D 5.2 “Retrofitting Consequences”

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ABSTRACT

This document covers the analyses and developments of task 5.2 “Retrofitting consequences” within work package 5 “Structures & weight” relating to retrofitting solutions for actual single hull inland navigation tankers into double hull vessels and alternative solutions for the lengthening of inland navigation vessels. Innovative designs using lightweight structures and new materials such as composites are considered in order to assess their capabilities and benefits.

Two vessels are considered for the investigations:

- Single hull inland navigation tanker: MV “Internautic I“ with a length over all of 80.0 m and a cargo capacity of 1980 t at a draught of 3.63 m
- Double hull multi-purpose cargo vessel: MV “HERSO I” with a length over all of 84.95 m and a cargo capacity of 1381.5 t at a draught of 2.70 m

In order to meet the upcoming ADN regulations for the carriage of dangerous goods in 2018 where only vessels equipped with a double hull are permitted, various alternative double hull designs are investigated towards their feasibility as retrofit solution, namely:

- Steel/polymer-foam/steel double side structure
- λ-shape alternative steel structure
- Rubber bags with supporting structure

For the lengthening investigations the following composite variants are considered:

- Solid glass fibre reinforced polymer section
- Glass fibre reinforced polymer sandwich section
- Solid carbon fibre reinforced polymer section
- Carbon fibre reinforced polymer sandwich section

These innovative solutions are compared to the mandatory base steel double hull, complying with the current classification rules of Germanischer Lloyd and ADN requirements if applicable, to reveal benefits and drawbacks using computer aided design (CAD) tools and finite element analyses (FEA). A risk assessment completes the evaluation of the novel technologies.

Related documents are D 5.3 “Crashworthiness”, in which the capabilities in terms of side impact and grounding are presented, D 5.4 “Production”, where the economic assessment is conducted, and D 6.1 “Structures” as well as D 7.1 “System integration”, where ships are lengthened by conventional methods.

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1 Executive Summary

(Author: CMT)

1.1 Problem Definition

The MoVeIT! project (Modernisation of Vessels for Inland waterway freight Transport) was started with the aim to develop cost efficient modernisations of inland water vessels.
Referring to the DOW, the aim of WP 5 is to find feasible solutions for:

- Lengthening of an existing inland navigation vessel
- Conversion of a single hull tanker to a double hull tanker with respect to ADN requirements

The operators of inland water vessel have to deal with long periods of low water levels caused by long periods of dryness as well as with renewed rules and requirements for their vessels. Ship lengthening makes it possible to reduce the draft without reducing the payload.
Due to upcoming new ADN regulations, a double hull structure will be mandatory after 2018 for all inland water vessels transporting dangerous goods. A large part of these vessels have currently a single hull structure and cannot therefore be used after 2018. To allow further use, the ships have to be retrofitted with a double hull or they will have to be used for other types of services.
Even though the conversion according to the ADN rules only considers inland navigation tankers, the lengthening task can be applied on all types of inland water way cargo ships. The general target of the work is to examine and understand the main critical parameters regarding the structures of the cargo ship.
Two reference ships were selected, one for each of the two structural modifications, i.e., ship lengthening and retrofitting of a double hull. The selected ships are representative for the current fleet. Due to the fact that a significant share of the inland navigation vessels is over-aged, it turned out to be difficult to collect technical documentation on the ship´s structures.

1.2 Technical approach

In WP 5 new lightweight materials and structural designs are considered in order to investigate the benefits and drawbacks of alternative retrofit solutions for the double hull and cargo holds of inland navigation vessels. Aft and fore ship are considered in WP 2, where the hydrodynamic assessment is performed, and the engine room is treated in WP 4. The implementation of feasible retrofit solutions (implying in accordance with the present rules and regulations) is documented in WP 6 and WP 7. As application cases two vessels have been identified: MV “Internautic I” representing the single hull tanker fleet and MV “HERSO I” representing the dry cargo fleet from one of the MoVeIT! consortium members Plimsoll.
Considerations regarding the assessment of crashworthy structures are presented in deliverable D 5.3 “Crashworthiness”. Production and cost evaluation including economic assessment is presented in deliverable D 5.4 “Production”.
Two different retrofit options are investigated within this present deliverable considering novel structures and materials for the application on inland waterway vessels:

- Lengthening of existing vessels
- Retrofit of existing single hull tankers towards double hull arrangements

The technical approach for the single-to-double hull conversion comprises the subsequent steps:

1. Defining requirements for the selected vessel MV “Internautic I“
2. Investigating requirements from the view of classification society, ADN code and other regulative bodies
3. Selection of retrofit variants with respect to the application of new materials and structural designs
4. Assessment of retrofit variants taking into account the structural strength of the vessel and optimisation of cargo carrying capacity to improve the overall efficiency of the vessel
5. Final evaluation

The technical approach for the lengthening hull conversion comprises the following steps:

1. Defining requirements for the selected vessel MV “HERSO I“
2. Investigating requirements from the view of classification society
3. Assessment of composite lengthening variants
4. Final evaluation

1.3 Results and Achievements

Throughout the performed work within WP 5 and especially task 5.2 “Retrofitting consequences” novel approaches for the retrofit of existing inland navigation vessels by unconventional means are introduced. Innovative concepts for the single-to-double hull retrofit of existing inland navigation tankers are developed:

- Steel/polymer-foam/steel double side, considering an inner steel shell which is adhesively bonded to a polymer-foam core to create a sandwich structure.
- λ-shape double side, considering an inner steel shell and a corrugated steel plating acting as foldable core in case of a side impact.
- Rubber bags, implemented into the existing steel hull with the aid of polystyrene blocks as supports.

Additionally, advanced solutions for the lengthening of inland navigation vessels by the application of solid and sandwich composites made from glass and carbon fibres:

- Composite section made of either solid glass fibre reinforced plastics or carbon fibre reinforced plastics.
- Composite section made of either glass fibre reinforced sandwich or carbon fibre reinforced sandwich structures.

The developments serve as base for the shipowners to decide on concrete conversions for their distinct and individual vessels.

1.4 Contribution to MoVeIT! Objectives

Within task 5.2 of WP 5 a set of options for the modernisation of over-aged inland navigation vessels is proposed and elaborated towards their technical feasibility. Novel design aspects and the integration of metallic and non-metallic structures are presented with respect to the objectives of the MoVeIT! project: minimise investments and maximise efficiency.

1.5 Exploitation and Implementation

The presented results of this task are obtained for particular case studies, but keeping in mind that the retrofit solutions can also be applied to other type of ships featuring similar structural and design characteristics. As the developed retrofit solutions involve new materials such as composites and polymer-foam which are offending against current classification rules and ADN requirements it is not feasible to implement the developed solutions as they are for ship yards and shipping companies at the moment. The results provide an overview of benefits and difficulties relating to requirements from classification societies, authorities and regulative bodies.

2 Introduction

(Author: CMT)

The report D 5.2 “Retrofitting consequences” deals with the development and assessment of alternative structures for inland navigation vessels with main focus on existing single hull tankers carrying dangerous goods and lengthening procedures. It is integral part within WP 5 “Structures & Weight” and involves close collaboration and exchange of input and results with the tasks T 5.3 “Crashworthiness” and T 5.4 “Production”.
For this reason, this report cannot be considered solitary but has to be put in context of the other deliverables within WP 5 to obtain a comprehensive understanding of the entire work package.

2.1 Objectives

Due to stronger upcoming prescriptive regulations inland navigation vessels handling dangerous cargo and therefore especially tankers require new designs for a safer operation in the future. In this context WP 5 aims to find technical solutions for the retrofit of single hull inland navigation tankers towards double hull structures to reduce the risk of a leakage in case of side collisions and grounding events. Keeping the economic situation of the ship owners in mind the solutions need to be easy to install accompanied with a minimum of cost and additional weight involved resulting in a good operational handling.
Consequently, selecting typical ship structures and modelling case studies as a result of the state-of-the-art analysis as performed in task T 5.1 is of importance revealing the needs towards regulations for retrofitting. The developed structural solutions consider conventional steel designs as well as new composite and lightweight metallic structures. Numerical methods are applied to calculate global strength, local stresses and weight for the developed retrofit structures. Special attention is put on the regulatory bodies such as ADN and classification society requirements.
In short, the development comprises the following actions according to the DoW:

- Analysing the requirements of the Common Structural Rules (CSR) for seagoing ships with respect to their applicability on inland navigation vessels.
- Developing numerical models for calculating global strength of existing vessels.
- Definition of the collision relevant parameters with respect to the application on inland waterway vessels, definition of collision scenarios.
- Find structures and joint technologies for retrofitting considering the defined parameters and risk (goal)-based design.
- Development and testing of numerical and CAD models.
- Combination of the vessel and the retrofit structures. Calculation and optimisation of the structures regarding global strength, weight and local stress.

The production and economic assessment of the different variants which are developed in this task is described in the deliverable D 5.4 “Production”.

Recent investigations towards the improvement of crashworthy side structures were made in the German national funded project ELKOS for RoRo ferries according to SOLAS 2009 (Improvement of the crashworthiness by integration of structural measures into the damage stability calculation of state-of-the-art RoRo ferries). The project, finalised in late 2013, aimed to combine ship design, damage stability calculation and structural mechanics. The focus has been on the development of crashworthy double side structures and bulbous bow structures with deformable elements to prevent the inner hull from fracture and hence also leakage. Considering the RoRo double hull remarkable results were obtained. The investigations revealed that an improved design, capable of absorbing twice as much collision energy as the standard structure, only improved the probability of leakage by approximately 4.8 %. This phenomenon is caused by the fact that the crashworthiness is statistically dominated by high energy collisions resulting to inner shell rupture in the standard and the improved double side case. Thus, not only the energy absorption is of importance, but also the statistical influence [(1)].

2.2 *Fleet and market observation*

The current western European tank fleet still consists of a significant amount of single hull tankers within the category “Type N”, intended the carriage of fluids. Statistics from the countries Switzerland, France, Germany, Netherlands, Belgium and Luxembourg show that approximately 85 % single hull vessels of “Type N” are still in service by April 2013 (Double hull: 215 units, single hull: 1231 units). Hence, there is great potential for the single-to-double hull retrofit. Single hull vessels in the current fleet of category “Type G” vessels, intended for the carriage of gas under pressure or/and refrigerated state, and category “Type C” vessels, intended for the carriage of fluids without a trunk, are negligible as indicated in Figure 1. The data originates from the “International Association the Rhine Ships Register” (IVR).

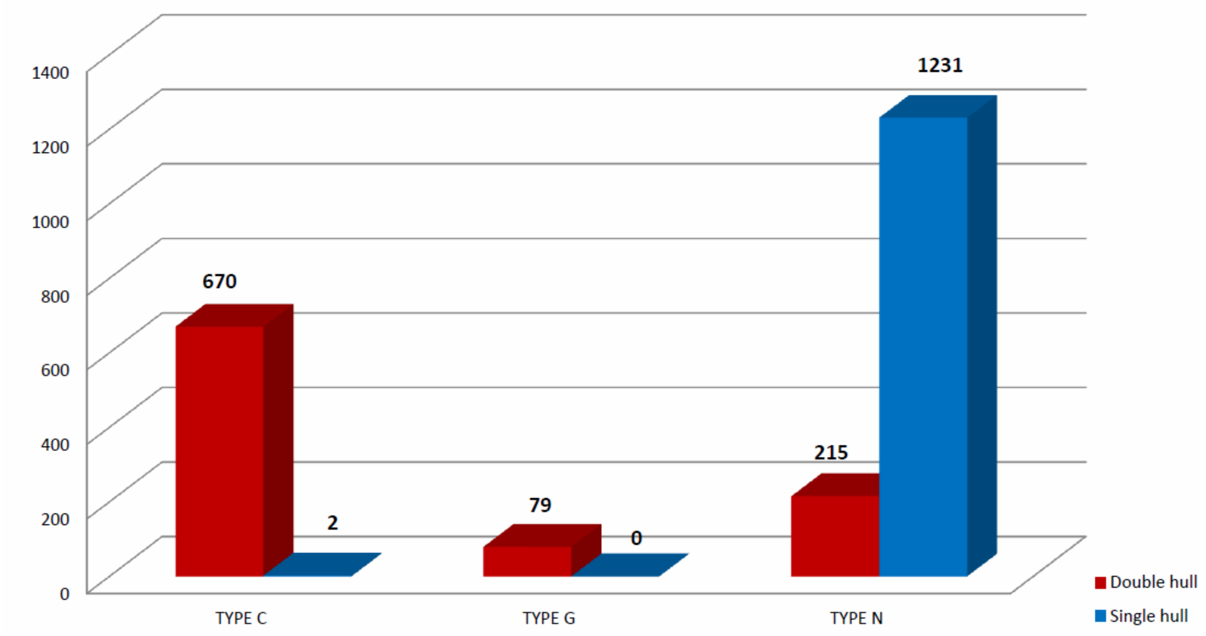

Figure 1: Total western European tank fleet (2)

Another issue regarding the retrofit of existing single hull vessels is the distribution of their year of construction. Figures from IVR indicate that there are still many old inland navigation vessels in service. According to Figure 2 half of the currently operating tanker fleet, comprising tank vessels, push tank barges and tank lighters, has been built before 1975 for the same set of western European countries as mentioned in the previous paragraph. The increase of newbuildings in the period from 2005 to 2012 can be related to the introduction of harsher requirements for the carriage of dangerous goods, where double hull vessels are mandatory [(2)].

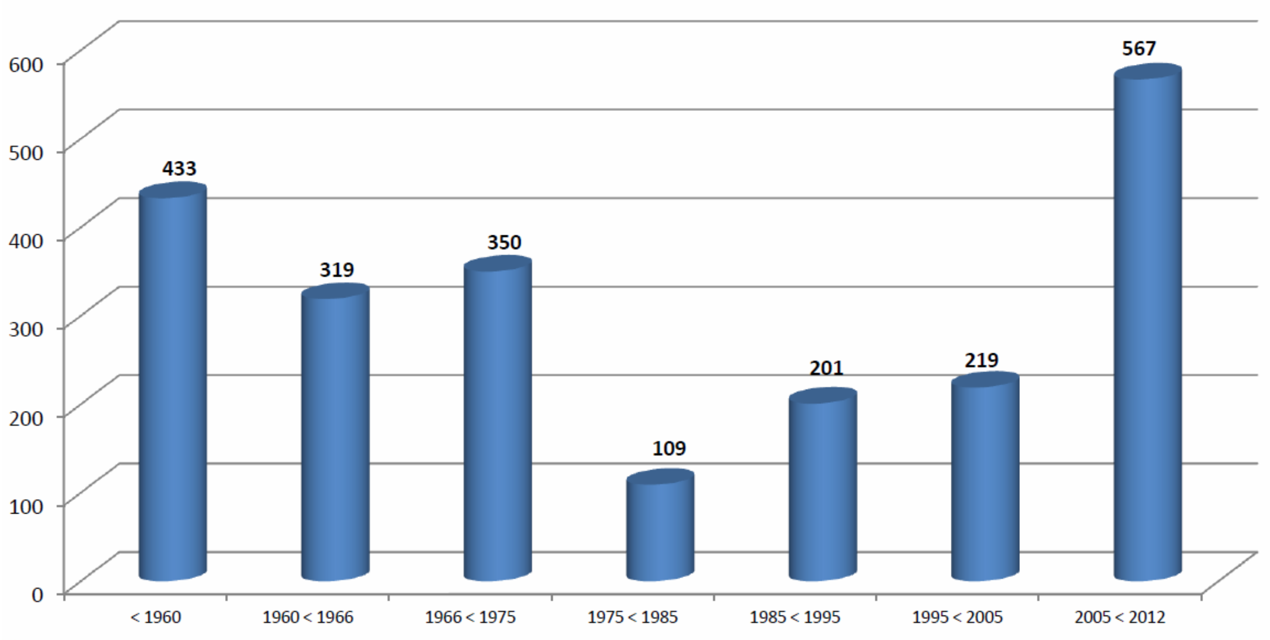

Figure 2: Years of construction for the western European tank fleet, as per 2012 [(2)]

Although the presented data does not cover the entire European fleet, especially not the eastern European region, it can be regarded as an indication on the composition of the current tank fleet in service. As a conclusion, a sufficient amount of single hull vessels should be available for single-to-double hull retrofit conversions. However, the share of conversions in relation to newbuildings has been of minor importance so far. This observation is backed by the figures taken from the published document “Inland Navigation in Europe – Market observation 2011-1” which indicate that conversions are not very popular for the inland shipping industry in general [(3), page 40]. The shares are presented in Figure 3 and include the countries mentioned in the previous paragraphs without France. A disadvantage of a conversion is that the building year of the vessel does not change which directly affects the insurance rates for the vessels in a negative way.

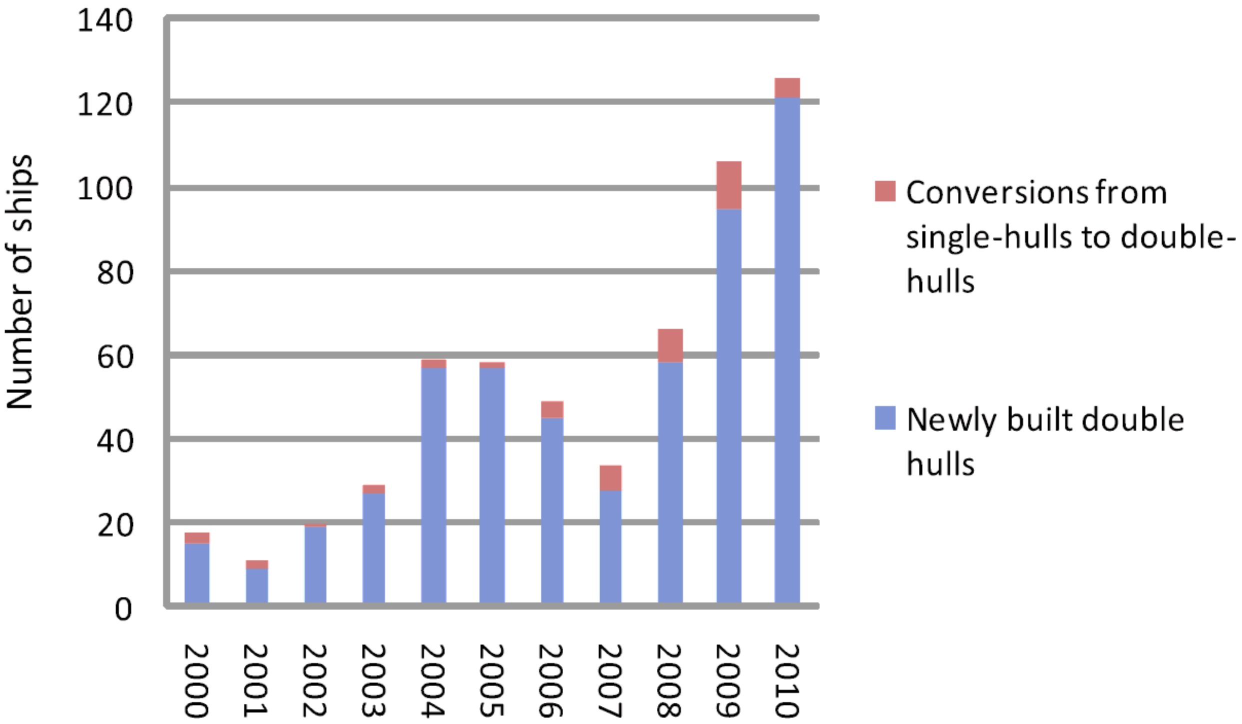

Figure 3: Annual growth of double hull ships [page 40 (3)]

Currently, the tank fleet is in the phase of being converted from single hull to double hull ships according to the transitional requirements of the ADN code which permit certain types of vessels to continue the carriage of dangerous goods in single hull ships until the transition period ends in 2018. This means that single hull vessels may continue operation in parallel with double hull vessels on European inland waterways. The deadlines for various types of cargo are presented in Table 1. The newbuilding activities of double hull vessels are therefore of importance as most of the single hull vessels have to be replaced, converted, sold outside the EU or scrapped by the end of 2018.

Table 1: Transition deadlines for inland tanker shipping [Ch. 1.6.7.4.2 (4)]

End of the transition deadline	
31.12.2015	31.12.2018
• Petrol • Various other petroleum distillates • Hydrocarbons	• Diesel • Gas oil • Light heating oil • Kerosene • Jet fuel • Turpentine oil substitute

In the past years the tank ship owners anticipated early the transition periods of the ADN code and started to invest in new ships fulfilling the future requirements resulting in a substantial increase of the available freight capacities. For this reason, an over-capacity of more than 35 % in the beginning of 2012 exists and will last for a longer period of time on the market with negative influences on the attained freight rates in the tanker shipping business. Especially in the period from 2008 to 2010 the newbuilding of double hull vessels has significantly increased as indicated in Figure 3 and only a few single hull ships have left the European market. Additionally, the individual size of the new vessels increases which results in an even higher increase in the available transportation capacity of the tank fleet. By the end of 2010 the transportation capacity share of double hull vessels was located around 75 % of the total tank fleet [(5), page 11].

The general demand for mineral oil product capacity has slightly regressed in the period from 2003 to 2010 and indications show evidence that this state will continue in the near future. In contrast, the chemical sector exhibits a growth resulting in an increase of the demand in the tanker transportation capacity in general in that period about 4 % [(5), page 11].

It has to be noted that chemical and oil companies increasingly rely on double hull vessels although they are not prescriptive for some cargos. Those companies are reluctant to ship their cargo with single hull vessels due to image aspects to obtain an environmentally friendly transportation mode.

3 Base vessels

(Author: CMT)

Two vessels are taken as reference ships for the retrofit investigations and are presented briefly in the following two subsections.

3.1 *Vessel for the single-to-double hull retrofit*

For the single-to-double hull investigations a suitable single hull inland navigation tanker in need of modernisation is identified allowing for the foreseen modifications relating to the description of work of WP 5. Due to a lack of single hull tankers in the shipping companies within the project consortium and very limited documentation available, a single hull vessel is chosen based on the fact that sufficient documentation in terms of drawings and technical details are available.

The reference vessel MV “Internautic I” has already been introduced in deliverable D 5.1. However, some important details are going to be presented again as they set the base for the retrofitting investigations.

The inland navigation tanker MV “Internautic I” was built at Bayerische Schiffbau GmbH in 1968 as a self-propelled vessel according to GL classification rules. The vessel’s main dimensions are: L_{OA} = 80.00 m, B_{OA} = 9.00 m and T = 3.70 m [(6)]. The hull geometry features a simplified main frame arrangement by applying a 45°-angled chine instead of a chine radius. The bottom and the trunk is longitudinally framed with a spacing of 645 mm, the side shell is transversally framed with a spacing of 500 mm. The total cargo capacity of 1980 t is divided into 5 separate holds which are split into a port and starboard tank. Looking from the aft, the 2 forward holds and the 4th and 5th hold have a length of 10.5 m whereas the 3rd hold has a length of 14.0 m. The individual tanks are separated by a corrugated longitudinal bulkhead and corrugated transversal bulkheads.

Pictures of the vessel are presented in Figure 4 and detailed information relating to the structures can be found in the general arrangement plan and the main frame section in Figure 5 and Figure 6 respectively.

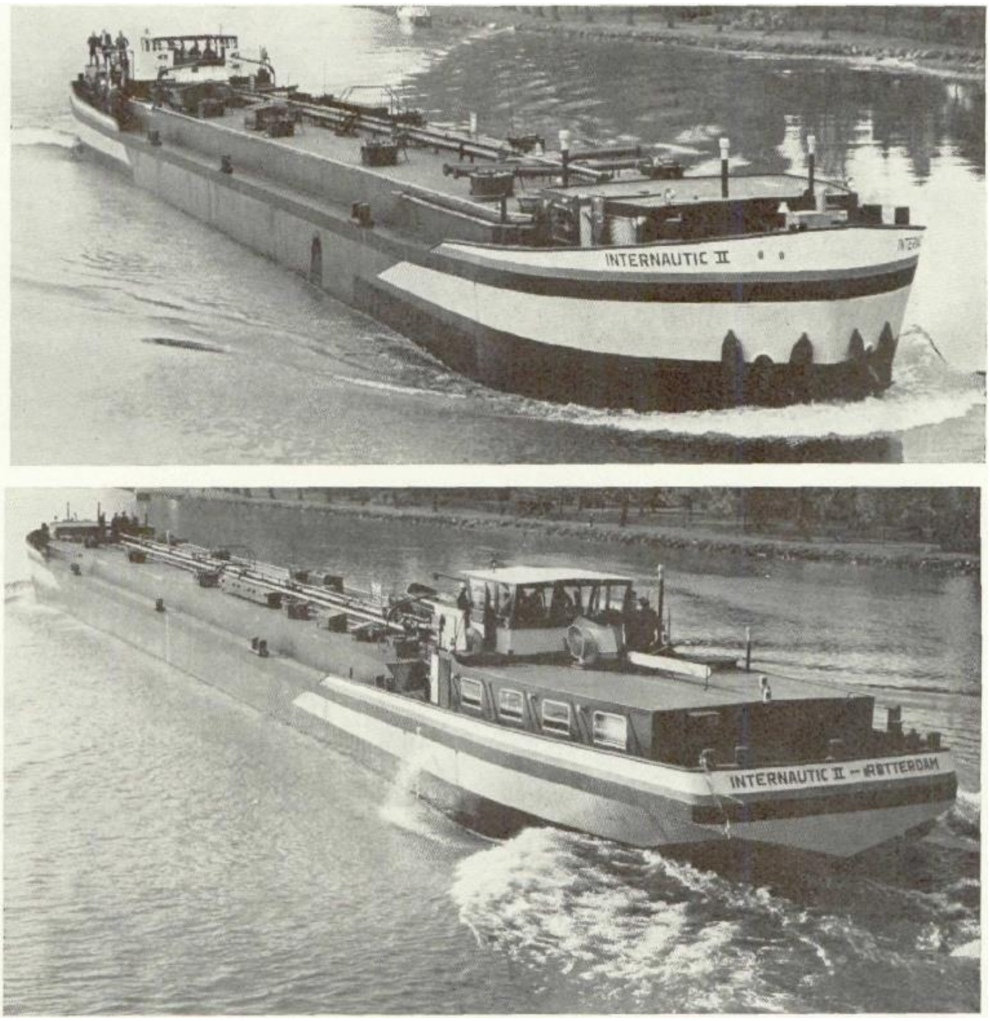

Figure 4: MV "Internautic 1" (Schiff und Hafen, issue 5/1969, volume 21)

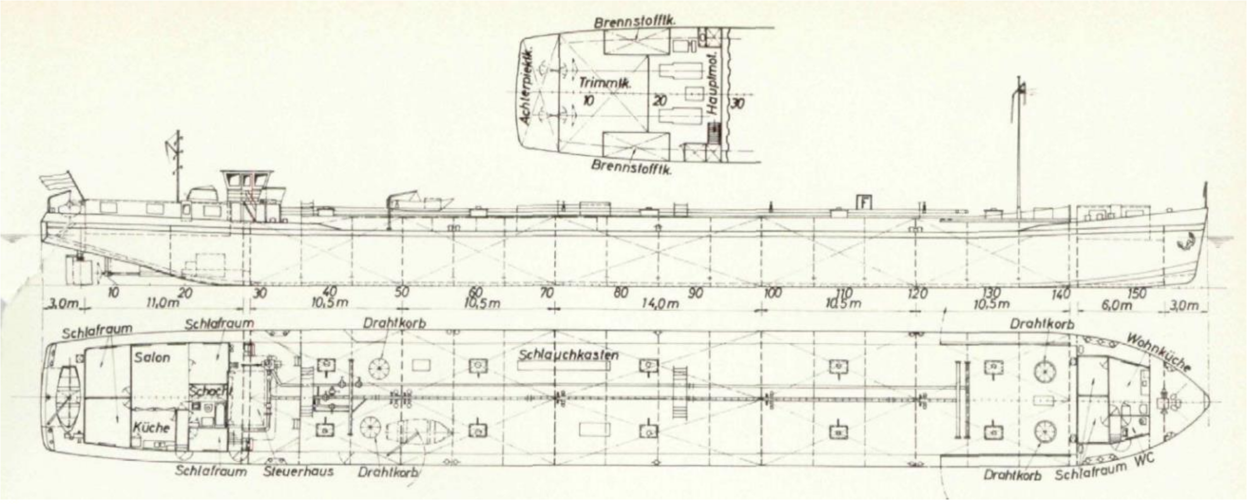

Figure 5: GA-plan MV "Internautic 1" (Schiff und Hafen, issue 5/1969, volume 21)

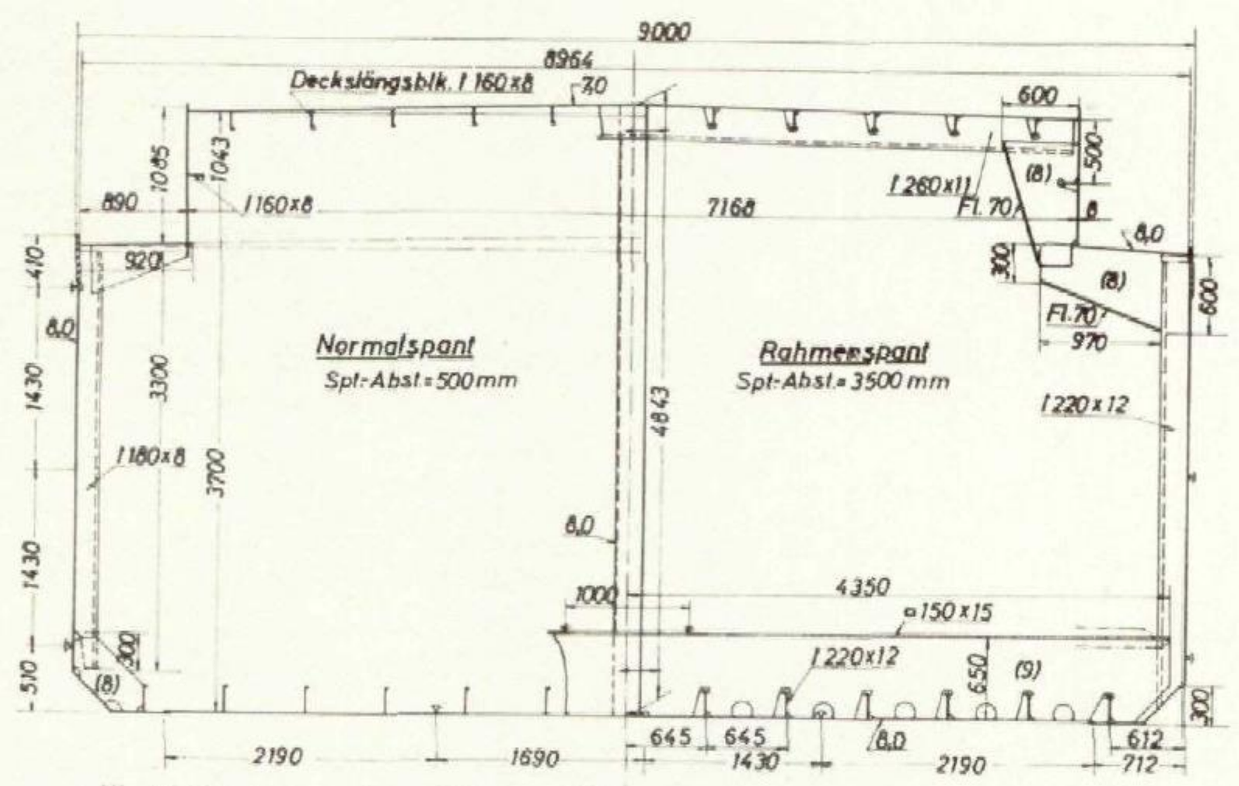

Figure 6: Main frame MV "Internautic 1" (Schiff und Hafen, issue 5/1969, volume 21)

A comprehensive collection of the main particulars for the calculations are presented in Table 2. The column “Remark” indicates from which source the value originates, “S&H” specifies “Schiff und Hafen, issue 5/1969, volume 21” and “estim.” specifies an estimation based on experience by the author.

