon the welded connection

As explained previously, three types of stresses namely nominal stress, hotspot stress, notch stress can be used for fatigue calculations, the selection depends upon the level of refinement of the mesh in FE analysis.

For this study, the hotspot and notch stresses has been evaluated using the stress concentration factors recommended by the classification society.

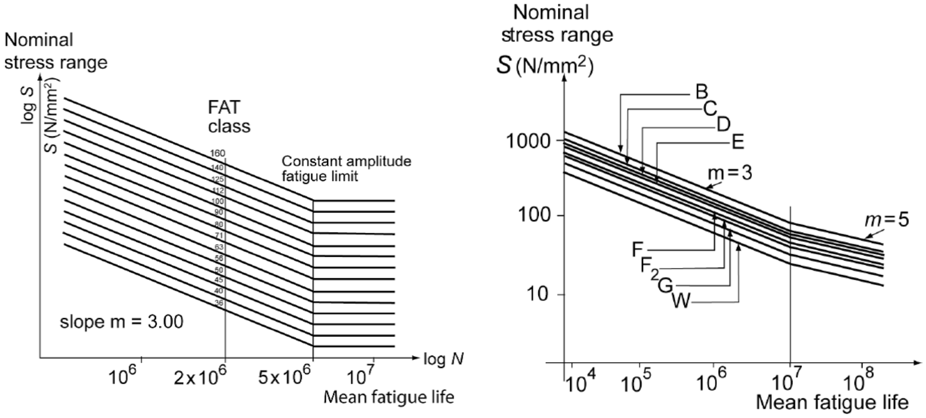


Figure 12: IIW and HSE S-N Curves

Source; *FATIGUE OF SHIP STRUCTURAL DETAILS, Dr. Dominique Beghin, SNAME, New Jersey*

4.3.11 *Evaluation of Cumulative Damage*

According to Palmgren and Miner rule, the total fatigue damage can be evaluated using following equation,

$$D = \sum_{i}^{J} \frac{n_i}{N_i} \tag{17}$$

In integral form the above equation can be written as,

$$D_{fat} = \int_{0}^{\infty} \frac{N_0 \, P_s(S)}{N(S)} \, dS \tag{18}$$

N_0 : Total number of encountered waves/Stress cycles

$P_s(S)$: Probability density function

$N(S)$: Number of constant amplitude cycles to failure (from S-N Curves)

The number of cycles corresponding to a particular stress range S can be written as N_0 P$_s(S)$ dS. Also, the S-N curve can be expressed in the exponential form as N=KS^{-m} (refer equation 16). Substituting in equation 18,

$$D_{fat} = \frac{N_0}{K} \int_{0}^{\infty} S^m P_s(S) \, dS \tag{19}$$

Recalling the equation of probability density function for Weibull distribution,

$$P_s(S) = \frac{\xi}{w} \left(\frac{S}{w}\right)^{(\xi-1)} e^{-\left(\frac{S}{w}\right)^{\xi}} \tag{20}$$

Combining equation 19 and equation 20 yields,

$$D_{fat} = \frac{N_0}{K} \int_{0}^{\infty} S^m \frac{\xi}{w} \left(\frac{S}{w}\right)^{(\xi-1)} e^{-\left(\frac{S}{w}\right)^{\xi}} \, dS \tag{21}$$

Simplifying the above equation by introducing a factor x defined as,

$$x = \left(\frac{S}{w}\right)^{\xi} \tag{22}$$

Equation 21 becomes,

$$D_{fat} = \frac{N_0}{K} w^m \int_0^\infty x^{(1+\frac{m}{\xi})} e^{-x}\, dx \tag{23}$$

The gamma function can be defined as follows,

$$\Gamma_k = \int_0^\infty e^{-x} x^{k-1}\, dx \tag{24}$$

Inserting gamma function on 23 yields the equation for the evaluation of fatigue damage,

$$D_{fat} = \frac{N_0}{K}\, w^m\, \Gamma\left(1 + \frac{m}{\xi}\right) \tag{25}$$

$$w = S_0\, (lnN_0)^{-\left(\frac{1}{\xi}\right)} \tag{26}$$

The final expression for the cumulative damage evaluation is as follows,

$$D_{fat} = \frac{N_0}{K} \left(\frac{S_0^{\xi}}{lnN_0}\right)^{\frac{m}{\xi}} \Gamma\left(1 + \frac{m}{\xi}\right) \tag{27}$$

where,

N_0 : Total number of encountered waves/Stress cycles

S_0 : Expected maximum Stress Range in N_0 cycles

K, m : Constants depending upon the welded connection

ξ : Weibull Shape Factor

Γ : Gamma Function

Uncertainties in Fatigue Strength Prediction

Numerous uncertainties associated with the evaluation of fatigue strength are due to the probabilistic approaches in the evaluation of stresses associated with wave loading, Human Factors, S-N curves etc.

5 SOFTWARE TOOLS

5.1 Mars Inland

MARS Inland software is capable of performing scantling calculations of platings and ordinary stiffeners for any transversal section along the vessel.

There are three modules in the main screen of the graphical user interface (GUI) :

- Basic Ship Data,
- Edit,
- Rule.

In Basic Ship Data (BSD) module, the main particulars of the vessel are defined. This module is divided into seven subsections as follows,

1. General,
2. Notations & Main Data,
3. Moment & Draughts,
4. Bow Flare,
5. Materials,
6. Frame Locations,
7. Calculations & Print.

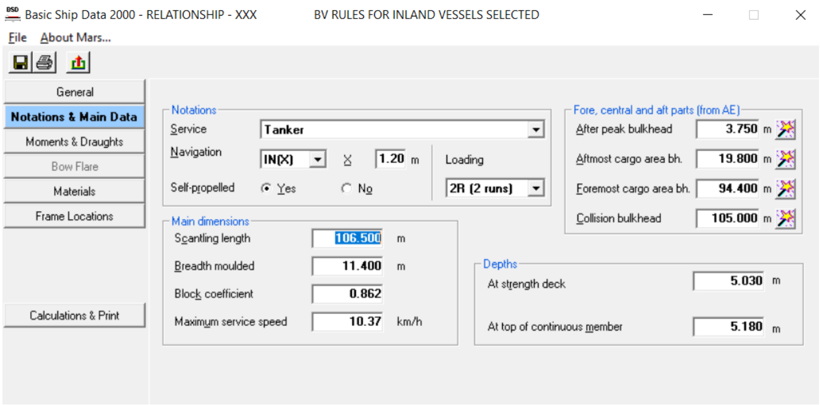
Each subsection has been explained below,

General

In this tab, general details about the vessel (name of the vessel, builder etc...) have been provided.

Notations & Main Data

Dimensional details, Service speed of the vessel, navigational notations have been specified here (refer figure 13).



Notations

Service: Tanker

Navigation: IN(X) X 1.20 m

Loading: 2R (2 runs)

Self-propelled: ● Yes ○ No

Main dimensions

Scantling length: 106.500 m

Breadth moulded: 11.400 m

Block coefficient: 0.862

Maximum service speed: 10.37 km/h

Fore, central and aft parts (from AE)

After peak bulkhead: 3.750 m

Aftmost cargo area bh.: 19.800 m

Foremost cargo area bh.: 94.400 m

Collision bulkhead: 105.000 m

Depths

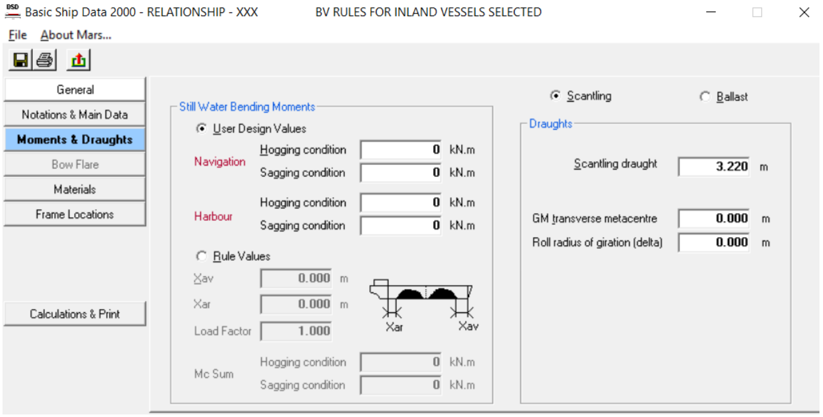
At strength deck: 5.030 m

At top of continuous member: 5.180 m

Figure 13: Notations & Main Data

Moments & Draughts

In this tab, Bending moments in hogging and sagging conditions can be provided as the user design values or else, the rule values will computed based on the provided details (refer figure 14). In this particular case, the moments have been calculated based on the rules. For that, the scantling draft has to be provided as an input parameter.



● Scantling ○ Ballast

Still Water Bending Moments

● User Design Values

Navigation: Hogging condition 0 kN.m; Sagging condition 0 kN.m

Harbour: Hogging condition 0 kN.m; Sagging condition 0 kN.m

○ Rule Values

Xav: 0.000 m

Xar: 0.000 m

Load Factor: 1.000

Mc Sum: Hogging condition 0 kN.m; Sagging condition 0 kN.m

Draughts

Scantling draught: 3.220 m

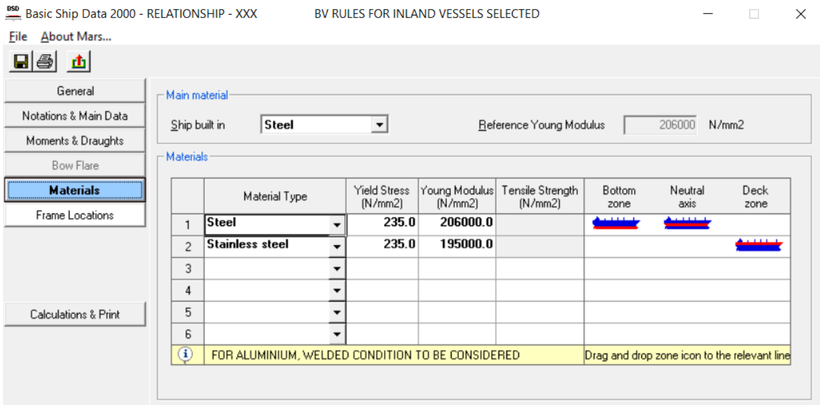
GM transverse metacentre: 0.000 m

Roll radius of giration (delta): 0.000 m

Figure 14: Moments & Draughts

Materials

The type/grade of material used for construction has been specified in this section (refer figure 15)



Ship built in: Steel

Reference Young Modulus: 206000 N/mm2

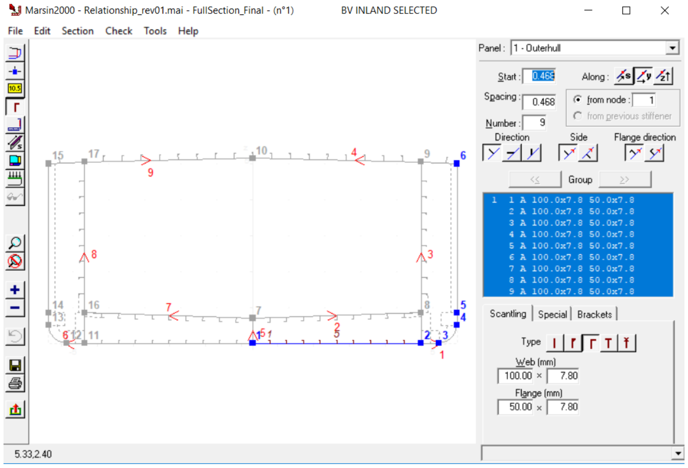
	Material Type	Yield Stress (N/mm2)	Young Modulus (N/mm2)	Tensile Strength (N/mm2)	Bottom zone	Neutral axis	Deck zone
1	Steel	235.0	206000.0				
2	Stainless steel	235.0	195000.0				
3							
4							
5							
6							
ⓘ	FOR ALUMINIUM, WELDED CONDITION TO BE CONSIDERED				Drag and drop zone icon to the relevant line		

Figure 15: Materials

Stainless steel material type has been selected for the deck zone.

Once the basic data has been specified, the next step is the modelling of section using the Edit module (refer figure 16). Since the structural members/plating do not have the same value of thickness in PS and SB sides, full section has to be modelled and evaluated.

Panels and nodes have been used to create the geometry of the section. Then, the dimensions of longitudinal and transverse stiffeners, thickness of the plates/strakes and also the compartments have been defined on the model. As previously mentioned, the measured thickness values have been given as the input values (instead of the gross values). The strength check has been carried out based on the net scantling approach.



Panel : 1 - Outerhull

Start : 0.468

Spacing : 0.468

Number : 9

● from node : 1

○ from previous stiffener

```
1  1 A 100.0x7.8 50.0x7.8
   2 A 100.0x7.8 50.0x7.8
   3 A 100.0x7.8 50.0x7.8
   4 A 100.0x7.8 50.0x7.8
   5 A 100.0x7.8 50.0x7.8
   6 A 100.0x7.8 50.0x7.8
   7 A 100.0x7.8 50.0x7.8
   8 A 100.0x7.8 50.0x7.8
   9 A 100.0x7.8 50.0x7.8
```

Web (mm): 100.00 × 7.80

Flange (mm): 50.00 × 7.80

Figure 16: Modelling in MarsInland

5.2 FEMAP/NX NASTRAN

FEMAP is one of the most popular and advanced software for the development of a finite element model. Most of the pre-processing jobs can carried out using FEMAP. Also, it can be used as simulation tool to visualize displacements and deformations. Besides, FEMAP is integrated with API programming and enables Macro program files.

NX-NASTRAN is integrated with FEMAP for post-processing jobs and to extract the results.

6 STRUCTURAL ANALYSIS

6.1 Overview

Strength check has been carried out based on the BV rules using the in house tool, MarsInland. The defined scantlings have been checked against all the associated BV rule requirements and criteria, which have been already incorporated in the tool. The main particulars and structural details of the vessel are provided in section 2; VESSEL UNDER INVESTIGATION.

Scantling check of plating and secondary supporting members (ordinary stiffeners) have been carried out based on the below BV rules (using MarsInland tool),

- NR 217.B1 DNI R04 E, PART B - Hull Design and Construction,
- NR 217.D1 DNI R04 E,PART D - Additional Requirements for Notations.

The strength check of primary supporting members (like Longitudinal Girders), Transversals and other critical areas have been done using direct calculation techniques, FEMAP/NX NASTRAN software.

6.2 Limit States

The serviceability limit states adopted for the hull structure (hull girder, primary supporting members, plating, and ordinary stiffeners) are summarized in Table 10.

Table 10: Serviceability limit states

	Yielding	Plate strength under lateral loads	Buckling
Hull girder	x		
Primary supporting members	x		x
Plating		x	x
Stiffener	x		x

6.3 Design Loads

For the study, following design loads have been evaluated using BV rules. [19]

6.3.1 *Hull Girder Loads*

Hull girder loads are still water and wave forces and moments which result as effects of local loads acting on the vessel as a whole and considered as a beam.

Still water Bending Moments

The still water bending moment depends upon the loading cases (Navigation/Harbor and Fully Loaded/Ballast). Classification society rules explicitly provides formulations for the evaluation of still water bending moment values depending upon the above load cases.

Wave Bending Moments

An additional bending moment induced due to the waves has to be taken into to account for the evaluation of total bending moment. This component depends upon the range of navigation of the vessel.

The range of navigation of the vessel under investigation is IN(1.2).

Based on BV rules, for range of navigation IN(0,6 < x ≤ 2), the absolute value of the wave-induced bending moment amidships is obtained, (in kN.m), from the following formula,

$$M_W = 0,021\, n\, C\, L^2\, B\, (C_B + 0.7) \tag{28}$$

M_W : Vertical wave bending moment
n : Navigation coefficient
C : Wave parameter
L : Rule Length of the vessel
B : Breadth of the vessel
C_B : Block Coefficient

Using the above rule formulations, the absolute values of design still water and wave bending moment values of the vessel has been computed and tabulated as follows,

Table 11: Design Still water and Wave bending moments

	Hogging (kNm)	**Sagging (kNm)**
Design S.W.B.M. - Navigation condition	43 172	52 947
Design S.W.B.M. - Harbour condition	45 976	58 163
Design Vertical Wave Bending Moment	34 862	34 862

Total Vertical Bending Moments

The total vertical bending moments at any hull girder transverse section is determined as specified in Table 12, considering the limit states.

F_{MT} represents the distribution factor along the length of the vessel (refer figure 17),

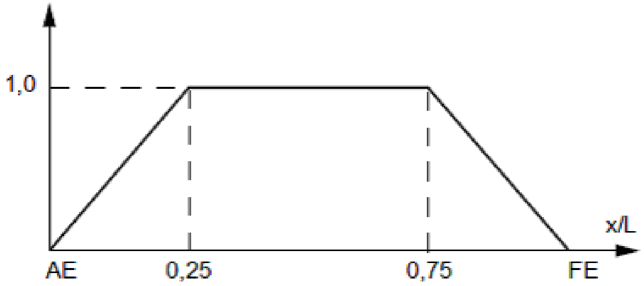


Figure 17: Distribution factor F_{MT}

Source; *Bureau Veritas, NR 217, Part B, Ch 3, Sec 2, Figure 2*

Table 12: Total vertical bending moments

Load case	**Limit state**	**Hogging**	**Sagging**
Navigation	Hull girder yielding	$M_{TH} = F_{MT}(M_H + M_W)$	$M_{TS} = F_{MT}(M_S + M_W)$
	Other limit states	$M_{TH} = F_{MT}(M_H + \gamma_W M_W)$	$M_{TS} = F_{MT}(M_S + \gamma_W M_W)$
Harbour	All limit states	$M_{TH} = F_{MT} M_H$	$M_{TS} = F_{MT} M_S$

Source; *Bureau Veritas, NR 217, Part B, Ch 3, Sec 2, Table 8*

γ_W : safety factor, taken equal to:

$\gamma_W = 1.00$ for $H_S = 0.6$

$\gamma_W = 0.625\ \gamma_{W1}$ for $H_S > 0.6$

Since Midship section is under consideration, the value of F_{MT} is 1.

6.3.2 *Local Loads*

Local loads are pressures and forces which are directly applied to the individual structural members: plating panels, ordinary stiffeners and primary supporting members.

Still water local loads are constituted by the hydrostatic external river pressures (Figure 18) and the static pressures and forces induced by the weights carried in the vessel spaces.

Wave local loads are constituted by the external river pressures due to waves (Figure 19) and the inertial pressures and forces induced by the vessel accelerations applied to the weights carried in the vessel spaces.