Table 2: Main particulars of MV "Internautic 1"

Short name	Name	Value		Remark
	Building year	1968		
L_{OA}	Ship length over all	80.00	m	S&H
L_{PP}	Length between perpendiculars	78.00	m	estim.
L_{WL}	Length of waterline	79.00	m	estim.
D	Depth	3.70	m	S&H
T_{empty}	Empty draught	0.80	m	estim.
T_{max}	Maximum draught	3.633	m	derived
B_{OA}	Breadth over all	9.00	m	S&H
$B_{moulded}$	Breadth moulded	8.964	m	S&H
v	Speed of the vessel	19.44	km/h	estim.
Depl	Displacement at T max	2350	t	estim.
C_B	Block-coefficient	0.942		derived
d_{av}	Distance from forward cargo bulkhead to bow	9.50	m	estim.
d_{ar}	Distance from aft cargo bulkhead to stern	14.50	m	estim.
L hold 1	Length of hold 1	10.50	m	S&H
L hold 2	Length of hold 2	10.50	m	S&H
L hold 3	Length of hold 3	14.00	m	S&H
L hold 4	Length of hold 4	10.50	m	S&H
L hold 5	Length of hold 5	10.50	m	S&H

Short name	Name	Value		Remark
B_{tank}	Breadth of hold (port and starboard)	4.482	m	S&H
H_{tank}	Height of the hold	4.843	m	S&H
h_{HC}	Height hatch coaming	1.043	m	S&H
b_{SD}	Breadth side deck	0.890	m	S&H
s	Ordinary frame spacing bottom in hold	0.645	m	S&H
S	Web frame spacing bottom in hold	3.50	m	S&H
s	Ordinary frame spacing side in hold	0.50	m	S&H
S	Web frame spacing side hold	3.50	m	S&H
	Framing in bottom (transverse or longitudinal)	longit.		S&H
	Framing in side structure (transverse or longitudinal)	transv.		S&H
h_{BG}	Height of floor	0.65	m	S&H
LSW	Light ship weight	330	t	estim.
$Cargo_{max}$	Cargo capacity at T max	1980	t	S&H
	Weight of supplies (fuel, lub oil, water, crew, ...)	40	t	estim.
	Loading/unloading in one run			estim.
	Main engine power (Thomassen LO 17/6) 2 engines	2 x 500	kW	S&H

3.2 *Vessel for the lengthening retrofit*

For the lengthening retrofit within WP 5 it was decided to investigate the possibilities for a fully composite section of the inland navigation vessel MV “HERSO I” which is operated by the consortium member Plimsoll. In WP 7 a standard lengthening procedure using conventional mild steel structures is described.

The 1962 built vessel has a length over all of 84.95 m, a moulded breadth of 9.50 m and a maximum scantling draught of 2.70 m. A single dry bulk hold with a length of 57.50 m reaches from the engine room bulkhead to the forward hold bulkhead. The hold itself is covered with stackable hatch covers. The maximum cargo capacity at scantling draught sums up to 1381.5 t and the light ship weight including outfitting and supplies accounts for 596.0 t which is rather high for a double hull inland navigation vessel. In comparison to the actual light ship weight the GL rules for inland navigation vessels derive a standard weight of approximately 400 t. Hence, it can be stated that the vessel’s structure is fairly heavy which leads to additional weights which have to be taken into account for the bending moment calculations. On the other hand, the total amount of cargo proposed by the GL rules sums up to 1649 t. Compared to the actual amount of cargo of 1381.5 t it is 267.5 t less. The vessel is presented in Figure 7.

The ship’s structure was built from mild steel in conventional manner incorporating a double bottom with a height of 400 mm and a double side with a width of 1000 mm, both in transversal framing. Side frames, deck beams, floors and additional stiffeners are fitted every 0.5 m according to the general frame spacing scheme. Additional details such as scantlings of the bulkheads and their supporting structural members are missing. Absent information on specific data is assumed and indicated as required in the further lengthening process of MV “HERSO I”. Specific input relating to the locations of divisions such as fore/aft peak, engine room, accommodation and other compartments are missing and therefore not available.

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Figure 7: MV "HERSO I"

The summarised main particulars of MV “HERSO I” are presented in Table 3. Please note that the remark “info BME” indicates information provided by Budapest University of Technology and Economics.

Table 3: Main particulars of MV “HERSO I”

Short name	Name	Value		Remark
	Building year	1962		
L_{OA}	Ship length over all	84.95	m	drawing
L_{PP}	Length between perpendiculars	83.50	m	drawing
L_{WL}	Length of waterline	84.50	m	assumed
D	Depth	2.90	m	drawing
T_{empty}	Empty draught	0.81	m	drawing
T_{max}	Maximum draught	2.70	m	drawing
$B_{moulded}$	Breadth moulded	9.5	m	drawing
v	Speed of the vessel – with barge fully loaded	11	km/h	info BME
Depl	Displacement at T_{max}	1977.5	t	info BME
C_B	Block-coefficient	0.923		derived
d_{av}	Distance from forward cargo bulkhead to bow	10.00	m	info BME
d_{ar}	Distance from aft cargo bulkhead to stern	17.50	m	info BME
L_{hold}	Length of the hold	57.50	m	info BME
B_{hold}	Breadth of the hold	7.45	m	info BME
H_{hold}	Height of the hold	4.00	m	info BME
h_{HC}	Height hatch coaming	1.50	m	drawing

Short name	Name	Value		Remark
b_{SD}	Breadth side deck	1.00	m	drawing
s	Ordinary frame spacing bottom in hold	0.50	m	info BME
s	Ordinary frame spacing side in hold	0.50	m	info BME
	Double hull is divided in 4 watertight compartments with bulkheads in cargo area			info BME
	Framing in bottom structure	transv.		info BME
	Framing in side structure	transv.		info BME
h_{DB}	Height double bottom	0,40	m	drawing
b_{DS}	Breadth double side	1.00	m	drawing
LSW	Light ship weight	596.0	t	info BME
$Cargo_{max}$	Cargo capacity at T_{max}	1381.5	t	info BME
$Cargo_{2.5}$	Cargo capacity at $T_{2.5\ m}$	1185.0	t	info BME
$Cargo_{2.0}$	Cargo capacity at $T_{2.0\ m}$	813.0	t	info BME
$Cargo_{1.6}$	Cargo capacity at $T_{1.6\ m}$	520.0	t	info BME
	Weight of supplies & outfitting	130.8	t	assumed
	Main engine power (Deutz RBV 8M 545)	780	kW	info BME

4 Class and statutory regulations

(Author: SMILE FEM & CMT)

This chapter provides an overview on the prescriptive regulations regarding inland navigation vessels equipped for the carriage of dangerous goods and gives insight on how regulations for seagoing ships can be applied on inland navigation vessels.

4.1 Class requirements from GL

The rules for inland navigation vessels have been updated and amended by GL in 2011. All investigations are according to the GL rules before they merged with DNV to DNVGL.
Key sections, used for the general calculation of structures for tankers, are summarised in the following [(7)]:

- GL Part 2, Chapter 2, Section 1 “General”
- GL Part 2, Chapter 2, Section 2 “Materials and Structure Design Principles”
- GL Part 2, Chapter 2, Section 3 “Design Load Principles”
- GL Part 2, Chapter 2, Section 4 “Hull Girder Strength”
- GL Part 2, Chapter 2, Section 5 “Hull Scantlings”
- GL Part 2, Chapter 4, Section 2 “Other Type and Service Notations”

The method to determine the scantlings of the ship’s steel structure is to calculate net plate thicknesses or section moduli of stiffeners based on different load cases which affect the structural part. The maximum value has to be regarded as the governing dimension in most cases. The net thickness represents the minimum required dimension or section modulus without taken corrosion into account. The gross thickness depends on different values for corrosion addition defined by GL regarding environmental exposure influences in a range from 0.5 mm to 2.0 mm for each face of the plate or stiffener.
The transport of dangerous goods on inland navigation vessels in the GL rules is treated in

- GL Part 2, Chapter 4, Section 3 “Transport of Dangerous Goods“.

It is stated in paragraph A 1.1.3 that “The basis of the following requirements is the ADN Regulations, Edition 2011. In any case the actual edition of the Regulations for the transport of dangerous goods has to be observed. For vessels not falling under ADN, GL may approve equivalent arrangements providing the same level of safety.”. Consequently, fundamental basis for the GL rules considering dangerous goods is the ADN regulations which are adopted to GL rules.

The subsequent remarks towards classification issues are based on comments from DNVGL expert Mr Torsten Dosdahl:

General:

- **Quality of the weld seams**: It is not sufficient to monitor the welding parameters and draw the conclusion that the weld is executed properly
  → Consequently, the weld seams have to be visually investigated and assessed.
- **Data and documentation on vessels**: Very low, especially for older ships,

during the past time of operation many alterations to the hull structure have been often conducted
→ An extensive survey of the current structure has to be performed before the actual retrofit can begin.

- **Wear of outer hull platings**: Mechanical wear on the outside is much higher than the degradation of the platings caused by corrosion.
- **Class inspection intervals for tank vessels**: Every 5 years extensive inspection on the building slip, every 2.5 years intermediate inspection in floating condition (for vessels above 25 years of age the intermediate inspection has to take place on the building slip as well)
- **Reparability of structures**: The ability of repair of the structures have to be kept in mind
  → Technologies for repair procedures have to be assessed and provided so that the ship owners and shipyards are aware of the capabilities of the solutions.
- **Newbuildings/retrofittings**: A useful concept for the retrofit of single hull vessels has to be brought to maturity phase until the end of 2015, otherwise no major quantity of single hull vessels will exist anymore.
- **Media resistance of involved polymers**: It has to be demonstrated that the involved plastics and foam are resistant against the cargo media in the hold
- **Capability of inspection**: Bonded structures are not accessible for visual inspection as it is currently required by the class.

Safety:

- **Collision**: Collisions involving pointed and obtuse angles are occurring
  No preferences are obvious.
- **Aim in case of collision**: Cargo shall be prevented from leakage.
  → By now the measure for this aim is set as absorbed collision energy of the hull structure (The probability of occurrence is recognised to be proportional to the distance of the inner side measured from the outer side).
  → Beside the ADN procedure to demonstrate collision equivalency a risk assessment might be conducted.
- **Fire**: Plastics and composite structures are generally recognised as problematic for the use in the cargo area and not allowed by class and ADN rules, except for coatings of the holds.
  → A risk based design approach has to be conducted.

Materials:

- Repairs and conversions of vessels shall be treated in the same way as it applies for new buildings including the latest developments in technical knowledge. The materials which are used for the conversion or repair have to comply with the requirements of the rules for new vessels. (Pt. 2, Ch. 1, Sec. 1 C, 6.4.3).
- Materials for inland navigation vessels have to comply with the “GL Rules for Materials and Welding (II)” in general (Pt. 2, Ch. 2, Sec. 2 A, 1.1.1)
- Only base materials which have been approved by GL can be applied (Pt. 2, Ch. 2, Sec. 2 A, 1.1.1).
- In general, steel with different mechanical properties is considered to be the common material for the construction of hulls and structures (Pt. 2, Ch. 2, Sec. 2 A, 2).
- Steel can be replaced by aluminium alloys if equivalent strength is retained (Pt. 2, Ch. 2, Sec. 2 A, 3.1.1).

- On tankers a special rule applies: Aluminium alloys are only authorised forward of fore cofferdam and aft of aft cofferdam (Pt. 2, Ch. 2, Sec. 2 A, 3.1.2).
- Other materials such as plastics or wood are to be considered by GL on a case-by-case basis where GL states the requirements to be fulfilled (Pt. 2, Ch. 2, Sec. 2 A, 4.1.2).

4.2 ADN 2013 requirements

The international carriage of dangerous goods by inland waterways in the European Union is managed in the regulations of ADN (Accord Européen Relatif au Transport International des Marchandises Dangereuses par Voies de Navigation Intérieures). If a vessel transports dangerous goods according to the defined types of cargo it has to comply with the ADN code [(4)].

For the present application case MV “Internautic I” the preconditions regarding the ADN requirements are presented in the subsequent sections.

4.2.1 Ship type

The base vessel with single hull features a trunk and is expected to have open or closed cargo holds depending on the cargo. According to ADN requirements the vessel is recognised to be classed as “Type N” vessel, i.e. tank vessel intended for the carriage of liquids [(5), page 28 et seqq.]. The different configurations are presented in Figure 8. After retrofitting, the vessel will feature a mainframe section as indicated in the picture.

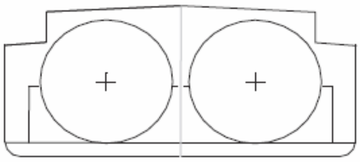
Type N :

Type N Condition of cargo tank 2, 3 or 4
Type of cargo tank 2

Type N Condition of cargo tank 2, 3 or 4
Type of cargo tank 2

Type N Condition of cargo tank 2, 3 or 4
Type of cargo tanks 1
(also by flush-deck)

Type N Condition of cargo tank 2, 3 or 4
Type of cargo tank 3
(also by flush-deck)



Type N Condition of cargo tank 2, 3 or 4
Type of cargo tank 1
(also by flush-deck)

Figure 8: Tanker types according to ADN definitions (Type N) [(5), page 28 et seqq.]

4.2.2 Type of liquid

The assumed types of hazardous liquid cargo to be transported by MV “Internautic I” are presented in Table 4 [(5), 3.2.3 table C, page 510 et seqq.].

Table 4: Types of liquid carried by MV "Internautic I"

Liquid	Ship type	Tank condition	Tank type	Max fill level of liquid [%]	Density of liquid [kg/m³]
Petrol	N	closed (No 2)	3 (tank shell is not hull)	97	720
Diesel fuel		open (No 2)			850
Petroleum distillates		closed (No 2)			765

4.2.3 Special regulations and exceptions

According to ADN, exceptions from the usual structures can be only allowed with respect to the following special regulations:

- **Special regulations for tankers can be permitted after proposal** (Sec. 1.5.2)
  - The duration of the special regulation can cover maximum two years and can be extended to three years once (Sec. 1.5.2.1.2)
- **Procedures for the evidence of equivalency** (Sec. 1.5.3.1)
  - The responsible authorities can allow deviations in terms of structural modifications or different applied materials
- **Deviations for testing purposes** (Sec. 1.5.3.2)
  - For a distinct period of time deviations of the current rules can be permitted for testing purposes

4.2.4 Rules for construction

Some hints for the construction of double hull vessels intended for the application case MV “Internautic I” are summarised in the following. Where applicable the general rules are filled with distinct input data in order to derive prescriptive figures. It has to be noted that the set of information is only related to standard design of tankers except for the element “Alternative designs” treating the double side structure.

- **Ship hull & tank holds have to be built with steel or comparable metal** (Sec. 9.3.3.0.1 & 9.3.3.0.2)
  - No composite materials are allowed
  - Independent tanks can be built from similar material (similar in terms of mechanical properties and resistance against temperatures and fire)
- **The use of plastic materials or rubber within the cargo area is only permitted for coating of cargo tanks** (Sec. 9.3.3.0.3 c)
- **Maximum permissible capacity of cargo tanks** (Sec. 9.3.3.11.1 a)
  - L*B*H’ = 80.0*9.0*4.29 = 3086 m³

  - Maximum capacity per tank is: 180+(L*B*H’-600)*0.0635 = 338 m^3
- **Maximum permissible cargo tank length** (Sec. 9.3.3.11.1 d)
  - For ships with L > 50 m: 0.20*L = 0.20*80 = 16.0 m
- **Minimum double side width** (Sec. 9.3.3.11.7)
  - Distance from cargo tank wall to outer shell is minimum 600 mm
- **Minimum double bottom width** (Sec. 9.3.3.11.7)
  - Distance from cargo tank bottom to outer shell is minimum 500 mm
- **All double-hull spaces have to be arranged in a way that they may be completely inspected and cleaned** (Sec. 9.3.3.11.9)
  - Openings shall have a minimum cross-section of 0.36 m^2
  - Minimum penetration width shall be not less than 500 mm, 450 mm in double bottom area
- **Alternative designs** (Sec. 9.3.4)
  - Where the distance between the hull and the cargo tank is smaller than required a higher crashworthiness of the structure has to be proven. This has to be executed by comparing the risk of a conventional construction, complying with the ADN regulations, with the risk of the alternative construction (Sec 9.3.4.1.2)
  - The calculation procedure is carried out according to 13 basic steps (Sec. 9.3.4.3)
  - The main risk assessment approach is according to the formula R = P * C, wherein R is the risk, P the probability of cargo tank rupture and C the consequence of cargo tank rupture (Sec. 9.3.4.2)

4.3 CSR requirements

4.3.1 Comment to the Common Structural Rules for Oil Tankers

4.3.1.1 General

This section summarises the Common Structural Rules package systematically and in accordance with its given structure. It is further compared to the ADN rules as well as the GL rules for inland navigation vessels to investigate whether the INOT rules already include similar regulations or if they do not apply due to different service and environmental conditions. Therefrom, a first initial evaluation is derived regarding the applicability of the CSR to the INOT rules. Therefrom, a more in-depth proposal to further advance the structural rules of inland waterway tankers is deduced.

4.3.1.2 CSR 1. Introduction

CSR 1.1 Introduction to Common Structural Rules for Oil Tankers

CONTENT:

This section comprises the main restrictions concerning the application of the Common Structural Rules, it links the document to the requirements of the individual classification society rules that may have to be applied and also presents an schematic layout of the rules.

COMMENT:

Specific introductions to the individual INOT rules already exist. No adaptation is necessary. cf. ADN 1-1; GL I-2-1-1-A

4.3.1.3 CSR 2. Rule Principles

CSR 2.1 Introduction + CSR 2.1 Introduction + CSR 2.3 Design Basis

CONTENT:

Here, a short and comprehensive summary of the main aspects underlying the Common Structural Rules is given. Furthermore, references to IMO and IACS regulations were made defining the hierarchy among the individual rules.

COMMENT:

These rather general remarks are already implemented in the INOT rules or do not apply as some aspects are specifically intended for ocean-going oil tankers.

CSR 2.4 Design Principles + CSR 2.5 Application of Principles

CONTENT:

These two sections present the underlying design principles of the rules and how they have been applied in the development of the rule requirements in terms of loads, structural capacity models and assessment criteria as well as construction and in-service aspects.

COMMENT:

The design load combinations are based on static and dynamic loads. The static loads are similar to the GL rules. The dynamic loads as result of wave bending are to be ignored as no significant wave height is to be expected.

Furthermore, Principles of Safety Equivalence as well as remarks regarding Material and Welding are standard classification society procedures and therefore not to be adopted.

4.3.1.4 CSR 3. Rule Application

CSR 3.1 Notations + CSR 3.2 Documentation, Plans and Data Requirements + CSR 3.3 Scope of Approval

CONTENT:

These sections explain which steps need to be carried out and which documentations, plans and data are required to comply with the Common Structural Rules.

COMMENT:

These remarks are considered to be general class society procedure and therefore can be neglected.

CSR 3.4 Equivalence Procedure

CONTENT:

The Rules apply in general to double hull oil tankers of normal form, proportions, speed and structural arrangements as defined in Section 2.3. For Ships of novel design the classification society is to be contacted at an early stage in the design process to establish the applicability of the Rules and additional information required for submission. A systematic review may be required to document equivalence with the Rules.

COMMENT:

This is general class society procedure and therefore will not be considered further

CSR 3.5 Calculation and Evaluation of Scantling Requirements

CONTENT:

The calculation and evaluation of scantling requirements are performed at load calculation
points, defined by the shape and dimension of the respective Elementary Plate Panels (EPP), stiffeners or primary support members. The precise location of these load calculation points as well as other aspect of the idealization is defined.
COMMENT:
This is a very important section as many parameters are defined, relevant for further calculations. All aspects are treated in a very comprehensive manner that well exceeds the ADN/GL requirements. cf. GL-I-2-2-2-B-6.1.2

4.3.1.5 CSR 4. Basic Information

CONTENT:
This section presents the terminology and basic dimensioning that is used in the Common Structural Rules.
COMMENT:
These remarks can be considered to be general class society procedure and therefore can be neglected.

4.3.1.6 CSR 5. Structural Arrangement

CSR 5.1 General
CONTENT:
Here, a short introduction to the following sections is given.
COMMENT:
This introduction is of no relevance for the vessel's design and therefore can be neglected.

CSR 5.2 Watertight Subdivision
CONTENT:
This sub-section defines the minimum number and position of watertight bulkheads and also specifies the position of the collision and aft peak bulkhead.
COMMENT:
Similar considerations are already made for INOTs in ADN and GL. No adaptation is recommended. cf. ADN 9.3.1.11; GL I-2-2-5-E-5

CSR 5.3 Double Hull Arrangement
CONTENT:
The protection with double bottom and side tanks for every cargo tank is required. The double bottom depth ranges from 1.0 m to 2.0 m depending on B. The double side width ranges from 1.0 m to 2.0 m depending on the deadweight of the ship.
COMMENT:
A minimum depth and width of the double hull structure is already defined by the ADN but no adaptation to the vessel's size is implemented. As the maximum size of the cargo holds are identical for all ship sizes, the risk of a potential oil outflow is limited, and therefore no adaptation is recommended. cf. ADN 9.3.1.11.2

CSR 5.4 Separation of Spaces
CONTENT:
A complete separation of cargo tanks is required. The design of cofferdams is further specified.
COMMENT:

This section is identical to the INOT rules. cf. GL I-2-2-5-E-4.6

CSR 5.5 Access Arrangements

CONTENT:

Reference is made to SOLAS 1974, Chapter II-1, Part A-1, Regulation 3-6 specifying access into and within spaces in, and forward of, the cargo tank region.

COMMENT:

Basic requirements are already made in the ADN-Rules.

4.3.1.7 CSR 6. Materials and Welding

CSR 6.1 Steel Grades

CONTENT:

This section mainly deals with the definition of the higher strength steel factor k and requirements concerning the steel grade with regard to the structural member category and its position. Further, special considerations for the usage of aluminum alloys were made.

COMMENT:

Most remarks can be considered to be general class society procedure and therefore can be neglected. cf. GL-I-2-2-2-A-3

CSR 6.2 Corrosion Protection Including Coatings + CSR 6.3 Corrosion Additions

CONTENT:

Standards for the corrosion protection were defined. A corrosion protection system can comprise protective coatings and cathodic protection systems. Further, corrosion additions for typical structural members within the cargo tank region were specified.\\

COMMENT:

The requirements made in the CSR concerning the corrosion protection are very detailed. The INOT rules may adopt certain aspects of the CSR rules as an effective corrosion protection is a major factor to ensure a vessel's structural strength during the whole life time cycle. Different environmental conditions have to be considered.

CSR 6.4 Fabrication + CSR 6.5 Weld Design and Dimensions

CONTENT:

It defines requirements for quality of workmanship and fabrication standards, as well as weld design and dimensions.

COMMENT:

This subject is already covered by the GL-Rules and therefore is not recommended for adoption. cf. GL-I-2-1-A-1.4.3; GL-I-2-1-A-3.1.2

4.3.1.8 CSR 7. Loads

CSR 7.1 Introduction

CONTENT:

Here, definitions of the coordinate system as well as sign conventions are presented.

COMMENT:

The sub-section only comprises general information that do not comprehend any regulations in itself and is therefore not considered for adoption.

CSR 7.2 Static Load Components

CONTENT:
The formulas to determine the minimum hull girder hogging and sagging still water bending moment for seagoing operations as well as the minimum hull girder still water shear force are presented. Further, local static loads are defined.
COMMENT:
The derivation of static hull girder loads is similar to GL inland navigation vessel rules. The Still Water Bending Moments (SWBM) are dependent from L to the power of 2, B, C_b and C_{wv}. The wave coefficient C_{wv} is not considered in the INOT’s Rules as only marginal waves are assumed. The formulas differ in its coefficients as the geometric dimensions vary between inland navigation vessels and ocean going vessels. The formulas to determine the local loads are mainly of the same structure and are considered to reflect the specific loads adequately. cf. GL-I-2-2-4-B-6; GL-I-2-2-3-C-5; GL-I-2-2-3-C-6

CSR 7.3 Dynamic Load Components
CONTENT:
The dynamic loads consider vertical wave bending moment and shear force, horizontal wave bending moment, dynamic wave pressure and dynamic tank pressures.
COMMENT:
All of the above mentioned loads can be neglected for INOTs, since no roll or pitch motions are to be taken into account for the lack of significant swell.

CSR 7.4 Sloshing and Impact Loads
CONTENT:
Sloshing pressures in tanks, bottom slamming pressures and bow impact loads are given in this sub-section.
COMMENT:
The above mentioned dynamic loads are not considered in the INOT rules as they result from wave induced ship motion. No such motion is to be expected for inland waterway vessels and therefore can be neglected.

CSR 7.5 Accidental Loads
CONTENT:
The pressure in compartments and tanks in flooded condition or damaged condition is to be taken as $P_{in-flood}$, which is practically the pressure of the seawater at the specific water-level.
COMMENT:
This load case is not yet covered.

CSR 7.6 Combination of Loads
CONTENT:
In Table 7.6.1 three design load combinations - static, static + dynamic and accidental - are defined. The dynamic loads consist of several dynamic load cases. For each dynamic load case dynamic load combination factors are given.
COMMENT:
For both inland navigation vessels and ocean going vessels, static loads are taken into account. Since no dynamic loads are considered for inland waterway vessels no design load combination recognizing static and dynamic loads is required. Accidental loads are not yet included in INOT rules but may represent a relevant load case.

4.3.1.9 CSR 8. Scantling Requirements

CSR 8.1 Longitudinal Strength

CONTENT:

The design requirements concerning the longitudinal strength of the vessel firstly state that a loading guidance has to be provided. The loading guidance information is to include an approved loading manual and loading computer system. These will define operational limitations which all the following calculations will be based on.

To account for an adequate Hull Girder Bending Strength the net vertical hull girder moment of inertia I_{v-min} and the net vertical hull girder section modulus Z_{v-min}, which are based on some basic geometric properties of the vessel, need to be comply with. In addition, the net hull girder section modulus about the horizontal neutral axis, $Z_{v-net50}$, is not to be less than the rule required hull girder section modulus, Z_{v-req}, which is deviated from the permissible hull girder hogging or sagging still water bending moment $M_{sw-perm}$.

To assess the Hull Girder Shear Strength the net hull girder shear strength capacity, $Q_{v-net50}$, is not to be less than the required vertical shear force, Q_{v-req}.

Plate panels and longitudinals subject to hull girder compression and shear stresses need to be checked for Hull Girder Buckling Strength.

This chapter also provides a simplified fatigue control measure against the dynamic hull girder stresses in the longitudinal deck structure. This is not mandatory but, is recommended to be applied in the early design stage.

Further, requirements concerning the Tapering and Structural Continuity of Longitudinal Hull Girder Elements are made.

COMMENT:

The INOT rules also require a loading manual but do not yet require a loading computer system, which might be adequate for safer loading and unloading procedures.

The Hull Girder Bending Strength assessment of both CSR as well as INOT rules are very similar in their basic calculations, but the requirements presented in the CSR contain a few additional considerations that take into account a variation of structural hull designs and appear to be slightly more strict. cf. GL-I-2-2-4-C

A dedicated Hull Girder Shear Strength assessment as described in the CSR is not implemented in the ADN and GL rules for inland waterway vessels. It is rather taken into account by local requirements applying to certain structural members.

The recommendations concerning the Hull Girder Fatigue Strength, as mentioned in CSR 8.1.5, are not mandatory but only attempt to give guidance at an early design stage. They can be neglected.

Concerning the Tapering and Structural Continuity of Longitudinal Hull Girder Elements, both INOT and CSR rules require adequate tapering and the continuance of the moment of inertia and section modulus requirements. In addition, the Common Structural Rules include regulations about the extent of higher strength steel.

CSR 8.2 Cargo Tank Region

CONTENT:

The chapter comprises scantling requirements about the hull structure within the cargo tank region of the ship, for the shell, deck, inner bottom and bulkhead plating, stiffeners and primary support members.

Firstly, a Minimum Net Thickness for Plating and Local Support Members as well as Primary Support Members is given. It is dependent on the rule length L_2.

The scantling requirements concerning the Hull Envelope Plating, the Hull Envelope Framing, the Inner Bottom and the Bulkhead all relate to the tables 8.2.4 to 8.2.7 which take into account the geometric properties of the vessel and the design pressure. The formulas also adapt to certain structural arrangements like the frame spacing and different load cases.

Within the scantling requirements for Primary Support Members in the cargo tank region, a variety of formulas, specific to certain structural members, is given.

COMMENT:

The specifications for the Hull Envelope Plating, the Hull Envelope Framing, the Inner Bottom and the Bulkhead are all similar to formulas given in the GL rules. cf. GL-I-2-2-5 table 5.2 and table 5.3

The regulations dealing with the Primary Support Members are more detailed than the ones presented in the INOT rules.

CSR 8.3 Forward of the Forward Cargo Tank

CONTENT:

This chapter defines own requirements for the arrangement and scantling of the forward part of the vessel with respect to different shapes and design loads of this section. It comprises the aspects of Bottom Structure, Side Structure, Deck Structure, Tank Bulkheads, Watertight Boundaries, Superstructure, Miscellaneous Structures and Scantling Requirements.

COMMENT:

Both CSR and INOT rules present a whole package of regulations concerning the general arrangement of structural members as well as its dimensioning. Comparing both systems of rules the CSR include a few more parameters. For example the scantling requirements include a correction factor for the panel aspect ratio and an acceptance criterion depending on the load combination. cf. GL-I-2-2-6-A

CSR 8.4 Machinery Space

CONTENT:

The requirements of this Chapter apply to machinery spaces situated in the aft end region, aft of the aftermost cargo tank bulkhead and forward of, and including, the aft peak bulkhead. The chapter comprises considerations concerning the arrangement and scantling in which many of the paragraphs refer to previous ones, e.g. section 8.3, Forward of the Forward Cargo Tank. Further, explicit recommendations for the design of machinery foundations are made.

COMMENT:

Both CSR and INOT rules offer a broad package of requirements for the machinery space. The main difference is in the scantling assessment, which, for the GL rules, is based on general geometric properties of the vessel, whereas the CSR explicitly calculate the bending stress with respect to design bending moment, hull girder moment of inertia and the permissible bending stress factors according to safety factors.

CSR 8.5 Aft End

CONTENT:

This chapter comprises requirements regarding the aspects of Shell Structure, Deck Structure, Tank Bulkheads, Watertight Boundaries and Miscellaneous Structures. In essence, they reflect considerations made in previous paragraphs. Often it is referred to section 8.3, Forward of the Forward Cargo Tank, but there are also paragraphs, which deal with special aspects of the aft end region like Stiffening of Floors and Girders in the

Aft Peak, ore Stern thruster tunnels. Further attention is paid to additional deck loads such as induced by the steering gear, mooring windlasses, and other deck machinery.
COMMENT:
Both systems of rules offer comprehensive packages of regulations regarding the special requirements of the aft end of a vessel. The INOT rules, as referred to in the GL rules, even appear to be a bit more detailed than the ones in the CSR.

CSR 8.6 Evaluation of Structure for Sloshing and Impact Loads
CONTENT:
The requirements of this section cover the strengthening requirements for localized sloshing loads that may occur in tanks carrying liquid and local impact loads that may occur in the forward structure.
COMMENT:
As no significant wave induced ship motion is considered for inland navigation vessels, local loads resulting from sloshing and bow impact can be neglected.

CSR 8.7 Application of Scantling Requirements to Other Structure
CONTENT:
The requirements of this section apply to plating, local and primary support members where the basic structural configurations or strength models assumed in section 8.2 to 8.5 are not appropriate. These are general purpose strength requirements to cover various load assumptions and end support conditions.
COMMENT:
Both rule packages handle scantling requirements to other structures in different ways. The CSR rules cover these structural elements in one section with a rather general approach while the GL rules for inland navigation vessels define specific regulations for example for superstructures and deckhouses, hatch covers or the arrangements for hull and superstructure openings. cf. GL-I-2-2-6

4.3.1.10 CSR 9. Design Verification

CSR 9.1 Hull Girder Ultimate Strength
CONTENT:
The hull girder ultimate capacity check is categorized as an ultimate limit state. It is an explicit control of one of the most critical failure modes of a double hull tanker. Failure in hogging is not considered to be critical for conventional double hull tankers due to the way they are loaded and due to the conventional structural arrangement. Hence only sagging is included within the current rules. The criteria defines the Sagging Still Water Bending Moment and the Sagging Vertical Wave Bending Moment as acting loads which are compared to the Sagging Vertical Hull Girder Ultimate Bending Capacity, defined in Appendix A-1.1.1. In addition, Partial Safety Factors for the design load combinations calibrated through structural reliability analyses are applied.
COMMENT:
Failure in sagging is identified as one of the most critical failure modes for seagoing double hull tankers. It mainly considers wave induced bending moments and is based on a rather probabilistic approach. Inland navigation vessels are not subject to significant wave loads and therefore the adoption of this criterion does not appear to be adequate.

CSR 9.2 Strength Assessment (FEM)
CONTENT:

The CSR require a strength assessment of the hull structure using finite element analysis. It consists of a cargo tank analysis to assess the strength of longitudinal hull girders, primary support members and transverse bulkheads and a fine mesh analysis to assess detailed stress levels in local structural details. Requirements are presented concerning for example the structural model, loads and loading conditions, boundary conditions and safety factors. Further requirements regarding the structural assessment are given in Appendix B.

COMMENT:

Both CSR and GL rules include very extensive regulations for the FEM strength assessment. In comparison to the CSR, a strength assessment by utilizing the finite element method is not mandatory for inland navigation oil tankers. It is further stipulated that the direct calculation may be adopted instead of rule scantling formulae or for the analysis of structural members not covered by the Rules. cf. GL-I-2-2-2-G

CSR 9.3 Fatigue Strength

CONTENT:

This section, together with Appendix C, defines the minimum rule requirements for design against fatigue failure. It has to be applied to structural details such as for example end connections of longitudinal stiffeners and the knuckle between inner bottom and hopper plate. The total stress range for fatigue assessment is to be determined from a fine mesh finite element analysis. Both nominal stress approach and hot spot stress approach are accepted.

COMMENT:

A fatigue strength analysis is not part of the INOT rules since no wave induced loads, which account for most of the cyclic loads, are considered. Although not within the scope of these INOT rules, other secondary cyclic loading, such as low cycle, or vibration induced fatigue, may also result in significant levels of stress range and may need to be specially considered.

4.3.1.11 CSR 10. Buckling and Ultimate Strength

CSR 10.1 General

CONTENT:

Within section 10 the buckling and ultimate strength criteria as required in section 8 and 9 are defined.

COMMENT:

Both CSR and INOT rules define buckling criteria.

CSR 10.2 Stiffness and Proportions

CONTENT:

Here, an extensive set of formula is presented defining minimum values of main proportions controlling the buckling of primary support members is presented.

COMMENT:

The CSR offers a broader set of criteria to initially dimension for example plates and local support members as well as proportions of brackets and its corresponding edge reinforcements. The GL also defines minimum values for moments of inertia of the longitudinal and transverse stiffeners.

CSR 10.3 Prescriptive Buckling Requirements

CONTENT:

This section contains the methods for determination of the buckling capacity, definitions of buckling utilization factors and other measures necessary to control buckling of plate panels, stiffeners and primary support members.
COMMENT:
Both rule packages contain similar tables defining buckling factors and reduction factors and apply similar formula to determine the buckling utilization factor.

CSR 10.4 Advanced Buckling Analyses
CONTENT:
Plates and stiffened panels may be subjected to combined stress fields as well as effects like nonlinear geometrical behavior, inelastic material behavior, initial imperfections etc. In that case, the buckling strength is to be derived in accordance with the method described in Appendix D.
COMMENT:
No advanced buckling analysis is implemented in the rules and guidelines for inland navigation oil tankers.

4.3.1.12 General Requirements

CSR 12.1 Allowable Thickness Diminutions for Hull Structure
CONTENT:
The purpose of this section is to provide criteria for the allowable thickness diminution of the ships’ hull structure. That includes requirements regarding the assessment of thickness measurements, the definition of categories of corrosion and the renewal criteria.
COMMENT:
The CSR as well as the INOT rules take account of corrosion phenomena and provide mandatory corrosion additions which need to be added to the net scantling requirements. They further define intervals for class renewal surveys where thickness measurements are performed and the vessels scantlings are checked. The CSR does also provide criteria for pitting, edge and groove corrosion, which are not included in the INOT rules. cf. GL-I-2-1-3-G

4.3.1.13 App.A HULL GIRDER ULTIMATE STRENGTH

CONTENT:
For the verification of the structural hull design in sagging condition, which is described in section 9.1, the vertical hull girder ultimate bending capacity has to be derived. Here in the Appendix A, procedures are introduced to calculate the required bending capacity. As standard routine, the single step ultimate capacity method, as simplified method based on an incremental-iterative approach, is defined. It includes different failure modes such as elasto-plastic failure and buckling. Alternatively, a non-simplified incremental-iterative procedure and non-linear finite element analysis may be applied.
COMMENT:
No procedure is yet implemented in the INOT rules to determine the ultimate bending moment capacity of a vessels hull at the state of collapse.

4.3.1.14 App.B STRUCTURAL STRENGTH ASSESSMENT

CONTENT:
This appendix defines requirements for the structural strength analysis by means of finite element assessment in accordance with 9.2. The mandatory FE analysis

comprises a global cargo tank structural strength analysis, a local fine mesh structural strength analysis and evaluation of hot spot stress for fatigue analysis.

COMMENT:

The CSR include very detailed requirements concerning the structural modeling and application of loads. In contrast, the INOT rules are not as restrictive as the CSR and allocate more responsibility towards the design office and classification society. The CSR further comprises a local fine mesh analysis procedure with very precise specifications regarding the investigated structural details. Also a procedure representing openings like man holes in primary support member webs is implemented.

4.3.1.15 App.C FATIGUE STRENGTH ASSESSMENT

CONTENT:

This section defines the procedure for a simplified fatigue assessment which is to be used to evaluate the fatigue strength of the ships structural details. The fatigue assessment uses a nominal stress approach based on beam theory. The applied loads include static loads, wave induced loads, impact loads, sloshing, cyclic loads resulting from main engine or propeller induced vibration, transient loads such as thermal loads and residual stresses.

COMMENT:

Wave induced loads are considered to be the major factor regarding vessels fatigue strength. No fatigue strength assessment is included in the INOT rules since no wave induced loads are considered for inland waterway vessels. If fatigue due to other secondary cyclic loading is acknowledged to be a critical failure mode, a fatigue assessment procedure may be applied to INOTs.

4.3.1.16 App.D BUCKLING STRENGTH ASSESSMENT

CONTENT:

Here, further requirements for the advanced buckling analysis are described. It is based on nonlinear analysis techniques.

COMMENT:

No advanced buckling strength assessment is implemented in the rules and guidelines for inland navigation oil tankers.

4.3.2 Proposal to further advance the structural Rules of Inland Waterway Tankers

4.3.2.1 General

In the previous section, the major differences between the Common Structural Rules for Double Hull Oil Tankers and the rules and guidelines for inland navigation oil tankers have been identified. They have been further evaluated for their applicability to inland navigation vessels. Thereby, a set of rules has been obtained, which will now be investigated in detail.

4.3.2.2 Accidental loads, CSR 7.5

Accidental loads result as a consequence of an accident or operational mishandling of the ship. The Common Structural Rules define an increased tank pressure due to flooding of compartments as a separate load case, which every vessel has to comply with. It is checked that the local static loads in compartments and tanks do not exceed the structural capacity of the plating and local support members. This is done for internal watertight subdivision structures such as decks, the inner bottom and longitudinal and transverse bulkheads. This measure may help maintain the structural integrity of the vessel after an accident, which practically means no further breakage occurs due to flooding of compartments and therefore limit the damage to both man and nature. CSR 2.4.2.3.4, 2.4.2.7.1, 7.2.2.3.4

This load case is not yet covered by the INOT rules but it might help increase the safety of such vessels as inland waterway vessels are also exposed to collision, grounding, operating errors and fatigue.

4.3.2.3 Local calculation points, CSR 3.5

Both the calculation of design loads and the evaluation of local scantling requirements in the CSR are to be performed at local calculation points. Their position is defined by an extensive set of regulation.

The INOT rules also utilize local calculation points but their regulations do not match the complexity of the CSR requirements. This may lead to impermissible simplifications of the model, hence the INOT rules may adopt some of the CSR requirements to improve accuracy of the calculations.

4.3.2.4 Longitudinal Strength, CSR 8.1

The scantling requirements concerning the longitudinal strength assessment are a very complex set of regulations. Besides many commonalities in their basic structure and also some explicit formula, the CSR contain additional considerations. These may include minimum requirements of the net vertical hull girder moment of inertia, which depends on basic parameters of the vessel. The CSR also pays special attention to vessels with trunk deck or continuous hatch coaming and large camber, defining the effective deck height by a number of formulas. Including these requirements into the rules and guidelines of inland navigation oil tankers may set expedient limits to certain design rules and may ensure a conservative interpretation of such, with regard to a variation of structural hull designs.

In addition, the CSR include a dedicated Hull Girder Shear Strength assessment which is not implemented in the INOT rules. There, hull girder shear strength is rather taken into account by separate requirements applied to individual structural members. A consistent shear strength assessment may improve overall strength and transparency of calculations.

Further, the Common Structural Rules include regulations about tapering and structural continuity of longitudinal hull girder elements with respect to the extent of higher strength steel. This is not covered by the INOT rules but may be considered to improve flexibility in the choice of material and to ensure correct idealization of the mechanical phenomena.

4.3.2.5 Cargo Tank Region, CSR 8.2

Unlike INOT rules, the Common Structural Rules contain minimum requirements for the net thickness for plating as well as local and primary support members. They are not derived from extensive calculations, taking into account design loads, geometric properties of structural members etc., but short and comprehensive formulas, which only pay attention to the vessel's length.

This additional approach, if implemented in the rules and guidelines of inland navigation oil tankers, may set a reasonable minimum level to the scantling requirements of such structural members.

4.3.2.6 Strength Assessment (FEM), CSR 9.2

In the CSR, a strength assessment of the hull structure using finite element analysis is mandatory. The FE analysis consists of two parts. These are on the one hand a cargo tank analysis to assess the strength of the main structural members of the cargo tank region. The other on is a fine mesh analysis to check detailed stress levels in local structural details.

In contrast, the INOT rules do not include a compulsive finite element analysis. However this would certainly improve the accuracy of the whole design process and adds an additional cycles to the assessment procedure, if made mandatory, but it will also increase newbuilding costs.

4.3.2.7 Fatigue Strength, CSR 9.3

The Common Structural Rules for Double Hull Oil Tankers do include a mandatory fatigue strength assessment. Thereby it is checked that for a variety of structural details the fatigue capacity exceeds the expected fatigue damage.

No such analysis is part of the INOT rules since wave induced loads, which are a major cause regarding fatigue damage, are not considered for inland navigation vessels. However, other secondary cyclic loading may also result in significant levels of stress range, so implementing a fatigue assessment procedure may be reasonable for inland navigation vessels as well.

4.3.2.8 Buckling strength assessment, CSR 10.2

Both CSR and INOT rules include extensive sections concerning the buckling strength of plane panels as well as supporting members.

The CSR additionally comprises requirements for the assessment of brackets and edge reinforcements. This may be considered for inland navigation vessels as well, as it extends the buckling strength assessment to another group of important structural members.

4.3.2.9 Ship in Operation Renewal Criteria, CSR 12

Corrosion is a permanent threat to both ocean going and inland waterway vessels. Therefore, thickness measurements are required for both groups of vessels to assess the ships’ structure against the specified renewal criteria. In addition, the Common Structural Rules also define renewal criteria for pitting, grooving and edge corrosion. These are local corrosion phenomena that may cause serious material losses which are not necessarily considered by general thickness measurements.

To improve safety of inland navigation oil tankers, it is recommended to adapt these CSR requirements which help to set clear indications for severe corrosion.

4.3.2.10 HULL GIRDER ULTIMATE STRENGTH, App.A

Within the Appendix A, a complex procedure is presented, that helps to determine the ultimate bending moment capacity of a vessels hull at the state of collapse. This is not yet part of the INOT rules where only the hull girder normal stress is checked.

If hull girder bending is also considered to be a critical failure mode for inland navigation oil tankers, this procedure may help increase resilience of such vessels. This might be the case even though the bending moments are not as high as for seagoing ships, but for their slender hull forms, the SWBM may be critical for global failure of INOTs as well.

4.3.3 Result summary

Researching concepts to reducing the risk of leakage for inland navigation oil and product tankers is one of the major goals of the Project ‘Move It!’. In addition to the development of retrofitting concepts for the existing fleet, this can also be achieved by advancing the classification rules for future new buildings.

Therefore the Common Structural Rules for Oil Tankers, which were developed for seagoing vessels, have been screened for its applicability to inland navigation oil and product tankers. During a systematic comparison between the CSR, ADN and GL rules for inland navigation oil and product tankers, a set of nine prospective rule innovations has been identified. These are further investigated in an in-depth analysis to identify their benefits and deficiencies.

In conclusion, nine aspects of the CSR are recommended to be adopted for inland navigation tankers, ranging from additional load cases, more advanced calculation techniques, minimum scantling requirements and advanced corrosion assessments to the compulsory utilization of numerical investigations. This will help improving the structural safety of inland navigation oil tankers but will also increase the engineering effort needed to develop a new ship design. In an increasingly competitive environment, balancing both strong ecological and economic interests is a permanent process. Concerning that, this investigation provides basis for further discussion.

4.4 Other requirements

4.4.1 GGVSEB 2013 requirements

Exceptions from normal designs and procedures have also to comply with the “Gefahrgutverordnung Straße, Eisenbahn und Binnenschifffahrt” (Regulation for dangerous goods for road, Train and inland waterway shipping in Germany) to mention just a few [(8)]:

- **Exceptions** (§ 5)
  - Exceptions can be requested for the German waterways for the sections 1 to 9 of the ADN code, except for subsection 1.5.2, which applies for tankers (Paragraph 3)
  - For this reason exceptions are not permitted for tankers
- **Guideline 2008/68/EG has to be regarded**
  - The guideline regulates the transportation and handling of dangerous

goods In countries of the European Union

- **Guidelines RSEB 2013 (Durchführungsrichtlinien Gefahrgut) “Execution guidelines for dangerous goods”**
    - Procedure for proposed exceptions are given (Paragraph 5)

4.4.2 BinSchUO 2008

Other requirements especially for Germany are provided by the “Binnenschiffsuntersuchungsordnung” (Rules for the examination of inland navigation vessels in Germany) where minimum requirements for selected parts regarding construction, arrangement and outfitting are published [(9)].

- **Shipbuilding** (Appendix II, Part II, Ch. 3)
    - Structural strength of the hull hast to comply with the loads applied to the hull
    - A strength calculation has to prove the sufficient dimensions of the structural members according to the designated classification society
    - Minimum thicknesses are defined for various plates

5 Alternative single-to-double hull retrofit variants

(Author: CMT)

5.1 Minimum allowable freeboard

For the determination of the loads and forces and of course for the cargo capacity the minimum allowable freeboard has to be identified. The required minimum freeboard of the vessel has to comply with the regulations published by the European Union in 2006 [(10), pages 48 - 50]. Every vessel has to fulfil minimum freeboard requirements to be taken into account for safe operation in designated waters. The minimum allowable freeboard limits the maximum possible draught of the vessel and also the resulting cargo carrying capacity in the holds.

In order to opt for a conservative approach, reductions of the allowable freeboard due to superstructures are neglected concerning for instance possible crew changes caused by the lengthening process. Solely the sheer is regarded with its maximum allowable values forward S_v (1000 mm) and aft S_a (500 mm). The abscissa of the sheer located at $0.25xS_v$ and $0.25xS_a$ taken from the forward end of the vessel is 12.00 m and from the stern 21.00 m respectively. The effective sheer is calculated according to the following formulae:

- $Se_v = S_v * 4 * X_v / L$
- $Se_a = S_a * 4 * X_a / L$

The minimum freeboard is derived from the equation below:

- $F = 150 * (Se_v + Se_a) / 15$

In order to calculate the maximum draught of the vessel a deck plating thickness of t = 8 mm applied. The maximum allowable draught of the vessel derives to:

- $T_{max} = D + t - F$

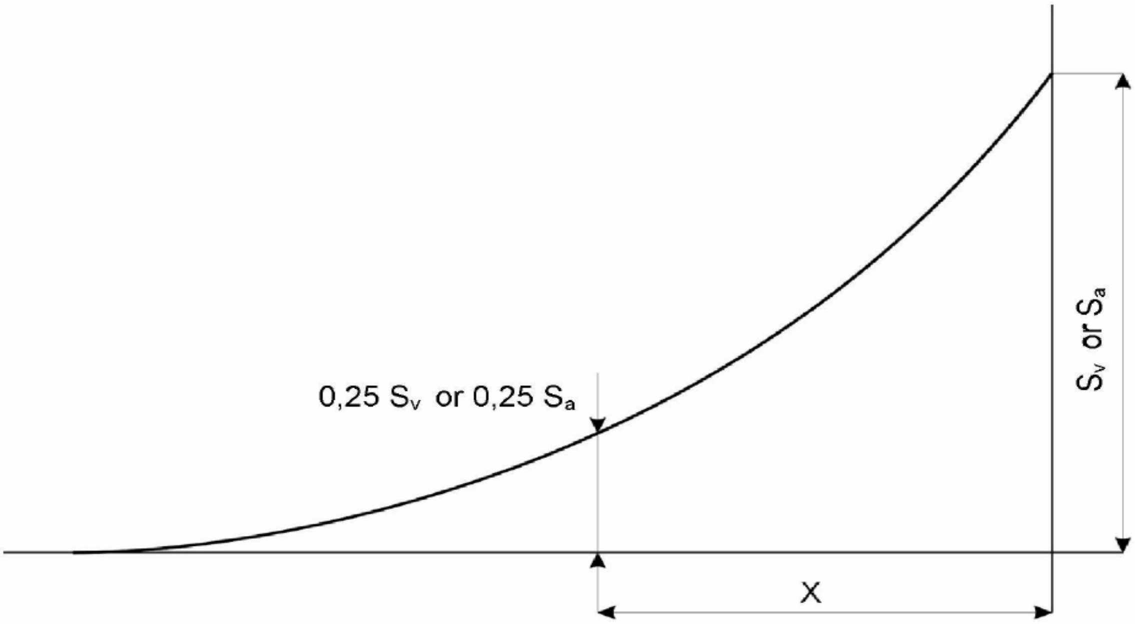


Figure 9: Sheerline

The results of the freeboard calculation are presented in Table 5. The maximum draught derives to 3.633 m for the condition fully loaded.

Table 5: Minimum permissible freeboard of MV “Internautic I”

L	Ship length	[m]	80.000
S_v	Forward sheer	[m]	1.000
X_v	Abscissa at 0.25xSv	[m]	12.000
Se_v	Effect. fwd. sheer	[m]	0.600
S_a	Aft sheer	[m]	0.500
X_a	Abscissa at 0.25xSa	[m]	21.000
Sa_v	Effect. aft sheer	[m]	0.525
F	Min. freeboard	[mm]	75
t	Deck plating	[mm]	8
D	Depth	[m]	3.700
T_{max}	Max. draught	[m]	3.633

5.2 Corrosion additions

For the evaluation of the base vessel the net thicknesses of the existing structural members have to be regarded because the corrosion addition is not intended to contribute to the structural strength of the hull. For this reason, the approach is presented in the subsequent sections.

5.2.1 Standard corrosion additions according to GL

The scantlings of the structural members of the vessel are to be determined according to net thickness approach of the GL. The net thicknesses contribute to the structural strength of the hull. Hence, for the thicknesses to be built corrosion additions have to be added depending on the location of the structural member of interest and rounding off the resulting value to the nearest half millimetre [(7), Ch.2 Sec. 2 B 2.2]. The standard corrosion additions for the plates, frames and other stiffeners are presented in Table 6 and provide an overview.

Table 6: Corrosion additions according to GL

Item	Corrosion addition		
	Inner face [mm]	Outer face [mm]	Total [mm]
Bottom plate	0.75	0.50	1.25
Inner bottom	0.50	0.75	1.25
Longitudinal frames	0.50	0.50	1.00
Floor	0.50	0.50	1.00
Floor face	0.75	0.50	1.25
Bulkhead cargo	0.50	0.50	1.00
Chine radius	0.50	0.50	1.00
Side plating	0.50	0.50	1.00
Inner side plating	0.50	0.50	1.00
Side frame	0.50	0.50	1.00
Inner side frame	0.50	0.50	1.00
Side web girder	0.50	0.50	1.00
Sheer strake	0.50	0.50	1.00
Deck	0.75	0.50	1.25
Deck beam	0.50	0.50	1.00
Deck girder (longitudinal)	0.50	0.50	1.00
Hatch coaming	0.50	0.50	1.00
Hatch coaming sec. stiffener	0.50	0.50	1.00
Hatch coaming vertical stiffener (stay)	0.50	0.50	1.00

5.2.2 Corrosion reduction according to RRR (Russian River Register)

For the detailed assessment of the base vessel MV “Internautic 1” the current net thicknesses of the structural members have to be determined. Measured plate and stiffener thicknesses were not available for the vessel. Therefore, the net thicknesses are calculated according to the following approach: Instead of deducing the standard corrosion additions from GL annual corrosion values taken from the RRR are applied.

The specific corrosion rate depends also on the location of the structural member. The period of usage is assumed to range from the initial construction in 1968 to 2013 which sums up to 45 years as indicated in Table 7. Thus, the resulting values have to be deduced from the plate and stiffener thicknesses of the base vessel in order to obtain the net scantlings for further evaluation of the retrofit variant (11).

Table 7: Corrosion reduction for MV "Internautic I" according to RRR

Item	Corrosion		
	[mm/year]	[years]	[mm]
Bottom plate	0.05	45	2.3
Inner bottom	n/a		n/a
Longitudinal frames	0.05		2.3
Floor	0.05		2.3
Floor face	0.05		2.3
Bulkhead cargo	0.04		1.8
Chine radius	0.08		3.6
Side plating	0.05		2.3
Inner side plating	n/a		n/a
Side frame	0.06		2.7
Inner side frame	n/a		n/a
Side web girder	0.06		2.7
Sheer strake	0.05		2.3
Deck	0.03		1.4
Deck beam	0.03		1.4
Deck girder (longitudinal)	0.03		1.4
Hatch coaming	0.03		1.4
Hatch coaming sec. stiffener	0.03		1.4
Hatch coaming vertical stiffener (stay)	0.03		1.4

The different retrofit solutions are going to be implemented into the existing single hull of the vessel MV “Internautic 1” for comparison purposes. For the evaluation it is assumed that the existing structures of the hull have been exposed to corrosion over a time span of 45 years. By doing so, a reduction of the section moduli of the existing components is taken into account.

As an example, the difference of the plate thicknesses is presented in the following two figures.

For the assessment of the base single hull vessel two variants are considered:

- “Single hull without corrosion”: The structures are considered with their net thicknesses, i.e. with deduction of the corrosion addition defined by the GL class.
- “Single hull with corrosion”: The structures are considered to be exposed to corrosion for 45 years according to the formulae of RRR.

For the implementation of the novel retrofit solutions the “Single hull with corrosion” variant forms the base.

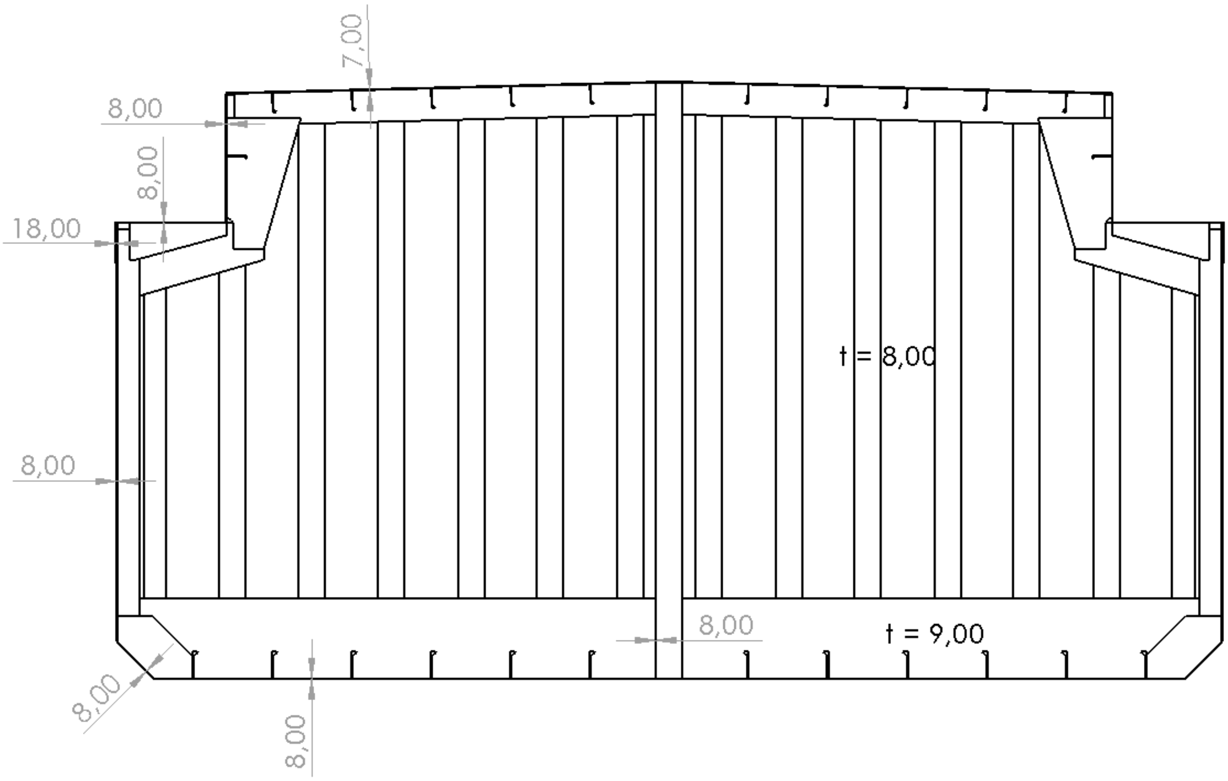


Figure 10: Plate thicknesses as built of MV “Internautic I”

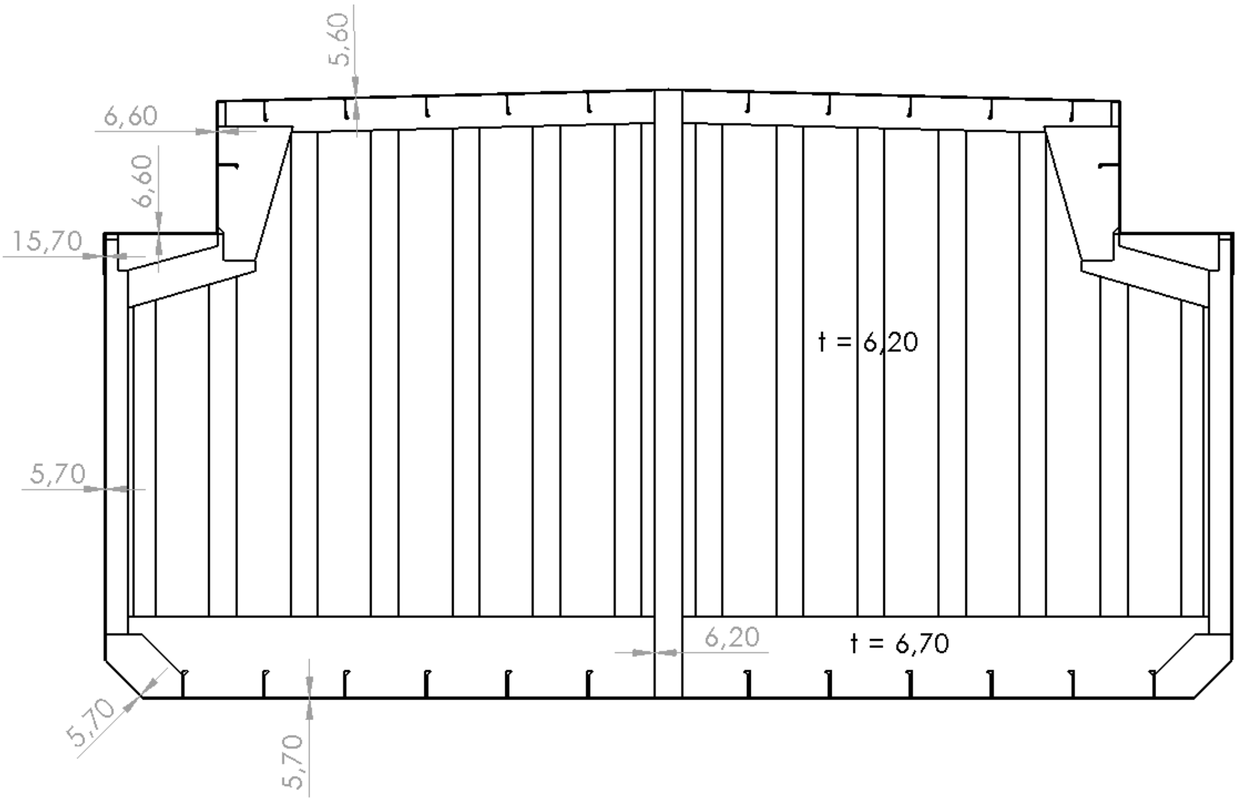


Figure 11: Plate thicknesses after corrosion deduction of MV “Internautic I”

5.3 Retrofit solutions

Key drivers for the development and introduction of novel structural solutions for single hull inland navigation vessels are reducing costs during manufacturing and in operation, increasing the benefit in terms of cargo capacity and reducing the risk of a tank leakage in case of an accident such as grounding or side collision. It is obvious that these desired properties depend on each other in such a way that a reduction in risk is combined with higher costs to achieve the improvements for instance. For this reason, a good balance of the influencing factors has to be achieved to obtain a reasonable and feasible implementation. The scheme is presented in Figure 12.

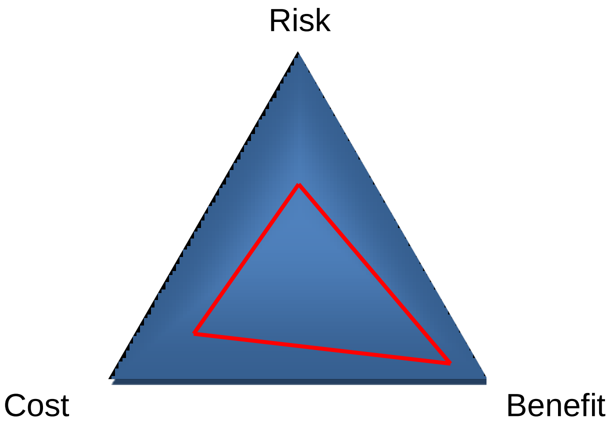


Figure 12: Dependence of risk, cost and benefit (example)

The risk of a commonly applied technical solution is integrated in the rules and regulations of classification societies, national rules and ADN code. Former accidents are incorporated in the definition of structures and arrangements of the vessel. Consequently, the maximum level of risk is defined by following the standard prescriptive rules. If other structures or materials are planned to be involved the risk has to be at least maintained or improved. Reducing costs is the main driver for the shipping companies as the economic competition forces them to optimise their fleet. Hence, the cargo benefit of the vessel has to be optimised.

5.3.1 Selection of variants

With respect to the above-mentioned characteristics a selection matrix has been established to assess the ideas for single-to-double hull retrofit variants. A list of important properties was established, rated by the WP 5 members and discussed afterwards during a technical meeting. Four general categories were distinguished and in each category except for the base steel double hull variant several options to implement a double hull into the single hull base vessel were identified:

- Base ADN steel double hull variant

- Alternative steel variants
    - **Ordinary outer steel structure**: Additional outer steel structure is fitted to build up a steel double hull.
    - **Perforated double hull steel structure**: Additional inner steel structure is fitted to build up a steel double hull with perforated web.
    - **λ-shape steel structure**: Additional inner steel structure with λ-shaped longitudinals or transversals is fitted to build up a steel double hull.
    - **X-shape steel structure**: Additional inner steel structure with X-shaped longitudinals or transversals is fitted to build up a steel double hull.
    - **Metal foam steel sandwich structure**: Additional inner steel structure with metallic foam is fitted to build up a steel double hull.