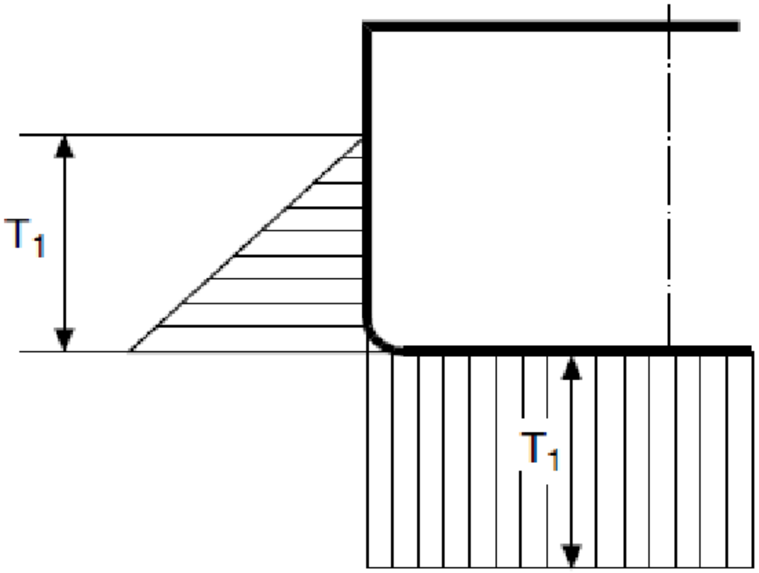


Figure 18: River still water pressure

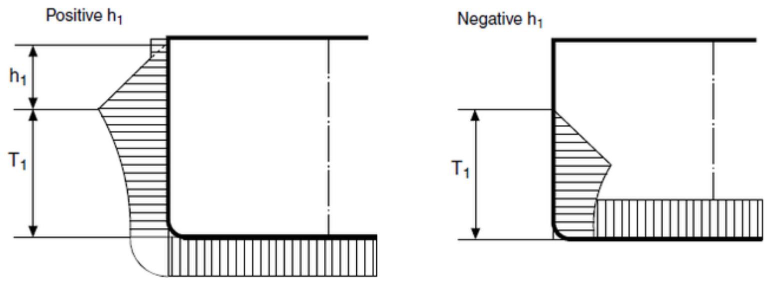


Figure 19: River wave pressure

Source; *Bureau Veritas, NR 217, Part B, Ch 3, Sec 4*

The local loads have been evaluated for two loading conditions - Fully Loaded and Lightship, defined by the loading coefficient (refer table 13) as follows,

Table 13: Values of loading coefficient γ

Load Case	**Loading Condition**	γ	
		River Counter Pressure	**River Design Pressure**
Harbour	1R and Nonhomload	0,150	1,000
	2R	0,575	0,575
Navigation	Full load	1,000	1,000
	Lightship	0,150	0,150

Source; *Bureau Veritas, NR 217, Part B, Ch 3, Sec 4, Table 1*

6.4 Partial Safety Factors

Partial safety factors has been considered based on rule formulations to account for uncertainties[19],

The partial safety factors for plating and ordinary stiffeners are provided in tables 14 and 15

- γ_{W1} : Partial safety factor covering the uncertainties regarding wave hull girder loads
- γ_{W2} : Partial safety factor covering the uncertainties regarding wave local loads
- γ_m : Partial safety factor covering the uncertainties regarding material
- γ_R : Partial safety factor covering the uncertainties regarding resistance

Table 14: Plating-Partial safety factors

Limit state	**Condition**	γ_{w1}	γ_{w2}	γ_{wR}	γ_{wm}
Strength check of plating subjected to lateral pressure	General	1.15	1.2	1.2	1.02
	Flooding (1)	NA	NA	1.05 (2)	1.02
	Testing	NA	NA	1.05	1.02
Buckling check		1.15	NA	1.1	1.02

(1) Applies only to plating to be checked in flooding conditions
(2) For plating of the collision bulkhead,γ_R = 1.25

Note 1: NA not applicable

Table 15: Ordinary Stiffeners-Partial Safety factors

Limit state	**Condition**	γ_{w1}	γ_{w2}	γ_R	γ_m
Yielding Check	General	1.15	1.2	1.02	1.02
	Flooding (1)	NA	NA	1.02 (2)	1.02
	Testing	NA	NA	1.02	1.02
Buckling check		1.15	1.2	1.1	1.02

(1) Applies only to Ordinary stiffeners to be checked in flooding conditions

(2) For ordinary stiffeners of the collision bulkhead,γ_R=1.25

Note 1: NA not applicable

Source; *Bureau Veritas, NR 217, Part B, Ch 5, Sec 1, Table 1/2*

6.5 Net Scantling Approach

All the scantlings obtained from BV rules (NR 217, Part B, Chapter 5) are net values i.e excluding the margin for corrosion.

The net scantlings were evaluated from the measured scantlings by deducting the corrosion margin defined in the following rule note,

- BV NR 597 DNI R01 E, Requirements for Thickness Measurements Applicable to Inland Navigation Vessels.

Table 16: Corrosion additions according to BV Rules

Compartment type		Corrosion addition (1)
Ballast tank		1.00
Cargo tank and fuel oil tank	Plating of horizontal surfaces	0.75
	Plating of non-horizontal surfaces	0.50
	Ordinary stiffeners and primary supporting members	0.75
Dry bulk cargo hold	General	1.00
	Inner bottom plating Side plating for single hull vessel Inner side plating for double hull vessel Transverse bulkhead plating	1.75
	Frames, ordinary stiffeners and primary supporting members	1.00
Hopper well of dredging vessels		2.00
Accommodation space		0.00
Compartments and areas other than those mentioned above		0.50
(1) Corrosion additions are applicable to all members of the considered item.		

The corrosion addition for each of the two sides of a structural member is t_{C1} or t_{C2}. The total corrosion addition t_C, in mm, for both sides of a structural member, is equal to: [20]

- for a plating with a gross thickness greater than 10 mm:
  $t_C = t_{C1} + t_{C2}$

- for a plating with a gross thickness less than or equal to 10 mm:

  t_C = 20% of the gross thickness of the plating, or $t_C = t_{C1} + t_{C2}$, whichever is smaller

For an internal member within a given compartment, the total corrosion addition t_C is to be determined as follows:

- for a plating with a gross thickness greater than 10 mm:

  $t_C = 2\,t_{C1}$
- for a plating with a gross thickness less than or equal to 10 mm:

  t_C = 20% of the gross thickness of the plating, or $t_C = 2\,t_{C1}$, whichever is smaller

The corrosion additions for the structural members of the different compartments are specified in rules (refer table 16).

The net section modulus of bulb profiles are obtained from the following formula:

$$w = w_G\,(1 - \alpha\, t_C) - \beta\, t_C \tag{29}$$

where

w_G : Stiffener gross section modulus, in cm^3

w_G : Coefficients defined in Table 17.

Table 17: Coefficients α and β for bulb profiles

Range of w_G	α	β
$w_G \leq 200\,cm^3$	0.070	0.4
$w_G > 200\,cm^3$	0.035	7.4

The above criteria have been applied to evaluate the net scantlings from the measured thickness values.

Remark : Here the term ”net scantlings*” refers to those thickness values obtained by deducting the corrosion allowance (defined in Table 16) from the measured UT values, not from the Gross/As-built thickness values.

For Tank No 4 (PS and SB) in the midship section, net scantlings for platings are provided in Table 18 and Table 19.

Table 18: Net Scantlings of Platings (SB)

NET THICKNESS FROM UT MEASUREMENTS - AMIDSHIPS (STARBOARD SIDE)					
TANK NO 4 ; Frame No's 17-22					
SL NO	**Item**	**Thickness(mm)**		**Corrosion Addition(mm)**	**Net scantlings***
		Gross	**Measured**		
1	Sheerstrake	25	24.9	1.00+0.5 = 1.5	**23.4**
2	Stringer Plate	15	14.9	1.00+0.5 = 1.5	**13.4**
3	Bilge Plate	13	10.6	1.00+0.5 = 1.5	**9.1**
4	Web Frames bottom	12	10.6	1.00+1.00 = 2	**8.6**
5	Keel and Bottom Plates	10	9.5	MIN (1.00+0.5 ; 0.20*t)=1.5	**8.0**
6	Sideshell plate	10	8.4	MIN (1.00+0.5 ; 0.20*t)=1.5	**6.9**
7	CL Girder	8	7.8	MIN (1.00+1.00 ; 0.20*t)=1.56	**6.2**
8	Side Girders	8	7.8	MIN (1.00+1.00 ; 0.20*t)=1.56	**6.2**
9	Bottom Vertical Stringer	8	7.0	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.6**
10	Web Frames sides	9	8.4	MIN (1.00+1.00 ; 0.20*t)=1.7	**6.8**
11	Web Frames bottom(Bkhds)	8	7.0	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.6**
12	Side Vertical Stringer	10	9.4	MIN (1.00+1.00 ; 0.20*t)=1.87	**7.5**
13	Side Horizontal Stringers	8	7.5	MIN (1.00+1.00 ; 0.20*t)=1.5	**6.0**
14	Midsection Bilge Plate	8	7.0	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.6**
15	Midsection Bilge Plate Flange	8	7.0	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.6**
16	Intermediate bilge plate	10	8.8	MIN (1.00+1.00 ; 0.20*t)=1.76	**7.0**
17	Intermediate Bilge Plate Flange	8	7.0	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.6**
18	Gording Plate on Bulkhead (Bottom)	10	8.8	MIN (1.00+1.00 ; 0.20*t)=1.76	**7.0**
19	Watertight Webframe Stringer	10	9.4	MIN (1.00+1.00 ; 0.20*t)=1.87	**7.5**
20	Deck Plating	8	8.0	NA(Stainless Steel)	**8.0**
21	Innerside plating	8	8.0	NA(Stainless Steel)	**8.0**
22	Inner bottom plating	8	8.0	NA(Stainless Steel)	**8.0**

Table 19: Net Scantlings of Platings (PS)

NET THICKNESS FROM UT MEASUREMENTS - AMIDSHIPS (PORT SIDE)					
TANK NO 4 ; Frame No's 17-22					
SL NO	**Item**	**Thickness(mm)**		**Corrosion Addition(mm)**	**Net scantlings***
		Gross	**Measured**		
1	Sheerstrake	25	24.8	1.00+0.5 = 1.5	**23.3**
2	Stringer Plate	15	15.0	1.00+0.5 = 1.5	**13.5**
3	Bilge Plate	13	11.6	1.00+0.5 = 1.5	**10.1**
4	Web Frames bottom	12	10.8	1.00+1.00 = 2	**8.8**
5	Keel and Bottom Plates	10	8.0	MIN (1.00+0.5 ; 0.20*t)=1.5	**6.5**
6	Sideshell plate	10	8.4	MIN (1.00+0.5 ; 0.20*t)=1.5	**6.9**
7	CL Girder	8	7.8	MIN (1.00+1.00 ; 0.20*t)=1.56	**6.2**
8	Side Girders	8	7.8	MIN (1.00+1.00 ; 0.20*t)=1.56	**6.2**
9	Bottom Vertical Stringer	8	7.2	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.8**
10	Web Frames sides	9	8.4	MIN (1.00+1.00 ; 0.20*t)=1.7	**6.8**
11	Web Frames bottom(Bkhds)	8	7.2	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.8**
12	Side vertical Stringer	10	9.4	MIN (1.00+1.00 ; 0.20*t)=1.87	**7.5**
13	Side Horizontal Stringers	8	7.5	MIN (1.00+1.00 ; 0.20*t)=1.5	**6.0**
14	Midsection Bilge Plate	8	7.2	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.8**
15	Midsection Bilge Plate Flange	8	7.2	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.8**
16	Intermediate bilge plate	10	9.0	MIN (1.00+1.00 ; 0.20*t)=1.76	**7.2**
17	Intermediate Bilge Plate Flange	8	7.2	MIN (1.00+1.00 ; 0.20*t)=1.4	**5.8**
18	Gording Plate on Bulkhead (Bottom)	10	9.0	MIN (1.00+1.00 ; 0.20*t)=1.76	**7.2**
19	Watertight Web frame Stringer	10	9.4	MIN (1.00+1.00 ; 0.20*t)=1.87	**7.5**
20	Deck plate	8	8.0	NA(Stainless Steel)	**8.0**
21	Innerside plating	8	8.0	NA(Stainless Steel)	**8.0**
22	Inner bottom plating	8	8.0	NA(Stainless Steel)	**8.0**

6.6 Strength Check of Platings and Secondary Stiffeners

In this section, the scantling check of the platings and ordinary/secondary stiffeners have been carried out based on the aforementioned BV rules. MarsInland tool developed by Bureau Veritas has been used, which checks the compliance of the given scantlings with the BV rule requirements. The measured values (from UTM) of platings and secondary stiffeners has been provided as the gross values in MarsInland and the scantling check is carried out based on the net scantlings (Corrosion allowance deducted from the measured thickness values).

6.6.1 *Hull Girder Strength Check*

The section modulus at deck and bottom has been compared with the rule requirements as follows,

Table 20: Section Modulus Comparison

Section Modulus	**Distance From Baseline(m)**	**Rule**	**Actual**
Bottom (m3)	0	0.46	1.05
Deck (m3)	5.03	0.46	0.87

Since the actual section modulus is higher, the rule requirements are satisfied.

Now, a comparison has been carried out based on actual gross and net scantlings to check the values comply with the acceptance criteria (refer table 21).

Table 21: Gross/Net Moduli

Section Modulus	**Distance From Baseline(m)**	**Actual Gross**	**Actual Net**	**%**
Bottom (m^3)	0	1.05	0.91	**87.44**
Deck (m^3)	5.03	0.87	0.82	**93.45**

The percentage difference between the gross and net section modulus of the bottom section is not within the acceptable range. The measured thickness (minimum) values have been provided as the input and the net scantlings have been evaluated accordingly. For the deck area, stainless steel material has been used for the platings (no net thickness values) which accounts for lesser variation in gross and net section modulus.

However, the stress values are compared to check whether it is within the rule requirements.

Hull girder yielding check has been carried out based on BV rules NR 217, Part B, Section 2, Pt B, Ch 4, Sec 2.

Based on the beam theory, the hull girder normal stresses induced by vertical bending moments are obtained from following formulae:

- In hogging condition

$$\sigma_1 = \frac{M_{TH}}{Z} 10^3 \quad [N/mm^2] \tag{30}$$

- In sagging conditions

$$\sigma_1 = \frac{M_{TS}}{Z} 10^3 \quad [N/mm^2] \tag{31}$$

Checking criteria for hull girder stress are given by the following equation:

$$\sigma_1 = MAX\,(\sigma_H; \sigma_S) \leq 192/k\,[N/mm^2] \tag{32}$$

Table 22: Material Factor k

ReH , in N/mm2	**k**
235	1
315	0.78
355	0.72
390	0.68

Source; *Bureau Veritas, NR 217, Part B, Ch 2, Sec 3, Table 2*

k is the material factor (refer table 22), and is equal to 1 for normal grade shipbuilding steel $\left(R_{eH} = 235\ N/mm^2\right)$.

Stresses are to be checked on the deck and the bottom of the section. As it can be seen in Table 23, the

Table 23: Hull girder stresses

Items	Distance from baseline (m)	Hogging σ_H (N/mm^2)	Sagging σ_H (N/mm^2)
Bottom	0.0	85.34	96.03
Deck	5.03	106.55	113.77

stress values for both hogging and sagging conditions are below the limit criteria. So, hull girder stresses are within the rule requirements.

6.6.2 *Scantling Check of Platings*

Scantling check of platings were carried out to ensure that the input thickness values of the vessel from UT measurements comply with the rule requirements. The net thickness values should be higher than the required values proposed by the classification society.

Following formulations has been taken into consideration to carryout the scantling check in different locations.

Table 24: Rule formulations for net scantlings of platings

Plating	Net Thickness Formulation	Framing
Bottom	$t_1 = 1,1 + 0,03Lk^{0,5} + 3,6s$ $t_2 = 14,9C_aC_rs\sqrt{\frac{\gamma_r\gamma_m p}{\lambda_L R_y}}$	Longitudinal
Inner Bottom	$t_1 = 1,5 + 0,016Lk^{0,5} + 3,6s$ $t_2 = 14,9C_aC_rs\sqrt{\frac{\gamma_r\gamma_m p}{\lambda_L R_y}}$	Longitudinal
Side	$t_1 = 1,68 + 0,025Lk^{0,5} + 3,6s$ $t_2 = 17,2C_aC_rs\sqrt{\frac{\gamma_r\gamma_m p}{\lambda_L R_y}}$	Transverse
Inner Side	$t_1 = 2 + 0,003Lk^{0,5} + 3,6s$ $t_2 = 14,9C_aC_rs\sqrt{\frac{\gamma_r\gamma_m p}{\lambda_L R_y}}$	Longitudinal
Deck Plating (Flush Deck)	$t_1 = 0,57 + 0,031Lk^{0,5} + 3,6s$ $t_2 = 14,9C_aC_rs\sqrt{\frac{\gamma_r\gamma_m p}{\lambda_L R_y}}$	Longitudinal

The buckling thickness should comply with the below formulations,

$$t_3 = \frac{b}{\pi}\sqrt{\frac{12\gamma_R\gamma_m\sigma_b(1-\nu^2)}{EK_1F_1}}10^3 \quad for \quad \sigma_b \leq \frac{R_{eH}}{2} \tag{33}$$

$$t_3 = \frac{b}{\pi}\sqrt{\frac{3R_{eH}^2(1-\nu^2)}{EK_1F_1R_{eH}-\gamma_R\gamma_m\sigma_b}}10^3 \quad for \quad \sigma_b > \frac{R_{eH}}{2} \tag{34}$$

The net scantlings (corrosion allowance deducted from the measured UT readings) have been compared with the required rule values.

The results of the scantling check for platings are tabulated in Table 25. The actual net thickness values are compared with the maximum required rule values (among $t_1/t_2/t_3$) to check whether all the requirements are satisfied.

Table 25: Scantling Check of Platings-Results

Plating	**Net Thickness**		**Definition**
	Actual Thickness(mm)	**Maximum Rule Thickness(mm)**	
Bottom	6.5	6	1
Inner Bottom	8	5.5	2
Side Shell	6.9	7.5	3
Inner Side Shell	8	5	2
Deck Plate (Flush Deck)	8	6.5	3
Stringer Plate	13.4	8.5	3
CL Girder/Side Girders	6.2	6.9	3
Bilge	9.1	4.5	1
(1) Minimum rule thickness t_1. Maximum of the values calculated on each E.P.P.			
(2)Thickness t_2 based on external or internal design pressure and on a stress factor λ_T or λ_L coming from the overall bending stress The output value of Load Thick t_2 is the maximum one.			
(3)Buckling thickness t_3. value calculated on critical E.P.P.			

It can be observed from the results that the sideshell plating, centerline and side girders has not complied with the buckling thickness requirement(t_3), but it satisfies the minimum required rule values(t_1/t_2). Refer Figure 20 to check the scantlings of side girder for example.

6.6.3 *Scantling Check of Secondary Stiffeners*

Scantling check of secondary stiffeners have been carried to ensure compliance with the rule requirements. The actual section modulus and shear area based on the net scantling approach has been compared with the required rule values. Similar to the procedure followed for platings, comparison of actual net scantlings were carried out with maximum required rule values, so that every rule aspect is fulfilled (tables 26 and 27).

Table 26: Net Thickness of Stiffener Web

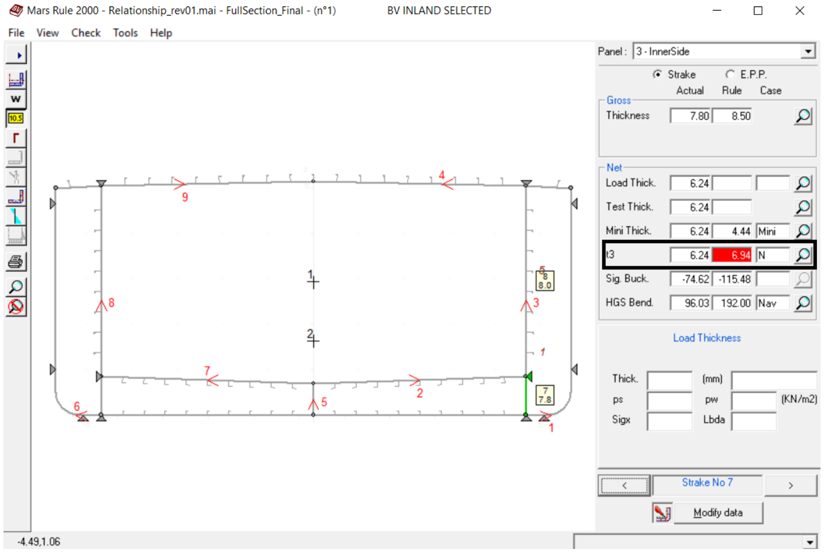
Longitudinals	**Net Thickness**	
	Actual Thickness(mm)	**Minimum Rule Thickness(mm)**
Bottom	6.2	4.5
Inner Bottom	7	4.5
Inner Side Shell	6	4.5
Deck	7	4.5

Table 27: Shear Area/Section Modulus (Actual v/s Required);Net Values

Longitudinals	**Shear Area(cm^2)**		**Definition from rules**	**Section Modulus(cm^3)**		**Definition from rules**
	Actual	**Rule**		**Actual**	**Rule**	
Bottom	5.85	2.03	2	45.81	58.17	3
Inner Bottom	8.59	3.67	2	108.38	79.85	3
Inner Side Shell(Lower)	9.55	3.2	2	92.59	32.15	3
Inner Side Shell(Upper)	8.36	3.05	2	70.01	62.88	3
Deck	11.17	2.43	2	105.92	72.29	3
(1) Shear area based on external or internal design pressure (A_{sh} Load)						
(2) Shear area based on test pressure (A_{sh} Test)						
(3) Modulus based on external or internal design pressure and on a stress factor depending on the overall bending stress (W Load)						
(4) Modulus based on test pressure (W Test)						

From Table 27, it is observed that the maximum rule values for shear area are based on test pressure and for section modulus, maximum values are based on load values (Design pressure/Bending Stress).