- Polymer-foam/composite and polymer-foam/steel variants
    - **SPS steel polymer sandwich structure**: The inner hull is built from steel with polymers in between as sandwich core.
    - **Steel with polymer-foam**: The inner hull is built from steel bonded to polymeric foam as sandwich core.
    - **Composite with polymer-foam (inner hull)**: The inner hull is built from solid composites bonded to polymeric foam as sandwich core.
    - **Composite with polymer-foam (outer hull)**: Additional outer composite/foam shell is fitted to the existing steel hull.

- Independent tank variants
    - **Rubber bags**: The inner hull is built by a flexible independent rubber tank sitting on supporting structure.
    - **Independent composite tank**: An independent and self-supporting composite sandwich tank forms the inner hull.

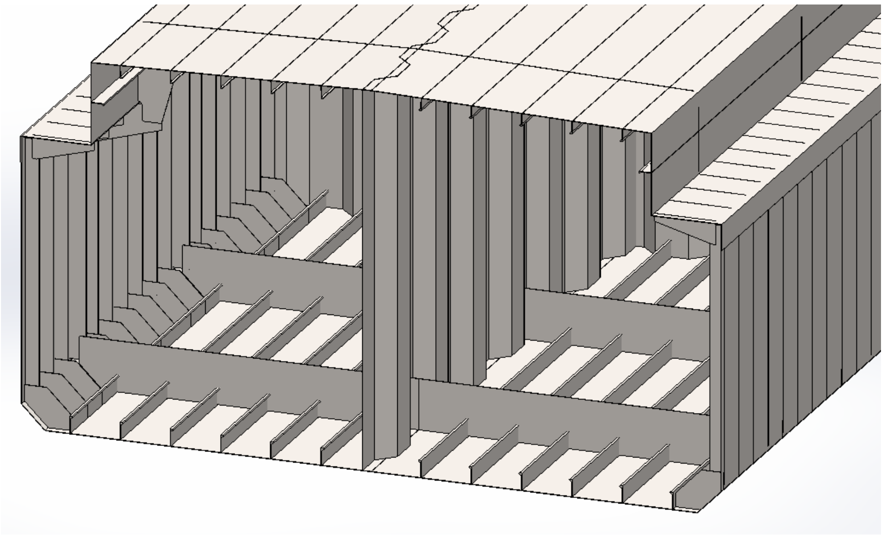
It was agreed in the meetings that one variant of each category is selected for the investigations. The ordinary ADN steel inner hull is taken as base solution to compare with in the future studies. Variants which intend to change the main dimensions of the vessel are recognised to be not regarded as a completely new vessel would arise with different demands. The SPS steel-polymer idea is discarded because investigations from University of Belgrade revealed that the weight savings for barges using SPS is only located between 5 % to 8 % and not by 50 % as reported in some sources [(12), page 127]. X-shape steel structures do not fit in general into the existing framing scheme. For this reason, the implementation of such structures is regarded to be costly and time-consuming. With respect to the previously described circumstances four different variants are identified to serve for the single-to-double hull retrofit investigations with the highest ratings, namely:

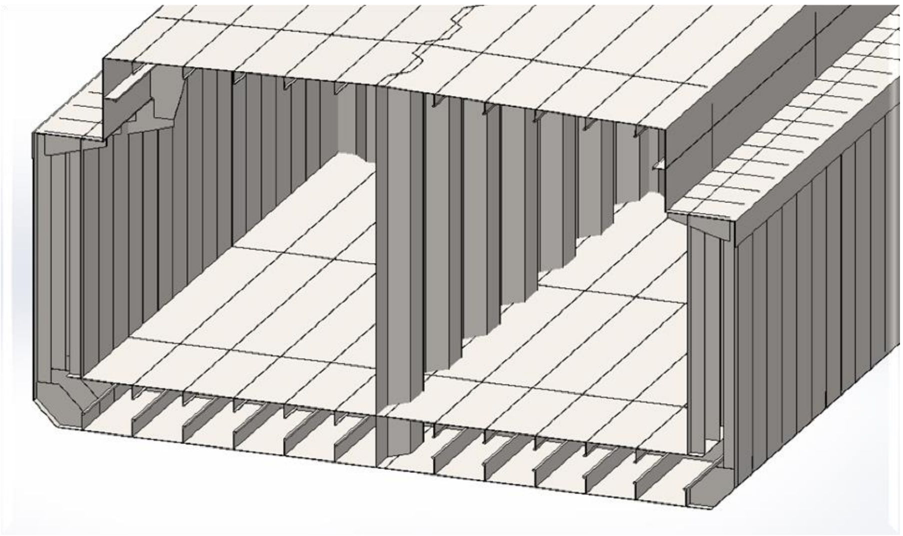
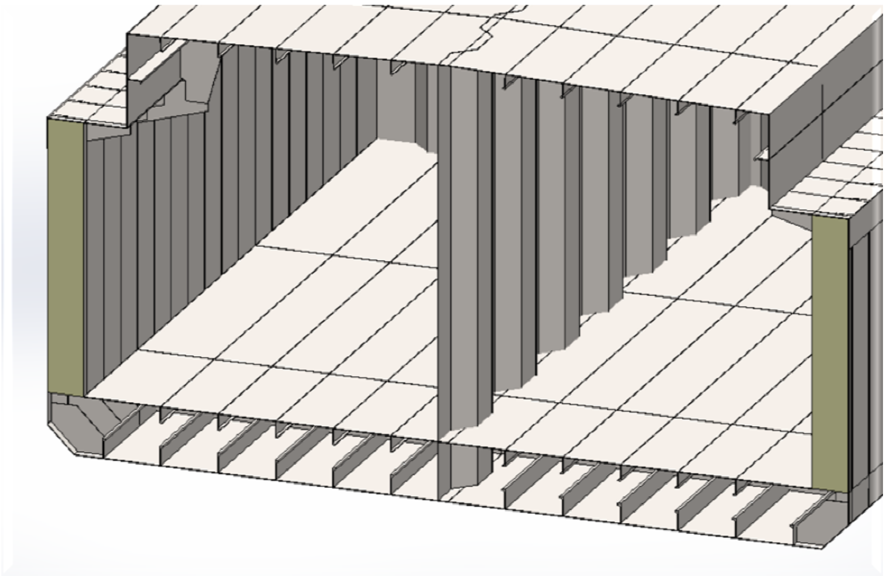
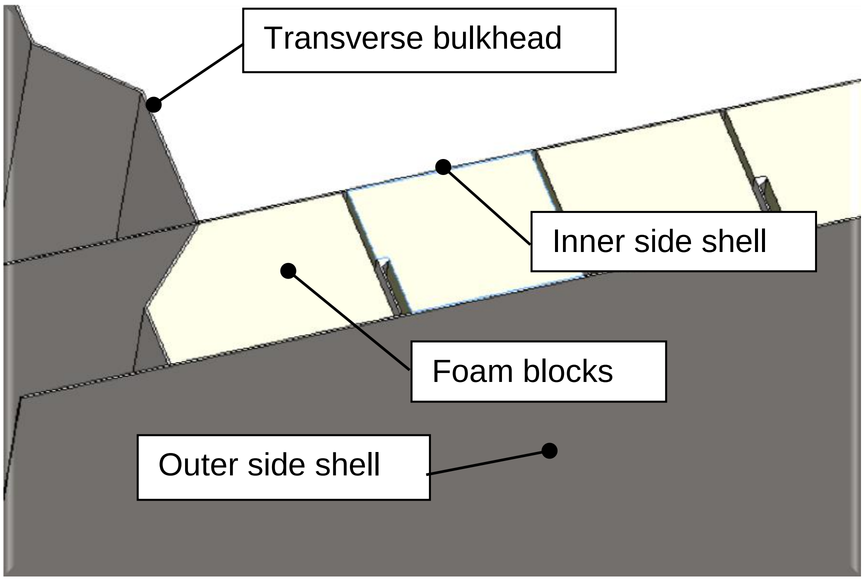
1. **ADN steel double hull**
2. **Steel/polymer-foam double hull**
3. **λ-shape steel double hull**
4. **Rubber bags**

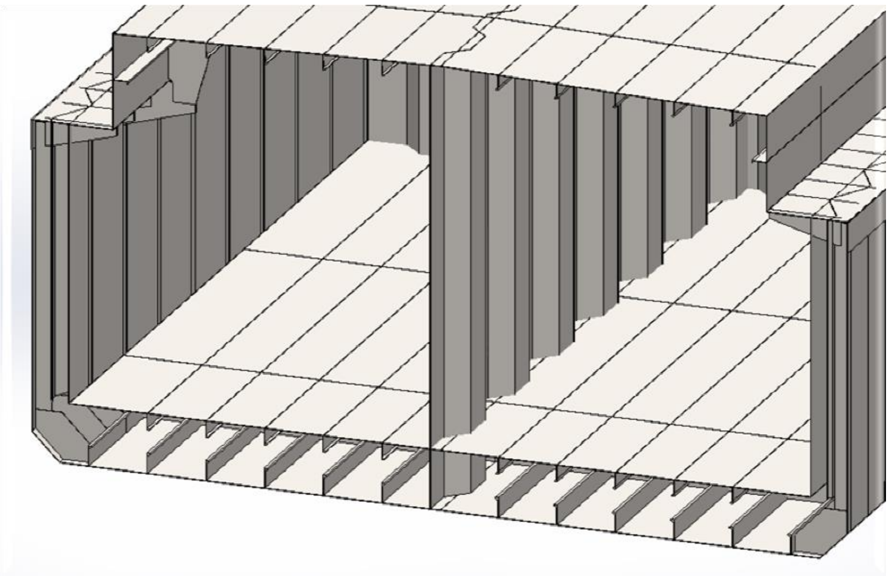
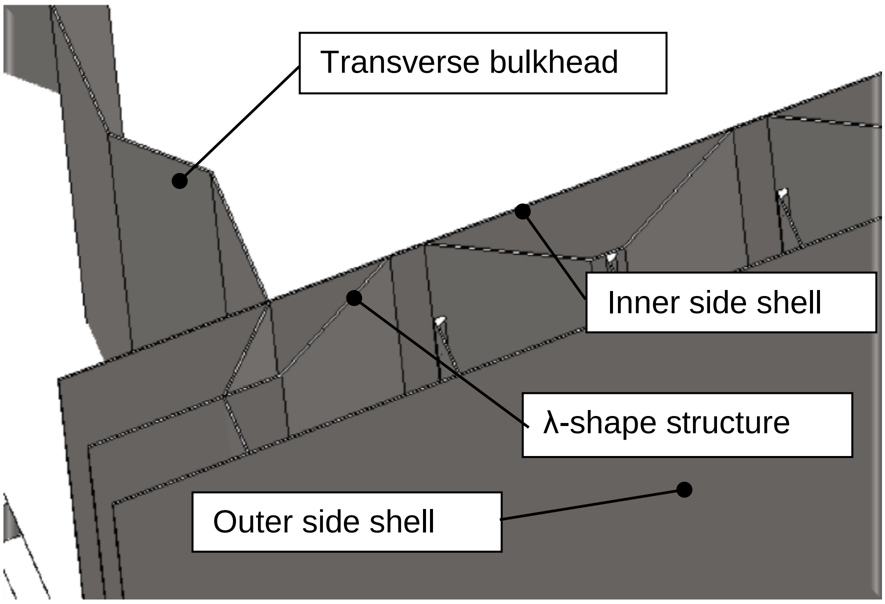
As the ADN code only provides regulations for side impact crashworthiness and not for the double bottom in grounding condition it is assumed that the double bottom is designed as standard steel double hull as it fits best with the already existing steel structure of the vessel such as floors and it is most likely the cheapest variant. The double bottom height is predefined by the height of the floors. Consequently, no benefits are expected to be achieved with a standard double bottom height and alternative structures which will result in higher costs and incompliance with the existing rules and regulations.

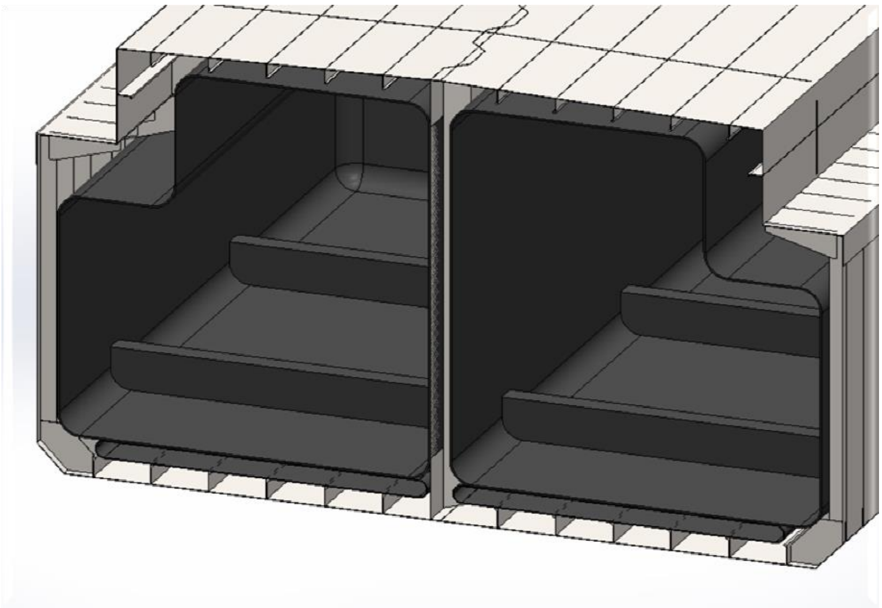
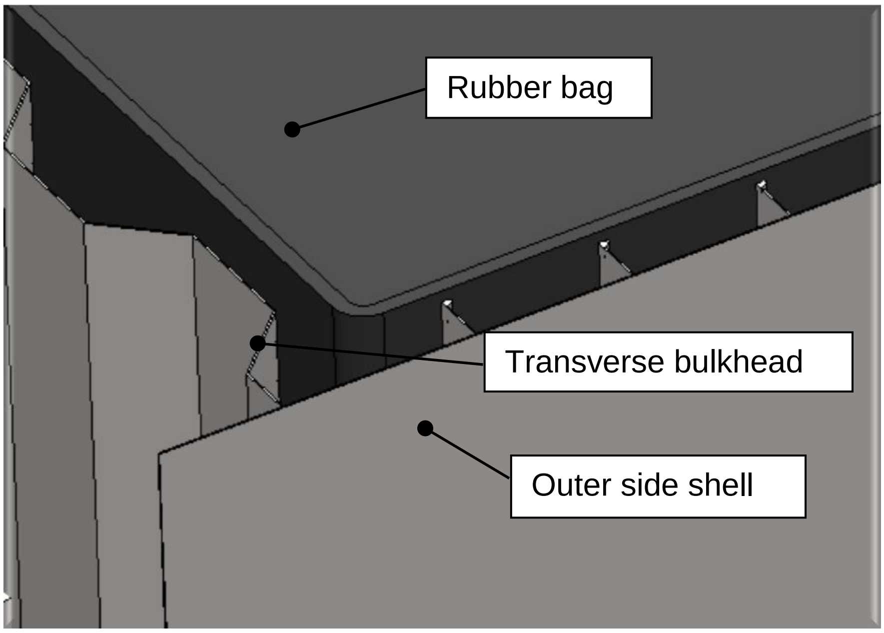
The selected variants are illustrated as examples in Table 8.

Table 8: Different single-to-double hull retrofit variants

Base	Single hull with corrosion	

1	Double hull according to ADN regulations	
2	Steel/polymer-foam/steel double hull	 

		
3	λ-shape double hull	

		
4	Rubber bags	

5.3.2 Evaluation of the retrofit solutions

The following subsections provide an overview of the evaluation regarding the selected retrofit solutions which will be investigated specifically considering technical and regulatory aspects. The rubber bag solution will be introduced and described in more detail as similar solutions have not been considered in the literature yet.

For all solutions, except for the rubber bag variant, a standard double bottom is considered as the height of the structures is predefined by the height of the existing webframes. Therefore, alternative structures have no benefit in the bottom for this present application case which does not imply that alternative structures in the double bottom will not have any benefits for different vessels.

Production and cost aspects of the presented solutions are presented in the corresponding deliverable D 5.4 “Production”.

5.3.2.1 ADN steel double hull

The ordinary steel double hull according to current classification rules and present ADN requirements consists of a stiffened outer shell and a stiffened inner shell which defines the cargo hold of the vessel. The stiffeners in the double side and in the double bottom can be arranged longitudinally or transversally as applicable and desired.

For the present application case MV “Internautic I” a transversally framed outer side structure and a longitudinally framed bottom structure already exists. For this reason the inner bottom is integrated with longitudinal frames and the inner side with transversal frames to maintain consistency.

According to ADN requirements the minimum double side width for steel double hulls is 600 mm and for the double bottom 500 mm [(4): Sec. 9.3.3.11.7]. With respect to the present circumstance that the existing floors have a height of 650 mm the inner bottom is arranged at that height stiffened by longitudinal bulb flat profiles at a frame spacing of 645 mm. The inner side is integrated within the allowable limit of 600 mm stiffened by transversal frames arranged in a spacing of 500 mm.

In the following, advantages and disadvantages of the standard ADN steel double hull are briefly summarised and presented.

Pros:

- Proven concept (longitudinal and/or transverse framing for double bottom and double side)
- Matured material (steel)
- Well-known production techniques on common shipyards in Europe
- Visual inspection of the double hull is executable for a class surveyor as usually requested and performed
- Fulfils class requirements as it is standard double hull design
- Fulfils ADN requirements as it is standard double hull design
- Proven reparation techniques for steel and welding on common shipyards in Europe
- Recycling of steel structure

Cons:

- Reduction of cargo capacity by more than 22 % in comparison to the single hull variant (MV “Internautic I”-case)
- Complex implementation (holds have to be opened widely to get access for the processing)
- Buoyancy loss in case of outer shell rupture (vessel submerges additionally)
- New charging/discharging pump system necessary

5.3.2.2 Steel/polymer-foam/steel double hull

The implementation of a double hull by the application of polymer-foam and an inner steel plating has already been introduced by TNO in 1999 and continued by Alexander Kulzep in 2001 [(13)]. It has been investigated how double hull structures can benefit from the application of polymer-foam as sandwich layer in between an outer and an inner steel plating. Although, the investigations have been performed for RoRo vessels with a double side thickness of 2520 mm they allow inference on their capabilities for inland navigation vessels. It is stated that the polymer-foam filled steel double hull is capable of increasing the energy absorption by approximately 60 % accompanied by a

20 % heavier hull structure. The polymer-foam is considered to be closed-celled because that type of foam is less vulnerable to humidity as it does not take up water.
In the present application case the polymer-foam has to be integrated into the already existing steel structure with its frames and additional stiffeners. Thus the foam is included as blocks which are bonded to the outer and inner side shell. The inner shell does not have any additional stiffeners as it is thoroughly supported by the polymer-foam.
Again, the characteristics are summarised subsequently.

Pros:

- Similar crash resistance (has to be demonstrated according to the procedure for alternative designs, ADN Sec. 9.3.4)
- No loss of buoyancy in case of outer shell rupture (foam acts as lifting body)

Cons:

- Not ADN requirements compliant
- Involvement of foam and adhesives (breaches the ADN requirements that no composite materials are allowed and the structures have to be built with steel or comparable metal, ADN Sec. 9.3.3.0.1 & 9.3.3.0.2)
- Production techniques not proven (processing of the foam and adhesive bonding on common shipyards)
- Expected difficulties in repair procedures (cutting and welding has to be processed with special regard to the involved foam and adhesive)
- No visual inspection of the involved structural steel components possible, only inner and outer platings can be inspected (ADN Sec. 9.3.3.11.9)
- Foam and adhesive have to be chemically resistant in case of inner shell rupture
- Not class compliant as it offends against the ADN requirements
- New charging/discharging pump system necessary

5.3.2.3 λ-shape steel double hull

Alternative steel double hull structures have been investigated in various designs and arrangements for double hulls on sea-going ships and especially for inland navigation vessels. Different shapes have been systematically investigated towards the influence of design in the SAND.CORe project [(14)]. Crash simulations revealed that Y-shape structures can improve the energy absorption capabilities by approximately 40 %, however, arranged in a way that the Y opens to the outer side plating. That arrangement is not very preferable as retrofit procedure because transverse frames at the outer side shell already exist which can be used and integrated in the design.
Additionally, investigations on Y- shape and X-shape side structures were made by TNO (Institute for Technical Applied Physics, The Netherlands) and Schelde Naval Shipbuilding (The Netherlands) comprising real scale side collision tests and corresponding simulations [(15)]. A patent has been filed for the Schelde Y-shape structures and variations in 1999 for the arrangement as described above [(16)].
Due to the retrofitting procedure (existing transverse frames at the outer side shell) the alternative structural steel elements are arranged in a mirrored way, i.e. the openings are turned to the inside of the vessel to allow for an enhanced integration into the existing structure.
A summary of the advantages and disadvantages of the λ-structures is presented below.

Pros:

- Increase of cargo capacity by more than 3 % in comparison to the standard double hull (MV “Internautic I”-case)
- Similar crash resistance (has to be demonstrated according to the procedure for alternative designs, ADN Sec. 9.3.4)
- No loss of buoyancy in case of outer shell rupture (closed Y-sections act as lifting bodies)
- Steel structures involved (proven production techniques for common European shipyards)

Cons:

- Not ADN requirements compliant
- No visual inspection and cleaning possible caused by closed spaces (breaches the ADN requirement for accessibility of the double hull structures, ADN Sec. 9.3.3.11.9)
- Expected difficulties in repair procedures (due to the closed λ-shaped profiles)
- Not class compliant as it offends against the ADN requirements
- Expected heavier structures (up to 5 %), higher draught than the foam/steel variant for same amount of cargo
- New charging/discharging pump system necessary

5.3.2.4 Rubber bags

Carrying hazardous liquid cargo in special developed reinforced rubber bags appears to be beneficial due to the simplicity of the arrangement.

The solution consists basically of reinforced rubber bags which are in use for land based fuel storage and partially also transportation in civil and military applications. Such rubber-coated or polyurethane bags are fabricated to a size with a volume of more than 300 m³. Suppliers are for instance AIRE Industrial [(17)], Portable Tank Group [(18)] or ContiTech [(19)].

Rubber-coated fabrics are superior to polyurethane tank shells according to the technical specifications from ContiTech incorporating major features such as:

- Materials to be coated: Kevlar, metal sheets, steel, cotton, polyamide, polyester, foil, glass, viscose
- Coated fabric/layer can be varied in quantity and thickness
- Fully vulcanised seam joints (no glued joints)
- Inner and outer rubber coating may consist of different compositions
- Service temperature range from -40°C to +100°C (typical), -60°C to +250°C (extreme)
- Shell thicknesses range from 0.1 mm to 10 mm
- Typical lifetime is 10 years
- No active maintenance is required
- Wash plates and inner webs can be integrated
- High impermeability of the rubber
- Composition of the rubber compound can be adapted to various media such as diesel, fuel, water, etc.
- Tanks can be tailor-made, preferably with pillow shape (see Figure 13)

Collapsible tanks feature a fabric (the type of material can be varied according to the actual demands) typically coated on both sides with synthetic rubber. The rubber coating can be adapted to the conditions on the outside with a weather-resistant type and on the inside with a fuel-resistant type of compound to tune the shell to the demands. Even multiple layers of fabric can be combined to a complete shell. The collapsible tank is manufactured from rubber sheets which are joined by hot-vulcanising processes at the production plant to ensure high strength. Works on the building site such as repairs can be executed by bonding or cold-vulcanising processes which result in lower strength. Bonded seams are only applicable for temporarily repairs. An important factor which has to be taken into account is the diffusion rate of the intended cargo through the rubber material. Although the rubber is considered to be leak-proof a small amount of cargo is expected to diffuse through the shell. The diffusion rate for diesel is 1 to 2 g/m² per day for instance which is far below the minimum requirement for the German army of < 6 g/m² per day. For this reason, air control and exchange with the aid of sensors might be necessary.

Figure 13: Examples for collapsible pillow fuel tanks made from rubber coated fabric [(19)]

The general shape of the tanks is flat (pillow shape). However, it can be forced into other possible shapes by adjacent walls of the cargo holds of the vessel during filling. Due to manufacturing circumstances the normal shaped pillow tanks are considered in over-size to fit into the holds and unfold during the filling process without a complex tank shape. Cargo intake and outlet will be located at the bottom to facilitate the unfolding process of the collapsed tank during filling.

Caused by the existing internal structure of the application case MV “Internautic I” special care has to be taken to ensure a flat surface to support the flexible tanks in the considered holds. The webframes remain with their height of 650 mm as they are, but a solution to cover the longitudinal frames at the bottom and the transverse frames at the sides has to be found.

The considered variants to act as supports are the following:

- Composite sandwich panel supports
- Steel panel supports
- Aluminium panel supports
- Polystyrene block supports

The support arrangement is intended to either cover the frames with panels or fill the space in between. An impression of the bottom supports is presented in Figure 14. Same applies also for the outer sides to the hull.

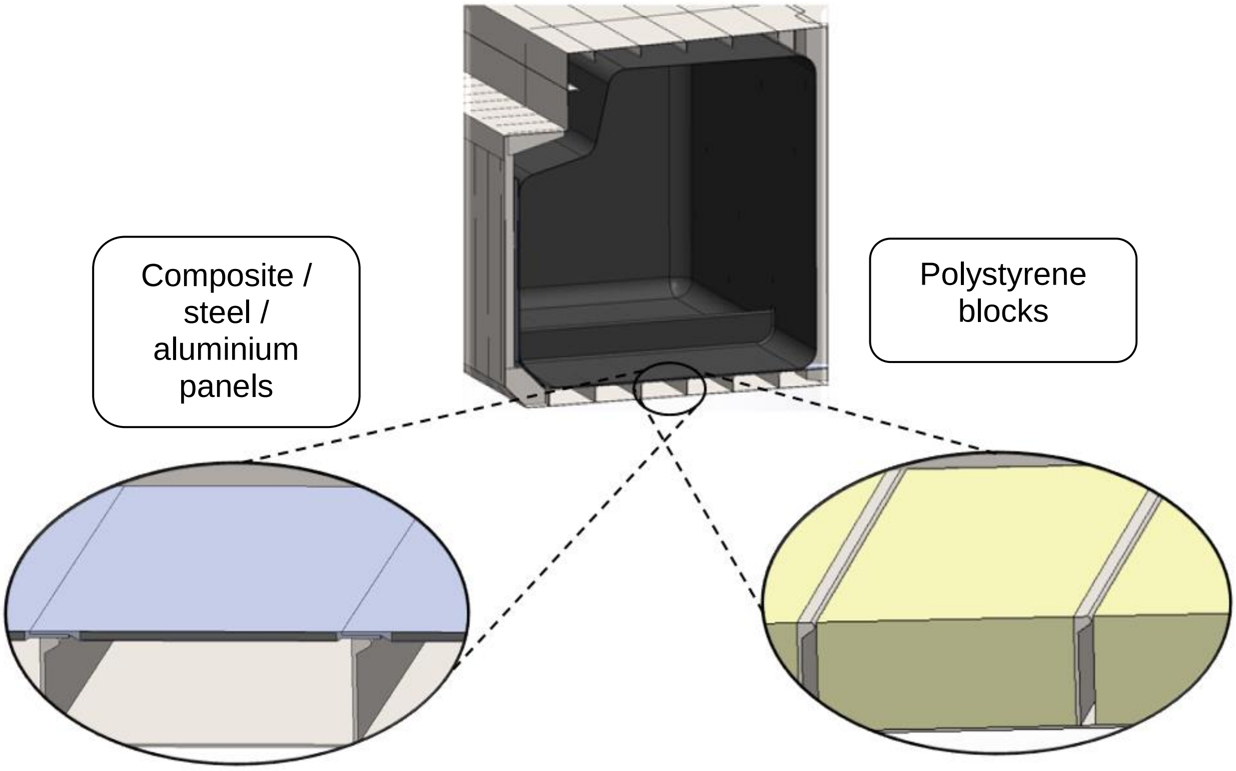


Figure 14: Support arrangement for flexible cargo tanks

The corresponding mass estimation is presented in Table 9 and Table 10 for the above introduced support solutions. The scantlings for the composite and steel panels are determined through FEA to obtain a first impression on the required dimensions. The scantlings of the aluminium panels are derived from standard sandwich panels supplied by CEL Components. For the polystyrene blocks with a density of 28 kg/m³ (Styrodur 2500 C) it is assumed that the material is capable of carrying the distributed load of the cargo. Material properties are taken from the price list provided by ISOVER [(20)].

Table 9: Masses for supporting panels

Panel		Bottom	Chine	Side	Total
Length [mm]		3500	3500	2720	
Width [mm]		645	400	500	
Area [m²]		2.26	1.40	1.36	
Total area [m²]		430	40	300	770
Composite	Per unit area [kg/m²]	10.3	10.3	8.1	
	∑ [kg]	4500	500	2500	7500
Steel	Per unit area [kg/m²]	33.5	33.5	33.5	
	∑ [kg]	14500	1500	10200	26200

Panel		Bottom	Chine	Side	Total
Aluminium	Per unit area [kg/m²]	6.8	6.8	6.5	
	∑ [kg]	2900	300	2000	5200

Table 10: Masses for supporting blocks

Block		Bottom	Chine	Side	Total
Length [m]		3.49	0.46	2.47	
Width [m]		0.60	-	0.46	
Height [m]		0.22	-	0.22	
Volume [m³]		0.46	0.10	0.25	0.81
Polystyrene	Density [kg/m³]	28	28	28	
	∑ [kg]	2500	600	1600	4700

A comparison of the masses indicates that the aluminium panel support and the polystyrene block support involve the least weights and are therefore favourable. Cost estimations and economic investigations are presented in deliverable D 5.4 “Production”.

For a pillow tank with the dimensions 14.2 m length and 8.5 m width, designed to fit into the greater hold with a length of 14.0 m, experts from ContiTech calculated a shell thickness of 1.6 mm. The shell is made of double-side rubber coated polyamide fabric and weighs approximately 500 kg. At this stage no reinforcements or special designed intakes or outlets are considered in detail.

In case of a side impact or grounding incident where the rubber bags in the cargo holds are going to be compressed and relief is essential to avoid bursting of the bags an additional smaller bag can be located folded on the deck. Compressed cargo is then able to fill the emergency bag to reduce pressure.

The advantages and disadvantages are presented subsequently.

Pros:

- Increase of cargo capacity by 12 % in comparison to the standard double hull (MV “Internautic I”-case)
- Low maintenance required during operation
- Steel structures can be repaired with common techniques as applied on European shipyards
- Bags can be easily removed and changed in case of cargo change or worn out rubber
- Reinforced rubber bags are already used for fuel storage in military applications and for road transportation of liquids such as fuel or chemicals
- Steel structures can be visual inspected as required by class and ADN requirements after partial removal of the rubber bags (ADN Sec. 9.3.3.11.9)
- No closed spaces

Cons:

- Not ADN requirements compliant
- Rubber applied in cargo area (offends against the ADN requirement that the holds have to be built with steel or equivalent metal, ADN Sec. 9.3.3.0.1 & 9.3.3.0.2)
- Not class compliant as it offends against the ADN requirements
- No similar crash resistance by measures of energy absorption for double hulls for alternative designs (ADN Sec. 9.3.4)
- Additional supports at the bottom required and at the sides as well
- New charging/discharging pump system necessary
- Rubber is leakproof but allows a certain diffusion rate of the cargo
- Corrosion aspects in mixed aluminium-steel structures are of importance

5.4 *Cargo optimisation*

The implementation of a double hull involves always a greater reduction of the cargo carrying capacity in comparison to the single hull vessel MV “Internautic I” which is going to be retrofitted. The present section provides an overview of the approximated cargo capacity with implemented double hull in dependence of the double bottom height and the double side width. The corresponding figures are presented in Table 11 and Figure 15.

Table 11: Cargo variation caused by alteration of double side width and double bottom height

Cargo [m^3]		Double side width [mm]					
		200	300	400	500	600	700
Double bottom height [mm]	200	2112.9	2073.2	2033.5	1993.8	1954.1	1914.4
	300	2065.0	2026.4	1987.9	1949.3	1910.7	1872.2
	400	2017.1	1979.7	1942.2	1904.8	1867.3	1829.9
	500	1969.3	1932.9	1896.6	1860.3	1824.0	1787.6
	600	1921.4	1886.2	1851.0	1815.8	1780.6	1745.4
	700	1873.5	1839.4	1805.4	1771.3	1737.2	1703.1

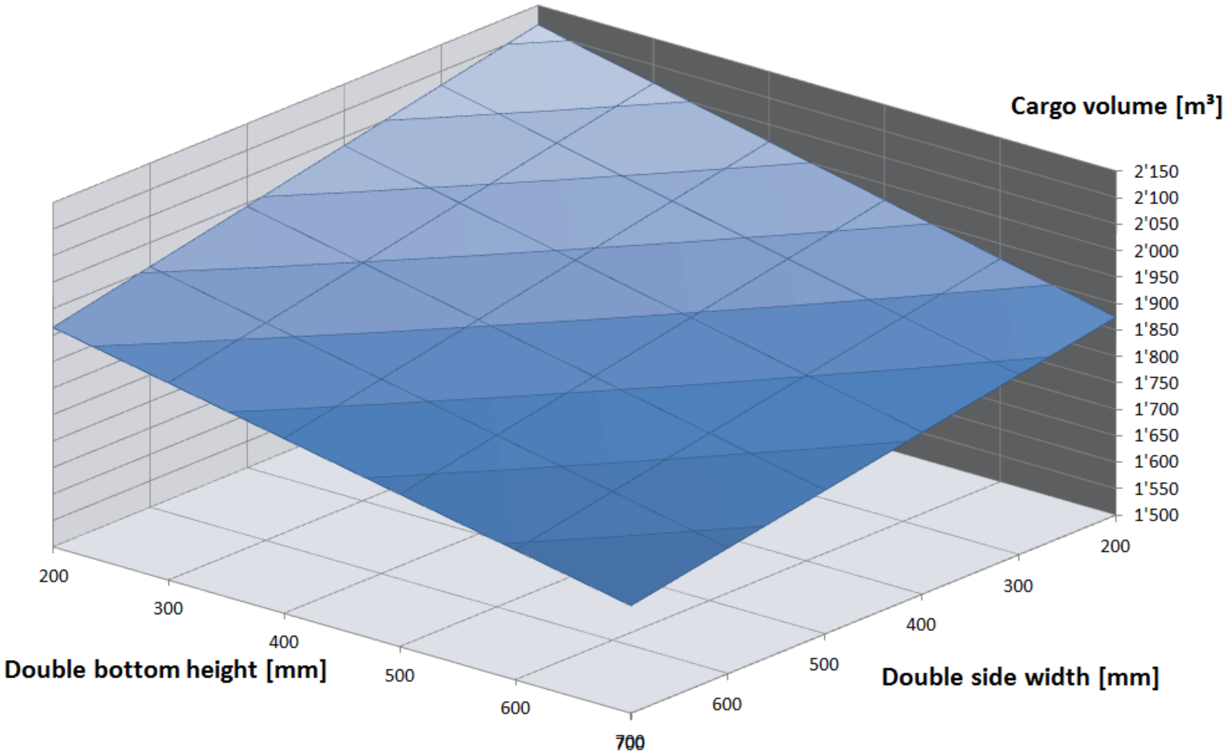


Figure 15: Cargo volume variation for double hull implementation

An overview of the expected cargo carrying capacity of the different retrofit variants is summarised in the following table. The masses for the additional inner structures and materials are derived from the CAD models which have been established to serve as base for the FE analyses and for demonstration purposes. The scantlings of the additional structures are determined by the GL software “GL ND” for inland navigation vessels to receive a good approximation. The double bottom is assumed to be built as standard variant for the double hull implementation except for the variant “Rubber bags” because the ADN requirements are only prescriptive for side impact collisions and not for grounding scenarios. The height of the double bottom is therefore predetermined by the height of the already existing floors of MV “Internautic I”.

The additional weights and the approximated cargo reduction are given in comparison to the single hull variant exposed to corrosion. The density of cargo is generalised to a density of 900 kg/m³ to allow for a broad variety of different types of liquids.

Table 12 indicates the obtained figures of each double hull variant in relation to the base single hull of MV “Internautic I”. If a standard ADN double hull is considered the reduction of cargo capacity amounts to over 22 %, for the rubber bag variant it is calculated to be less than 11 %. This evidences that the loss of cargo capacity can be cut to half by using the rubber bags instead.

Table 12: Masses for different retrofit variants

		Single hull without corrosion	Single hull with corrosion	ADN steel double hull	Steel/polymer-foam/steel double hull	λ-shape steel double hull	Rubber bags
Double bottom height	[mm]	n/a	n/a	650	650	650	n/a
Double side width	[mm]	n/a	n/a	600	600	400	n/a
Cargo volume	[m³]	2290.1	2290.1	1758.9	1758.9	1828.2	2026.4
Max filling level	[%]	97 %	97 %	97 %	97%	97 %	97 %
Density of liquid	[kg/m³]	900	900	900	900	900	900
Total mass in holds	[t]	1980.0	1980.0	1535.5	1535.5	1596.0	1769.1
Variation to single hull	[%]	basis	basis	-22.4	-22.4	-19.4	-10.7
Mass of ship in cargo area (57.0 m)	[t]	183.5	142.5	193.8	204.8	202.3	157.2
Thereof additional steel/composite mass	[t]	n/a	-41.0	51.2	51.7	59.8	9.7
Thereof additional foam/rubber mass	[t]	n/a	n/a	n/a	10.6	n/a	5.0
Mass per meter ship in cargo area	[t/m]	3.22	2.50	3.40	3.59	3.55	2.76

The expected draught reduction caused by the implementation of the different double hull variants is presented in Table 13. For all variants the draught decreases due to the lower cargo carrying capacity. The additional structures have a minor influence. The standard ADN double hull results in a draught reduction of 0.61 m whereas the rubber bags variant exhibits a lower reduction of about 0.25 m.

Table 13: Draught reduction for double hull variants in comparison to the single hull vessel

		Single hull	ADN steel double hull	Steel/polymer-foam double hull	λ-shape steel double hull	Rubber bags
Draught	[m]	3.63	3.02	3.05	3.03	3.38
ΔT	[m]	n/a	-0.61	-0.59	-0.60	-0.25

5.5 *Loads and forces*

Bending moment and shear force have been calculated with the aid of the software “GL Poseidon ND” for inland navigation vessels. All other loads were calculated according to rules and regulations for inland navigation vessels of GL [(7) Pt 2, Ch 2, Sec 3 C].

The cargo pressure is derived from the assumed total amount of cargo carried by each retrofit variant and the corresponding accumulated bottom area of the holds. The sea pressure is derived from the total displacement of the retrofitted vessel and the corresponding draught in comparison to the base variant “Single hull without corrosion”.
Loads caused by additional structures such as inner bottom and inner side components, foam or rubber are taken into account by distributing them equally onto the inner face of the outer bottom for simplification purposes. By this means, the additional structures contribute to the total load onto the hull structure without taking gravity into account.
A detailed summary of the loads is given in Table 14. For the comparison of the different retrofit variants one loading condition is regarded: fully loaded vessel.

Table 14: Loads and forces for different retrofit variants

Bending moment and shear force			
Design bending moment (hogging without cargo)	[kNm]	14823	
Design shear force (hogging without cargo)	[kN]	608	
Deck pressure			
Weather deck	[kPa]	4.913	
Cargo pressure on bottom			
Single hull without corrosion	[kPa]	38.540	Cargo: 1980 t Bottom area: 504.0 m²
Single hull with corrosion	[kPa]	38.540	Cargo: 1980 t Bottom area: 504.0 m²
ADN steel double hull	[kPa]	34.485	Cargo: 1535.5 t Bottom area: 436.8 m²
Steel/polymer-foam/steel double hull	[kPa]	34.485	Cargo: 1535.5 t Bottom area: 436.8 m²
λ-shape steel double hull	[kPa]	34.096	Cargo: 1596.0 t Bottom area: 459.2 m²
Rubber bags	[kPa]	34.862	Cargo: 1769.1 t Bottom area: 497.8 m²
Sea pressure on outer bottom			
Single hull without corrosion	[kPa]	35.640	Displacement: 2350.0 t Draught: 3.633 m
Single hull with corrosion	[kPa]	35.032	Displacement: 2350.0 t Draught: 3.571 m
ADN steel double hull	[kPa]	29.793	Displacement: 1956.7 t Draught: 3.037 m
Steel/polymer-foam/steel double hull	[kPa]	29.901	Displacement: 1936.9 t Draught: 3.048 m
λ-shape steel double hull	[kPa]	30.823	Displacement: 2025.8 t Draught: 3.142 m
Rubber bags	[kPa]	33.236	Displacement: 2188.0 t Draught: 3.388 m
Loads caused by additional structures			
Single hull without corrosion	[kPa]	n/a	
Single hull with corrosion	[kPa]	n/a	
ADN steel double hull	[kPa]	0.997	

Steel/polymer-foam/steel double hull	[kPa]	1.331
λ-shape steel double hull	[kPa]	1.164
Rubber bags	[kPa]	0.286

5.6 *FE analyses*

To receive an impression on the stresses and a first idea towards the feasibility of the retrofit variants FE analyses are performed. They will reveal problem areas at an early stage of the development and indicate whether a design can be regarded for further investigations or performed out in principle.

For the present analyses a simplification has been made: The bulb flat profiles of the original structure are replaced by flat profiles with an equal section modulus around their horizontal axis, as shown in Table 15.

Table 15: Bulb flat to flat bar conversion

HP profile	**Location**		**Web thickness**	**2nd moment of inertia around Y-Y axis**	**Centre of gravity in Z-direction**	**Section modulus around Y-Y axis**	**Equivalent dimensions for flat bar**	
							Width	**Height**
			[mm]	[cm^4]	[cm]	[cm^4]	[mm]	[mm]
160x8	Deck	Without corrosion	8.0	412.4	9.5	43.4	8.5	175
		With corrosion	6.6	358.7	9.7	37.0	7.1	177
180x10	Inner bottom	Without corrosion	10.0	717	10.6	67.6	10.5	199
		With corrosion	n/a	n/a	n/a	n/a	n/a	n/a
180x8	Inner side	Without corrosion	8.0	611.1	10.9	56.1	8.5	199
		With corrosion	n/a	n/a	n/a	n/a	n/a	n/a
180x8	Side	Without corrosion	8.0	611.1	10.9	56.1	8.5	199
		With corrosion	5.3	456.2	11.5	39.7	5.8	203
220x12	Bottom	Without corrosion	12.0	1600.2	13.0	123.1	12.5	244
		With corrosion	9.7	1370.9	13.4	102.3	10.2	246
220x12	Side frame	Without corrosion	12.0	1600.2	13.0	123.1	12.5	244
		With corrosion	9.3	1330.1	13.5	98.5	9.8	246

260x11	Trunk beam	Without corrosion	11.0	2618.3	16.0	163.6	11.5	293
		With corrosion	9.6	2376.6	16.3	145.8	10.1	295

That simplification reduces the quantity of elements which need to be computed and simplifies the geometry resulting in a significant time reduction. The geometry is presented in the following. In general, the analyses are performed according to the guidelines published by GL for inland navigation vessels [(7) Pt. 2, Ch. 2, Sec. 2 G].

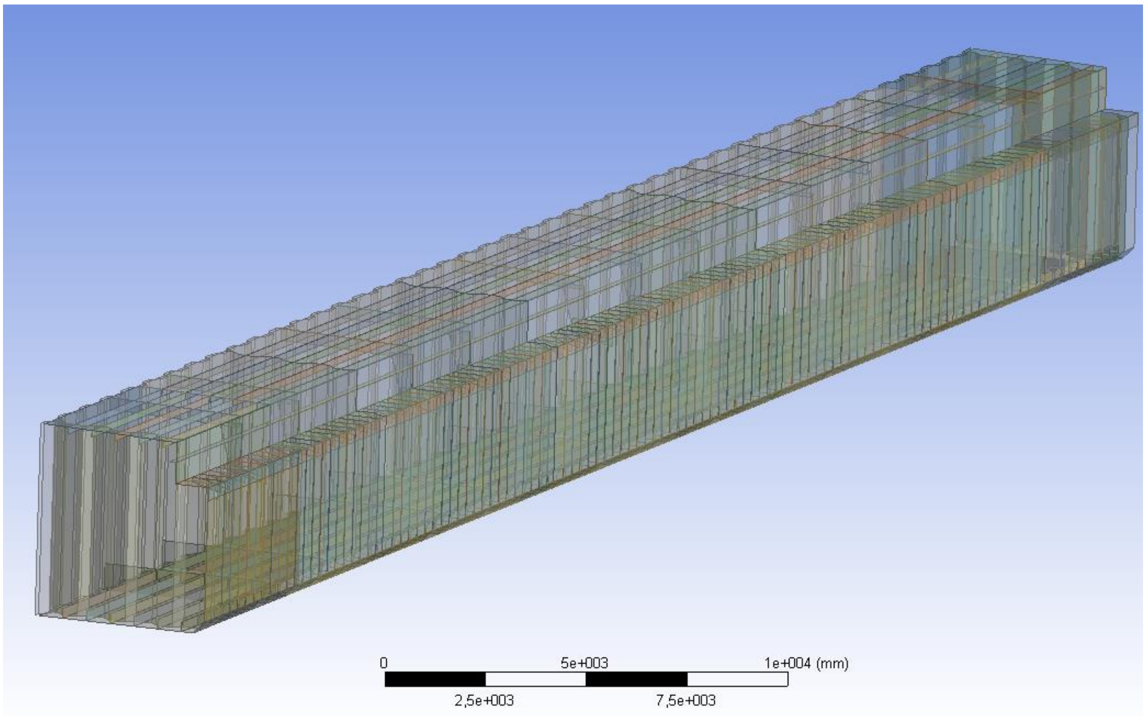


Figure 16: Half-model of the geometry of MV “Internautic 1”

The FE model is created in ANSYS 14.5 Workbench by using a combination of shell elements for the plates and solidshell elements for stiffeners and brackets. Half of the vessel’s geometry is implemented from the forward transverse bulkhead of the first hold to the aft transverse bulkhead of the last hold, i.e. the vessel is mirrored at the centreline plane except for the corrugated longitudinal bulkhead located on the centreline. The entire modelled section corresponds to a length of 57.0 m. Generally, the element size is set to 200 mm edge length resulting in approximately 50000 to 65000 elements, depending on the retrofit variant to be investigated. The meshed single hull structure is depicted in Figure 17 and in detail in Figure 18 (the corrugated longitudinal bulkhead is suppressed in this view).

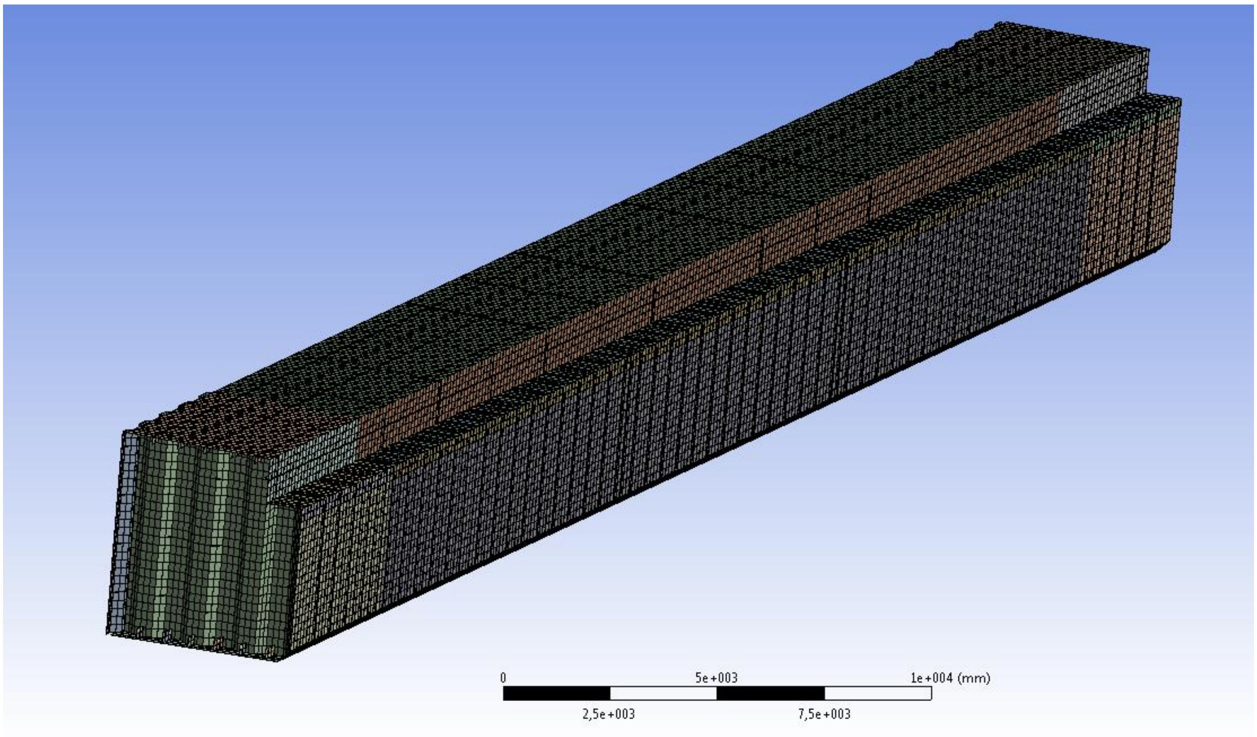


Figure 17: Mesh of the structures of MV "Internautic 1"

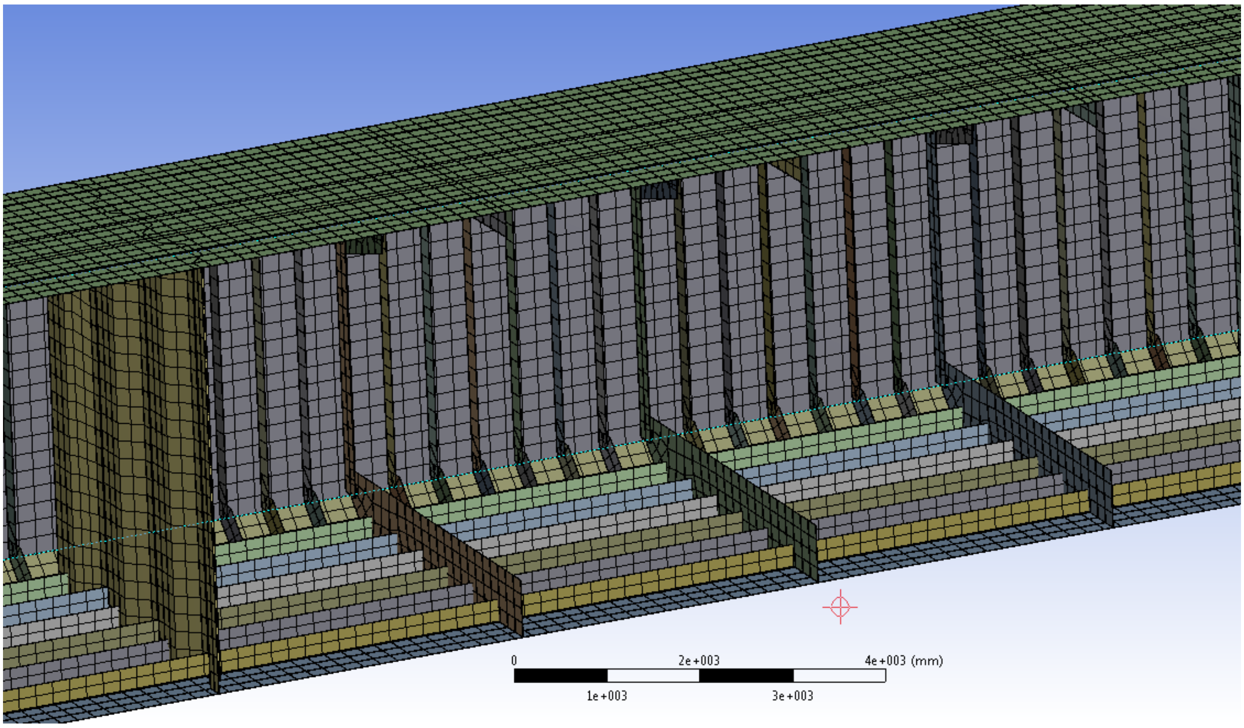


Figure 18: Mesh detail of the structures of MV "Internautic 1" (longitudinal bulkhead suppressed)

The materials used in the analyses are steel and polymer-foam as applicable. The material properties are presented below.

Table 16: Material properties used in FEA

		Steel grade A	XPS Styrofoam RTM
Density	[kg/m³]	7850	40
Young’s modulus	[MPa]	210000	0.025
Shear modulus	[MPa]	76900	0.010
Poisson ratio	[-]	0.3	0.250

Constraints:

- The left end of the model is fixed (Please refer to Figure 17)
- Symmetry conditions are applied to the structures located at the centreline except for the corrugated longitudinal bulkhead

Loads & Forces:

- Bending moment applied to the right hand side section of the model (The bending moment is calculated with the software “GL Poseidon ND”)
- Shear force applied to the right hand side section of the model (The shear force is calculated with the software “GL Poseidon ND”)
- External pressure caused by water onto the outer bottom and outer side
- Internal pressure caused by cargo onto the inner hold structure
- Loads caused by additional structures (additional means all retrofitted structures because they are not included in the calculation of the bending moment and shear force)

The checking criterion for the analyses is based on the recommendations of GL [(7) Pt. 2, Ch. 2, Sec. 2 E 4.3.2]:

$$0{,}98 \cdot \frac{R_{eH}}{\gamma_R} \geq \sigma_{VM}$$

0.98 * 235 MPa / 1.02 = 225.78 MPa

The evaluation area for the stresses ranges from the mid-section of the forward hold to the mid-section of the aft hold to avoid influences from the boundary conditions and the load application areas of the finite element model.

5.6.1 Single hull without corrosion

The analysis of the single hull built with steel structures according to the initial general arrangement plans from 1968 exhibit stresses well below the limit for von Mises equivalent stress. That current state involves the structures with net scantlings, which means that the corrosion additions according to GL rules are deduced and not taken into account. A detailed overview of the stresses of plates and stiffeners is given in section 5.6.7.

It can be stated that the initial vessel design still meets the requirements of the actual GL rules. An impression of the von Mises stress is presented in Figure 19.

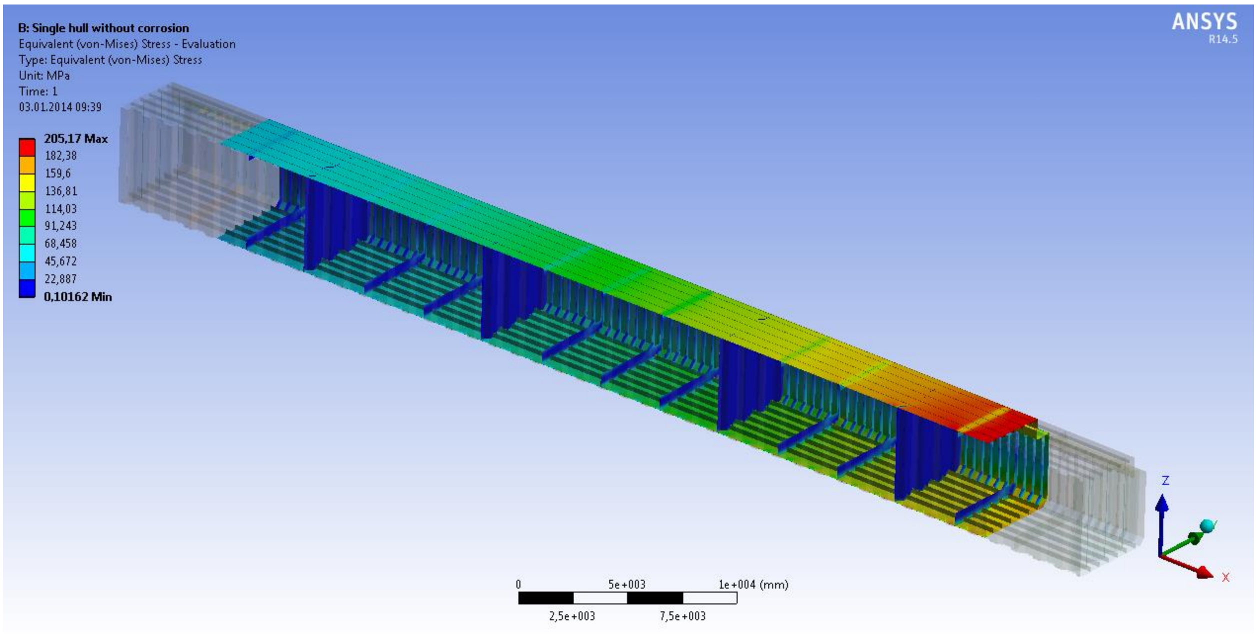


Figure 19: Von Mises stress for "Single hull without corrosion"

5.6.2 Single hull with corrosion

In contrast to the single hull without corrosion variant where all von Mises stresses are well below the limit the structures with deduced corrosion of 45 years show higher stresses as expected. The stresses of the following plates exceed the limit: Outer bottom, chine, longitudinal coaming and deck 01 (Top plating of the trunk). Besides, the outer bottom longitudinals and the deck 01 longitudinals exceed also the limit. A detailed overview of the stresses of plates and stiffeners is given in section 5.6.7.

The excessive stresses in the selected plates arise from the anticipated degradation of the material scantlings over 45 years and carrying the same amount of cargo. An impression of the von Mises stress is presented in Figure 20. The assumption of general degradation ensures that the analyses are performed using a conservative approach. In normal operation some of the plates would have been exchanged and repaired to build up the original strength of the structures. The high stresses in the stiffeners are discussed later on in section 5.6.7.

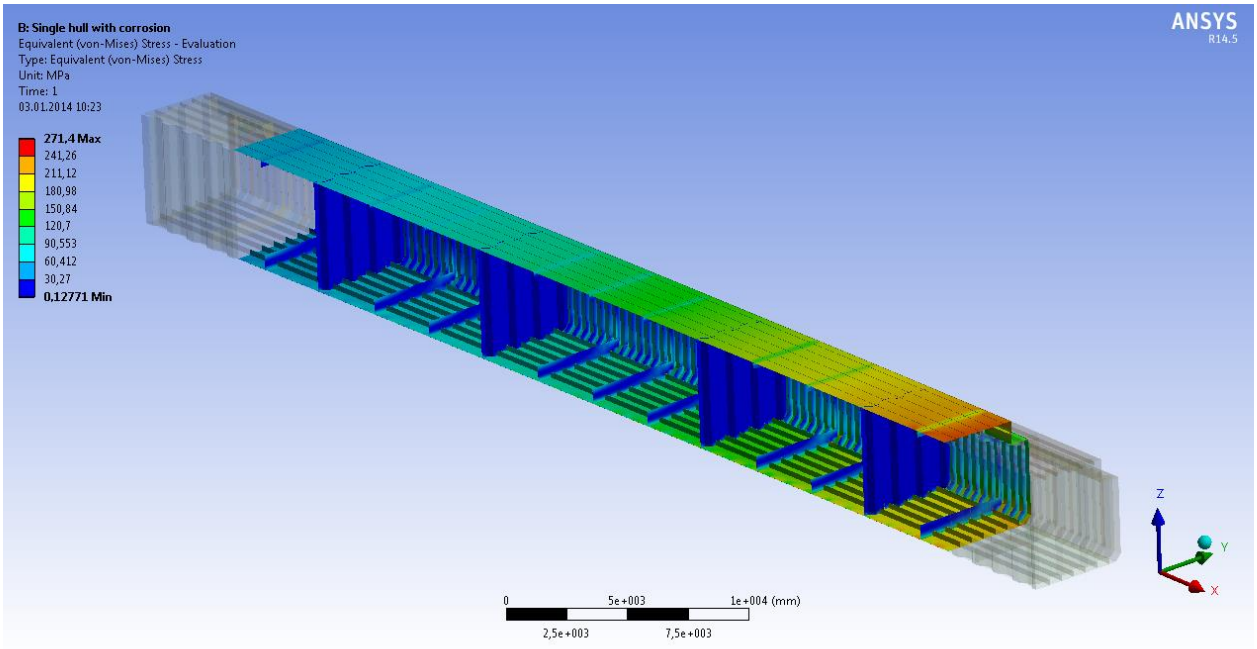


Figure 20: Von Mises stress for "Single hull with corrosion"

5.6.3 *ADN steel double hull*

The dimensions of the inner bottom and the inner side including their stiffeners are determined with the software “GL Poseidon ND” in order to obtain a starting point for the structural design. The dimensions are presented in the following table. The bottom structure remains the same for all the other retrofit solutions as already stated previously. Within the analysis the net scantlings (without corrosion addition) are taken into account.

Table 17: Inner bottom and inner side scantlings

		Without corrosion addition	With corrosion addition
Inner bottom plate	[mm]	5.5	6.5
Inner bottom longit. stiffener	[mm]	Bulb flat 180x9	Bulb flat 180x10
Inner side plate	[mm]	5.0	6.0
Inner side transv. frame	[mm]	Bulb flat 180x7	Bulb flat 180x8

For the applied loading condition all stresses of the plates are well below the maximum limit. That was expected as the total amount of cargo is reduced by implementing a double hull and the additional structures are designed according to the “GL Poseidon ND” software. The high stresses of the inner bottom longitudinals are discussed in general in section 5.6.7.

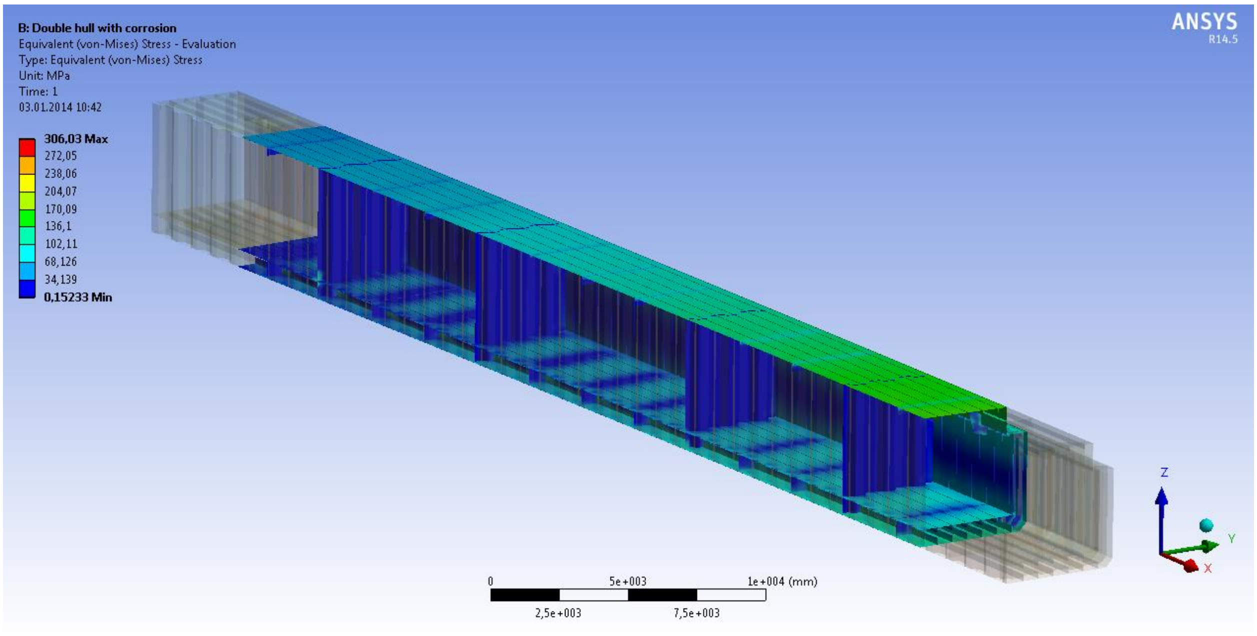


Figure 21: Von Mises stress for "ADN steel double hull"

5.6.4 *Steel/polymer-foam/steel double hull*

The polymer-foam is bonded in between the existing outer hull structure and an inner side plating. The dimensions are set to a net thickness of the inner side plating of 8.0 mm and a double side width of 600 mm resulting from suggestions of the crashworthiness analyses. The polymer-foam is integrated by blocks from the deck to the height of the inner bottom. Detailed information on the side impact simulation analyses can be found in the deliverable D 5.3 “Crashworthiness”. In the present configuration it can be stated that the scantlings are sufficient, but no increase in cargo carrying capacity can be obtained in comparison to the standard ADN steel double hull.