The bottom stiffener does not comply with the Section modulus (W Load) requirement (refer figure 21) i.e the modulus depending on the external/internal design pressure and upon the overall bending stress. However, it satisfies the section modulus requirement based on test pressure (W Test).



Mars Rule 2000 - Relationship_rev01.mai - FullSection_Final - (n°1) BV INLAND SELECTED

Panel : 3 - InnerSide

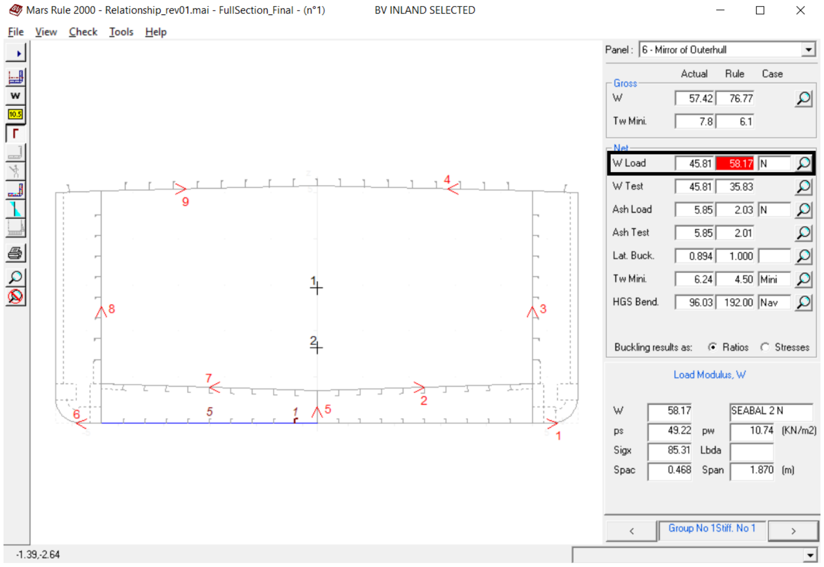
● Strake ○ E.P.P.

	Actual	Rule	Case
Gross			
Thickness	7.80	8.50	
Net			
Load Thick.	6.24		
Test Thick.	6.24		
Mini Thick.	6.24	4.44	Mini
t3	6.24	6.94	N
Sig. Buck.	-74.62	-115.48	
HGS Bend.	96.03	192.00	Nav

Load Thickness

Thick.		(mm)		
ps		pw		(KN/m2)
Sigx		Lbda		

Figure 20: Side Girder Buckling Thickness Failure



Mars Rule 2000 - Relationship_rev01.mai - FullSection_Final - (n°1) BV INLAND SELECTED

Panel : 6 - Mirror of Outerhull

	Actual	Rule	Case
Gross			
W	57.42	76.77	
Tw Mini.	7.8	6.1	
Net			
W Load	45.81	58.17	N
W Test	45.81	35.83	
Ash Load	5.85	2.03	N
Ash Test	5.85	2.01	
Lat. Buck.	0.894	1.000	
Tw Mini.	6.24	4.50	Mini
HGS Bend.	96.03	192.00	Nav

Buckling results as: ● Ratios ○ Stresses

Load Modulus, W

W	58.17		SEABAL 2 N	
ps	49.22	pw	10.74	(KN/m2)
Sigx	85.31	Lbda		
Spac	0.468	Span	1.870	(m)

Figure 21: Bottom Stiffener (W Load)

6.7 Strength Check of Primary Supporting Members (FEMAP/NX NASTRAN)

FEMAP integrated with NX-NASTRAN provides a platform to carry out the structural analysis using direct engineering calculations. A basic introduction about the software has already provided in this report (Section 5.2). Various steps followed to carryout the FEA have been explained in the following sub-sections.

6.7.1 *Modelling and Meshing*

From the provided GA, Midship section and other structural drawings (longitudinal/transverse sections), finite element modelling of the hull (From Frame No's 1 to 43) were carried out using FEMAP software. FE modelling was carried out based on the net scantlings (NR 217, Pt B, Ch 5, App 1, 3.1.2) generated for each structural element by deducting the corrosion allowance from the measured UT values(refer Section 6.5). The resulting net values for different elements in the midship area (Tank no 4; Frame No's 17-22, SB and PS) are already provided in Table 18 and Table 19. Similar tabulations has been generated for every structural element in each tank (SB and PS) to evaluate the net scantlings. These net values have been used for the FE modelling. Figure 22 represents the femap model with different properties assigned in different locations.

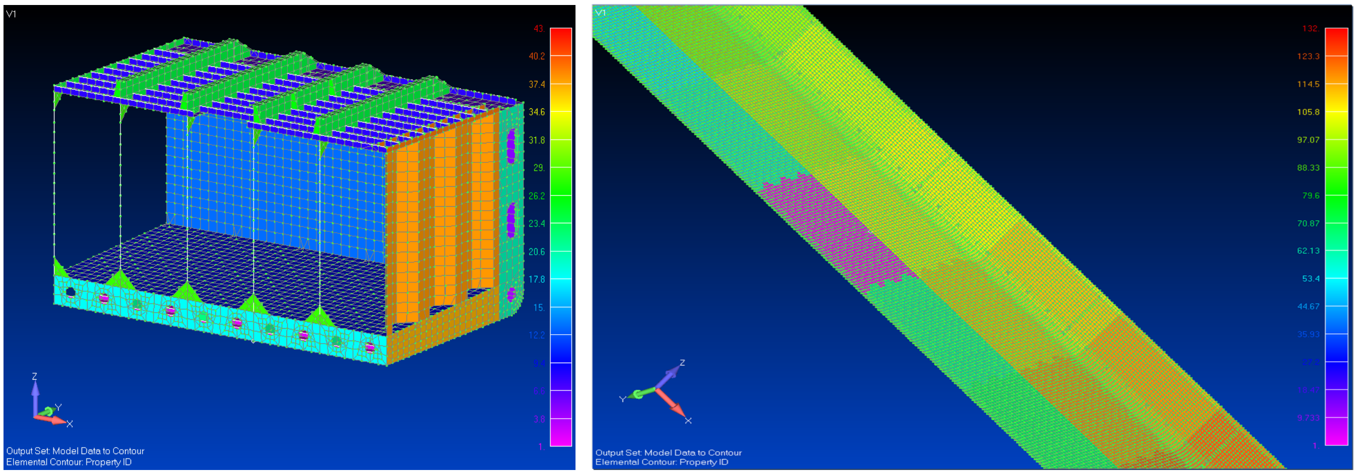


Figure 22: Tank no 4(Left) and Full model(Right); Different properties assigned

Finite element models are generated based on linear assumptions. BV provides following recommendations (NR 217, Pt B, Ch 5, App 1, 3.4.1) to be taken care during FE modelling,

- The quadrilateral elements are to be defined with an aspect ratio not exceeding 4,
- The quadrilateral element angles are to be greater than 60° and less than 120°,
- The triangular elements angles are to be greater than 30° and less than 120°.

To ease the meshing process, the stiffener flanges are modelled using beam elements. Also, the unit vectors and first edges were harmonized to obtain accurate results. In most of the cases, quadrilateral meshes were defined with recommended aspect ratios. Triangular meshes were only used in unavoidable areas (refer figure 23).

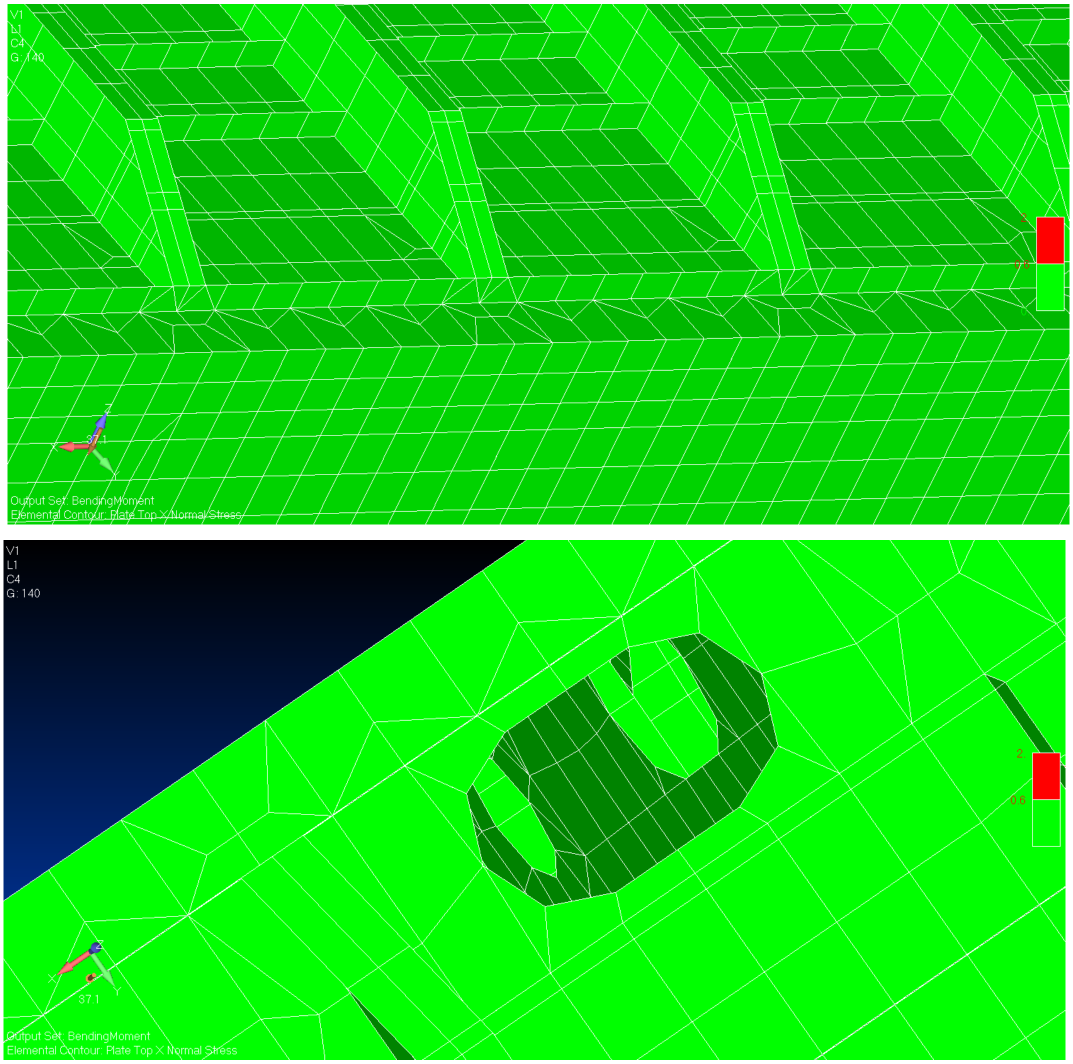


Figure 23: Mesh Quality

6.7.2 *Boundary Conditions and Application of Loads/Moments*

Case 1; Cantilever Beam applied with Bending Moment only

If a cantilever beam is applied with a bending moment on one side, the moment will be the same in all sections along the length of the beam (refer figure 24). The same concept has been employed in the FE model to study the stresses developed on the hull midship section. Maximum bending moments (Sagging/Hogging) were applied on one side of the FE model and the other side is imposed with fixed constrains (refer table 28).

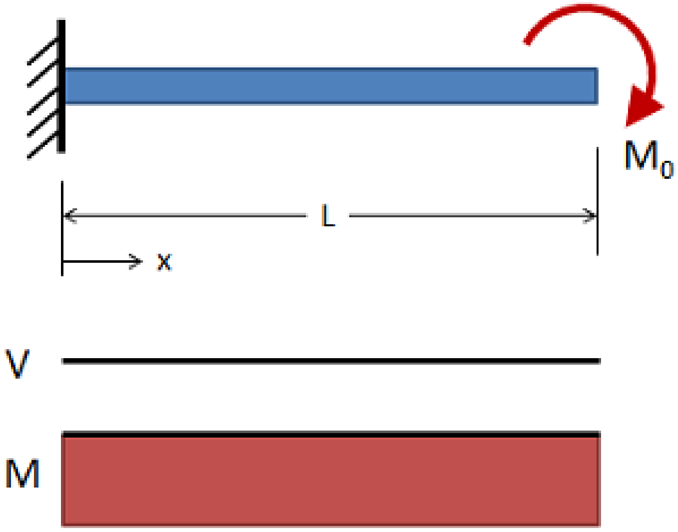


Figure 24: Cantilever Beam applied with BM (No Shear Force and constant BM)

Initially two rigid nodes are defined at both ends (fore and aft) of the FE model to apply constraints and moments (refer figure 25). Fixed Boundary conditions has been imposed on one end and the design bending moment values (Still Water + Wave BM) for both sagging and hogging cases evaluated based on rule formulations has been defined on the other end (Refer Section 6.3.1, Table 11).

Table 28: Boundary Conditions (Fixed)

Boundary Conditions	Translation in directions			Rotation around axes		
	x	y	z	x	y	z
Rigid Node at fore end	fixed	fixed	fixed	fixed	fixed	fixed
Rigid Node at aft end	fixed	fixed	fixed	fixed	fixed	fixed

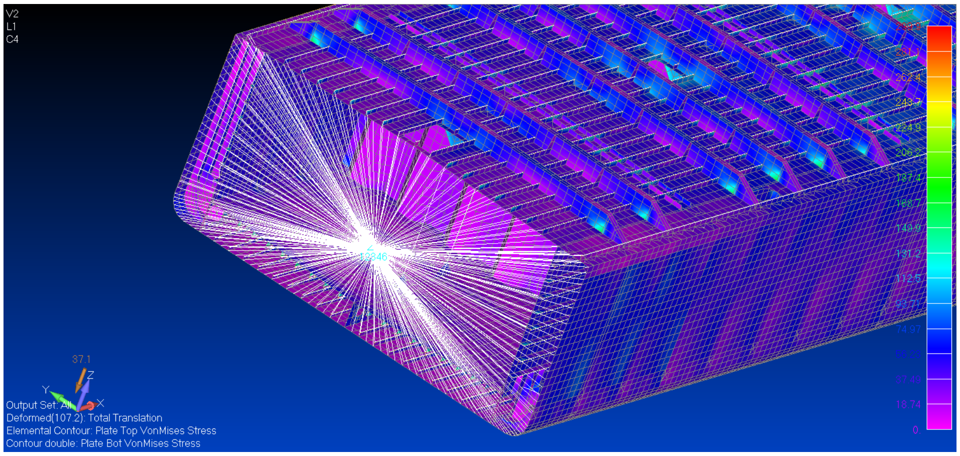
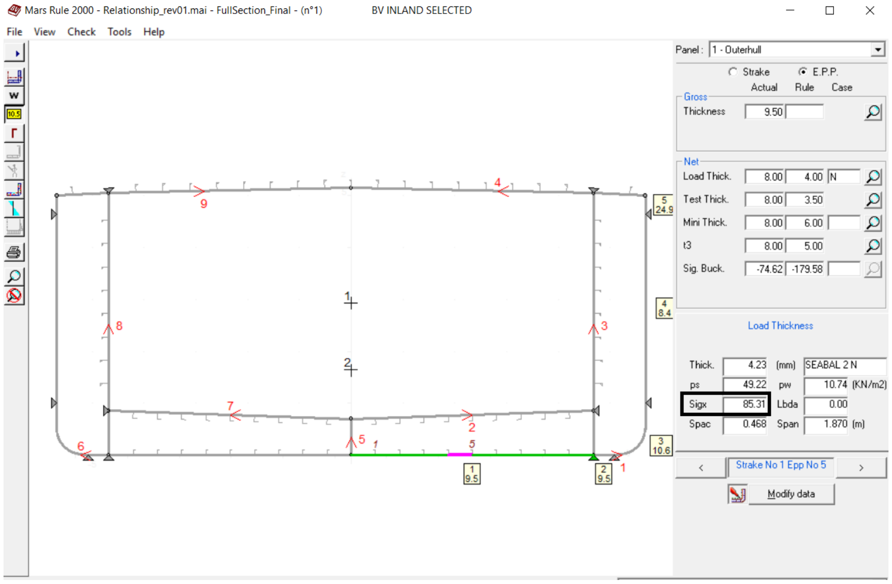


Figure 25: Rigid Node used to define constrains/moment

The most severe case was observed for sagging case (higher BM value). Since the applied maximum bending moment corresponds to the value in the midship section, the stress values in the midship areas have been studied.

A comparison of global stress values obtained from the rules and the finite element model have been carried out for validation (refer figures 26 and 27). The normal stress on the bottom shell plating in the midship section area have been taken from the MARS model and FE model for comparison (refer table 29).


Mars Rule 2000 - Relationship_rev01.mai - FullSection_Final - (n°1) BV INLAND SELECTED

Panel : 1 - Outerhull

○ Strake ● E.P.P.

	Actual	Rule	Case
Gross			
Thickness	9.50		
Net			
Load Thick.	8.00	4.00	N
Test Thick.	8.00	3.50	
Mini Thick.	8.00	6.00	
t3	8.00	5.00	
Sig. Buck.	-74.62	-179.58	

Load Thickness

Thick. 4.23 (mm) SEABAL 2 N
ps 49.22 pw 10.74 (KN/m2)
Sigx 85.31 Lbda 0.00
Spac 0.468 Span 1.870 (m)

Strake No 1 Epp No 5

Figure 26: Hull Girder Stress on Bottom Plating (MarsInland)

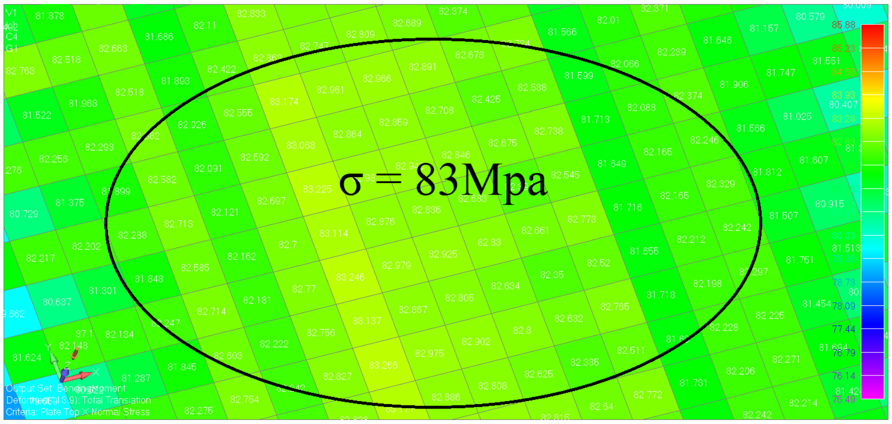


Figure 27: Hull Girder Stress on Bottom Plating in midship area (FEM)

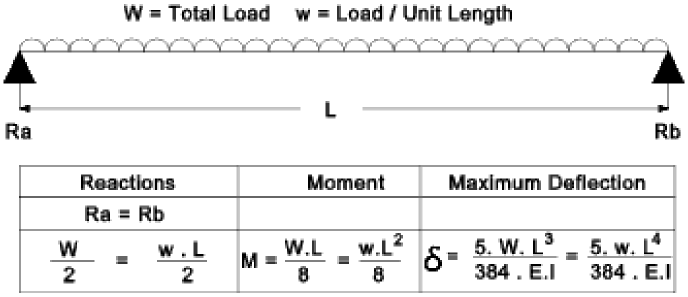
Table 29: Comparison of Tensile Stress values on Bottom Shell Plating(Sagging)

MarsInland(Mpa)	**FEM(Mpa)**	**% Difference**
85.31	83	2.7

As expected, both values are in close compliance, of course, lesser values are observed in the FE model. The algorithm is more advanced and accurate in the latter case but with more computational time. Stress evaluation in MARS (Rule Formulations) are based on the Beam theory.

Case 2; Simply Supported Beam Applied with Local Loads

For Case 2, simply supported boundary conditions has been imposed on both ends of the model as a conservative approach (refer table 30). Rigid nodes have been defined at both ends and constraints has been defined (refer table 30).