Table 18: Inner bottom and inner side scantlings

		Without corrosion addition	With corrosion addition
Inner bottom plate	[mm]	5.5	6.5
Inner bottom longit. stiffener	[mm]	Bulb flat 180x9	Bulb flat 180x10
Inner side plate	[mm]	8.0	8.5
Double side width	[mm]	600	

The occurring von Mises stresses for the indicated midship section in the platings are well below the allowable limit except for local stresses in the inner bottom longitudinal. That issue is discussed in section 5.6.7.

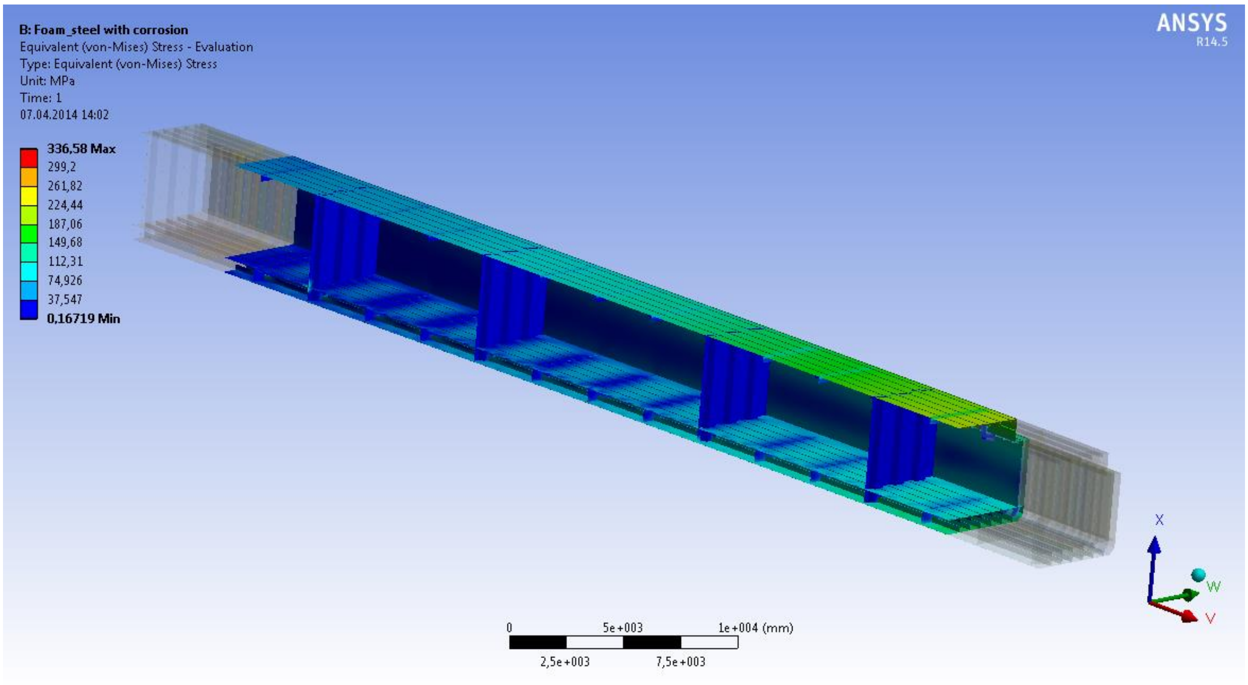


Figure 22: Von Mises stress for "Steel/polymer-foam/steel double hull"

5.6.5 *λ-shape steel double hull*

The λ-shape structures are integrated into the ship’s double side in order to improve the crashworthiness against side impacts and to be able to increase the cargo capacity by a certain amount in comparison to the ADN double hull. Detailed investigations on the crash energy absorption are presented in the deliverable D 5.3 “Crashworthiness”.

The corrugated profile ranges from the side deck to the height of the inner bottom (z = 650 mm). A general layout of the λ-shape structures is presented in Figure 23.

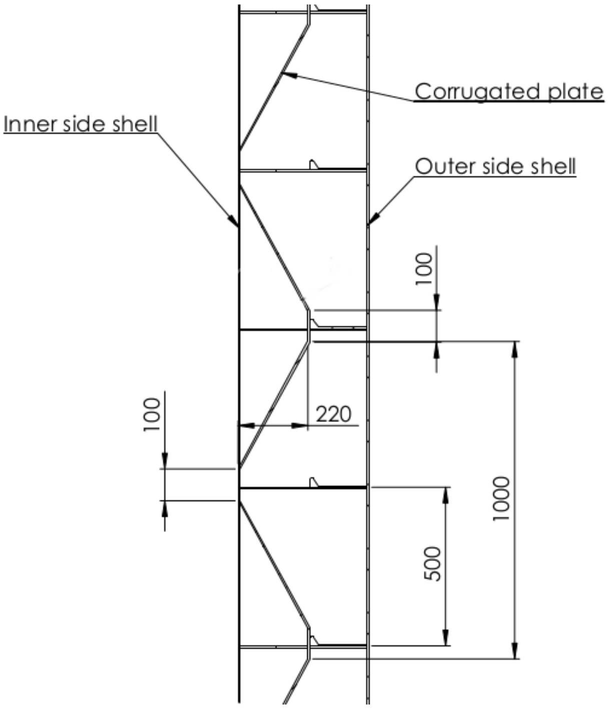


Figure 23: Detail of the corrugated side scantlings

The scantlings of the additionally implemented structures for the bottom and side shell are summarised in Table 20.

Table 19: Inner bottom and inner side scantlings

		Without corrosion addition	With corrosion addition
Inner bottom plate	[mm]	5.5	6.5
Inner bottom longit. stiffener	[mm]	Bulb flat 180x9	Bulb flat 180x10
Inner side plate	[mm]	4.5	5.0
Corrugated plate	[mm]	4.5	5.0
Double side width	[mm]	400	

The occurring von Mises stresses for the indicated midship section in the platings are well below the allowable limit except for local stresses in the inner bottom longitudinal. That issue is discussed in section 5.6.7.

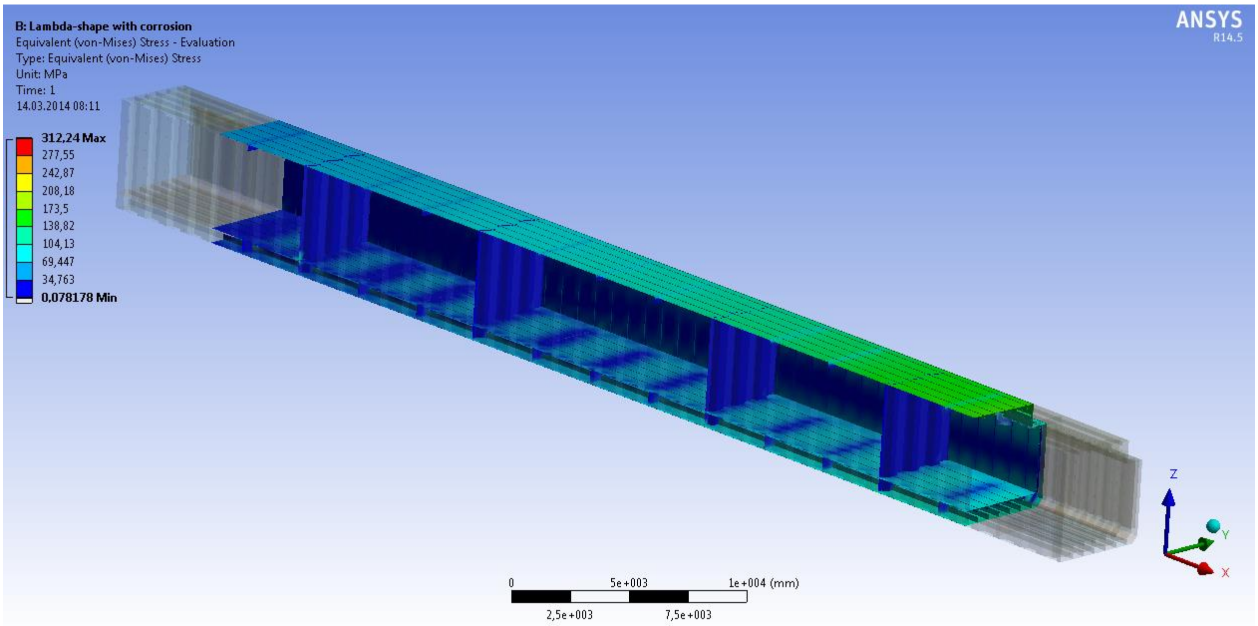


Figure 24: Von Mises stress for "λ-shape steel double hull"

5.6.6 *Rubber bags*

The analysis of the rubber bags variant is based on the model of single hull including corrosion deduction, taking less cargo mass and additional masses caused by the rubber bags and attachment devices into account. The additional masses are spread uniformly over the bottom of the holds. All stresses in the plates are below the maximum limit.

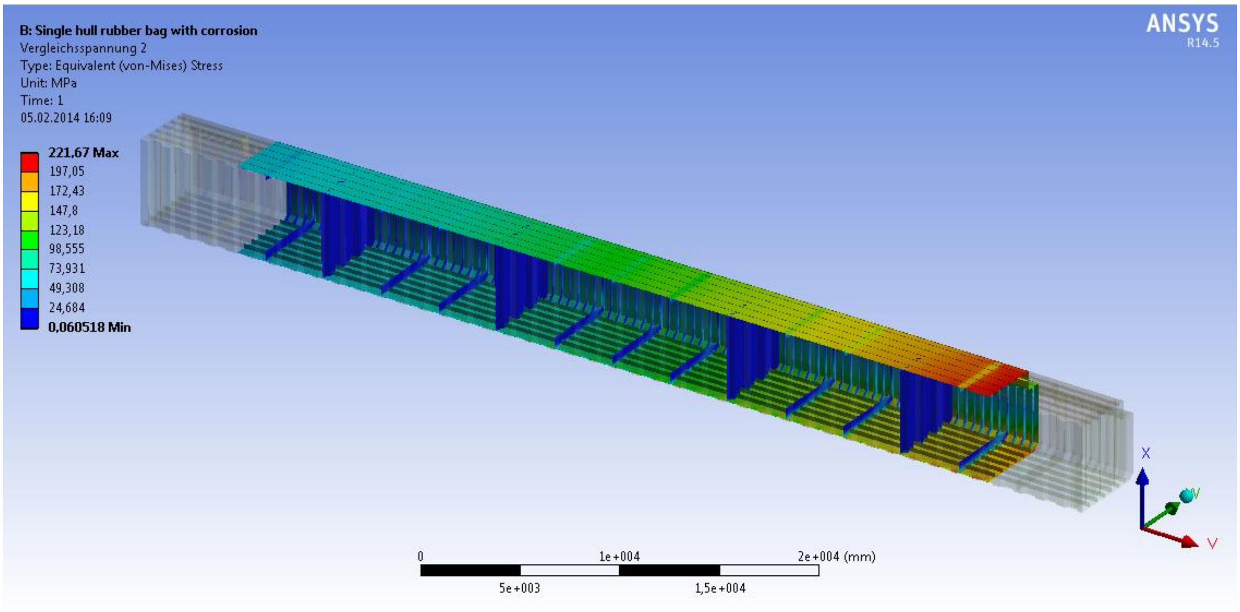


Figure 25: Von Mises stress for "Rubber bags" (Bags are not shown here)

5.6.7 *Summary of stresses*

Stresses of the selected plates are below the checking criterion and indicate that the designs are feasible in principle.

Table 20: Stresses of selected plates

Max v. Mises stresses		1. Single hull without corrosion	2. Single hull with corrosion	3. Double hull with corrosion	4. Steel / polymer-foam / steel with corrosion	5. λ-shape with corrosion	6. Single hull rubber bag with corrosion
Outer bottom	[MPa]	185.1	240.4	126.6	161.0	128.9	204.9
Inner bottom	[MPa]	n/a	n/a	127.1	116.2	96.8	n/a
Chine	[MPa]	182.4	238.1	121.8	150.8	120.5	203.3
Outer side	[MPa]	167.3	218.6	103.6	130.5	103.7	187.1
Inner side	[MPa]	n/a	n/a	112.4	148.4	115.4	n/a
Sheerstrake	[MPa]	119.7	139.7	110.8	147.6	112.2	120.8
Deck 1	[MPa]	133.3	155.3	117.3	147.6	121.8	133.8
Longit. coaming	[MPa]	193.9	233.1	161.8	209.4	162.9	203.8
Deck 01	[MPa]	205.2	247.8	171.7	221.5	173.5	209.7

Max v. Mises stresses		1. Single hull without corrosion	2. Single hull with corrosion	3. Double hull with corrosion	4. Steel / polymer-foam / steel with corrosion	5. λ-shape with corrosion	6. Single hull rubber bag with corrosion
Longit. bulkhead	[MPa]	130.4	172.3	105.7	131.5	105.7	150.9
Y-shape component	[MPa]	n/a	n/a	n/a	n/a	118.4	n/a

The Stresses of the selected longitudinal stiffeners exhibit a high stress level. The stress peaks occur at the outer faces of the simplified frames although the scantlings of the inner bottom longitudinals are derived from the GL formulae for inland navigation vessels. For this reason, it is assumed that the load carrying capacity is sufficient and that the stress peaks are induced by the simplification of the stiffeners.

The variant “Single hull with corrosion” exceeds the stress level at the top edge of the outer bottom longitudinals, also due to the simplification of the stiffeners.

An overview of the von Mises stresses at the inner bottom longitudinals as example for the variant “Double hull with corrosion” is presented in Figure 26. The fixation of the longitudinals at the floors exhibits a maximum von Mises Stress of 306.0 MPa. However, it can be concluded that stress peaks originate from the simplification of the stiffener geometry and the analyses are sufficient for comparison purposes as they are intended to provide an impression of how the modified hull will behave.

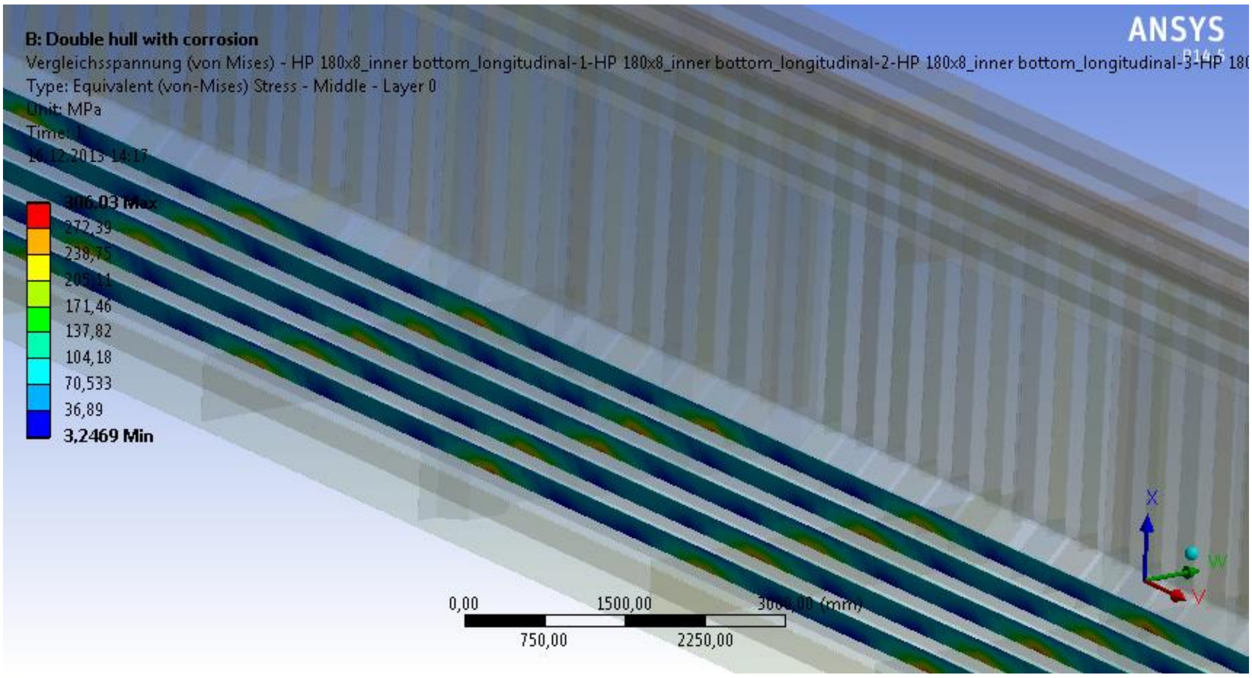


Figure 26: Von Mises stress at inner bottom longitudinals

Table 21: Stresses of selected longit. stiffeners

Max v. Mises stresses		1. Single hull without corrosion	2. Single hull with corrosion	3. Double hull with corrosion	4. Steel / polymer-foam / steel with corrosion	5. λ-shape with corrosion	6. Single hull rubber bag with corrosion
Outer bottom longit.	[MPa]	204.9	271.4	200.1	217.2	195.1	221.7
Inner bottom longit.	[MPa]	n/a	n/a	306.0	336.6	312.2	n/a
Deck 01 longit.	[MPa]	199.6	242.3	174.5	216.2	176.6	210.1

6 Composite lengthening retrofit

(Author: Sicomp)

6.1 Introduction

After having investigated standard steel lengthening solutions in WP 6 and WP 7, novel composite variants are elaborated. The aims of the study are to prove the feasibility of the composite lengthening solutions from a structural point of view and to show their weight advantages.

The lengthened section has a length of 16.5 m, as defined in D7.1, and is intended to be inserted at the midship section of the inland navigation vessel “HERSO I”.

Four different midship structures have been developed and investigated:

- 2 single skin (solid) laminate variants
    - 1 glass fibre reinforced plastics (GFRP)
    - 1 carbon fibre reinforced plastics (CFRP)
- 2 sandwich variants
    - 1 glass fibre reinforced plastic skins with balsa core
    - 1 carbon fibre reinforced plastic skins with balsa core

For each structure the scantlings of the different parts have been calculated in 2 steps. First the scantlings have been calculated analytically and then checked through FEA with a 3D model of the midship section.

During the development process the rules and regulations of GL for inland navigation vessels from 2011 [(7)] and the rules for classification of high speed, light craft and naval surface craft from DNV [(21)] have been used. Indeed on one side the composite section has to be developed on the same basis as the steel section, with the same bending moments, main stresses calculations, etc… On the other side these rules are made for steel ships and are not adequate for composite. For this reason the DNV rules for composite have to be used for the definition of the composite parts.

6.2. First step

For the first step in each structural variant the analytical calculation was done in an iterative manner for all the outer parts of the ship, that is to say the ones making the shell of the ship: double bottom, sides, coaming, etc. For the 2 single skin laminate variants the calculation started with the same scantlings as the ones used for the lengthened section in steel. All the scantlings are above the minimum requirements set by the DNV rules [(21)] shown in Table 22.

The minimum thickness requirements are based on the following formula for ships above 20 m long: $t_f = W_0 (1 + k (L–20)) / V_f . \rho f$, where W_0 is the minimum amount of reinforcement (g/m^2), L the length of the ship, V_f the volume fraction of fibre and ρ_f the density of fibre. W_0 and k are given by the DNV rules for each ship part.

For the 2 sandwich variants the calculation started with the minimum scantling requirements of the DNV rules [(21)] shown in Table 23 for the facing and the core was chosen to be 5 times thicker than the total thickness of the facings. The minimum scantling requirements for sandwich are based on the same formula as for the single skin laminates

Table 22: Minimum requirement for thickness of single (solid) skin laminates according to DNV

	t_{min}
Hull bottom, transom, outside of hull	8.64
Hull side, above deepest WL	8.64
Cargo deck	7.81
Weather deck not intended for cargo	3.29
Superstructure and deckhouse	6.08
Chine and transom corners to 0.01 L from chine edge	11.94
Structural/watertight bulkheads	3.29

Table 23: Minimum requirement for thickness of sandwich according to DNV

	glass facings	carbon facings
	t min [mm]	
Hull bottom, transom, outside of hull	4.94	3.29
Hull bottom and side, inside of hull	2.31	1.59
Hull side, above deepest WL	3.29	2.26
Cargo deck	4.34	2.89
Wet deck	1.25	1.25
Decks, underside skin	0.59	0.39
Superstructure and deckhouse, outside	1.74	1.16
Structural bulkhead	0.94	0.63

Then the maximum moment of inertia of the structure was calculated with the base scantlings for each variant and the maximum stresses in the structure derived for the following maximum bending moments: hogging 37427 kNm and sagging 25144 kNm (moments calculated in D7.1.).
These stresses were checked against the maximum allowed stress in the composite skin derived from [(21)]. The maximum allowed stresses are shown in Table 24.

Table 24: Maximal stress requirements in composite facings according to DNV

	GFRP	CFRP
Tension [MPa]	90	300
Compression [MPa]	-66	-135

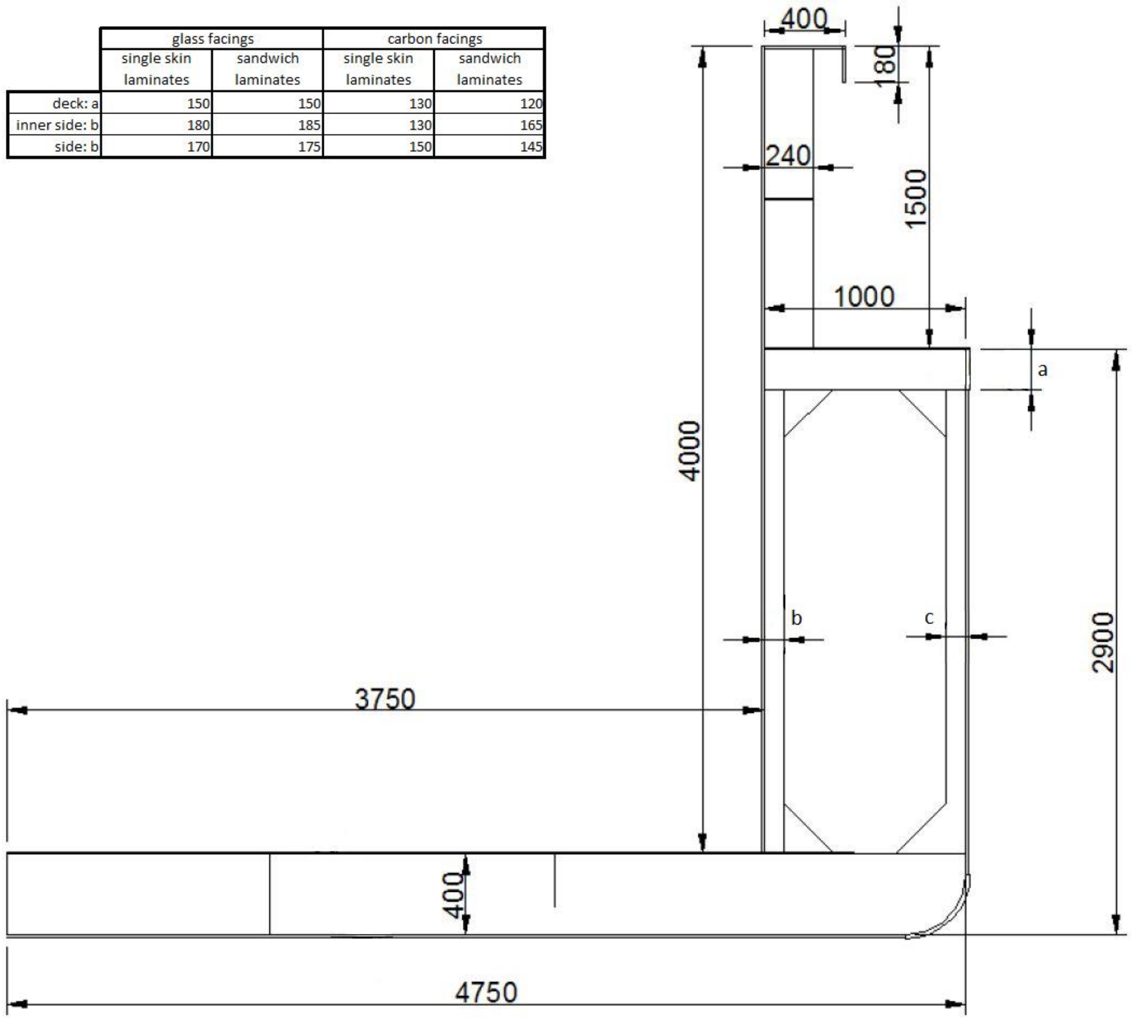
Following the check for the glass single skin variant the thickness of some of the parts was increased until the stresses reduced under the limits, while the thicknesses of some of the parts in the carbon single skin variant were decreased until the stresses stayed just under the limits, while keeping the thickness requirements of DNV (Table 22). For the 2 sandwich variants the stresses were under the limits and nothing was changed, as the thicknesses of the skins laminates were already set to the minimum required.

The scantlings of the inner parts i.e. floor, side frames, coaming stiffeners, etc., were calculated analytically from the minimum section modulus requirement set by DNV [(21)].

After these iterative calculations the scantlings of all the parts were also checked against buckling using the GL methods [(7)] and the thickness of some of the parts such as the bulkhead had to be increased. Indeed according to the DNV rules, the formulas developed for buckling of stiffened plate fields in steel provided conservative assumptions (for example the formulas in the GL rules) and can be transferred onto composites.

The scantlings of the parts at the end of the first step are shown in Table 25 within comparison with the scantlings of the steel lengthening section. The overall dimensions of the different parts stay the same as in the steel lengthening section except for the frames, see Figure 27.

The full tables of the scantlings with the derived moment of inertia and the maximum stresses are shown in Annex 11.2.



	glass facings		carbon facings	
	single skin laminates	sandwich laminates	single skin laminates	sandwich laminates
deck: a	150	150	130	120
inner side: b	180	185	130	165
side: b	170	175	150	145

Figure 27: Dimensions of the midship section

Table 25: Scantlings first step – (thickness of each part in mm)

		Steel	Glass facings				Carbon facings			
			Single skin laminates	Sandwich			Single skin laminates	Sandwich		
				Total	Facings	Core		Total	Facings	Core
Outer parts	Bottom	10.0	10.0	45.0	5.0 – 2.5	37.5	10.0	33.0	3.5 – 2.0	27.50
	Inner bottom	12.0	12.0	33.0	4.5 – 1.0	27.5	12.0	21.0	3.0 – 0.5	17.50
	Chine radius	20.0	20.0	45.0	5.0 – 2.5	37.5	20.0	33.0	3.5 – 2.0	27.50
	Side shell plating	8.0	14.6	36.0	3.5 – 2.5	30.0	9.0	27.0	2.5 – 2.0	22.50
	Inner side plating	12.0	25.0	33.0	4.5 – 1.0	27.5	12.0	21.0	3.0 – 0.5	17.50
	Sheer strake	20.0	25.4	36.0	3.5 – 2.5	30.0	11.5	27.0	2.5 – 2.0	22.50
	Longitudinal girders	10.0	10.0	12.0	1.0 – 1.0	10.0	10.0	8.4	0.7 – 0.7	7.00
	Deck & stringer plate	10.0	25.0	15.0	1.5 – 1.0	12.5	12.5	12.0	1.5 – 0.5	10.00
	Coaming	12.0	25.0	39.0	4.5 – 2.0	32.5	10.0	27.0	3.0 – 1.5	22.50
	Coaming stiffener top 1 (horiz.)	10.0	30.5	24.0	2.0 – 2.0	20.0	12.5	14.4	1.2 – 1.2	12.00
	Coaming stiffener top 2 (vert.)	10.0	30.5	24.0	2.0 – 2.0	20.0	12.5	14.4	1.2 – 1.2	12.00
	Coaming stiffener sec.	10.0	20.5	24.0	2.0 – 2.0	20.0	8.0	14.4	1.2 – 1.2	12.00
Inner parts	Floor	7.0	7.0	12.0	1.0 – 1.0	10.0	7.0	8.4	0.7 – 0.7	7.00
	Bulkhead	4.5	18.5	19.2	1.6 – 1.6	16.0	7.5	10.8	0.9 – 0.9	9.00
	Bulkhead vertical stiffeners	9.0	14.0	13.0	1.0 – 1.0	11.0	14.0	9.6	0.8 – 0.8	8.00
	Side frame trans.	10.0	13.0	12.0	1.0 – 1.0	10.0	11.0	8.4	0.7 – 0.7	7.00
	Inner side frame trans.	13.0	13.0	12.0	1.0 – 1.0	10.0	11.0	8.4	0.7 – 0.7	7.00
	Deck beam	9.0	13.0	12.0	1.0 – 1.0	10.0	11.0	8.4	0.7 – 0.7	7.00
	Coaming vertical stiffener	8.5	8.5	24.0	2.0 – 2.0	20.0	8.5	14.4	1.2 – 1.2	12.00
	Brackets	10.0	13.0	12.0	1.0 – 1.0	10.0	11.0	8.4	0.7 – 0.7	7.00

6.3. Second step

6.3.1. FE model

For the second step a section of the midship comprising 3 frames was modelled with shell 181 elements in ANSYS v14.5. The model is shown in Figure 28. This model was used for the 4 different variants. For each variant the thickness of the parts, the materials is changed and the size of the frame.

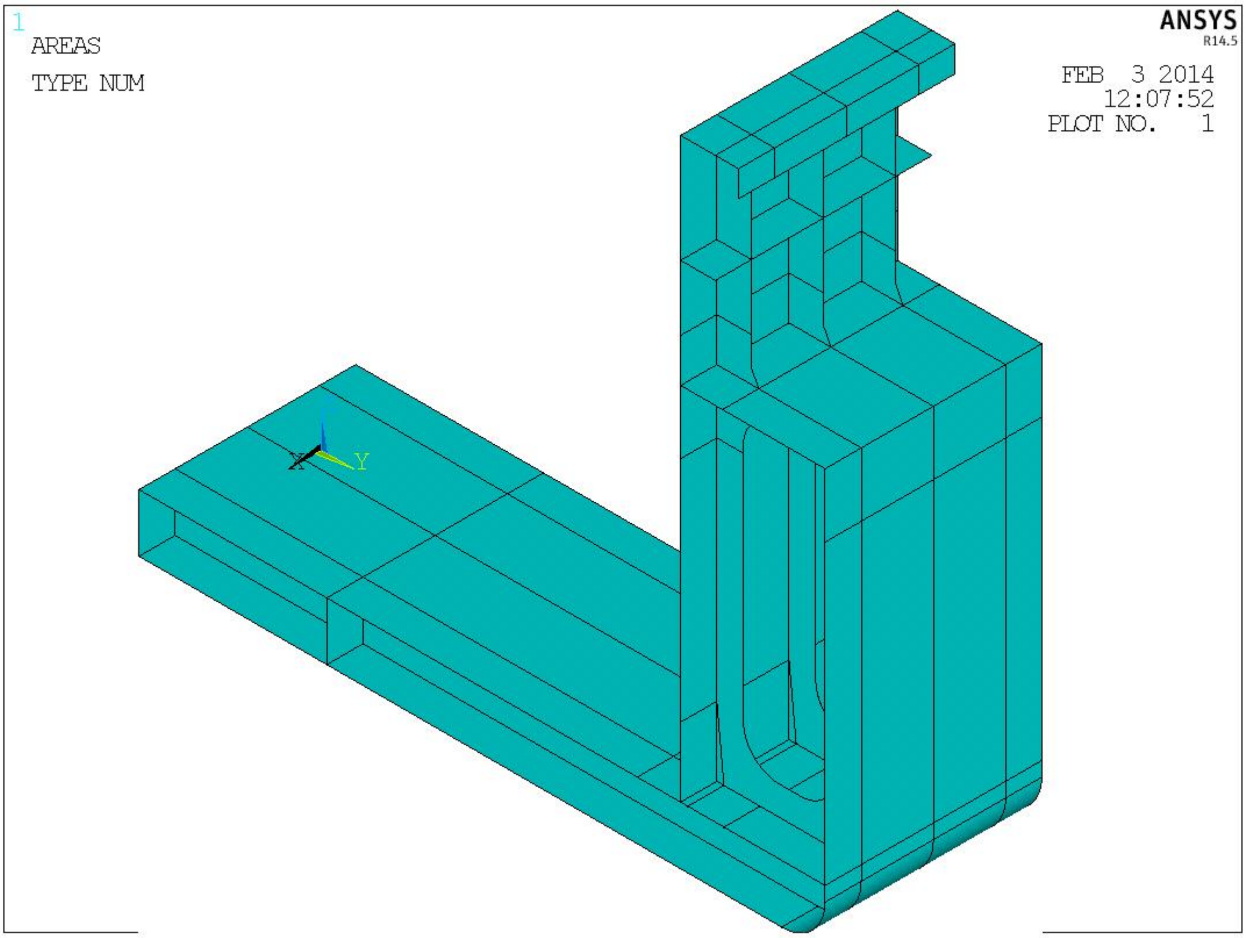


Figure 28: 3D model of the midship section

6.3.2. Boundary conditions and loads

The section is assumed to be simply supported along the top edges of the coaming and symmetry boundary conditions are applied on the transverse edges an on the centre-line girder (see Figure 29)

The loads derived from GL rules [(7)] and applied on the model are the following:

- Pressure on sides and bottom for z<=T: linear from p=29.5 kN/m^2 at z=0 m to p=29.5 kN/m^2 at z=2.7 m
- Pressure on sides and bottom for z>T: p=3.5 kN/m^2
- General Internal pressures: linear from p=32.3 kN/m^2 at z=0.4 m to p=0 kN/m^2 at z=4.4 m
- Pressure on exposed decks, weather deck p= 4.9 kN/m^2

Note: z is height from base of ship and T is the draught of the ship

The loads applied can be seen on Figure 30.

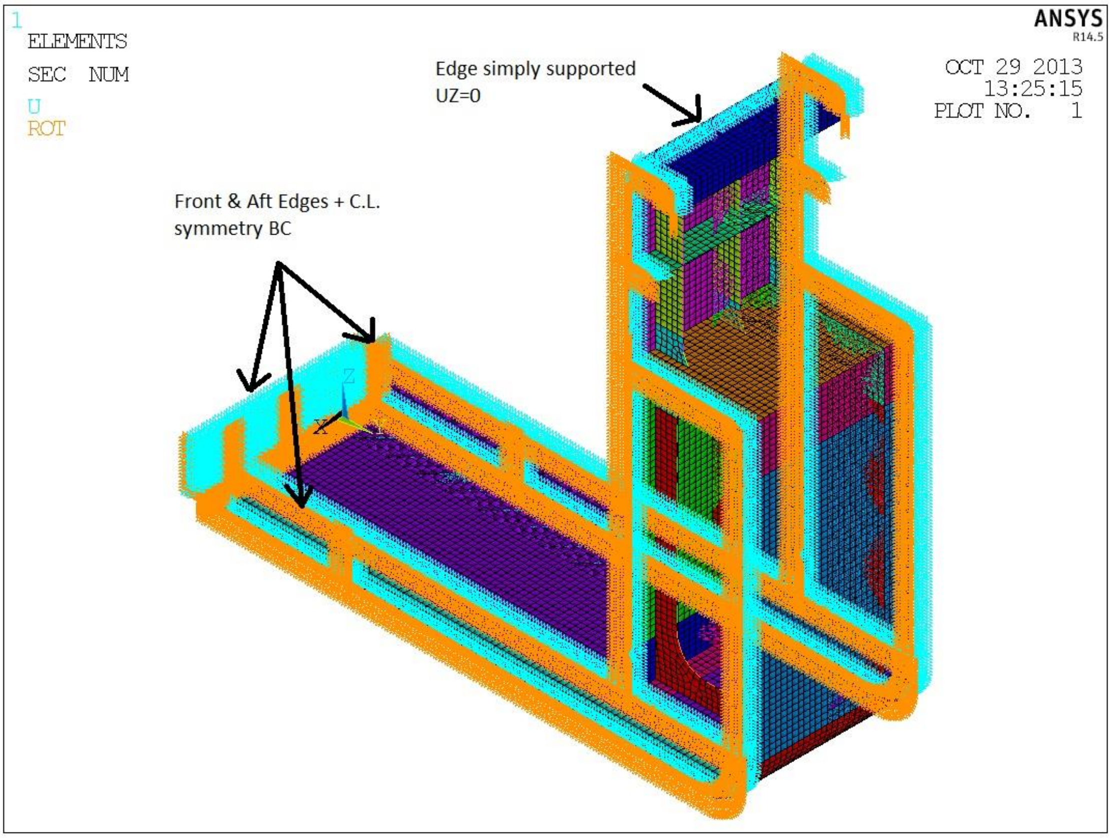


Figure 29: Boundary conditions

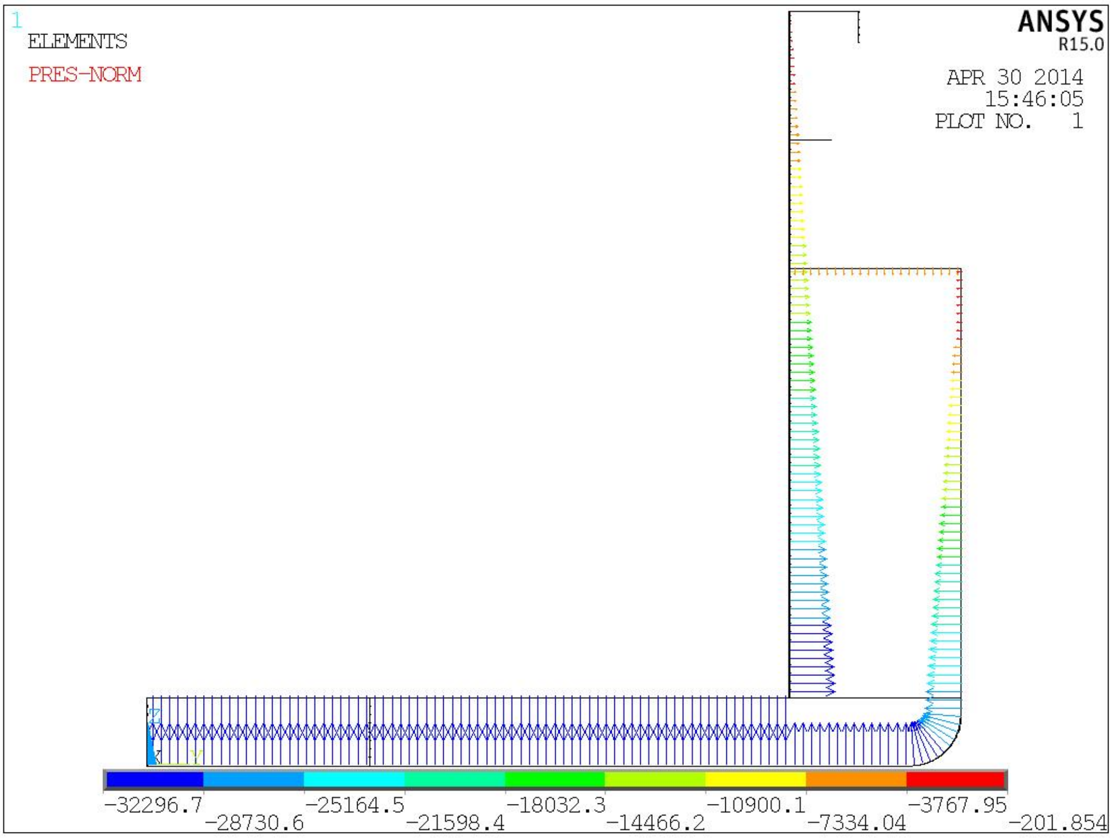


Figure 30: Loads

6.3.3. Results

Each model is solved and the stresses in the different parts are checked against the limits set in Table 24 and one additional requirement: the shear stress limit in the core for the sandwich structures, which is 1.2 MPa for balsa.

For the 2 models with single skin laminates the stresses are all below the limits. The scantlings defined during the first step are considered as final.

On the other hand the models with the sandwich show regions of high stress located in the skins of the frame and in the skins of the floor around the base of the inner side. Also for the sandwich structure the shear stress in the core of the deck, the inner side and the inner bottom is above the limit along the connections to the frames.

These stress concentrations can be seen on Figure 31, Figure 32 and Figure 33, which are the stress plots for the final design of the glass single skin laminate. The stresses are given along local axes i.e.: the local X-axis is parallel to the global X-axis for all the longitudinal parts and parallel to the global Z-axis for all the transverse parts. The local Y-axis is parallel to the global Y-axis for all the parts.

The locations of the stress concentrations for the final models stayed at the same place as on the original models.

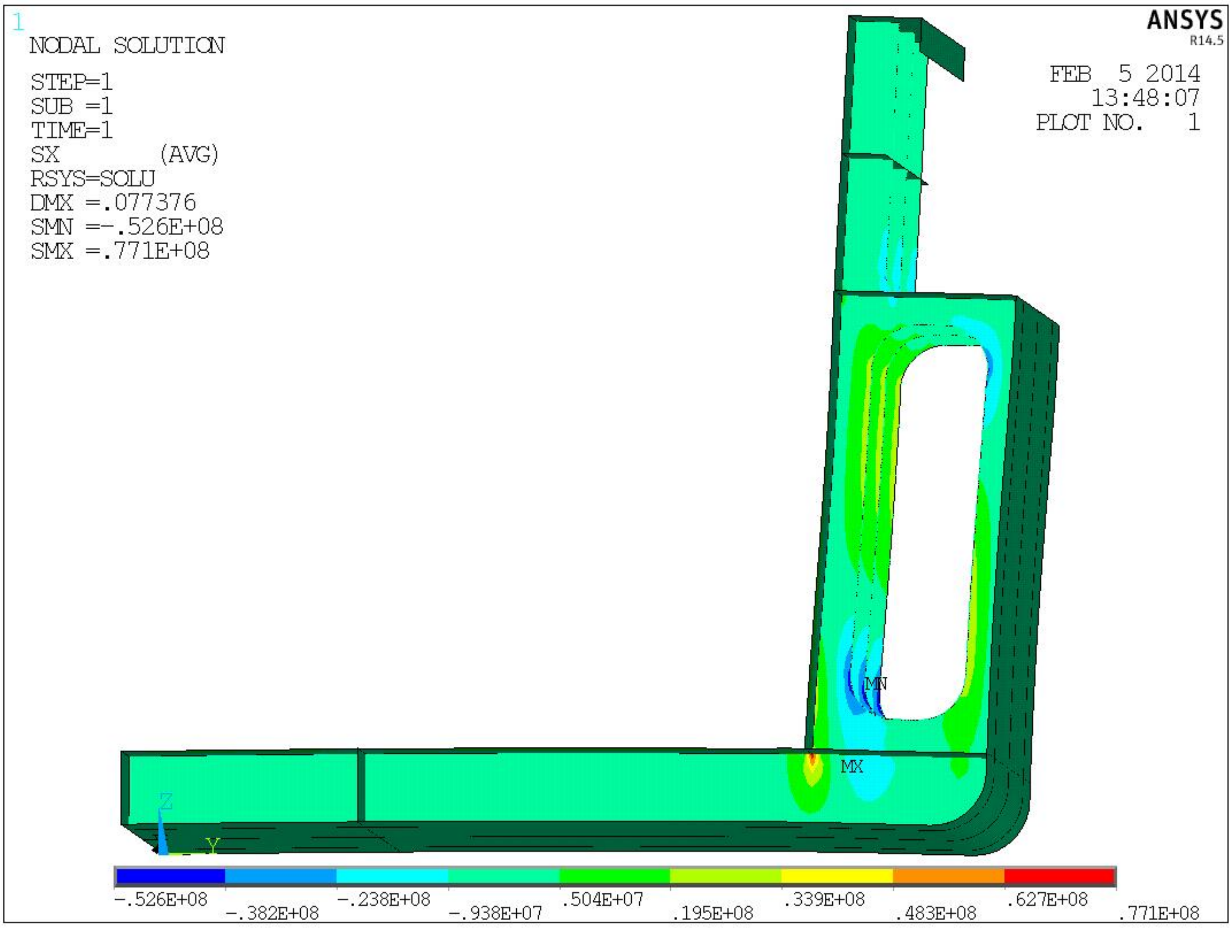


Figure 31: Stress along local X-axis in glass sandwich variant

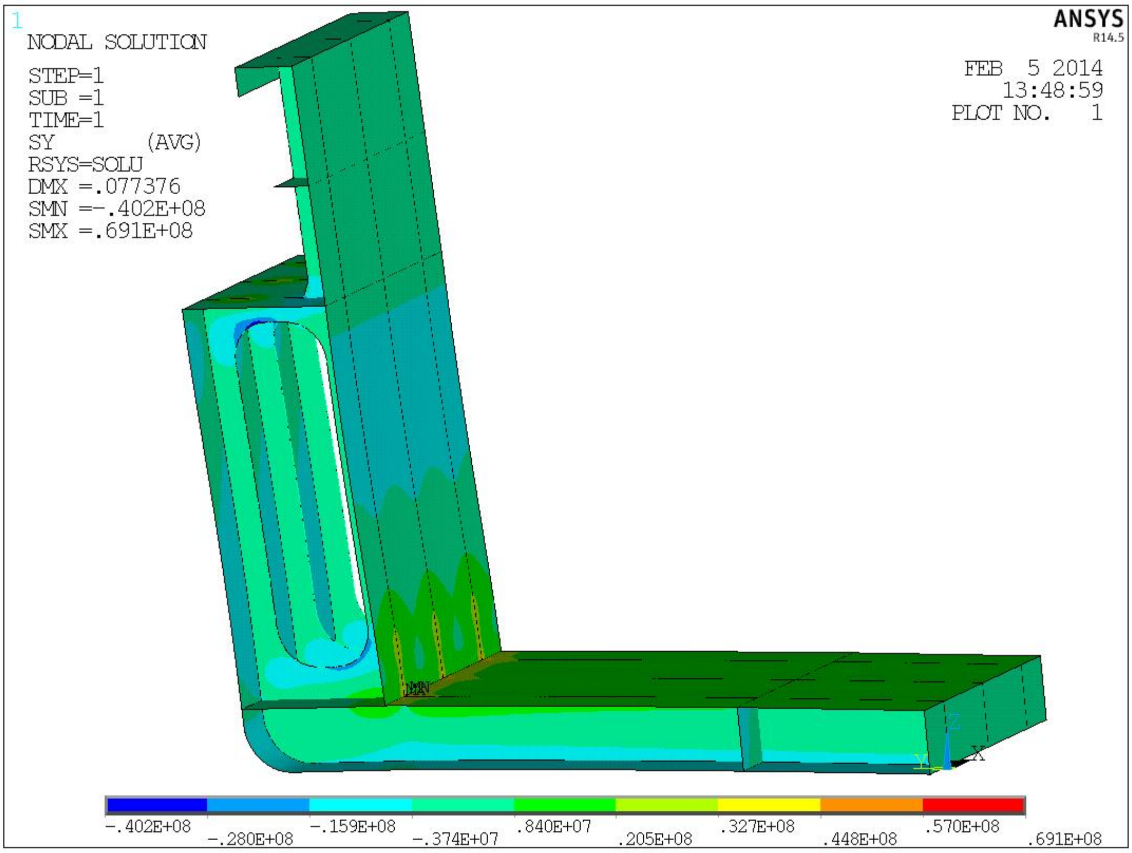


Figure 32: Stress along local Y-axis in glass sandwich variant

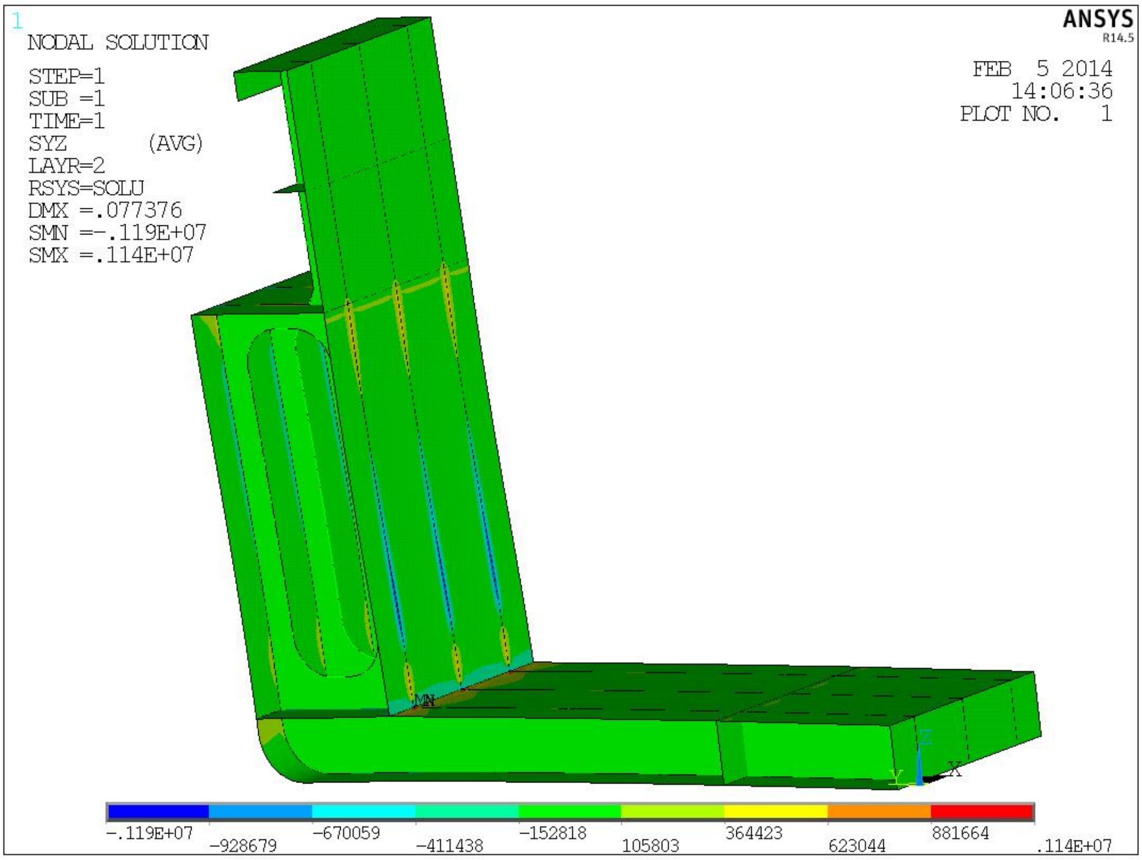


Figure 33: Shear stress in core of glass sandwich variant

The out of plane stress (Z axis) is not given by the shell elements used in the models and cannot be shown. The 3 different shear stresses XY, YZ and XZ were checked but only the plot with the highest stress is shown: i.e. YZ.
The stress plots for the other final variants, which are similar, are shown in Annex 11.2.

In order to reduce the stress of both sandwich structures first the thickness of the frame is increased and then the thickness of the floor until the stresses are just under the limits. For the sandwich structure in carbon it was also necessary to increase the thickness of the inner bottom and inner side in order to have the shear stress under the limit.
The normal stress in the facings (along the X and Y axis) and the shear stress in the core (YZ) occurring in the final design of each variant is shown in Table 26. The out of plane stress (Z axis) is not given by the shell elements used in the models.
The final scantlings of the parts are shown in Table 29.

Table 26: Max and min stresses in final designs

		Glass facings		Carbon facings	
		Single skin laminates	Sandwich	Single skin laminates	Sandwich
σ_X [MPa]	Compression	-62	-53	-83	-116
	Tension	64	77	70	115
σ_Y [MPa]	Compression	-41	-40	-59	-65
	Tension	59	70	71	112
τ_{YZ} [MPa]		-	-1.14	-	-1.10
			1.19		1.20

The mass of each section is calculated from the density of the different materials (see Table 27), the final scantlings of each section and several assumptions.
For the joints between panels it is assumed that:

- The joints are block joints made with overlamination on all the surface of the joint (see D5.4 for more information on the joints)
- The joint overlaminated with glass fibre have weight of 2.7kg/m [(22)]
- The joint overlaminated with carbon fibre have weight of 1.5kg/m

It was also assumed that the joint between the ship and the composite section are also block joint in order to be able to get an idea of the weight of the joints. In order to know the real weight of these connections, real designs of the joints have to be developed with FE analyses.
The weight of 5.63 tonnes for upgrading the existing steel parts and the weight of 2.75 tonnes for the hatch covers used in Table 28 are coming from D7.1. The weight of the hatch covers in composite are derived from the same ratio weight composite panels/ total steel weight.

Table 27: Data for mass calculation

	Glass Laminate	Carbon Laminate	Balsa Core	Adhesive
Density [kg/m^3]	1845	1461	155	1320

The masses are summarised in Table 28 with a comparison to the steel variant.

Table 28: Total masses

		Glass		Carbon		Steel
		Single skin	Sandwich	Single skin	Sandwich	
Section	Panels	21.90	11.98	12.21	7.71	
	Joints between panels	4.46	4.46	2.49	2.49	
	Total	26.37	16.44	14.7	10.2	67.06
Joints steel/composite section		0.56	0.56	0.35	0.35	
Upgrading of existing steel parts		5.63	5.63	5.63	5.63	5.63
Hatch cover		0.90	0.49	0.5	0.32	2.75
Overall		32.90	22.56	20.83	16.15	75.44

The detailed masses for each part of the sections are shown in Annex 11.2. From Table 28 it can be seen that the composite sections are from 2.3 to 4.7 times lighter than the steel section. The sandwich variants are the lightest (average 1.4 lighter than single skin).

6.4 Conclusion

The study has proven the feasibility of the composite lengthening solutions from a structural point of view. It gives an idea to the shipyards the amount of weight which could be spared through the use of composites, but it should be clearly stated that the solutions developed are only concept designs. No developments have been made on the connection composite lengthening / steel ship. Extensive detail analyses should be carried out, in particular global loading, in order to get a final design and to be able to make a real comparison with the steel lengthening solutions.

It is also important to note that to correctly compare the steel structure to the composite ones, the costs must be estimated. It is known that composite material and their assembly into a structure is more expensive than steel. The material and production costs are calculated in deliverable D5.4.

Table 29: Final scantlings – (thickness of part in mm)

		Steel	Glass facings				Carbon facings			
			Single skin laminates	Sandwich			Single skin laminates	Sandwich		
				Total	Facings	Core		Total	Facings	Core
Outer parts	Bottom	10.0	10.0	45.0	5.0 – 2.5	37.5	10.0	33.0	3.5 – 2.0	27.50
	Inner bottom	12.0	12.0	33.0	4.5 – 1.0	27.5	12.0	27.0	3.5 – 1.0	22.50
	Chine radius	20.0	20.0	45.0	5.0 – 2.5	37.5	20.0	33.0	3.5 – 2.0	27.50
	Side shell plating	8.0	14.6	36.0	3.5 – 2.5	30.0	9.0	27.0	2.5 – 2.0	22.50
	Inner side plating	12.0	25.0	33.0	4.5 – 1.0	27.5	12.0	27.0	3.5 – 1.0	22.50
	Sheer strake	20.0	25.4	36.0	3.5 – 2.5	30.0	11.5	27.0	2.5 – 2.0	22.50
	Longitudinal girders	10.0	10.0	12.0	1.0 – 1.0	10.0	10.0	8.4	0.7 – 0.7	7.00
	Deck & stringer plate	10.0	25.0	15.0	1.5 – 1.0	12.5	12.5	12.0	1.5 – 0.5	10.00
	Coaming	12.0	25.0	39.0	4.5 – 2.0	32.5	10.0	27.0	3.0 – 1.5	22.50
	Coaming stiffener top 1 (horiz.)	10.0	30.5	24.0	2.0 – 2.0	20.0	12.5	14.4	1.2 – 1.2	12.00
	Coaming stiffener top 2 (vert.)	10.0	30.5	24.0	2.0 – 2.0	20.0	12.5	14.4	1.2 – 1.2	12.00
	Coaming stiffener sec.	10.0	20.5	24.0	2.0 – 2.0	20.0	8.0	14.4	1.2 – 1.2	12.00
Inner parts	Floor	7.0	7.0	**24.0**	**2.0 – 2.0**	**20.0**	7.0	**25.2**	**2.1 – 2.1**	**21.00**
	Bulkhead	4.5	18.5	19.2	1.6 – 1.6	16.0	7.5	10.8	0.9 – 0.9	9.00
	Bulkhead vertical stiffeners	9.0	14.0	13.0	1.0 – 1.0	11.0	14.0	9.6	0.8 – 0.8	8.00
	Side frame trans.	10.0	13.0	**42.0**	**3.5 – 3.5**	**35.0**	11.0	**21.0**	**1.75 – 1.75**	**17.50**
	Inner side frame trans.	13.0	13.0	**42.0**	**3.5 – 3.5**	**35.0**	11.0	**21.0**	**1.75 – 1.75**	**17.50**
	Deck beam	9.0	13.0	**42.0**	**3.5 – 3.5**	**35.0**	11.0	**21.0**	**1.75 – 1.75**	**17.50**
	Coaming vertical stiffener	8.5	8.5	24.0	2.0 – 2.0	20.0	8.5	14.4	1.2 – 1.2	12.00
	Brackets	10.0	13.0	**42.0**	**3.5 – 3.5**	**35.0**	11.0	**21.0**	**1.75 – 1.75**	**17.50**

7 Risk assessment

(Author: CMT)

Where alternative structures and uncommon solutions are applied which do not match the current rules of the classification societies and other regulative authorities, a risk based design approach is the appropriate method to identify relevant risks and failure modes. The risks are rated to reveal major threats to the new design and counteractions are proposed to demonstrate equivalency of safety and functionality.

The qualitative analysis which is presented in this report is based on the document “DNV Recommended Practice - Qualification of New Technology” where the procedure to implement new technology is proposed [(23)].

The HAZID (Hazard identification) is focused on threats to structural, economic and environmental tasks in order to determine uncertainties caused by little knowledge concerning the novel technology. The threat assessment which is part of the risk based design approach is divided into two sub-categories: consequence levels and probability levels as presented in Table 30 and Table 31. Based on their determined risk (see Table 32) the failure modes are ranked.

Table 30: Consequence levels

Level	Description	Definition
5	Total loss	Total loss Fatal injury
4	Major damage	Major structural damage Serious impact on health
3	Damage	Structural damage Impact on health
2	Minor damage	Minor structural damage Minor impact on health
1	Insignificant	Negligible structural damage Negligible impact on health

Table 31: Probability levels

Level	Description	Definition
A	Improbable	Incident will not be experienced
B	Remote	Incident is unlikely to occur during lifetime
C	Occasional	Incident can occur during operation or production
D	Probably	Incident will occur several times
E	Frequent	Incident will occur frequently

Table 32: Risk levels

Level	Description
High	Not acceptable risk at all, redesign/changes required
Medium/high	Medium to high risk, acceptable but redesign preferable
Medium	Medium risk, acceptable but redesign is worth a try
Low/medium	Low to medium risk, risk reducing action might be necessary
Low	Low risk, further risk reducing action not necessary

The risk ranking is obtained by matching the two levels in the following risk matrix. Failure modes form medium to high are considered to be crucial and shall be observed in the further design process.

Table 33: Risk matrix

		Probability				
		A	**B**	**C**	**D**	**E**
Consequence	**5**	medium	medium/high	medium/high	high	high
	4	low/medium	medium	medium/high	medium/high	high
	3	low/medium	low/medium	medium	medium/high	medium/high
	2	low	low/medium	low/medium	medium	medium/high
	1	low	low	low/medium	low/medium	medium

Numerous hazards are identified for the single-to-double hull retrofit and composite lengthening variants with respect to structural, economic and environmental aspects. A summary is presented in the subsequent sections.

7.1 *Hazards of single-to-double hull retrofit solutions*

The hazards identified for the single-to-double hull retrofit solutions are summarised and presented in Table 34 to Table 36. Each solution is treated individually with respect to special circumstances and demands. The allocation of probability and consequence is performed by expert estimation. One or more risk control options are suggested to minimise the occurring risks.