Reactions	Moment	Maximum Deflection
Ra = Rb		
$\frac{W}{2} = \frac{w.L}{2}$	$M = \frac{W.L}{8} = \frac{w.L^2}{8}$	$\delta = \frac{5.W.L^3}{384.E.I} = \frac{5.w.L^4}{384.E.I}$

Figure 28: Simply Supported Beam with UDL

All the local loads have been applied on the finite element model of the ship, so that the design bending moment values will be obtained. Table 31 represents the local loads applied during fully-loaded and ballast conditions. The body weight has been applied in both the cases.

Table 30: Boundary Conditions (Simply Supported)

Boundary Conditions	Translation in directions			Rotation around axes		
	x	y	z	x	y	z
Rigid Node at fore end	fixed	fixed	fixed	fixed	free	fixed
Rigid Node at aft end	fixed	fixed	fixed	fixed	free	fixed

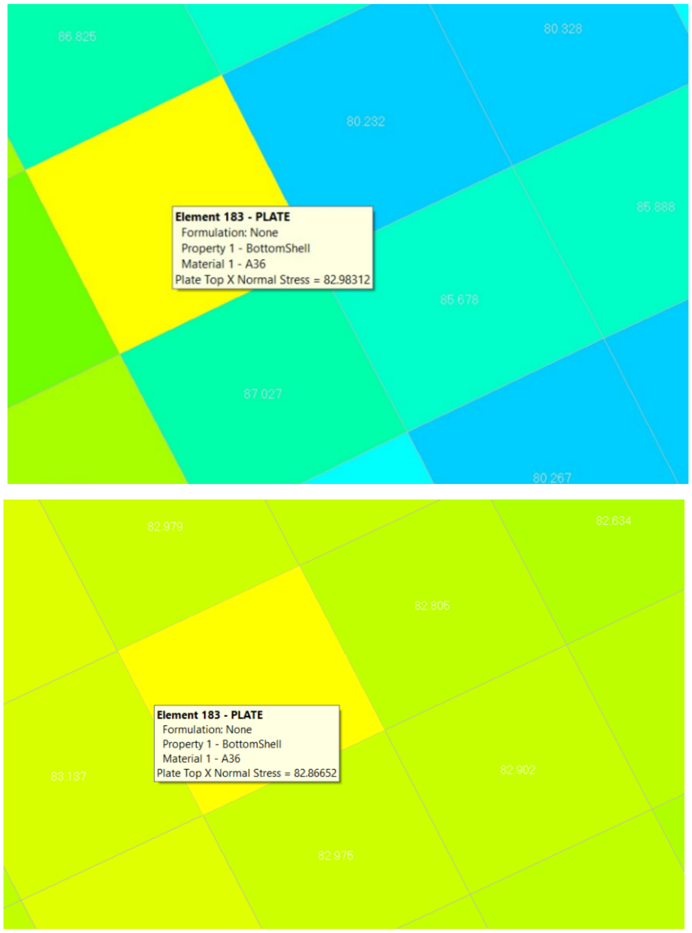
Table 31: Local Loads

Location	**Fully - Loaded (Sagging)**	**Ballast (Hogging)**
Inner Bottom	Cargo Loads(Static+Inertial)	Ballast Water Pressure(Static+Inertial)
Inner Side	Cargo Loads(Static+Inertial)	Ballast Water Pressure(Static+Inertial)
Deck	Tank Setting Pressure	-
Bulkheads	Cargo Loads(Static+Inertial)	-
Bottom	River Pressure(Static+Wave)	Ballast Water Pressure(Static+Inertial) River Counter Pressure(Static+Wave)
Bilge	River Pressure(Static+Wave)	Ballast Water Pressure(Static+Inertial) River Counter Pressure(Static+Wave)
Outer Side Shell	River Pressure(Static+Wave)	Ballast Water Pressure(Static+Inertial) River Counter Pressure(Static+Wave)
Remark: For Inner Bottom, the ballast water pressure exist because the double bottom and side wing tanks allows the flow of ballast water through the openings on the side girders (DB and Side tanks together can be considered as a single compartment).		

Conventionally, If there is no full model available, the idea is to apply the local loads separately and the resulting stresses are added to the hull girder stresses. The methodology followed in this case is explained as follows,

Since the model is not full (span wise), the application of local loads along the length of the model does no give the evaluated bending moment value. The only possibility is to adjust the weight of the model (by changing the density/acceleration due to gravity) to make it up to the calculated value of bending moment. Here, the acceleration due to gravity of the model has been changed to obtain the design bending moment value.

For validation, the normal stress values on the bottom plating (at midship section) on the application of only the hull girder bending moment and all local loads on the entire model has been compared. Fully loaded condition is considered (Sagging case).



Element 183 - PLATE
Formulation: None
Property 1 - BottomShell
Material 1 - A36
Plate Top X Normal Stress = 82.98312

Element 183 - PLATE
Formulation: None
Property 1 - BottomShell
Material 1 - A36
Plate Top X Normal Stress = 82.86652

Figure 29: Stresses due to all Local Loads (Top) and Only Hull Girder Bending Moment (Bottom)

Table 32: Comparison of Stresses on Bottom Shell

Element ID	All Local Loads(Mpa)	Only BM(Mpa)
183	82.98	82.86

Elemental stress is the average of stress values on the surrounding nodes.

The stress values in both cases are comparable (refer table 32), which shows that the design bending moment is obtained with the application of all the local loads and by providing the correct scaling factor for the acceleration due to gravity (to modify the weight).

The above procedure is carried out to evaluate the resulting von-mises stress (considering hull-girder loads + local loads) and to make sure adequate strength is retained based on the criteria provided by the classification society.

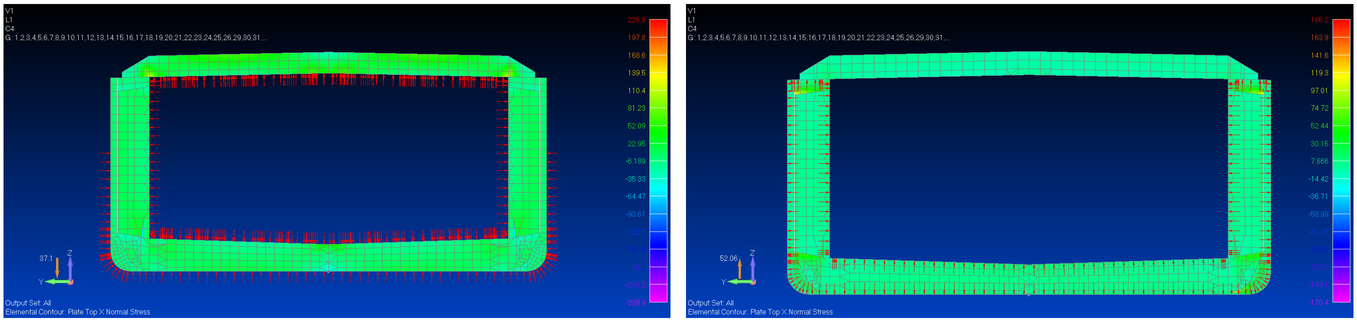


Figure 30: Cargo Loads (Left) and Ballast Loads (Right)

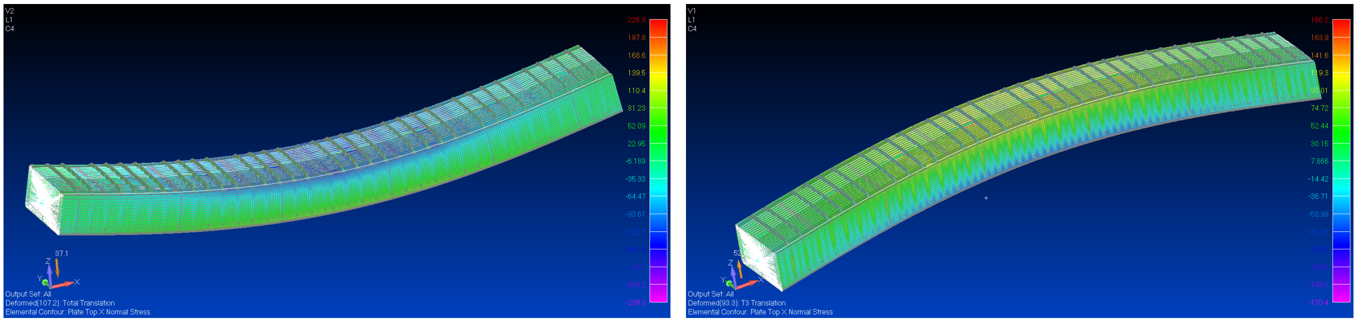


Figure 31: Sagging(Left) and Hogging(Right)

Figure 30 represents local loads in fully-loaded and ballast cases. Figure 31 shows corresponding sagging and hogging deformations.

6.8 Checking Criteria and Results

The most severe case is observed in the fully-loaded condition (Sagging) and the strength check has been carried out for this particular case. As a conservative approach, the design test pressure of 65kpa has been applied.

The checking criteria has been referred from BV rule (NR 217, Part B, Chapter 5, Section 1, 5.4.4).

The master allowable stress, σ_{MASTER}, in N/mm^2, is obtained from the following formula:

$$\sigma_{MASTER} = \frac{R_y}{\gamma_R \gamma_m} \tag{35}$$

where

R_y : yielding stress,

γ_R : resistance partial safety factor

γ_m : material partial safety factor

The master allowable stress, σ_{MASTER} is calculated as 219.42 N/mm^2

For the all types of analysis, it is to be checked that the equivalent Von-Mises stress σ_{VM} is in compliance with the following formula:

$$\sigma_{VM} \leq \sigma_{MASTER} \tag{36}$$

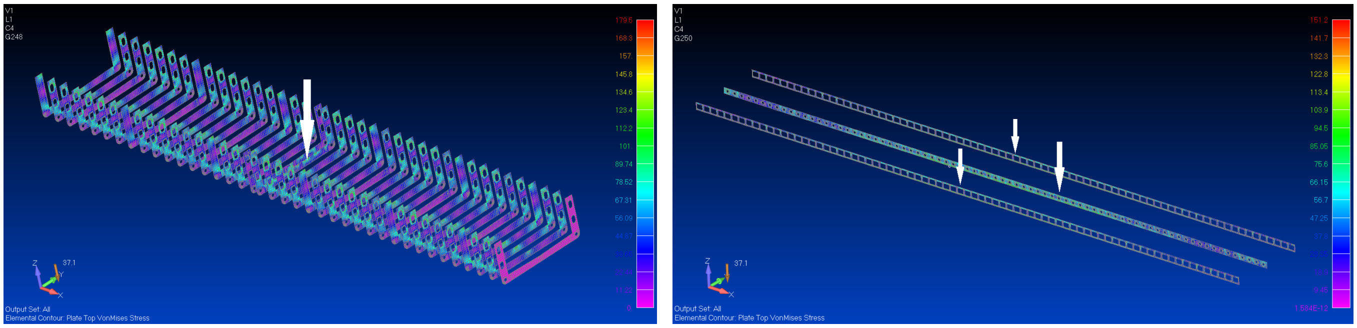
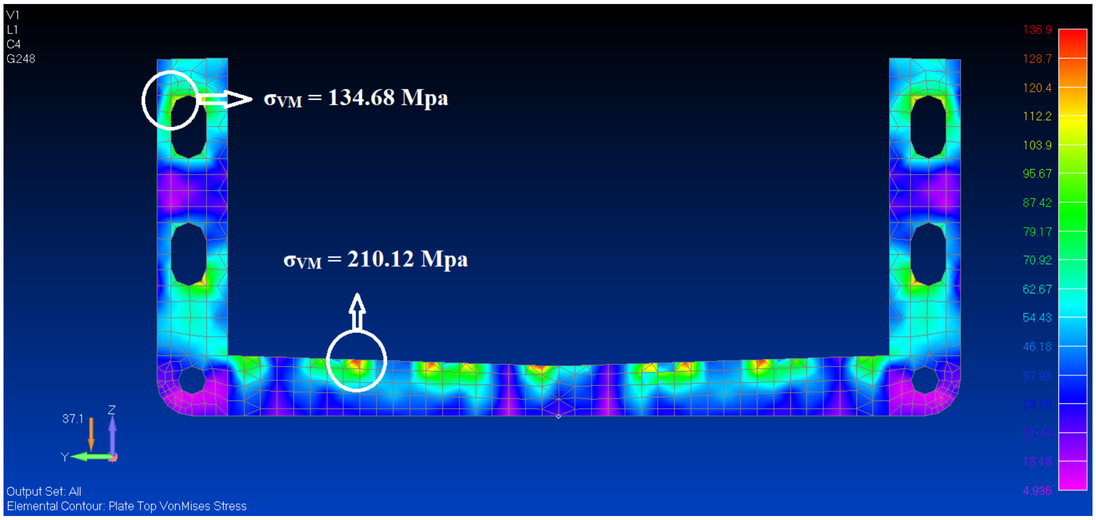


Figure 32: Max Von-mises Stress on Web Frames/Longitudinal Girders


σ_{VM} = 134.68 Mpa

σ_{VM} = 210.12 Mpa

Figure 33: Max Von-mises Stress on Web Frame (Frame No 23)

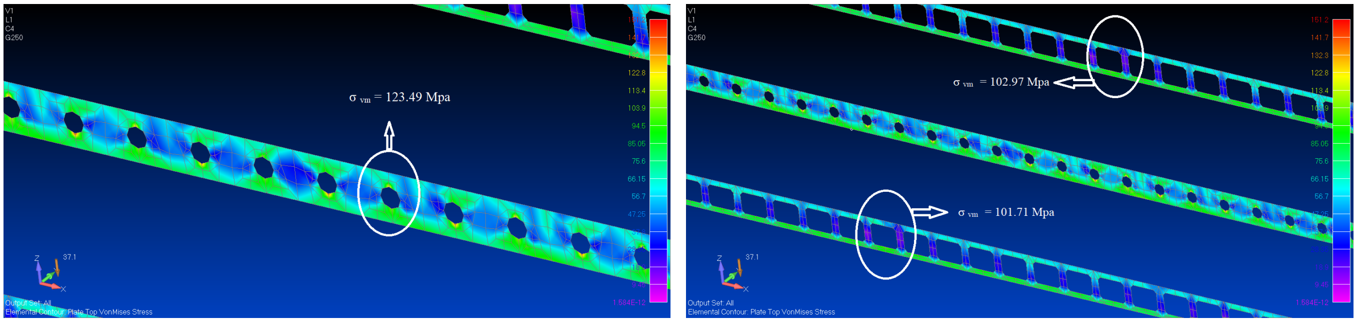


Figure 34: Max Von-mises Stress; CL Girder (Left Fig) and Side Girders (Right Fig)

The evaluated maximum values of von-mises stress are within the limits satisfying the rule requirements (refer figures 32, 33 and 34).

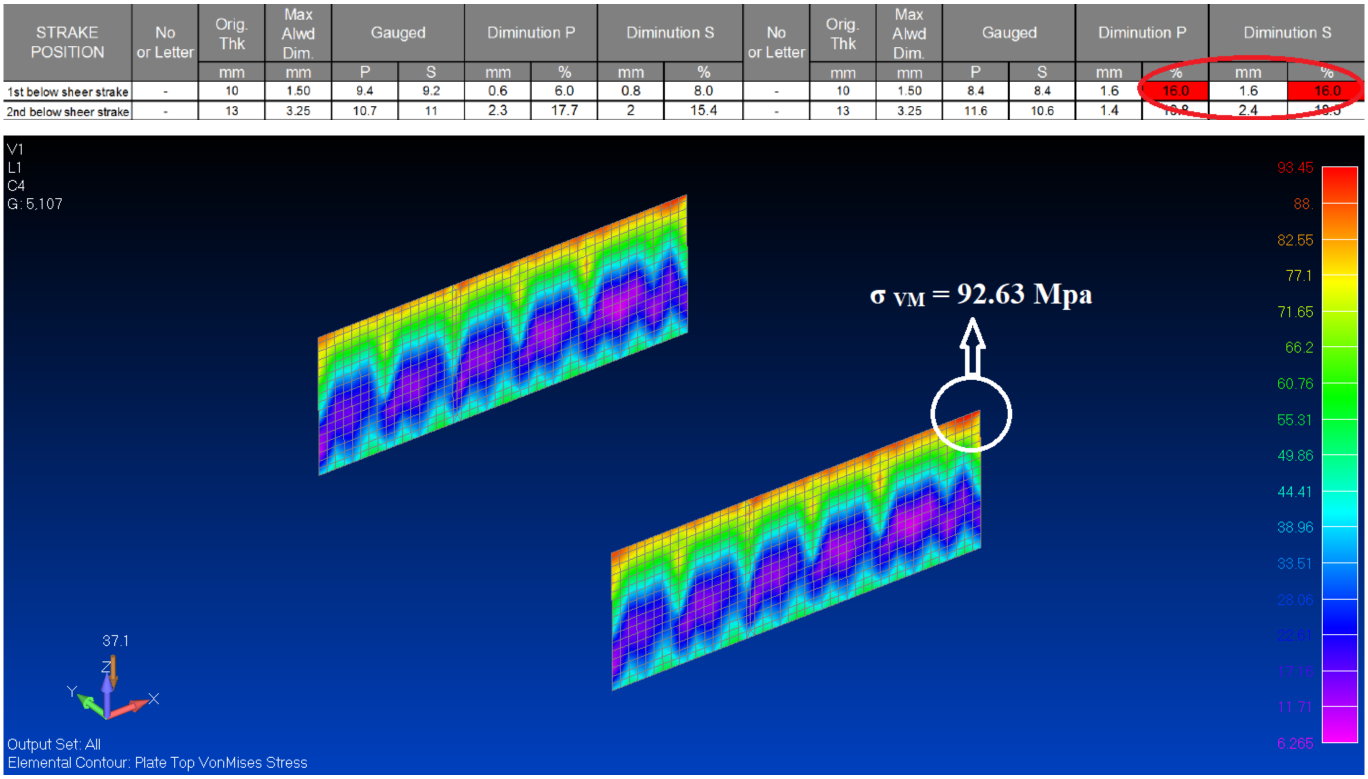
6.9 Critical Analysis

As per the UT gauging report, the zone assessment of bottom shell is not within the acceptable range proposed by the classification society (refer the UTM report, APPENDIX A). Also, the 1^{st} strake below the sheer strake (Midship ; Tank No 4) does not satisfy the rule acceptance criteria (refer figure 35). However, in the direct calculations(FEM), the stress levels on both cases are in line with the rule requirements.

The acceptance criteria in the rules are based on the comparison of gross values and measured thickness values. Finite element results are based on the net thickness values (corrosion allowance deducted from the measured thickness values). Still, the FEA results are acceptable.

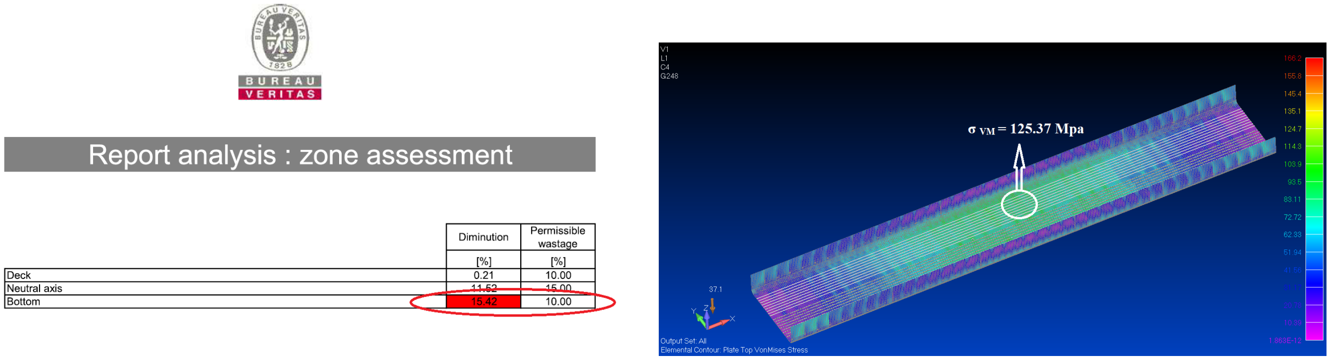
Similarly, the scantlings of bottom stiffeners and primary supporting members (center line and side girders) based on rule values do not satisfy all the required criteria. But, it satisfies the checking criteria based on the output from FEA and can be considered as acceptable (Figure 36).

The above observation implies that the classification society rules are conservative and the scantlings can be optimized using the direct engineering techniques, reducing the weight and cost, without compromising the structural integrity.



STRAKE POSITION	No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S		No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S	
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%
1st below sheer strake	-	10	1.50	9.4	9.2	0.6	6.0	0.8	8.0	-	10	1.50	8.4	8.4	1.6	16.0	1.6	16.0
2nd below sheer strake	-	13	3.25	10.7	11	2.3	17.7	2	15.4	-	13	3.25	11.6	10.6	1.4	10.8	2.4	18.5

Figure 35: Acceptance criteria (Top) and VM$_{max}$ on 1st strake below sheer strake (Bottom)



Report analysis : zone assessment

	Diminution [%]	Permissible wastage [%]
Deck	0.21	10.00
Neutral axis	11.52	15.00
Bottom	15.42	10.00

Figure 36: Acceptance criteria (Left Fig) and VM$_{max}$ on bottom panel (Right Fig)

7 FATIGUE ANALYSIS

7.1 Overview

A deterministic/simplified method proposed by the classification society has been adopted to evaluate the fatigue damage/fatigue strength. Detailed description about the method has been provided in section 4.3.8 of this report.

Following BV guidance document has been followed to carryout the study.

NI 575, Appendix 4, Guide for Fatigue Analysis adapted to inland navigation conditions (Derived from NR 467, Part B, Chapter 7, Section 4, Fatigue check of structural details for sea-going vessels).

Fatigue analysis for secondary supporting members (ordinary stiffeners) has been carried out based on the stresses evaluated using BV rules. For primary supporting members and other hot-spot areas, the stress values (stress range) has been taken directly from the finite element model and appropriate stress concentration factors have been imposed.

Since the study is being carried out for an existing vessel, the net thickness has already been evaluated from provided UT measurements which are used for the analysis. Also, the navigation notation has already been defined as IN(1.2), which means the ship encounters waves with significant wave height of 1.2m (max). Fatigue damage/Fatigue Life has been evaluated for two cases; Fully loaded (60% of lifetime) and Ballast Conditions (40% of lifetime).

7.2 Structural Details Under Consideration

Fatigue failure is a localized phenomenon which depends on structural geometrical details and stress range. Based on the classification society recommendations, following structural details have been taken into consideration to carry out the study,

- Detail 1: end connection of bottom longitudinal secondary stiffeners with transversal bulkhead frame (figure 37),
- Detail 2: end connection of inner bottom longitudinal secondary stiffeners with transversal bulkhead frame (figure 37),
- Detail 3: end connection of inner side longitudinal stiffeners with side web frames (figure 37),
- Detail 4: connection of bottom longitudinal secondary stiffeners welded with web frame and collar plate (figure 38),
- Detail 5: connection of inner bottom longitudinal secondary stiffeners welded with web frame and collar plate (figure 38),
- Detail 6: connection of inner side longitudinal stiffeners welded with web frame (Scallop) (figure 38) ,
- Detail 7: connection of deck longitudinal stiffeners welded with transverse vertical plates (Scallop) (figure 39),
- Hot spot locations observed from the Finite element model analysis (Hatch corners, Openings on Central/Side Girders).

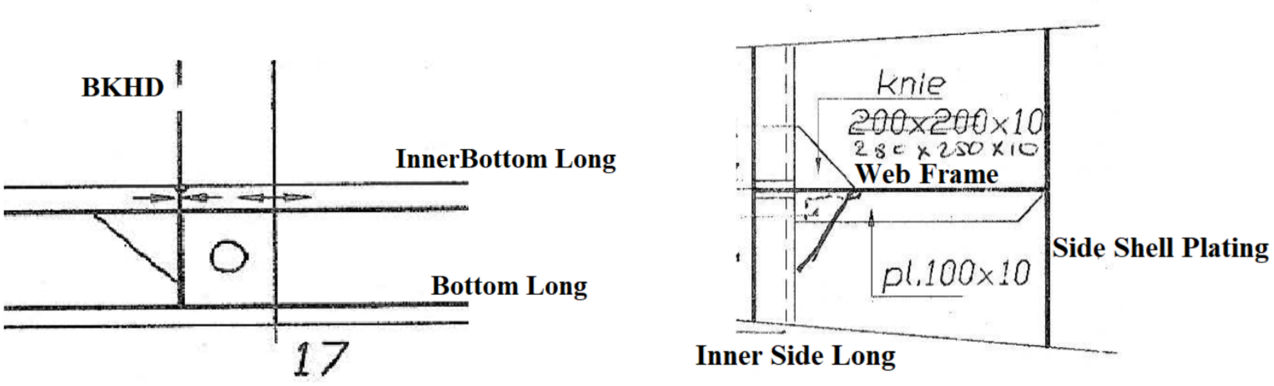


Figure 37: Detail 1 and 2 (Left ; Profile view) and Detail 3 (Right;Top view)

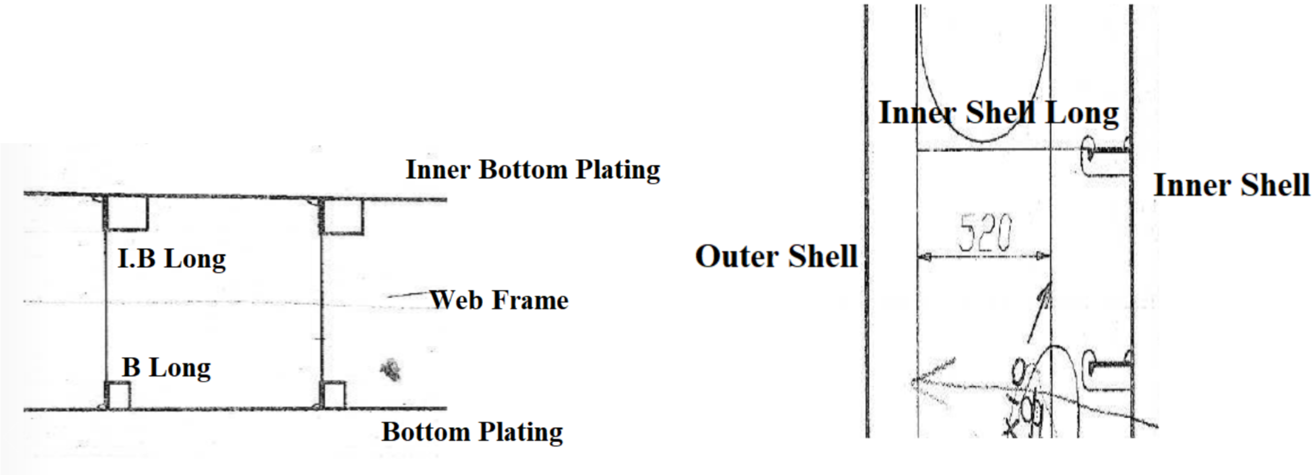


Figure 38: Detail 4 and 5 (Left) and Detail 6 (Right)

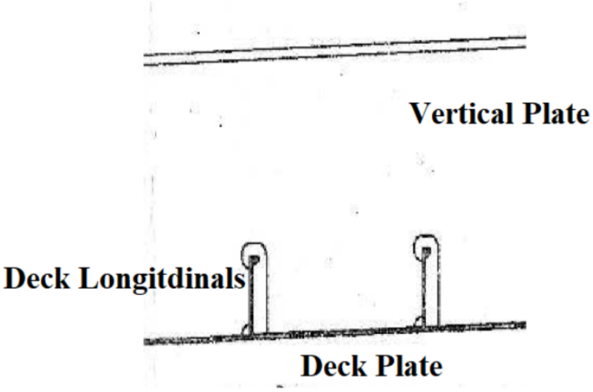


Figure 39: Detail 7

7.3 Load Model

Fatigue check has to be carried out based on the stress range induced on the hotspots due to the time variation of local loads and hull girder loads. The load cases are divided into maximum and minimum cases corresponding to local loads and hull girder loads.

Fatigue check has been carried out based on ”upright vessel condition during navigation” case.

7.3.1 *Load Points*

The designed loads have been evaluated on following points based on BV rules (NR 217, Part B, Ch 2).

Plating

The elementary plate panel is the smallest unstiffened part of plating.

Unless otherwise specified, the loads are to be calculated:

- For longitudinal framing, at the lower edge of the elementary plate panel or, in the case of horizontal plating, at the point of minimum y-value among those of the elementary plate panel considered,
- For transverse framing, at the lower edge of the strake.

Ordinary Stiffeners

- Lateral pressure : Loads are to be calculated at mid-span of the ordinary stiffener considered,
- Hull girder stresses : The normal stresses are calculated in way of the attached plating of the stiffener considered.

Primary Supporting Members

- Lateral pressure : Loads are to be calculated at mid-span of the primary supporting member considered,

- Hull girder stresses : The normal stresses are to be calculated in way of the neutral axis of the primary supporting member with attached plating.

7.3.2 *Partial Safety Factors*

For fatigue check of structural details, following partial safety factors have been considered to cover various uncertainties (refer table 33),

Table 33: Fatigue Check-Partial Safety Factors

Partial Safety Factors covering following uncertainites	**Symbol**	**Value**	
		General	**Details at the end of Ordinary Stiffeners**
Still water hull girder loads	γ_{s1}	1,00	1,00
Wave hull girder loads	γ_{w1}	1,05	1,15
Still water pressure	γ_{s2}	1,00	1,00
Wave pressure	γ_{w2}	1,10	1,20
Resistance	γ_R	1,02	1,02

For each load case, stresses corresponding to maximum and minimum hull girder loads and local pressures have been evaluated.

7.3.3 *Local Loads and Hull Girder Loads*

Following local loads have been considered,

- Still water and Wave lateral loads induced by the river pressure,
- Static and Inertial loads induced by the liquid cargo and ballast water.

The external wave pressures and internal inertial pressures (maximum and minimum values) are defined in table 34 and table 35.

For conservative results, the river pressure in the way of wave trough has been used for the calculation of river counter pressure (P_{Em}).

Table 34: External Wave Pressure

Location	**Wave Pressure P$_w$ (kN/m^2)**	
	Max	**Min**
Bottom and sides below waterline(z ≤ T$_1$)	$\alpha^{\frac{1}{4}} \frac{9.81 h_1}{2} (\frac{T_1 + z}{T_1})$	$-\alpha^{\frac{1}{4}} \frac{9.81 h_1}{2} (\frac{T_1 + z}{T_1})$
Sides above the waterline (z> T$_1$)	$9.81(T_1 + \alpha^{\frac{1}{4}} h_1 - z)$	0,0
Note; For case 1, the minimum pressure should not be taken less than $\frac{\gamma_s}{\gamma_w} 9.81(z - T_1)$,$\alpha = \frac{T_1}{T}$		

Table 35: Inertial Pressures

Cargo	**Load case**	**Inertial pressures(kN/m^2)**
Liquids	max	$P_w = \rho_L(-0.5 a_{x1} l_b - a_{z1}(Z_{TOP} - z))$
	min	$P_w = \rho_L(0.5 a_{x1} l_b + a_{z1}(Z_{TOP} - z))$

The maximum and minimum hull girder loads have been calculated for the considered loading conditions. In fully-loaded (Sagging) case, maximum bending moment will be developed if the ship encounters a sagging wave (wave crests on fore/aft ends and trough on the midship) and minimum moment if it is a hogging wave (wave troughs on both ends and crest on the middle). Similarly, the maximum and minimum bending moments have been calculated for hogging case considering the opposite scenario. Taking into account the partial safety factors defined in table 33, For

Fully-Loaded Condition

$$M_{max} = M_{sw,S} + 0.625 \gamma_{w1} M_{w,S} \tag{37}$$

$$M_{min} = M_{sw,S} + 0.625 \gamma_{w1} M_{w,H} \tag{38}$$

Ballast Condition

$$M_{max} = M_{sw,H} + 0.625 \gamma_{w1} M_{w,H} \tag{39}$$

$$M_{min} = M_{sw,H} + 0.625 \gamma_{w1} M_{w,S} \tag{40}$$

M_{max} : Maximum total BM corresponding to the loading condition (SWBM + WBM)

M_{min} : Minimum total BM corresponding to the loading condition (SWBM + WBM)

$M_{sw,S}$: Still Water BM in sagging case/fully loaded condition

$M_{w,S}$: Wave BM for sagging wave (wave crest on fore and aft end and trough on midship)

$M_{sw,H}$: Still Water BM in hogging case/ballast loaded condition

$M_{w,H}$: Wave BM for hogging wave (wave crest on midship and troughs on fore/aft ends)

Based on the above formulations, the maximum and minimum hull girder bending moments have been evaluated for the two loading conditions and tabulated as follows,

Table 36: Maximum and Minimum BM values for navigation condition (IN 1.2)

Loading Conditions	**Bending Moment Values(kNm)**					
	Msw,H	**Msw,S**	**Mw,H**	**Mw,S**	**M$_{max}$**	**M$_{min}$**
Ballast	43172		34862	-34862	68229	18115
Fully-Loaded		-52947	34862	-34862	-78004	-27890
Note : Partial Safety Factor, γ_{w1} = 1.15						

The local loads on the locations of secondary longitudinal stiffeners has been calculated based on the aforementioned rules for two loading conditions and tabulated as follows,

Table 37: Local Loads in Ballast Condition

Location	**Distance from Bottom, Z(m)**	**P$_{SE}$**	**P$_{WE(max)}$**	**P$_{WE(min)}$**	**P$_{SB}$**	**P$_{WB(max)}$**	**P$_{WB(min)}$**
		(kN/m^2)					
Bottom	0	4.74	3.14	-3.14	11.28	4.51	-4.51
Inner Bottom	0.72				4.27	4.08	-4.08
	0.84				3.09	4	-4
Inner Side	1.38				40.42	6.39	-6.39
	4.53				9.51	4.49	-4.49
Deck	5.04	6.82			NA	NA	NA
	5.18	6.82			NA	NA	NA

Table 38: Local Loads in Fully-loaded Condition

Location	**Distance from Bottom, Z(m)**	$\mathbf{P}_{SE}$	$\mathbf{P}_{WE(max)}$	$\mathbf{P}_{WE(min)}$	$\mathbf{P}_{SC}$	$\mathbf{P}_{WC(max)}$	$\mathbf{P}_{WC(min)}$
		(kN/m^2)					
Bottom	0	31.59	5.04	-5.04	NA	NA	NA
Inner Bottom	0.72				96.66	5.03	-5.03
	0.84				95.59	4.96	-4.96
Inner Side	1.38				90.79	4.67	-4.67
	4.53				62.97	2.96	-2.96
Deck	5.04				57.23	2.61	-2.61
	5.18				49.99	2.17	-2.17

7.4 Stresses

The governing factor contributing fatigue damage is the stress range. For evaluating the same, stresses corresponding to the maximum and minimum hull girder loads and local pressures has to be calculated for each load case. For secondary ordinary stiffeners, the stresses are evaluated based on rule formulations and for primary structural members, the stresses are taken directly from the developed finite element model to evaluate the stress range.

For the evaluation of fatigue damage, hot spot/notch stresses has to be taken into consideration.

7.4.1 *Ordinary Secondary Stiffeners*

The stress range has been evaluated based on BV rules. Different types of stresses have been evaluated as follows,

Nominal Local Stress

The nominal local stresses(N/mm^2) for different load cases (maximum and minimum) have been calculated based on the following formulation,

$$\sigma_l = \frac{\gamma_{s2} p_s + \gamma_{w2} p_w}{12w} s l^2 10^3 \tag{41}$$

where,

w : Net Section modulus(cm^3), of the stiffener with an attached plating of width b$_p$

s, l : Spacing and Span of the ordinary stiffeners respectively

Elementary Hot Spot Stress Range

The elementary hot-spot stress range (N/mm^2) for different load cases (maximum and minimum) have been calculated based on the following formulation,

$$\Delta\sigma_{G,j} = \mid \sigma_{G(max)} - \sigma_{G(min)} \mid + K_l \; \Delta\sigma_{DEF,j} \tag{42}$$

where,

$$\sigma_{G(max)} = K_N \; (K_h \sigma_h + K_l K_s \sigma_l)_{max} \tag{43}$$

$$\sigma_{G(min)} = K_N \; (K_h \sigma_h + K_l K_s \sigma_l)_{min} \tag{44}$$

$$\Delta\sigma_{DEF,j} = \frac{4(\Delta\delta)EI}{wl^2} 10^{-5} \tag{45}$$

$\Delta\sigma_{DEF,j}$: Nominal stress range due to the local deflection of the ordinary stiffener (N/mm^2)

σ_h : Nominal hull girder stress for maximum and minimum load cases (N/mm^2)

σ_l : Nominal local stress for maximum and minimum load cases (N/mm^2)

K_N : Coefficient taking into account of North Atlantic Navigation (taken equal to 1)

K$_S$ is the coefficient taking into account the stiffener section geometry (refer figure 40) defined as follows (without being taken less than 1,0),

$$K_S = 1 + \left(\frac{t_f (a^2 - b^2)}{2 w_B} \right) \left(1 - \frac{b}{a + b} (1 + \frac{w_B}{w_A}) \right) 10^{-3} \tag{46}$$

a, b : Eccentricities of the stiffener(mm)

t_f : Face plate net thickness(mm)

b_f : Face plate width(mm)

w_A, w_B : Net section moduli of the stiffener without attached plating(cm^3) in A and B (Figure 40) about its Neutral axis parallel to the stiffener web

$\Delta\delta$: Local range of deflection (mm) of ordinary stiffener

I : Net moment of Inertia (cm^4) of the ordinary stiffener with an attached plating (width calculated based on rules)

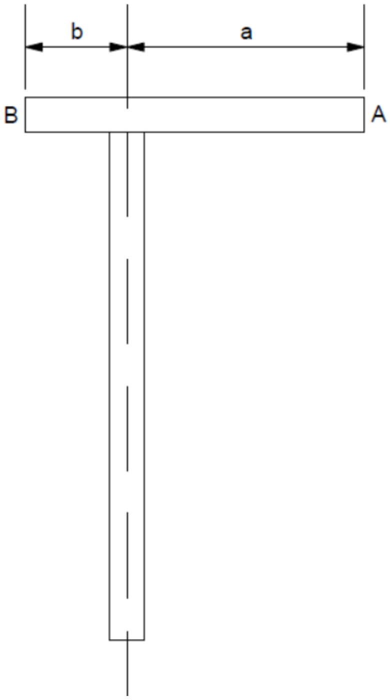


Figure 40: Geometry of a stiffener section

Elementary Notch Stress Range

Finally, the elementary notch- stress range (N/mm^2) to evaluate the fatigue damage can be calculated as follows,

$$\Delta\sigma_{N,j} = K_{C,j}\Delta\sigma_{NO,j} \tag{47}$$

$$\Delta\sigma_{NO,j} = 0,7 K_F K_M \Delta\sigma_{G,j} \tag{48}$$

$$K_{C,j} = \frac{0,4 R_{e,H}}{\Delta\sigma_{NO,j}} + 0,6 \quad (0,8 \leq K_{C,j} \leq 1) \tag{49}$$

where,

K_F : Fatigue Notch Factor

K_m : Stress concentration factor due to misalignment (taken not less than 1)

$\Delta\sigma_{G,j}$: Elementary Hotspot Stress Range (Defined in previous section)

The stresses/stress range has been calculated based on the above rule formulations and tabulated as follows,

Table 39: Stresses in Ballast Condition(N/mm^2)

Location	**Z(m)**	σ_l **max**	σ_l **min**	σ_h **max**	σ_h **min**	$\Delta\sigma_{DEF}$	σ_G **max**	σ_G **min**	$\Delta\sigma_G$	$\Delta\sigma_N$
Bottom	0	46.62	-7.79	74.62	19.81	38.7	198.26	8.83	253.29	**374.12**
Inner Bottom	0.72	11.41	-0.78	52.12	13.84	48.83	93.11	16.26	152.53	**253.23**
	0.84	9.83	-2.13	48.34	12.83	48.83	84.7	11.94	148.45	**229.08**
Inner Side	1.38	73.53	50.07	31.19	8.28	52.99	134.42	76.64	118.73	**183.21**
	4.53	31.9	8.82	67.95	18.04	47.35	119.2	32.1	141.55	**218.43**
Deck	5.18	11.12	11.12	88.4	23.47	53.31	135.85	51.44	172.36	**253.59**

Table 40: Stresses in Fully-Loaded Condition(N/mm^2)

Location	**Z(m)**	σ_l **max**	σ_l **min**	σ_h **max**	σ_h **min**	$\Delta\sigma_{DEF}$	σ_G **max**	σ_G **min**	$\Delta\sigma_G$	$\Delta\sigma_N$
Bottom	0	111.7	75.78	85.31	30.5	38.7	353.41	204.25	213.02	**329.59**
Inner Bottom	0.72	127.9	112.9	59.58	21.3	48.83	361.86	278.66	158.88	**241.11**
	0.84	126.5	111.7	55.26	19.76	48.83	353.1	273.93	154.85	**237.37**
Inner Side	1.38	147.4	130.2	35.66	12.75	52.99	238.57	189.25	110.26	**170.15**
	4.53	142.3	127.1	77.68	27.77	47.35	272.59	195.61	131.43	**202.8**
Deck	5.18	98.32	88.12	101.07	36.14	53.31	316.52	212.9	191.58	**271.4**

Primary Supporting Members

Stresses developed in the primary supporting members have been taken directly from the finite element model (refer table 42) for fatigue damage evaluation.

Sign convention ; Tensile stresses are taken positive and compressive stresses are considered negative.

Table 41: Stress Extraction Points (Co-ordinates From FEMAP)

Hot Spot Areas	**Element ID**	**Node ID**	**X(mm)**	**Y(mm)**	**Z(mm)**
Deck Hatch Corner	81447	71360	8882.50	520	5139
Wing Tank Manhole Corner	127856	109303	5610	5305	5043
Opening on CL Girder	75730	66250	10752.50	0	200
Opening on Side Girder	201126	166101	15430	-4680	140

Table 42: Maximum and Minimum Nominal Stresses in two Loading Conditions

	Ballast Case		**Fully-Loaded Case**	
Hot Spot Areas	σ_n **Max**	σ_n **Min**	σ_n **Max**	σ_n **Min**
Deck Hatch Corner	152.44	41.40	-173.34	-62.30
Wing Tank Manhole Corner	186.16	54.46	-202.20	-70.50
Opening on CL Girder	-125.23	-32.75	149.24	56.75
Opening on Side Girder	-81.62	-17.77	94.65	30.80

7.5 S-N Curves

Different approaches can be used to assess the fatigue capacity of welded joints. Prototype testing is the most direct method of assessment of fatigue strength of structural details. But it is cost-effective for structures which are fabricated in series. For ships, this method is not considered feasible. Another method is the fracture mechanics approach by the application of fatigue crack growth laws which enables to predict the crack propagation life cycles from initial crack to final failure. For this study, the fatigue capacity has been determined by the implementation of the S-N curve approach. S-N curves gives the relationship between the stress range and constant amplitude cycles to failure. [25]

Detailed explanation about the S-N curves has already been provided in sections 4.3.9 and 4.3.10 of this report.

For different welded joints, there are many tests being performed in the laboratory to determine the S-N curves and the results has been summarized in several publications,

U.K. HSE Basic S-N Curves; The U.K. Health and Safety Executive (2001) (HSE) proposed a new set of eight S-N curves (Table 43) corresponding to non-corrosive conditions. The HSE classification depends on the geometrical arrangement of the detail, the direction of fluctuating stress, method of fabrication and type of connection.

Table 43: HSE S-N Curve Parameters

S-N Curve	**K_p(N ≤ 10^7)**	**K'_p(N >10^7)**	**Stress Range at N=10^7 cycles (S_q)**
B	5.802 x 10^{12}	4.036 x 10^{16}	83.4
C	3.459 x 10^{12}	1.704 x 10^{16}	70.2
D	1.520 x 10^{12}	4.329 x 10^{16}	53.35
E	1.026 x 10^{12}	2.249 x 10^{15}	46.8
F	6.316 x 10^{11}	1.002x 10^{15}	39.8
F2	4.331 x 10^{11}	5.341 x 10^{14}	35.1
G	2.481 x 10^{11}	2.110 x 10^{14}	29.15
W	9.278 x 10^{10}	4.097 x 10^{13}	21
The weld configurations corresponding to each S-N curve type has been provided in APPENDIX B			

Further to the classification rule recommendations, curve B has been selected for the evaluation of fatigue damage for Inland Vessels. However, an investigation has been carried out to observe the fatigue damage for different S-N curves corresponding to each structural detail under consideration.

7.6 Fatigue Analysis Using BV Rules

For the structural detail under consideration, fatigue damage has been evaluated for Fully-loaded and Ballast conditions separately and the cumulative damage has been calculated accordingly. Based on the evaluated stresses, selected S-N curve data and other parameters, the elementary fatigue damage ratio has been calculated based on the following rule formula (Equation 50).

Fatigue Damage Ratio

$$D_j = \frac{N_t}{K_p}\frac{(\Delta\sigma_{N,j})^3}{(-lnP_R)^{3/\xi}}\mu_j\Gamma_c\left(\frac{3}{\xi}+1\right) \tag{50}$$

Various parameters in the equation has been explained in detail as follows,

$\Delta\sigma_{N,j}$: Elementary Notch Stress Range (Calculated in table 39,table 40)

$$\mu_j = 1 - \frac{\Gamma_N\left(\frac{3}{\xi}+1,\nu_j\right) - \Gamma_N\left(\frac{5}{\xi}+1,\nu_j\right)\nu_j^{\frac{-2}{\xi}}}{\Gamma_c\left(\frac{3}{\xi}+1\right)} \tag{51}$$

$$\xi = \xi_0\left(1,04 - 0,14\frac{\mid z - T_1 \mid}{D - T_1}\right) \tag{52}$$

without being taken less than 0,9 ξ_0

$$\xi_0 = \frac{73 - 0,07L}{60} \tag{53}$$

without being taken less than 0,85

T_1 : Draft(m) corresponding to Fully-Loaded or Ballast Loading Condition

$$\nu_j = -\left(\frac{S_q}{\Delta\sigma_{N,j}}\right)^{\xi} lnP_R \tag{54}$$

For S-N curve B ,

K_p : Coefficient taken equal to 5,802.10^{12}

S_q = 83,405

The total number of cycles N_t is calculated as,

$$N_t = \frac{631\ \alpha_0}{T_A}10^6 \tag{55}$$

where,

α_0 : Sailing Factor

T_A : Average Time Period(s)

$$T_A = 4\ log\ L \tag{56}$$

Fatigue analysis has been carried out for a probability of exceedence of 10^{-5} and for four different sailing factors.

The incomplete gamma function calculated for X = 3/ξ or X = 5/ξ is defined as follows,

$$\Gamma_N(X+1,\nu_j) = \int_0^{\nu} t^x e^{-t}\, dt \tag{57}$$

The complete gamma function calculated for X = 3/ξ,

$$\Gamma_C(X+1) = \int_0^{500} t^x e^{-t}\, dt \tag{58}$$

Cumulative Damage Ratio and Fatigue Life

The cumulative damage ratio has been evaluated based on following expression,

$$D = \frac{K_{cor}}{\beta_{IF}}(\alpha D_F + (1-\alpha)D_B) \tag{59}$$

For a given fatigue damage, the fatigue life is given by,

$$FatigueLife = \frac{1}{\gamma}\frac{DesignLife}{D} \tag{60}$$

Where,

α : Part of vessel's life in fully-loaded condition (For tankers α = 0,6)

β_{IF} : Improvement fatigue life factor for grinding technique (generally taken as 2,2)

D_F : Cumulative Damage Ratio in Fully-Loaded Condition

D_B : Cumulative Damage Ratio in Ballast Condition

K_{cor} : Corrosion Factor (For Cargo tanks , K_{cor} = 1,5 and For Ballast tanks (having effective coating protection), K_{cor} = 1,1)

Checking Criteria

The cumulative damage evaluated for a given structural detail should be less than unity. However, considering the partial safety factor to take into account various uncertainties, the fatigue damage ratio should be within the limits expressed as follows,

$$D = \frac{K_{cor}}{\beta_{IF}}(\alpha D_F + (1 - \alpha) D_B) \leq \frac{1}{\gamma} \tag{61}$$

γ : Partial Safety Factor

The Fatigue life should not be less than 20 years.

Remark : According to Common structural rules (01 Jan 2017), the fatigue life should not be taken less than 25 years, but as a conservative approach the requirement has been set to 20 years for this study.

7.7 Results

Fatigue Damage/Fatigue Life has been evaluated for the selected structural details. Fatigue analysis has been carried out for four different sailing factors (10%,40%,60% and 85%).

Bureau Veritas procedure is based on the "notch stress" approach, which uses S-N curve, type B for the calculation of fatigue damage [25]. The computation results have been plotted in Table 44 and Table 45.

Higher damages/shorter fatigue life can be observed in the deck and bottom areas since the normal stresses are higher in these locations (extreme ends from the neutral axis). The results are also graphically represented (refer figure 41) for the comparison of fatigue damage ratios in different locations.

Table 44: Fatigue Damage Ratio For Different Sailing Factors (IN 1.2)

ID	Structural Details	Sailing Factors (α_0)			
		10%	**40%**	**60%**	**85%**
A	Detail 1 : End connection of bottom longitudinal secondary stiffeners with transversal bulkhead frame	0.033	0.133	0.200	0.283
B	Detail 2 : End connection of inner bottom longitudinal secondary stiffeners with transversal bulkhead frame	0.024	0.094	0.141	0.200
C	Detail 3 : End connection of inner side longitudinal stiffeners with side web frames	0.027	0.108	0.162	0.230
D	Detail 4 : Connection of bottom longitudinal secondary stiffeners welded with web frame and collar plate	0.031	0.123	0.184	0.260
E	Detail 5 : Connection of inner bottom longitudinal secondary stiffeners welded with web frame and collar plate	0.020	0.080	0.120	0.170
F	Detail 6 : Connection of inner side longitudinal stiffeners welded with web frame(Scallop)	0.014	0.055	0.082	0.116
G	Detail 7 : Connection of deck longitudinal stiffeners welded with transverse vertical plates(Scallop)	0.020	0.079	0.118	0.168
H	Deck Hatch Corners (Tank No 5)	0.055	0.218	0.327	0.463
I	Wing Tank Manhole Corners(Tank No 5)	0.059	0.237	0.356	0.505
J	Openings on CL Girder (Tank No 5)	0.033	0.132	0.197	0.280
K	Openings on Side Girder (Tank no 5)	0.008	0.030	0.045	0.064

Table 45: Fatigue Life (Years) For Different Sailing Factors (IN 1.2)

ID	**Structural Details**	**Sailing Factors** (α_0)			
		10%	**40%**	**60%**	**85%**
A	Detail 1 : End connection of bottom longitudinal secondary stiffeners with transversal bulkhead frame	606.06	150.38	100.00	70.67
B	Detail 2 : End connection of inner bottom longitudinal secondary stiffeners with transversal bulkhead frame	833.33	212.77	141.84	100.00
C	Detail 3 : End connection of inner side longitudinal stiffeners with side web frames	740.74	185.19	123.46	86.96
D	Detail 4 : Connection of bottom longitudinal secondary stiffeners welded with web frame and collar plate	645.16	162.60	108.70	76.92
E	Detail 5 : Connection of inner bottom longitudinal secondary stiffeners welded with web frame and collar plate	1000.00	250.00	166.67	117.65
F	Detail 6 : Connection of inner side longitudinal stiffeners welded with web frame(Scallop)	1428.57	363.64	243.90	172.41
G	Detail 7 : Connection of deck longitudinal stiffeners welded with transverse vertical plates(Scallop)	1000.00	253.16	169.49	119.05
H	Deck Hatch Corners (Tank No 5)	363.64	91.74	61.16	43.20
I	Wing Tank Manhole Corners(Tank No 5)	338.98	84.39	56.18	39.60
J	Openings on CL Girder (Tank No 5)	606.06	151.52	101.52	71.43
K	Openings on Side Girder (Tank no 5)	2500.00	666.67	444.44	312.50

The most severe damage can be observed at the wing tank manhole corner (ID;I). At sailing factor of 85% the fatigue damage value is 0.505 and and the fatigue life is evaluated as 39.60 years. However, the values are within the limits of the acceptance criteria. The fatigue damage values for the above detail (I) considering different sailing factors are plotted in figure 42.

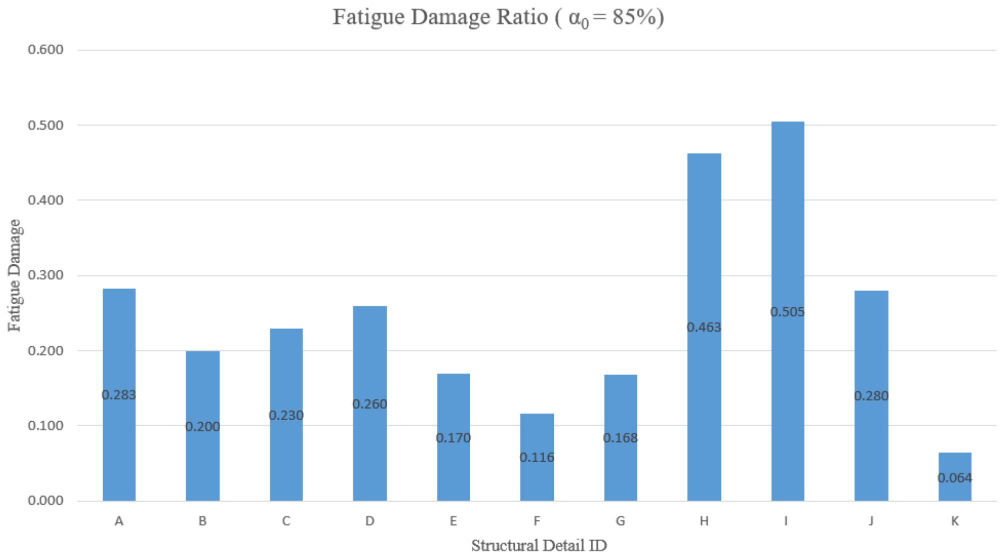


Figure 41: Fatigue damage at various structural details

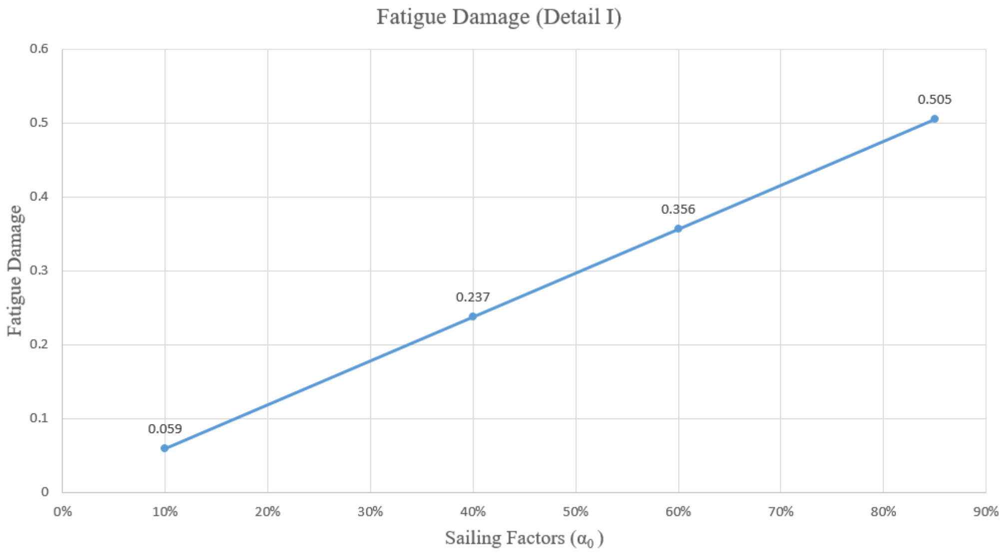


Figure 42: Fatigue damage of Detail I for different sailing factors

The Fatigue damage ratio follows a linear relationship with the sailing factor, since the total number of cycles is in a linear relationship with the fatigue damage and the sailing factor (Refer equations 50 and 55).

7.8 Fatigue Damage/Fatigue Life For Various S-N Curves

In this section, a comparison study has been carried out to investigate the variation of fatigue damage ratio with respect to the selection of S-N Curve. Different S-N curves in compliance with the structural detail configuration has been selected for this study (refer APPENDIX B). The nominal stress values have been taken directly from the finite element model and appropriate stress concentration factors defined by BV has been applied to evaluate the hot-spot and notch stresses.

Fatigue damage has been carried out for the selected structural details considering the sailing factor of 85% (most severe case) for different S-N curves,

Table 46: Stress Extraction Points (from FE Model)

ID	Structural Details	Element ID	Node ID	X(mm)	Y(mm)	Z(mm)
1	Detail 1 : End connection of bottom longitudinal secondary stiffeners with transversal bulkhead frame	62187	5536	3740	2340	0
2	Detail 2 : End connection of inner bottom longitudinal secondary stiffeners with transversal bulkhead frame	175191	111884	3740	-468	585
3	Detail 3 : Connection of inner side longitudinal stiffeners welded with web frame(Scallop)	188452	153450	6545	-4807	4530
4	Detail 4 : Connection of bottom longitudinal secondary stiffeners welded with web frame and collar plate	9660	192	1870	3276	0
5	Detail 5 : Connection of inner bottom longitudinal secondary stiffeners welded with web frame and collar plate	4960	222	1870	4212	835
6	Detail 6 : Connection of deck longitudinal stiffeners welded with transverse vertical plates(Scallop)	81538	70634	8415	520	5284

In accordance with the above structural configurations, following S-N curves have been selected for the study.

Table 47: HSE S-N Curve Parameters

S-N Curve	**K$_p$(N ≤ 10^7)**	**K'$_p$(N >10^7)**	**Stress Range at N=10^7 cycles (S$_q$)**
B	5.802 x 10^{12}	4.036 x 10^{16}	83.4
C	3.459 x 10^{12}	1.704 x 10^{16}	70.2
D	1.520 x 10^{12}	4.329 x 10^{16}	53.35
E	1.026 x 10^{12}	2.249 x 10^{15}	46.8
F	6.316 x 10^{11}	1.002x 10^{15}	39.8
F2	4.331 x 10^{11}	5.341 x 10^{14}	35.1
G	2.481 x 10^{11}	2.110 x 10^{14}	29.15
W	9.278 x 10^{10}	4.097 x 10^{13}	21
The weld configurations corresponding to each S-N curve type has been provided in APPENDIX B			

The evaluated fatigue damage and fatigue life has been presented in Table 48 and Table 49.

Table 48: Fatigue Damage Ratio of structural details for various S-N Curves (α_0 = 85%, IN(1.2))

ID	Structural Details	S-N Curve Type		
		C	**F**	**F2**
1	Detail 1 : End connection of bottom longitudinal secondary stiffeners with transversal bulkhead frame	0.011	0.106	0.167
2	Detail 2 : End connection of inner bottom longitudinal secondary stiffeners with transversal bulkhead frame	0.009	0.074	0.113
3	Detail 3 : Connection of inner side longitudinal stiffeners welded with web frame(Scallop)	0.004	0.032	0.049
4	Detail 4 : Connection of bottom longitudinal secondary stiffeners welded with web frame and collar plate	0.006	0.062	0.097
5	Detail 5 : Connection of inner bottom longitudinal secondary stiffeners welded with web frame and collar plate	0.003	0.022	0.034
6	Detail 6 : Connection of deck longitudinal stiffeners welded with transverse vertical plates(Scallop)	0.077	0.514	0.761

Table 49: Fatigue Life (Years) of Structural Details (α_0 = 85%, IN(1.2))

ID	**Structural Details**	**S-N Curve Type**		
		C	**F**	**F2**
1	Detail 1 : End connection of bottom longitudinal secondary stiffeners with transversal bulkhead frame	1818.18	188.68	119.76
2	Detail 2 : End connection of inner bottom longitudinal secondary stiffeners with transversal bulkhead frame	2222.22	270.27	176.99
3	Detail 3 : Connection of inner side longitudinal stiffeners welded with web frame(Scallop)	5000.00	625.00	408.16
4	Detail 4 : Connection of bottom longitudinal secondary stiffeners welded with web frame and collar plate	3333.33	322.58	206.19
5	Detail 5 : Connection of inner bottom longitudinal secondary stiffeners welded with web frame and collar plate	6666.67	909.09	588.24
6	Detail 6 : Connection of deck longitudinal stiffeners welded with transverse vertical plates(Scallop)	259.74	38.91	26.28

Maximum fatigue damage value of 0.761 and minimum fatigue life of 26.28 years can be observed at the connection of deck longitudinal stiffener with the vertical plate (Detail 6) for curve F2. This can be justified by the higher stresses/stress range at the deck and bottom areas.

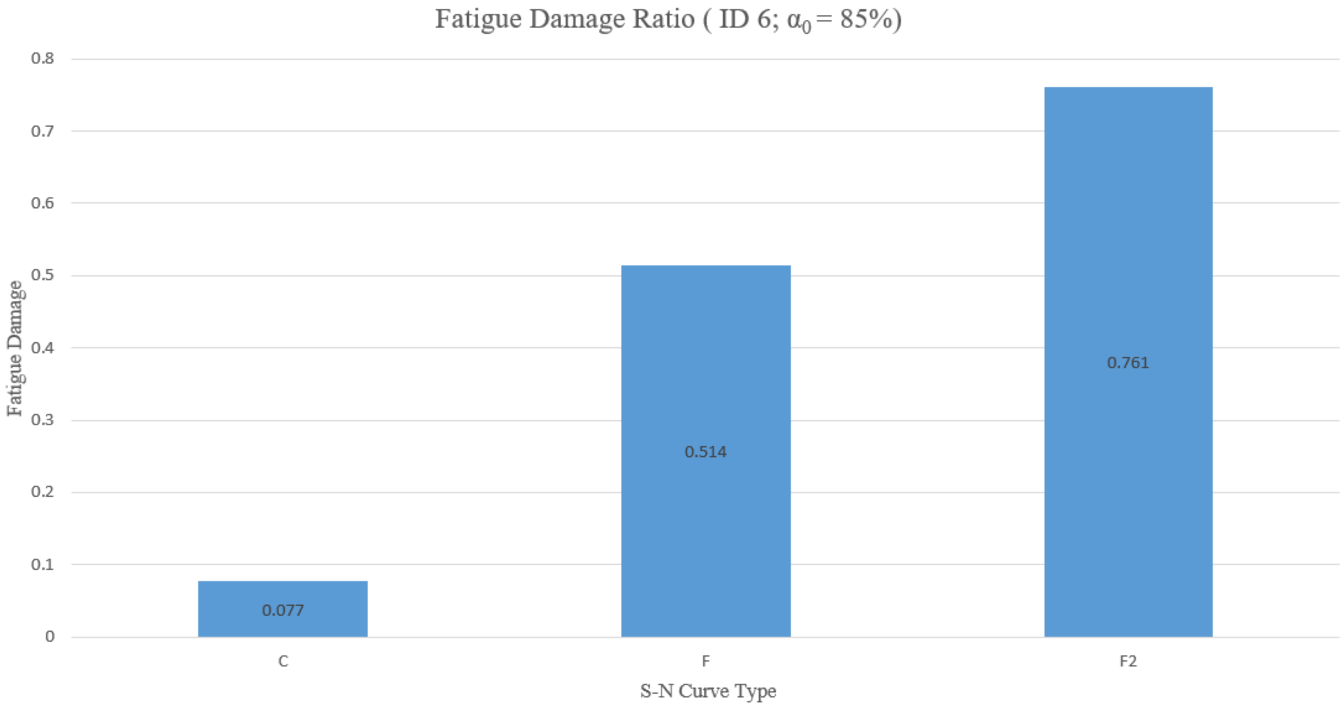


Figure 43: Fatigue damage of Detail 6 for different S-N curves

It can be observed that the fatigue damage values are higher with the S-N curves with lower limit of allowable stress(S_q). The results are more conservative when F2 curve is used. Fatigue damage is highly sensitive to the stress range and the selection of S-N curve.

7.9 Critical Analysis

Fatigue is a localized phenomenon due to the alternative tensile and compressive stresses (stress range) induced predominantly by waves. The total bending moment (still water + wave bending moments) in maximum and minimum cases has the highest variations depending upon the wave bending moment (refer section 7.3.3, equations 37 to 40). The wave bending moment in turn depends upon the significant wave the vessel encounters (Section 6.3.1, Design Loads, Equation 28). Higher the variation in bending moments(max and min), higher the variation in the tensile and compressive stresses(stress range) which elevates the fatigue damage. Therefore, fatigue damage is directly related to the wave bending moment value and the significant wave height.

In this study, the inland vessel under consideration encounters a maximum wave height of 1.2m which is incapable of inducing any fatigue damage or fatigue cracks. However, fatigue analysis has been carried out to justify the above argument.

Simplified/Deterministic approach based on a two parameter Weibull distribution proposed by the classification society has been followed for the fatigue analysis which gives more conservative results. However, a spectral approach based on Rayleigh's distribution, taking into consideration the stress transfer functions can be carried out for optimized results. Also, fatigue analysis involves numerous uncertainties including human factors, which makes the results more skeptical.

Fatigue damage is highly sensitive to the stress range (proportional to the cube of the notch stress range (Equation 50). So, the evaluation of stresses range should be carried out accurately to obtain proper results of fatigue damage/fatigue life. The stresses derived from the classification rules are more conservative when compared to the stresses extracted from the FEMAP model which are reflected in the results.

A comparison study has been carried out on the fatigue damage/fatigue life of the most critical location (Detail 6 ; Connection of deck longitudinal stiffeners welded with transverse vertical plates). Fatigue damage evaluation has been carried based on the stresses calculated based on the rules and stresses extracted from the finite element model. The parameters of Curve F2 (the most conservative curve) has been used in both cases for comparison. The result has been tabulated as follows,

Table 50: Fatigue Damage comparison for Detail 6 using Type F2 S-N Curve

ID	**Structural Detail**	**Stresses evaluated using Rules**	**Stresses extracted from FE model**	**% Difference**
6	Detail6 :Connection of deck longitudinal stiffeners welded with transverse vertical plates(Scallop)	1.096	0.761	30.57

From above table, it can be observed that fatigue damage is beyond the limits in the first case where the stresses are evaluated using classification society rules. On the other hand, the fatigue damage ratio is acceptable in the later case when the stresses from the finite element model are used. The conservative approach adopted by the classification society rules is clearly depicted in the above observation.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

In this study, an investigation has been carried out to check the structural strength and to evaluate the fatigue damage/ fatigue life of various critical details of a type C tank vessel (greater than 15 years of age). Fatigue analysis of inland vessels navigating at wave heights of 1.2m has rarely been subjected to research. This has been carried out here, which is one of the distinctive attribute of this study. Thickness measurements and acceptance criteria were based on BV rules (NR 597).

Conservative approach has been adopted in every stages of this study. The measured thickness (UTM) has been considered as the gross scantlings and the net scantlings have been evaluated by deducting corrosion allowance from the measured values. Scantling check has been carried out based BV rules (NR 217 , Part B and Part D rules). Also, structural analysis has been carried out using FEM tools based on the net scantlings (corrosion allowance deducted from the measured thickness values). Hot-spot areas have been identified from the global FE analysis. Fatigue analysis of the critical structural details has been carried out based on deterministic/simplified method characterized by a two parameter Weibull distribution. For primary supporting members and other hot-spot areas, stresses have been taken directly from the FE model and for secondary stiffeners, the stresses evaluated using BV rules have been used for the fatigue analysis. Appropriate stress concentration factors has been imposed on the nominal stresses to evaluate the hot-spot and notch stresses. Based on BV recommendations, S-N curve (HSE, Type B) has been used for evaluation. As an extended scope, fatigue damage comparison has been carried out for different S-N curves (Types C, F, F2) by extracting the stresses from the FE Model. The salient conclusions drawn from the thesis work are enumerated hereafter:

1. Considering BV rule requirements, the impact of thickness reduction due to corrosion has not considerably affected the strength of most of the structural items except the bottom longitudinals (Actual Section modulus($45.81cm^3$) < Required ($58.17cm^3$)) and the local buckling failure of centerline and side girder strakes,

2. For primary supporting members and transverse frames, the strength analysis using FEA gives a maximum von-mises stress of 210.12 N/mm^2, which can be considered as acceptable (Permissible von-mises stress is 219.42 N/mm^2),

3. The highest value of fatigue damage ratio (D = 0.505) is observed on the wing-tank manhole radius in the deck area for a sailing factor of 85% due to higher normal stresses and resulting stress range on the deck. Fatigue damage ratio has rapid changes with respect to the stress range (directly proportional to the cube of the notch stress range, refer equation 50),

4. Fatigue damage is highly sensitive to the selection of S-N curves. The most conservative results are obtained with type F2 curves (with lower S_q values). Maximum fatigue damage value of 0.761 is noted on the intersection of deck stiffeners with the transverse vertical plates,

5. Corrosion and resulting deterioration of welds and scantlings have a considerable impact on the fatigue life of structural details. However, the damages are within the acceptable limits,

6. Even in the corroded condition, the structural strength of the vessel is retained. There are some structural items which do not comply with the rule criteria. However, when direct calculations were performed(FEM), stress levels of the same structural items were found to be acceptable. The outcome of this investigation has also proved that even in this deteriorated condition and considering the stress range induced by the design loads, the critical structural details under consideration are devoid of any fatigue damages. Minimum Fatigue life of 26.28 years can be noted for the most critical detail with the most conservative S-N curve (Type F2). Hence, the scantlings of the vessel have been designed in the a safe and conservative manner.

8.2 Recommendations

1. Partial safety factors proposed by the classification society should be reconsidered and modified by proper validation techniques like similar investigations. For instance, the partial safety factors for fatigue (refer table 33) should be reduced to obtain optimized results,

2. Stress concentrations can be avoided by proper construction techniques recommended in the class rules, also strength issues can be resolved by adequate reinforcements,

3. A conservative method has been used for the fatigue analysis for the present study. The results can be optimized by the application of a probabilistic approach. Also, a comparison study can be carried out for both methods to determine the percentage of variation in the fatigue damage/fatigue life. Thereby, the simplified method can be subjected to modifications for optimized results.

9 ACKNOWLEDGEMENTS

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Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study.

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A APPENDIX: UT Report of the Investigated Vessel

BUREAU VERITAS

REPORT ON THICKNESS MEASUREMENT OF DECK AND SHEERSTRAKE PLATING AT TRANSVERSE SECTIONS

🟥 Excessive corrosion
🟧 Substantial corrosion
🟩 Repaired

N-Av Orig. Thk Not Available

Vessel's name : RELATIONSHIP **BV Register N° : 36 B 893** **Report N° : DoS/689**

Frame N°	Transverse Section at Tank 2									Transverse Section at Tank 4									
STRAKE POSITION	No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S		No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S	
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%
Not applicable																		
Stringer Plate	-	15	3.75	15	15	0		0		-	15	3.75	15	14.9	0		0.1	0.7
1st strake inboard																		
2nd strake inboard																		
3rd strake inboard																		
4th strake inboard																		
5th strake inboard																		
6th strake inboard																		
7th strake inboard																		
8th strake inboard																		
9th strake inboard																		
10th strake inboard																		
11th strake inboard																		
12th strake inboard																		
13th strake inboard																		
14th strake inboard																		
Centre strake inboard																		
Sheer strake	-	24	6.00	24.9	24.8	-0.9	-3.7	-0.8	-3.3	-	25	6.25	24.8	24.9	0.2	0.8	0.1	0.4

Operator's signature

Surveyor's signature

F.J.G. Slokkers

M.Ravesteijn

BUREAU VERITAS

REPORT ON THICKNESS MEASUREMENT OF DECK AND SHEERSTRAKE PLATING AT TRANSVERSE SECTIONS

🟥 Excessive corrosion
🟧 Substantial corrosion
🟩 Repaired

N-Av Orig. Thk Not Available

Vessel's name : RELATIONSHIP **BV Register N° : 36 B 893** **Report N° : DoS/689**

Frame N°	Transverse Section at Tank 7																	
STRAKE POSITION	No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S		No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S	
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%
Not applicable																		
Stringer Plate	-	15	3.75	15	14.9	0		0.1	0.7									
1st strake inboard																		
2nd strake inboard																		
3rd strake inboard																		
4th strake inboard																		
5th strake inboard																		
6th strake inboard																		
7th strake inboard																		
8th strake inboard																		
9th strake inboard																		
10th strake inboard																		
11th strake inboard																		
12th strake inboard																		
13th strake inboard																		
14th strake inboard																		
Centre strake inboard																		
Sheer strake	-	24	6.00	24.9	24.8	-0.9	-3.7	-0.8	-3.3									

Operator's signature

F.J.G. Slokkers

Surveyor's signature

M.Ravesteijn

BUREAU VERITAS

REPORT ON THICKNESS MEASUREMENT OF SIDE AND BOTTOM SHELL PLATING AT TRANSVERSE SECTIONS

🟥 Excessive corrosion
🟧 Substantial corrosion
🟩 Repaired

N-Av Orig. Thk Not Available

Vessel's name : RELATIONSHIP								BV Register N° : 36 B 893												Report N° : DoS/689
Frame N°	Transverse Section at Tank 2									Transverse Section at Tank 4										
STRAKE POSITION	No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S		No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S			
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%		
1st below sheer strake	-	10	1.50	9.4	9.2	0.6	6.0	0.8	8.0	-	10	1.50	8.4	8.4	1.6	16.0	1.6	16.0		
2nd below sheer strake	-	13	3.25	10.7	11	2.3	17.7	2	15.4	-	13	3.25	11.6	10.6	1.4	10.8	2.4	18.5		
3rd below sheer strake	-	10	2.50	8.4	9	1.6	16.0	1	10.0	-	10	2.50	8	7.6	2	20.0	2.4	24.0		
4th below sheer strake																				
5th below sheer strake																				
6th below sheer strake																				
7th below sheer strake																				
8th below sheer strake																				
9th below sheer strake																				
10th below sheer strake																				
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13th below sheer strake																				
14th below sheer strake																				
15th below sheer strake																				
16th below sheer strake																				
17th below sheer strake																				
18th below sheer strake																				
19th below sheer strake																				
20th below sheer strake																				
Keel strake	-	10	2.50	8.3	9.2	1.7	17.0	0.8	8.0	-	10	2.50	8.2	7.6	1.8	18.0	2.4	24.0		

Operator's signature

F.J.G. Slokkers

Surveyor's signature

M.Ravesteijn

BUREAU VERITAS

REPORT ON THICKNESS MEASUREMENT OF SIDE AND BOTTOM SHELL PLATING AT TRANSVERSE SECTIONS

🟥 Excessive corrosion
🟧 Substantial corrosion
🟩 Repaired

N-Av Orig. Thk Not Available

Vessel's name : RELATIONSHIP **BV Register N° : 36 B 893** **Report N° : DoS/689**

Frame N° Transverse Section at Tank 7

STRAKE POSITION	No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S		No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S	
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%
1st below sheer strake	-	10	1.50	8.1	8.4	1.9	19.0	1.6	16.0									
2nd below sheer strake	-	13	3.25	9.3	12	3.7	28.5	1	7.7									
3rd below sheer strake	-	10	2.50	8.5	8	1.5	15.0	2	20.0									
4th below sheer strake																		
5th below sheer strake																		
6th below sheer strake																		
7th below sheer strake																		
8th below sheer strake																		
9th below sheer strake																		
10th below sheer strake																		
11th below sheer strake																		
12th below sheer strake																		
13th below sheer strake																		
14th below sheer strake																		
15th below sheer strake																		
16th below sheer strake																		
17th below sheer strake																		
18th below sheer strake																		
19th below sheer strake																		
20th below sheer strake																		
Keel strake	-	10	2.50	8.7	9	1.3	13.0	1	10.0									

Operator's signature

F.J.G. Slokkers

Surveyor's signature

M.Ravesteijn

REPORT ON THICKNESS MEASUREMENT OF LONGITUDINAL MEMBERS AT TRANSVERSE SECTIONS

🟥 Excessive corrosion
🟧 Substantial corrosion
🟩 Repaired

N-Av Orig. Thk Not Available

Vessel's name : RELATIONSHIP **BV Register N° : 36 B 893** **Report N° : DoS/689**

Frame N°	Transverse Section at Tank 2									Transverse Section at Tank 4								
Structural items	No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S		No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S	
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%
Inner side long. flange	-	8	1.60	7.8	7.8	0.2	2.5	0.2	2.5	-	8	1.60	7.5		0.5	6.3		
Inner side long. flange	-	8	1.60	7.7	7.7	0.3	3.8	0.3	3.8	-	8							
Inner side long. flange	-	8	1.60	7.7	7.8	0.3	3.8	0.2	2.5	-	8	1.60	7.6	7.7	0.4	5.0	0.3	3.8
Inner side long. flange	-	8	1.60	7.7	7.9	0.3	3.8	0.1	1.3	-	8							
Inner side long. flange	-	8	1.60		7.7			0.3	3.8	-	8	1.60	7.7	7.5	0.3	3.8	0.5	6.3
Inner side long. flange	-	8	1.60	7.8	7.9	0.2	2.5	0.1	1.3	-	8	1.60		8			0	
Inner side long. flange	-	8	1.60	7.9	7.9	0.1	1.3	0.1	1.3	-	8							
Inner bottom girder flange	-	9	1.80	9.1	9	-0.1	-1.1	0		-	9	1.80	9	8.9	0		0.1	1.1
Inner bottom girder flange	-	9	1.80	9.1	9.1	-0.1	-1.1	-0.1	-1.1	-	9	1.80	9	8.8	0		0.2	2.2
Inner bottom girder flange	-	9	1.80	9		0				-	9							
Bottom girder flange	-	7	1.40	7	6.9	0		0.1	1.4	-	7	1.40	7.8	8.1	-0.8	-11.4	-1.1	-15.7
Bottom girder flange	-	7	1.40	6.9	7	0.1	1.4	0		-	7	1.40	8.2		-1.2	-17.1		
Bottom girder flange	-	7	1.40	7		0				-	7	1.40	8		-1	-14.3		

Operator's signature

F.J.G. Slokkers

Surveyor's signature

M.Ravesteijn

BUREAU VERITAS

REPORT ON THICKNESS MEASUREMENT OF LONGITUDINAL MEMBERS AT TRANSVERSE SECTIONS

🟥 Excessive corrosion
🟧 Substantial corrosion
🟩 Repaired

N-Av Orig. Thk Not Available

Vessel's name : RELATIONSHIP **BV Register N° : 36 B 893** **Report N° : DoS/689**

Frame N°	Transverse Section at Tank 7																	
Structural items	No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S		No or Letter	Orig. Thk	Max Alwd Dim.	Gauged		Diminution P		Diminution S	
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%
Inner side long. flange	-	8	1.60	7.8	7.8	0.2	2.5	0.2	2.5									
Inner side long. flange	-	8	1.60	7.7	7.7	0.3	3.8	0.3	3.8									
Inner side long. flange	-	8	1.60	7.7	7.8	0.3	3.8	0.2	2.5									
Inner side long. flange	-	8	1.60	7.7	7.9	0.3	3.8	0.1	1.3									
Inner side long. flange	-	8	1.60		7.7			0.3	3.8									
Inner side long. flange	-	8	1.60	7.8	7.9	0.2	2.5	0.1	1.3									
Inner side long. flange	-	8	1.60	7.9	7.9	0.1	1.3	0.1	1.3									
Inner bottom girder flange	-	9	1.80	9	8.9	0		0.1	1.1									
Inner bottom girder flange	-	9	1.80	9	8.8	0		0.2	2.2									
Inner bottom girder flange	-	9	1.80		9.1			-0.1	-1.1									
Bottom girder flange	-	8	1.60	8	7.9	0		0.1	1.3									
Bottom girder flange	-	8	1.60	8	8	0		0										
Bottom girder flange	-	8	1.60		8			0										

Operator's signature

F.J.G. Slokkers

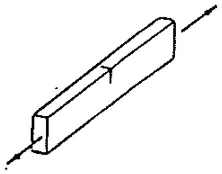
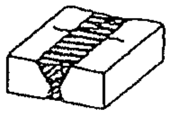
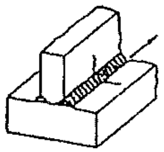
Surveyor's signature

M.Ravesteijn

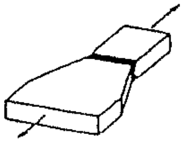
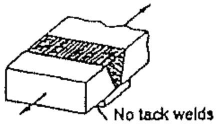
Report analysis : zone assessment

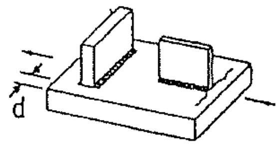
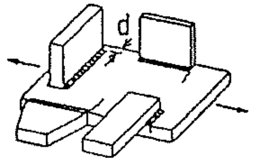
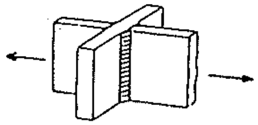
	Diminution [%]	Permissible wastage [%]
Deck	0.21	10.00
Neutral axis	11.52	15.00
Bottom	15.42	10.00

B APPENDIX: U.K DEn Basic Design S-N Curves

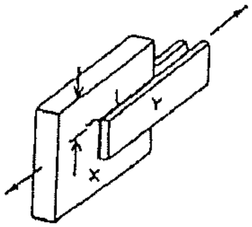
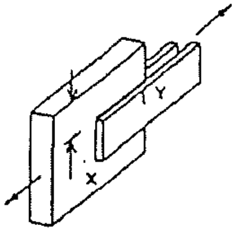
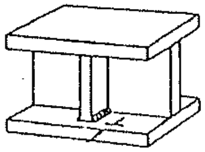
DEn Welded Joint Classification		
Joint Classification	Description	Examples
Category 1		
B	1) Parent metal in the as-rolled condition with no flame-cut edges or with flame-cut edges ground or machined.	
C	2) Parent material in the as-rolled condition with automatic flame-cut edges and ensured to be free from cracks.	
Category 2		
B	1) Full penetration butt welds with the weld cap ground flush with the surface and with the weld proved to be free from defects by NDT.	
C	2) Butt or fillet welds made by an automatic submerged or open arc process and with no stop-start positions within their length.	
D	3) As (2) but with stop-start positions within the length.	

DEn Welded Joint Classification
(cont'd)

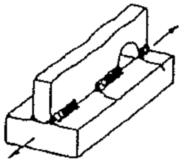
Joint Classification	Description	Examples
Category 3	Full penetration butt joints welded from both sides between plates of equal width and thickness or with smooth transition not steeper than 1 in 4:	
C	1) with the weld cap ground flush with the surface and with the weld proved to be free from significant defects by NDT.	
D	2) with the welds made either manually or by an automatic process other than submerged arc and in flat position.	
F	3) Welds made on a permanent backing strip between plates of equal width and thickness or tapered with a maximum slope of 1/4.	

DEn Welded Joint Classification (cont'd)		
Joint Classification	Description	Examples
Category 4	1) Parent material (of the stressed member) or ends of butt or fillet welded attachments (parallel to the direction of applied stresses) on stressed members :	
F	- attachment length ℓ ≤ 150 mm - edge distance d ≥ 10 mm	
F2	- attachment length ℓ > 150 mm - edge distance d ≥ 10 mm	
G	2) Parent material (of the stressed member) at toes or ends of butt or fillet welded attachments on or within 10 mm of edges or corners.	
Category 5		
F	1) Parent metal of cruciform or T Joints made with full penetration welds and with any undercut at the corners of the member ground out.	
F2	2) As (1) with partial penetration or fillet welds with any undercut at the corners of the member ground out.	

Den Welded Joint Classification
(cont'd)

Joint Classification	Description	Examples
Category 5		
	3) Parent metal of load-carrying fillet welds transverse to the direction of stresses (member X) :	
F2	edge distance d ≥ 10 mm	
G	edge distance d < 10 mm	
G	4) Parent metal of load-carrying fillet welds parallel to the direction of stresses, with the weld end on plate edge (member Y).	
Category 6		
	1) Parent metal at the toe of weld connection of web stiffeners to girder flanges :	
F	edge distance d ≥ 10 mm	
G	edge distance d < 10 mm	

Den Welded Joint Classification
(cont'd)

Joint Classification	Description	Examples
Category 6		
E	2) Intermittent fillet welds	
F	3) As (2) but adjacent to cut-outs.	

C APPENDIX: FATIGUE DAMAGE CALCULATIONS; CURVE B (SECONDARY STRUCTURAL DETAILS)

Ballast Load Case (Sailing Factor = 10%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psb	pwb-max	pwb-min	sl-max-ball	sl-min-bal	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	206.3841	12.31277	256	395	0.838	331	0.094
B	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.267	4.075645859	-4.075646	11.4075272	-0.77654956	52.11587	13.83704	48.82705	106.5424	19.17211	168.9	260.7	0.961	250	0.066
C	1.02	3	4.9	6	5.09	57.81	6	0.4				13.93	4.764579543	-4.76458	42.0366547	17.5712529	53.78383	14.27989	47.34674	160.3429	54.55655	184.9	285.3	0.93	265	0.048
D	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	193.6991	8.944836	246.7	380.7	0.847	322	0.087
E	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.12	4.066609998	-4.06661	11.2107282	-0.946336	51.64381	13.71171	48.82705	91.83328	15.37909	154.6	238.5	0.994	237	0.056
F	1	3	5	6	5.138	68.36	6	0.4				9.516	4.493503695	-4.493504	31.8957729	8.82230488	67.94575	18.03996	47.34674	119.6281	32.23722	144.2	222.5	1	223	0.026
G	0.98	3.1	5.1	5	4.458	42.63	6.813	0.6	6.83	0	0				11.1158486	11.1158486	88.40186	23.47116	53.30562	114.3555	40.98383	134.1	207	1	207	0.029

Fully-Loaded Case (Sailing Factor = 10%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psc	pwc-max	pwc-min	sl-max-car	sl-min-car	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	358.8616	203.8379	216.9	334.8	0.881	295	0.046
B	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.66	5.031147913	-5.031148	127.917506	112.876971	59.58249	21.30367	48.82705	396.9868	302.774	175.8	271.2	0.947	257	0.033
C	1.06	2.8	4.7	5	3.6	31.53	4.694	0.6				66.95	3.206807454	-3.206807	151.467807	135.001331	61.48942	21.98549	47.34674	376.6473	285.8157	169.9	262.2	0.959	251	0.057
D	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	344.3592	198.6526	207.6	320.4	0.893	286	0.042
E	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.52	5.023015637	-5.023016	127.740387	112.724163	59.0428	21.1107	48.82705	368.7457	285.7296	161.1	248.7	0.978	243	0.028
F	1.03	2.9	4.9	5	4.108	44.11	5.299	0.6				62.97	2.962839191	-2.962839	142.341013	127.127278	77.68032	27.77453	47.34674	279.0027	202.1707	133.6	206.2	1	206	0.027
G	0.98	3.1	5.1	4	3.578	26.804	6.813	0.7				57.24	2.610440588	-2.610441	98.3205504	88.1166779	101.0672	36.13647	53.30562	242.1182	155.4716	147.4	227.5	1	227	0.045

Ballast Load Case (Sailing Factor = 40%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psb	pwb-max	pwb-min	sl-max-ball	sl-min-bal	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	206.3841	12.31277	256	395	0.838	331	0.378
B	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.267	4.075645859	-4.075646	11.4075272	-0.77654956	52.11587	13.83704	48.82705	106.5424	19.17211	168.9	260.7	0.961	250	0.263
C	1.02	3	4.9	6	5.09	57.81	6	0.4				13.93	4.764579543	-4.76458	42.0366547	17.5712529	53.78383	14.27989	47.34674	160.3429	54.55655	184.9	285.3	0.93	265	0.19
D	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	193.6991	8.944836	246.7	380.7	0.847	322	0.349
E	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.12	4.066609998	-4.06661	11.2107282	-0.946336	51.64381	13.71171	48.82705	91.83328	15.37909	154.6	238.5	0.994	237	0.223
F	1	3	5	6	5.138	68.36	6	0.4				9.516	4.493503695	-4.493504	31.8957729	8.82230488	67.94575	18.03996	47.34674	119.6281	32.23722	144.2	222.5	1	223	0.105
G	0.98	3.1	5.1	5	4.458	42.63	6.813	0.6	6.83	0	0				11.1158486	11.1158486	88.40186	23.47116	53.30562	114.3555	40.98383	134.1	207	1	207	0.117

Fully-Loaded Case (Sailing Factor = 40%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psc	pwc-max	pwc-min	sl-max-car	sl-min-car	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	358.8616	203.8379	216.9	334.8	0.881	295	0.184
B	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.66	5.031147913	-5.031148	127.917506	112.876971	59.58249	21.30367	48.82705	396.9868	302.774	175.8	271.2	0.947	257	0.133
C	1.06	2.8	4.7	5	3.6	31.53	4.694	0.6				66.95	3.206807454	-3.206807	151.467807	135.001331	61.48942	21.98549	47.34674	376.6473	285.8157	169.9	262.2	0.959	251	0.226
D	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	344.3592	198.6526	207.6	320.4	0.893	286	0.168
E	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.52	5.023015637	-5.023016	127.740387	112.724163	59.0428	21.1107	48.82705	368.7457	285.7296	161.1	248.7	0.978	243	0.113
F	1.03	2.9	4.9	5	4.108	44.11	5.299	0.6				62.97	2.962839191	-2.962839	142.341013	127.127278	77.68032	27.77453	47.34674	279.0027	202.1707	133.6	206.2	1	206	0.109
G	0.98	3.1	5.1	4	3.578	26.804	6.813	0.7				57.24	2.610440588	-2.610441	98.3205504	88.1166779	101.0672	36.13647	53.30562	242.1182	155.4716	147.4	227.5	1	227	0.179

Ballast Load Case (Sailing Factor = 60%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psb	pwb-max	pwb-min	sl-max-ball	sl-min-bal	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	206.3841	12.31277	256	395	0.838	331	0.566
B	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.267	4.075645859	-4.075646	11.4075272	-0.77654956	52.11587	13.83704	48.82705	106.5424	19.17211	168.9	260.7	0.961	250	0.395
C	1.02	3	4.9	6	5.09	57.81	6	0.4				13.93	4.764579543	-4.76458	42.0366547	17.5712529	53.78383	14.27989	47.34674	160.3429	54.55655	184.9	285.3	0.93	265	0.285
D	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	193.6991	8.944836	246.7	380.7	0.847	322	0.523
E	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.12	4.066609998	-4.06661	11.2107282	-0.946336	51.64381	13.71171	48.82705	91.83328	15.37909	154.6	238.5	0.994	237	0.334
F	1	3	5	6	5.138	68.36	6	0.4				9.516	4.493503695	-4.493504	31.8957729	8.82230488	67.94575	18.03996	47.34674	119.6281	32.23722	144.2	222.5	1	223	0.157
G	0.98	3.1	5.1	5	4.458	42.63	6.813	0.6	6.83	0	0				11.1158486	11.1158486	88.40186	23.47116	53.30562	114.3555	40.98383	134.1	207	1	207	0.176

Fully-Loaded Case (Sailing Factor = 60%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psc	pwc-max	pwc-min	sl-max-car	sl-min-car	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	358.8616	203.8379	216.9	334.8	0.881	295	0.275
B	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.66	5.031147913	-5.031148	127.917506	112.876971	59.58249	21.30367	48.82705	396.9868	302.774	175.8	271.2	0.947	257	0.199
C	1.06	2.8	4.7	5	3.6	31.53	4.694	0.6				66.95	3.206807454	-3.206807	151.467807	135.001331	61.48942	21.98549	47.34674	376.6473	285.8157	169.9	262.2	0.959	251	0.34
D	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	344.3592	198.6526	207.6	320.4	0.893	286	0.252
E	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.52	5.023015637	-5.023016	127.740387	112.724163	59.0428	21.1107	48.82705	368.7457	285.7296	161.1	248.7	0.978	243	0.169
F	1.03	2.9	4.9	5	4.108	44.11	5.299	0.6				62.97	2.962839191	-2.962839	142.341013	127.127278	77.68032	27.77453	47.34674	279.0027	202.1707	133.6	206.2	1	206	0.164
G	0.98	3.1	5.1	4	3.578	26.804	6.813	0.7				57.24	2.610440588	-2.610441	98.3205504	88.1166779	101.0672	36.13647	53.30562	242.1182	155.4716	147.4	227.5	1	227	0.269

Ballast Load Case (Sailing Factor = 85%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psb	pwb-max	pwb-min	sl-max-ball	sl-min-bal	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	206.3841	12.31277	256	395	0.838	331	0.803
B	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.267	4.075645859	-4.075646	11.4075272	-0.77654956	52.11587	13.83704	48.82705	106.5424	19.17211	168.9	260.7	0.961	250	0.559
C	1.02	3	4.9	6	5.09	57.81	6	0.4				13.93	4.764579543	-4.76458	42.0366547	17.5712529	53.78383	14.27989	47.34674	160.3429	54.55655	184.9	285.3	0.93	265	0.404
D	1.12	2.7	4.5	8	3.99	42.79	4.171	0.3	4.74	3.135293	-3.135293	11.28	4.506355263	-4.506355	46.618052	-7.79291613	74.61759	19.81137	38.70148	193.6991	8.944836	246.7	380.7	0.847	322	0.741
E	1.13	2.7	4.4	5	3.352	23.284	4.171	0.5				4.12	4.066609998	-4.06661	11.2107282	-0.946336	51.64381	13.71171	48.82705	91.83328	15.37909	154.6	238.5	0.994	237	0.473
F	1	3	5	6	5.138	68.36	6	0.4				9.516	4.493503695	-4.493504	31.8957729	8.82230488	67.94575	18.03996	47.34674	119.6281	32.23722	144.2	222.5	1	223	0.222
G	0.98	3.1	5.1	5	4.458	42.63	6.813	0.6	6.83	0	0				11.1158486	11.1158486	88.40186	23.47116	53.30562	114.3555	40.98383	134.1	207	1	207	0.249

Fully-Loaded Case (Sailing Factor = 85%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	pse	pwe-max	pwe-min	psc	pwc-max	pwc-min	sl-max-car	sl-min-car	sh-max	sh-min	DsDEF	sG-max	sG-min	DsG	DsNo	KC	DsN	DB
A	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	358.8616	203.8379	216.9	334.8	0.881	295	0.39
B	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.66	5.031147913	-5.031148	127.917506	112.876971	59.58249	21.30367	48.82705	396.9868	302.774	175.8	271.2	0.947	257	0.282
C	1.06	2.8	4.7	5	3.6	31.53	4.694	0.6				66.95	3.206807454	-3.206807	151.467807	135.001331	61.48942	21.98549	47.34674	376.6473	285.8157	169.9	262.2	0.959	251	0.481
D	0.98	3.1	5.1	7	6.306	102.812	6.813	0.3	31.6	5.037968	-5.037968				111.651811	75.7798796	85.30803	30.50181	38.70148	344.3592	198.6526	207.6	320.4	0.893	286	0.357
E	0.98	3.1	5.1	7	6.166	95.596	6.813	0.4				96.52	5.023015637	-5.023016	127.740387	112.724163	59.0428	21.1107	48.82705	368.7457	285.7296	161.1	248.7	0.978	243	0.239
F	1.03	2.9	4.9	5	4.108	44.11	5.299	0.6				62.97	2.962839191	-2.962839	142.341013	127.127278	77.68032	27.77453	47.34674	279.0027	202.1707	133.6	206.2	1	206	0.233
G	0.98	3.1	5.1	4	3.578	26.804	6.813	0.7				57.24	2.610440588	-2.610441	98.3205504	88.1166779	101.0672	36.13647	53.30562	242.1182	155.4716	147.4	227.5	1	227	0.381

D APPENDIX: FATIGUE DAMAGE CALCULATIONS; CURVE B (PRIMARY STRUCTURAL DETAILS)

Ballast Load Case (Sailing Factor = 10%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	152.44	41.4	111.04	166.6	291.48	0.92249	268.888	0.0783763
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	186.16	54.46	131.7	197.6	345.7125	0.8719	301.428	0.11641742
J	1.131639879	2.7	4.4	3.5	2.2	9.56	4.171	0.7229638	-125.23	-32.75	92.48	138.7	242.76	0.98721	239.656	0.08557761
K	1.134162503	2.6	4.4	5.2	3.04	23.284	3.717	0.5243152	-81.62	-17.77	63.85	95.78	167.60625	1	167.606	0.01919337

Fully-Loaded Case (Sailing Factor = 10%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	-173.34	-62.3	111.04	166.6	291.48	0.92249	268.888	0.0783763
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	-202.2	-70.5	131.7	197.6	345.7125	0.8719	301.428	0.11641742
J	0.983175	3.1	5.1	4.1	3.846	31.07	6.813	0.6939919	149.24	56.75	92.49	138.7	242.78625	0.98717	239.672	0.05046256
K	0.983175	3.1	5.1	5.8	5.556	71.85	6.813	0.4796914	94.65	30.8	63.85	95.78	167.60625	1	167.606	0.0119288

Ballast Load Case (Sailing Factor = 40%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	152.44	41.4	111.04	166.6	291.48	0.92249	268.888	0.31350519
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	186.16	54.46	131.7	197.6	345.7125	0.8719	301.428	0.46566969
J	1.131639879	2.7	4.4	3.5	2.2	9.56	4.171	0.7229638	-125.23	-32.75	92.48	138.7	242.76	0.98721	239.656	0.34231043
K	1.134162503	2.6	4.4	5.2	3.04	23.284	3.717	0.5243152	-81.62	-17.77	63.85	95.78	167.60625	1	167.606	0.0767735

Fully-Loaded Case (Sailing Factor = 40%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	-173.34	-62.3	111.04	166.6	291.48	0.92249	268.888	0.31350519
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	-202.2	-70.5	131.7	197.6	345.7125	0.8719	301.428	0.46566969
J	0.983175	3.1	5.1	4.1	3.846	31.07	6.813	0.6939919	149.24	56.75	92.49	138.7	242.78625	0.98717	239.672	0.20185024
K	0.983175	3.1	5.1	5.8	5.556	71.85	6.813	0.4796914	94.65	30.8	63.85	95.78	167.60625	1	167.606	0.04771522

Ballast Load Case (Sailing Factor = 60%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	152.44	41.4	111.04	166.6	291.48	0.92249	268.888	0.47025779
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	186.16	54.46	131.7	197.6	345.7125	0.8719	301.428	0.69850454
J	1.131639879	2.7	4.4	3.5	2.2	9.56	4.171	0.7229638	-125.23	-32.75	92.48	138.7	242.76	0.98721	239.656	0.51346564
K	1.134162503	2.6	4.4	5.2	3.04	23.284	3.717	0.5243152	-81.62	-17.77	63.85	95.78	167.60625	1	167.606	0.11516025

Fully-Loaded Case (Sailing Factor = 60%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	-173.34	-62.3	111.04	166.6	291.48	0.92249	268.888	0.47025779
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	-202.2	-70.5	131.7	197.6	345.7125	0.8719	301.428	0.69850454
J	0.983175	3.1	5.1	4.1	3.846	31.07	6.813	0.6939919	149.24	56.75	92.49	138.7	242.78625	0.98717	239.672	0.30277536
K	0.983175	3.1	5.1	5.8	5.556	71.85	6.813	0.4796914	94.65	30.8	63.85	95.78	167.60625	1	167.606	0.07157283

Ballast Load Case (Sailing Factor = 85%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	152.44	41.4	111.04	166.6	291.48	0.92249	268.888	0.66619854
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	186.16	54.46	131.7	197.6	345.7125	0.8719	301.428	0.9895481
J	1.131639879	2.7	4.4	3.5	2.2	9.56	4.171	0.7229638	-125.23	-32.75	92.48	138.7	242.76	0.98721	239.656	0.72740966
K	1.134162503	2.6	4.4	5.2	3.04	23.284	3.717	0.5243152	-81.62	-17.77	63.85	95.78	167.60625	1	167.606	0.16314368

Fully-Loaded Case (Sailing Factor = 85%)

ID	x	3/x	5/x	n	GN(3/x+1,n)	GN(5/x+1,n)	GC(3/x+1)	m	sn-max	sn-min	Dsn	DsS	DsNo	KC	DsN	DB
H	0.983175	3.1	5.1	3.6	3.152	20.846	6.813	0.7633191	-173.34	-62.3	111.04	166.6	291.48	0.92249	268.888	0.66619854
I	0.983175	3.1	5.1	3.3	2.714	15.704	6.813	0.8048316	-202.2	-70.5	131.7	197.6	345.7125	0.8719	301.428	0.9895481
J	0.983175	3.1	5.1	4.1	3.846	31.07	6.813	0.6939919	149.24	56.75	92.49	138.7	242.78625	0.98717	239.672	0.42893176
K	0.983175	3.1	5.1	5.8	5.556	71.85	6.813	0.4796914	94.65	30.8	63.85	95.78	167.60625	1	167.606	0.10139484