Table 34: Hazards of steel/polymer-foam/steel retrofit variant

Category		Hazard	Effect	Probability	Consequence	Risk ranking	Risk control option
Fire	1	Fire in cargo hold	Large fire at cargo hold with degradation of the load bearing ship structures and failure	A	5	medium	Fire detection system with automatic fire extinguishers
	2	Fire on deck	High temperature impact on the cargo holds as adjacent spaces	B	4	medium	Fire detection system with automatic fire extinguishers

Category		Hazard	Effect	Probability	Consequence	Risk ranking	Risk control option
	3	Fire at height of side shell	High temperature impact on the double side shell as adjacent space	A	3	low/medium	Fire detection system with automatic fire extinguishers
Impact	4	Side impact at cargo hold	Damage to the outer and inner shell caused by a collision with another vessel	B	4	medium	Optimisation of the side shell structure towards collision energy absorption
	5	Grounding	Damage to the outer and inner bottom caused by rocks or other obstacles in the waterway	C	3	medium	Optimisation of the bottom shell structure towards collision energy absorption
	6	Heavy unit handling	Damage to the steel deck structure	B	2	low/medium	Train workers on their handling skills
Structural	7	Excessive loads during loading/unloading	Excessive bending moment and shear load transferred to the hull structure during cargo handling	D	2	medium	Train shippers on the appropriate loading/unloading sequence of their vessel.
	8	Fatigue of plates and weld seams	Cracks in plates and weld seams caused by poor/under-sized design	B	2	low/medium	Incorporate a fatigue analysis of the structures in the design process and conduct inspections
	9	Debonding of adhesive	Loss of adhesion on the interface of steel primer and polymer-foam	B	2	low/medium	Incorporate bonding and surface preparation tests in the design process and conduct inspections
	10	Fatigue of adhesive	Degradation through load cycles during operation	B	2	low/medium	Incorporate bonding and surface preparation tests in the design process and conduct inspections
Environmental	11	Ageing of polymer-foam	Polymer-foam degrades through moisture and time	A	3	low/medium	Incorporate polymer-foam tests in the design process and conduct inspections
	12	High temperatures	Bonding and polymer-foam lose their load bearing capabilities	C	1	low/medium	Incorporate physical tests in the design process and conduct inspections
	13	Low temperatures	Bonding and polymer-foam lose their load bearing capabilities	C	1	low/medium	Incorporate physical tests in the design process and conduct inspections
	14	Corrosion in accessible spaces	Degradation of primer and steel surface caused by water and moisture	D	2	medium	Corrosion protection and periodic inspections
	15	Corrosion in closed spaces	Degradation of primer and steel surface caused by water and moisture	B	3	low/medium	Extensive corrosion protection
	16	Leakage of inner steel shell	Degradation of polymer-foam through cargo in case of leakage	B	4	medium	Incorporate physical tests in the design process and conduct inspections

Category	Hazard		Effect	Probability	Consequence	Risk ranking	Risk control option
Production	17	Bonding on shipyard	Bonding has to be executed on steel shipyards with no special bonding capabilities which leads to imperfections regarding surface preparation and bonding	B	4	medium	Train workers on their skills regarding polymer-foam processing, surface preparation and bonding
	18	Welding imperfections (complex steel structures)	Weld seams have to be partially performed with poor accessibility	B	4	medium	Application of partial automatic welding techniques, train welders on their skills
	19	Welding after bonding of polymer-foam	Heat zone of the weld seam impairs the polymer-foam and the bonding	B	5	medium/high	Ensure that there is no foam in the heat affected zone, fill in expandable foam after welding
	20	Access openings for integration of structures	Existing structures have to be cut in order to access the holds to integrate the additional structures	A	4	low/medium	Ensure appropriate cut-outs, preferably in non-load bearing structures
Other	21	Damage stability	In case of outer shell rupture water will ingress into the double hull	B	3	low/medium	Use closed-cell foam to avoid water uptake and to retain buoyancy

Table 35: Hazards of λ-shape retrofit variant

Category	Hazard		Effect	Probability	Consequence	Risk ranking	Risk control option
Fire	1	Fire in cargo hold	Large fire at cargo hold with degradation of the load bearing ship structures and failure	A	5	medium	Fire detection system with automatic fire extinguishers
	2	Fire on deck	High temperature impact on the cargo holds as adjacent spaces	B	4	medium	Fire detection system with automatic fire extinguishers
	3	Fire at height of side shell	High temperature impact on the double side shell as adjacent space	A	2	low	Fire detection system with automatic fire extinguishers
Impact	4	Side impact at cargo hold	Damage to the outer and inner shell caused by a collision with another vessel	B	4	medium	Optimisation of the side shell structure towards collision energy absorption
	5	Grounding	Damage to the outer and inner bottom caused by rocks or other obstacles in the waterway	C	3	medium	Optimisation of the bottom shell structure towards collision energy absorption
	6	Heavy unit handling	Damage to the steel deck structure	B	2	low/medium	Train workers on their handling skills
Structural	7	Excessive loads during loading/unloading	Excessive bending moment and shear load transferred to the hull structure during cargo handling	D	2	medium	Train shippers on the appropriate loading/unloading sequence of their vessel.
	8	Fatigue of plates and weld seams	Cracks in plates and weld seams caused by poor/under-sized design	C	3	medium	Incorporate a fatigue analysis of the structures in the design process and conduct inspections

Environmental	9	High temperatures	Structures lose their load bearing capabilities	C	1	low/medium	Conduct inspections
	10	Low temperatures	Structures lose their load bearing capabilities	C	1	low/medium	Conduct inspections
	11	Corrosion in accessible spaces	Degradation of primer and steel surface caused by water and moisture	D	2	medium	Corrosion protection and periodic inspections
	12	Corrosion in closed spaces	Degradation of primer and steel surface caused by water and moisture	C	3	medium	Extensive corrosion protection, leak-proof compartments, perhaps filled with non-reactive gas
Production	13	Welding imperfections (complex steel structures)	Weld seams have to be partially performed with poor accessibility	C	4	medium/high	Application of partial automatic welding techniques, train welders on their skills
	14	Access openings for integration of structures	Existing structures have to be cut in order to access the holds to integrate the additional structures	A	4	low/medium	Ensure appropriate cut-outs, preferably in non-load bearing structures
Other	15	Damage stability	In case of outer shell rupture water will ingress into the double hull	B	4	medium	Use closed spaces to retain buoyancy

Table 36: Hazards of rubber bag variant

Category		Hazard	Effect	Probability	Consequence	Risk ranking	Risk control option
Fire	1	Fire in cargo hold	Large fire at cargo hold with degradation of the load bearing ship structures and failure	A	5	medium	Fire detection system with automatic fire extinguishers
	2	Fire on deck	High temperature impact on the cargo holds as adjacent spaces	B	5	medium/high	Fire detection system with automatic fire extinguishers
	3	Fire at height of side shell	High temperature impact on the double side shell as adjacent space	A	3	low/medium	Fire detection system with automatic fire extinguishers
Impact	4	Side impact at cargo hold	Damage to the outer and inner shell caused by a collision with another vessel	B	4	medium	Optimisation of side supports and tear strength of rubber bag
	5	Grounding	Damage to the outer and inner bottom caused by rocks or other obstacles in the waterway	C	3	medium	Optimisation of bottom supports and tear strength of rubber bag
	6	Heavy unit handling	Damage to the steel deck structure	B	2	low/medium	Train workers on their handling skills
Structural	7	Excessive loads during loading/unloading	Excessive bending moment and shear load transferred to the hull structure during cargo handling	D	3	medium/high	Train shippers on the appropriate loading/unloading sequence of their vessel.
	8	Fatigue of plates and weld seams	Cracks in plates and weld seams caused by poor/under-sized design	A	2	low	Incorporate a fatigue analysis of the structures in the design process and conduct inspections

Environmental	9 High temperatures	Foam loses load bearing capabilities	C	1	low/medium	Incorporate physical tests in the design process and conduct inspections
	10 Low temperatures	Foam loses load bearing capabilities	C	1	low/medium	Incorporate physical tests in the design process and conduct inspections
	11 Corrosion in accessible spaces	Degradation of primer and steel surface caused by water and moisture	D	2	medium	Corrosion protection and periodic inspections
	12 Corrosion in closed spaces	Degradation of primer and steel surface caused by water and moisture	A	1	low	Extensive corrosion protection
	13 Ageing of rubber bag	Degradation of rubber bag material	D	4	medium/high	Incorporate physical tests in the design process and conduct inspections
Production	14 Welding imperfections (complex steel structures)	Weld seams have to be partially performed with poor accessibility	A	2	low	Application of partial automatic welding techniques, train welders on their skills
	15 Access openings for integration of structures	Existing structures have to be cut in order to access the holds to integrate the additional structures	A	4	low/medium	Ensure appropriate cut-outs, preferably in non-load bearing structures
Other	16 Damage stability	In case of outer shell rupture water will ingress into the double hull	B	4	medium	Use foam as supports to increase buoyancy
	17 Permeability of rubber	Gas/air mixture outside the rubber bag in the cargo hold	D	4	medium/high	Conduct permeability tests, install gas detection system in the holds

7.2 *Hazards of composite lengthening*

The occurring hazards for the composite lengthening retrofit are combined to one assessment for the 4 different solutions as they are similar in a general perspective. The summarised results are presented in Table 37.

Table 37: Hazards of composite lengthening

Category	Hazard	Effect	Probability	Consequence	Risk ranking	Risk control option
Fire	1 Fire in cargo hold	Large fire at cargo hold with degradation of the load bearing ship structures and failure	A	5	medium	Fire detection system with automatic fire extinguishers, use flame retardant resin
	2 Fire on deck	High temperature impact on the cargo holds as adjacent spaces	A	5	medium	Fire detection system with automatic fire extinguishers, use flame retardant resin
	3 Fire at height of side shell	High temperature impact on the double side shell as adjacent space	A	5	medium	Fire detection system with automatic fire extinguishers, use flame retardant resin

Impact	4	Side impact at cargo hold	Damage to the outer and inner shell caused by a collision with another vessel	B	4	medium	Optimisation of the side shell structure towards collision energy absorption
	5	Grounding	Damage to the outer and inner bottom caused by rocks or other obstacles in the waterway	C	3	medium	Optimisation of the bottom shell structure towards collision energy absorption, use abrasive resistant protection coating
	6	Heavy unit handling	Damage to the composite deck structure	B	2	low/medium	Train workers on their handling skills
Structural	7	Excessive loads during loading/unloading	Excessive bending moment and shear load transferred to the hull structure during cargo handling	D	2	medium	Train shippers on the appropriate loading/unloading sequence of their vessel.
	8	Fatigue of laminate or sandwich	Cracks in solid laminate or sandwich caused by poor/under-sized design	B	3	low/medium	Incorporate a fatigue analysis of the structures in the design process and conduct inspections
	9	Fatigue of steel/composite joints	Cracks at steel/composite joints	C	4	medium/high	Incorporate bonding and surface preparation tests in the design process and conduct inspections
	10	Debonding of adhesive	Loss of adhesion on the interface of steel primer and polymer-foam	C	3	medium	Incorporate adhesion tests of steel, steel primer and adhesive and conduct inspections
Environmental	11	High temperatures	Bonding, polymer-foam and matrix loose their load bearing capabilities	D	3	medium/high	Incorporate physical tests on high temperature behaviour of the joint in the design process and conduct inspections
	12	Low temperatures	Bonding, polymer-foam and matrix loose their load bearing capabilities	D	3	medium/high	Incorporate physical tests on low temperature behaviour of the joint in the design process and conduct inspections
	13	Water / sea-water	Adhesive loses load bearing capabilities due to water uptake	D	3	medium/high	Incorporate physical tests on behaviour of the joint after moisture uptake in the design process and conduct inspections
	14	UV-light	Adhesive loses load bearing capabilities due to embrittlement	D	3	medium/high	Incorporate physical tests on behaviour of the joint after UV-light exposure in the design process and conduct inspections
	15	Leakage of inner steel shell	Degradation of polymer-foam through cargo in case of leakage	B	4	medium	Incorporate physical tests in the design process and conduct inspections
Production	16	Bonding on shipyard	Bonding has to be executed on steel shipyards with no special bonding capabilities which leads to imperfections regarding surface preparation and bonding	B	4	medium	Train workers on their skills regarding polymer-foam processing, surface preparation and bonding

	17	Lamination of sections on shipyard	Hull sections have to be assembled on site with lamination	B	4	medium	Train workers on their skills regarding laminating processing, surface preparation
Other	18	Damage stability	In case of outer shell rupture water will ingress into the double hull	B	4	medium	Similar to standard steel double hull

7.3 *Gap analysis summary*

As concluding remarks several major gaps are identified and presented in this section without going into detail because the variants are elaborated as conceptual solutions. The single-to-double hull retrofit solutions and the composite lengthening are distinguished and provide a brief overview of issues to be investigated in more detail within a thorough and specific design for a retrofit of an inland navigation vessel.

Single-to-double hull retrofit:

1. Durability of bonded steel/polymer-foam joints
2. Compatibility of polymer-foam with liquid cargo in case of inner shell leakage
3. Structural integrity in fire of polymer-foam and rubber bags
4. Quality assurance on steel shipyard regarding bonding and composite works
5. Robustness and ageing of rubber bags
6. Permeability of rubber bags in closed cargo spaces
7. Producibility and reparability of steel/polymer-foam/steel variant
8. Survey of closed spaces
    a. Corrosion of plates and stiffeners
    b. Detection of failure in plates and stiffeners
9. Behaviour of rubber bag variant during collision and grounding caused by non-linear rubber material characteristics and large deformations of the rubber bags

Composite lengthening:

1. Steel/composite joints (connection of the existing steel hull to the new entire composite section)
    a. Load bearing capacity
    b. Fatigue performance of the constituent materials such as adhesive
    c. Robustness
    d. Structural behaviour in high and low temperatures
    e. Structural behaviour due to moisture uptake
    f. Structural behaviour due to UV-light exposure
2. Structural integrity of the entire composite section in case of fire on the vessel or outside the vessel
3. Robustness of composite cargo hold structures during loading/unloading operation
4. Quality assurance on steel shipyard regarding bonding and composite works
5. Compatibility of sandwich core with liquid cargo in case of inner laminate skin failure

8 Conclusions

Throughout the performed work within WP 5 and especially task 5.2 “Retrofitting consequences” novel approaches for the retrofit of existing inland navigation vessels by unconventional means are introduced. Different solutions considering unconventional materials or geometric designs in inland waterway shipping are presented and investigated: retrofitting of single hull inland navigation tankers by implementing different inner hull structures and retrofitting of inland navigation vessels by a composite hold section.

From a technical point of view all suggested solutions are feasible considering global and local strength of the hull with some minor issues which can be solved. Different approaches are presented for the single-to-double hull retrofit:

- Steel/polymer-foam/steel double side, considering an inner steel shell which is adhesively bonded to a polymer-foam core to create a sandwich structure.
- λ-shape double side, considering an inner steel shell and a corrugated steel plating acting as foldable core in case of a side impact.
- Rubber bags, implemented into the existing steel hull with the aid of polystyrene blocks as supports.

The subsequent developments are made for the composite lengthening of an inland navigation vessel cargo hold:

- Composite section made of either solid glass fibre reinforced plastics or carbon fibre reinforced plastics.
- Composite section made of either glass fibre reinforced sandwich or carbon fibre reinforced sandwich structures.

Finite element analyses are made to reveal critical stresses during the lay-out and design of the retrofit variants.

A major obstruction of implementing alternative constructions and uncommon materials on inland navigation vessels are the current prescriptive rules and regulations published by classification societies and national and European authorities. Hence, those rules provide a strict and conservative approach for the design and construction of the ships. The introduction of uncommon materials such as rubber, polymer-foam, adhesive or fibre reinforced plastics is difficult because the use of those materials is normally prohibited on inland cargo ships. Consequently, an enormous and time-consuming effort has to be made in order to convince the classification societies and other authorities by the application of risk control options. These extensive modifications usually result in higher expenses while keeping in mind that the inland shipping companies are reluctant to invest in such a difficult economic environment as it exists today.

Considering unconventional materials such as foams or plastics on-board ships, the influence of fire is a major concern of the classification societies and authorities. However, recent implementations of composites into ships as superstructures, other components or even complete vessels have been built from composites. Extensive risk analyses for the novel technologies and structures have been conducted at the Swedish shipyard Kockums for instance which evidences that the application of composites in shipbuilding industry is increasingly respected. As the loads on inland navigation vessels are much smaller in general as on sea-going ships, the implementation of novel materials and structures should be driven in a more proactive manner to improve the efficiency of the fleet.

Production related subjects are presented in a separate deliverable D 5.4 “Production” where manufacturing issues are treated as well as the final cost assessment of the retrofit variants including an economic assessment. The economic evaluation specifies the payback time of each solution considering a distinct operational profile and different cargo carrying capacities. Without the influence of the involved costs during production and operation, no detailed conclusion can be drawn on the general feasibility of each single retrofit solution.

However, from a technical point of view the retrofit solutions indicate that the design is feasible in general benefiting from additional cargo carrying capacity due to smaller double side widths incorporating the same crash energy absorption for some solutions.

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10.3 List of Abbreviations

ADN	Accord Européen Relatif au Transport International des Marchandises Dangereuses par Voies de Navigation Intérieures (European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways)
BinSchUO	Binnenschiffsuntersuchungsordnung (Rules for the examination of inland navigation vessels in Germany)
B_{OA}	Breadth over all
BU	University of Belgrade
CFRP	Carbon fibre reinforced plastics
CMT	Center of Maritime Technologies e.V.
CSR	Common Structural Rules
DNVGL	Det Norske Veritas Germanischer Lloyd
DoW	Description of work
EU	European Union
GFRP	Glass fibre reinforced plastics
GGVSEB	Gefahrgutverordnung Straße, Eisenbahn und Binnenschifffahrt (Regulation for dangerous goods for road, Train and inland waterway shipping in Germany)
GL	Germanischer Lloyd
HAZID	Hazard identification
INOT	Inland navigation oil and product tanker
IVR	International Association the Rhine Ships Register
kN/m^2	Kilo newton per square metre (pressure)
kNm	Kilo newton metre (bending moment)
L_{OA}	Length over all
m	Metre
mm	Millimetre
MPa	Mega pascal
p	Pressure
Sicomp	SWEREA Sicomp AB
SMILE FEM	SMILE FEM GmbH
SOLAS	International Convention for the Safety of Life at Sea
t	Thickness or metric tonnes as applicable

T	Draught
TNO	Institute for Technical Applied Physics, The Netherlands
WP	Work package
x	Coordinate (longitudinal)
y	Coordinate (transversal)
z	Coordinate (vertical)
σ_x	Normal stress in X-direction
σ_y	Normal stress in Y-direction
τ_{xy}	Shear stress in XY-plane

11 Annexes

11.1 Single-to-double hull variants

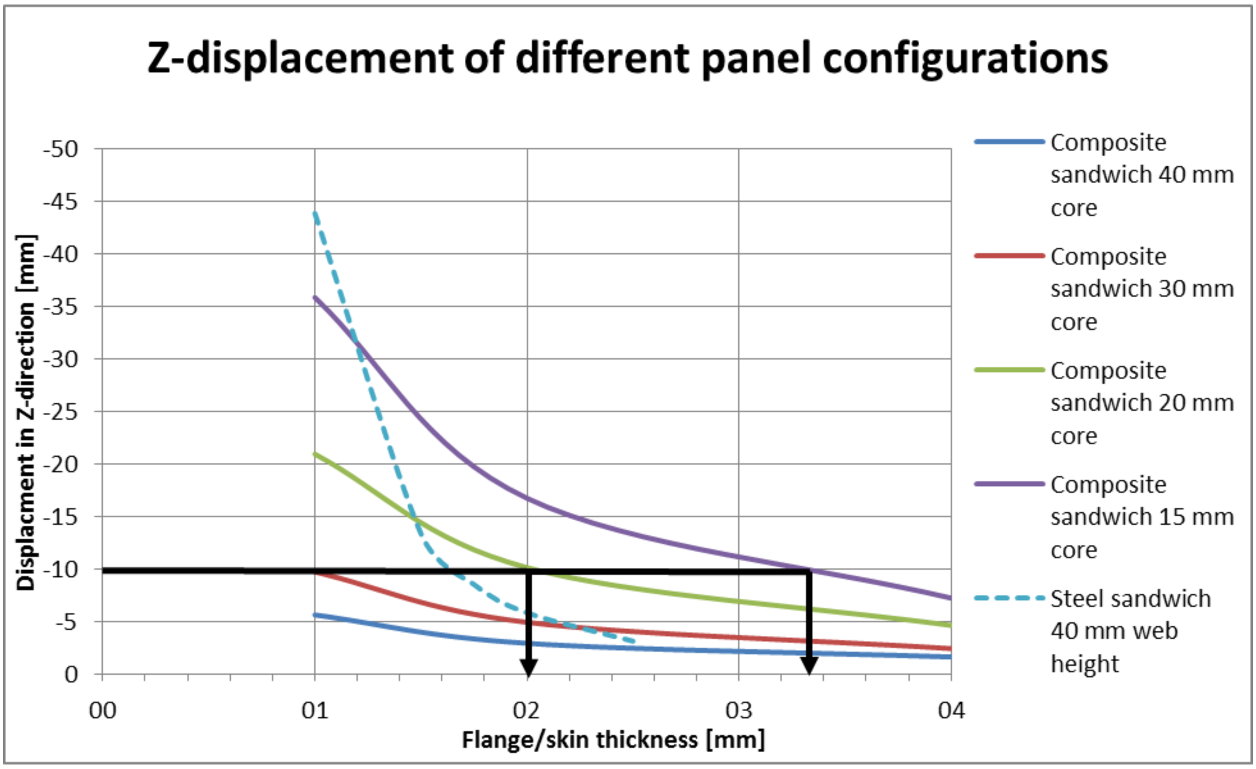
11.1.1 Rubber bag supports

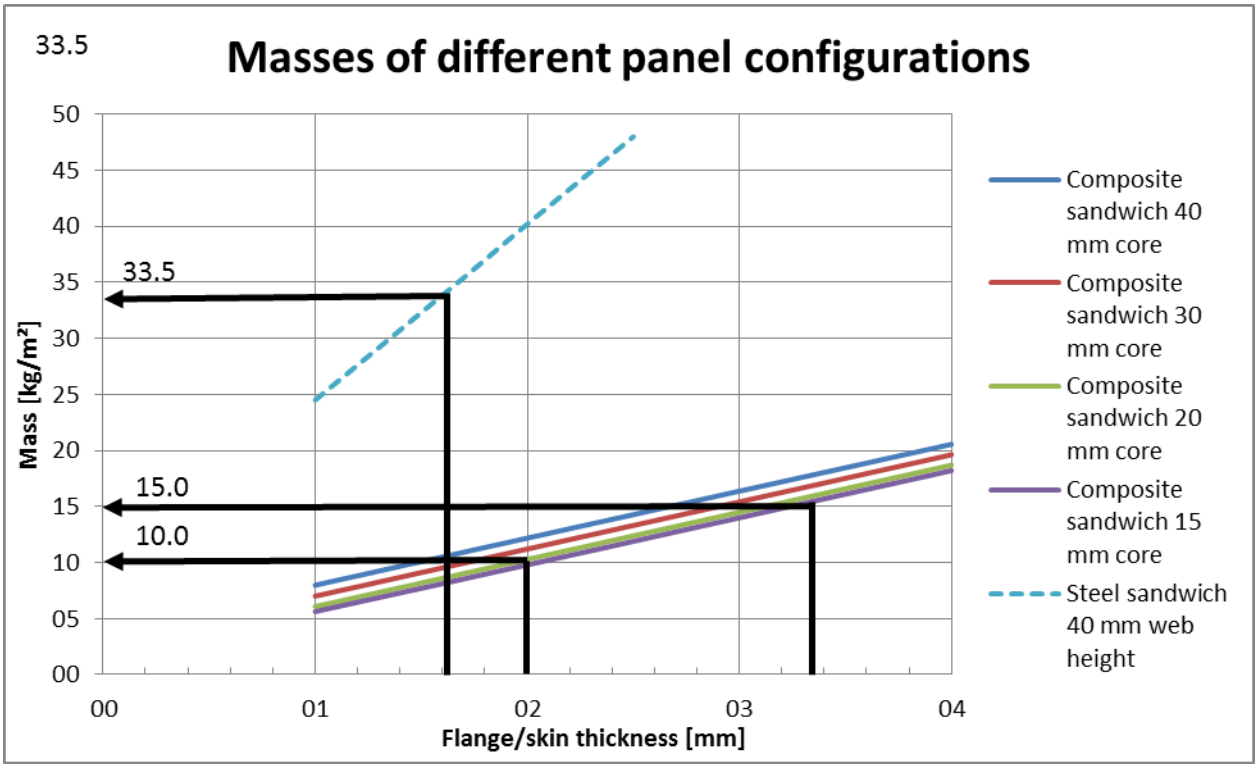
11.1.1.1 Bottom panels

Panel size:

length	3500
width	645

	Flange/skin thickness t [mm]	Web distance p [mm]	Web thickness ts [mm]	Web/core height hs [mm]	Mass m [kg/m²]	Displacement Z [mm]	Relative deflection d [%]
Composite sandwich panel	1.0	n/a	n/a	40	8.0	-5.7	-0.9
	2.0	n/a	n/a	40	12.2	-3.0	-0.5
	4.0	n/a	n/a	40	20.6	-1.7	-0.3
	1.0	n/a	n/a	30	7.0	-9.8	-1.5
	2.0	n/a	n/a	30	11.2	-5.0	-0.8
	4.0	n/a	n/a	30	19.6	-2.5	-0.4
	1.0	n/a	n/a	20	6.1	-21.0	-3.3
	2.0	n/a	n/a	20	10.3	-10.2	-1.6
	4.0	n/a	n/a	20	18.7	-4.7	-0.7
	1.0	n/a	n/a	15	5.6	-35.9	-5.6
	2.0	n/a	n/a	15	9.8	-16.8	-2.6
	4.0	n/a	n/a	15	18.2	-7.3	-1.1
Steel sandwich	1.0	120	3.0	40	24.5	-43.9	-6.8
	1.5	120	3.0	40	32.3	-13.4	-2.1
	1.75	120	3.0	40	36.2	-8.6	-1.3
	2.0	120	3.0	40	40.2	-5.9	-0.9
	2.5	120	3.0	40	48.0	-3.2	-0.5
	2.5	120	4.0	40	53.0	-3.0	-0.5

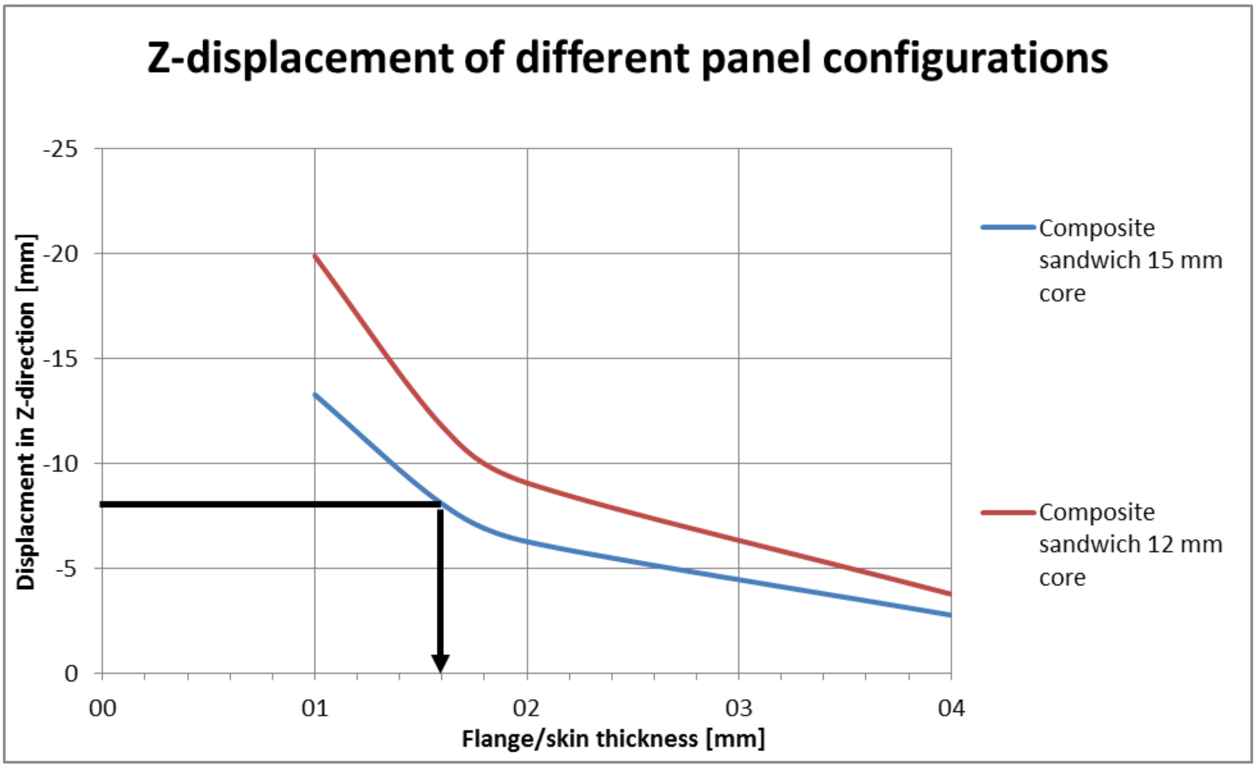

Z-displacement of different panel configurations
Displacment in Z-direction [mm]
-50
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
00
01
02
03
04
Flange/skin thickness [mm]
Composite sandwich 40 mm core
Composite sandwich 30 mm core
Composite sandwich 20 mm core
Composite sandwich 15 mm core
Steel sandwich 40 mm web height

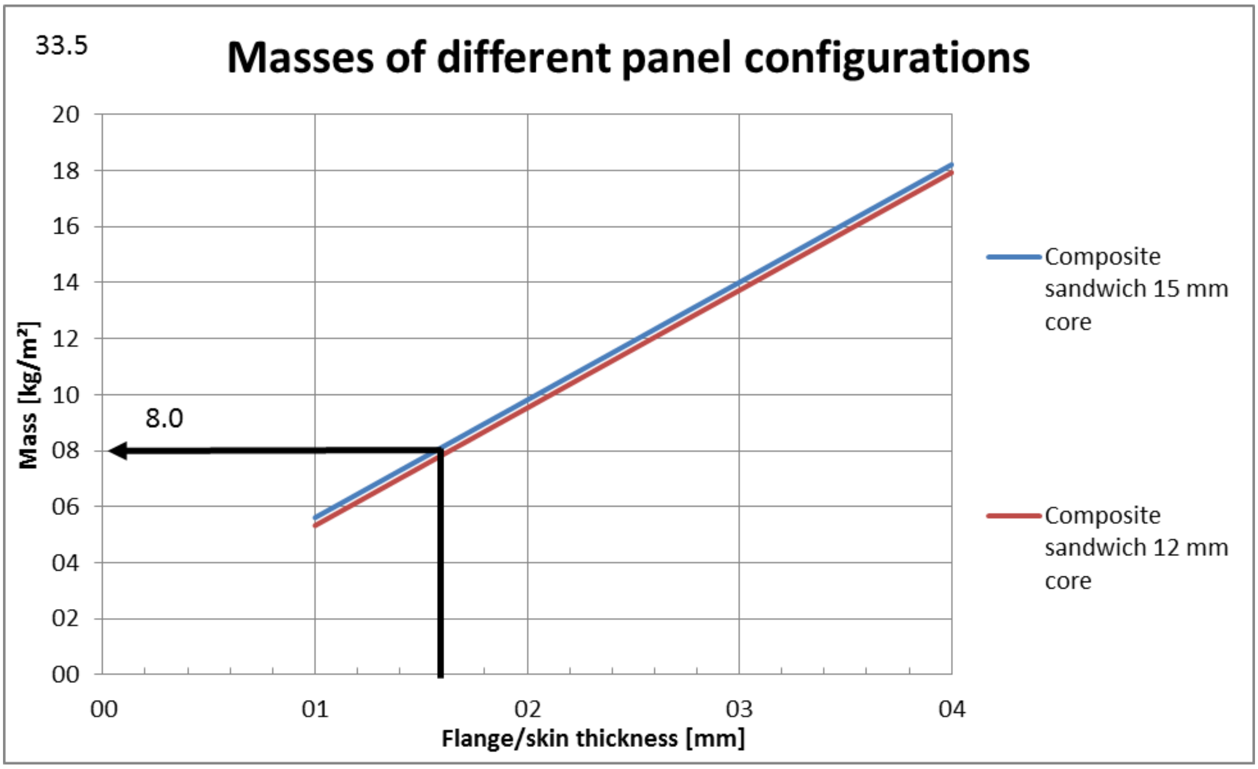

33.5
Masses of different panel configurations
Mass [kg/m²]
50
45
40
35
30
25
20
15
10
05
00
33.5
15.0
10.0
00
01
02
03
04
Flange/skin thickness [mm]
Composite sandwich 40 mm core
Composite sandwich 30 mm core
Composite sandwich 20 mm core
Composite sandwich 15 mm core
Steel sandwich 40 mm web height

11.1.1.2 Side panel

Panel size:	
length	2720
width	500

	Flange/skin thickness t [mm]	Web distance p [mm]	Web thickness ts [mm]	Web/core height hs [mm]	Mass m [kg/m²]	Displacement Z [mm]	Relative deflection d [%]
Composite sandwich panel	1.0	n/a	n/a	15	5.6	-13.3	-2.7
	1.6	n/a	n/a	15	8.1	-8.1	-1.6
	2.0	n/a	n/a	15	9.8	-6.3	-1.3
	4.0	n/a	n/a	15	18.2	-2.8	-0.6
	1.0	n/a	n/a	12	5.3	-19.9	-4.0
	1.6	n/a	n/a	12	7.8	-11.8	-2.4
	2.0	n/a	n/a	12	9.5	-9.1	-1.8
	4.0	n/a	n/a	12	17.9	-3.8	-0.8




33.5
Masses of different panel configurations
Mass [kg/m²]
20
18
16
14
12
10
08
06
04
02
00
8.0
00
01
02
03
04
Flange/skin thickness [mm]
Composite sandwich 15 mm core
Composite sandwich 12 mm core

11.1.2 *Panel mass summary*

Solutions with panels

		Bottom		Chine		Side	
		Starboard	Port	Starboard	Port	Starboard	Port
Hold 1	Section 1 (3.5 m)	6	6	1	1	7	7
	Section 2 (3.5 m)	6	6	1	1	7	7
	Section 3 (3.5 m)	6	6	1	1	7	7
Hold 2	Section 1 (3.5 m)	6	6	1	1	7	7
	Section 2 (3.5 m)	6	6	1	1	7	7
	Section 3 (3.5 m)	6	6	1	1	7	7
Hold 3	Section 1 (3.5 m)	6	6	1	1	7	7
	Section 2 (3.5 m)	6	6	1	1	7	7
	Section 3 (3.5 m)	6	6	1	1	7	7
	Section 4 (3.5 m)	6	6	1	1	7	7
Hold 4	Section 1 (3.5 m)	6	6	1	1	7	7
	Section 2 (3.5 m)	6	6	1	1	7	7
	Section 3 (3.5 m)	6	6	1	1	7	7
Hold 5	Section 1 (3.5 m)	6	6	1	1	7	7
	Section 2 (3.5 m)	6	6	1	1	7	7
	Section 3 (3.5 m)	6	6	1	1	7	7
	Parts ∑	96	96	16	16	112	112
	Parts ∑	192		32		224	

Panel dimensions

Length [mm]	3500	3500	2720
Width [mm]	645	400	500
Area [m^2]	2.26	1.40	1.36
Total area [m^2]	430	40	300

Mass

Composite	Per unit area [kg/m^2]	10.3	10.3	8.1
	∑ [kg]	4500	500	2500
Steel	Per unit area [kg/m^2]	33.5	33.5	33.5
	∑ [kg]	14500	1500	10200
Aluminium	Per unit area [kg/m^2]	6.8	6.8	6.5
	∑ [kg]	2900	300	2000

Solutions with solids

		Bottom		Chine		Side	
		Starboard	Port	Starboard	Port	Starboard	Port
Hold 1	Section 1 (3.5 m)	6	6	7	7	7	7
	Section 2 (3.5 m)	6	6	7	7	7	7
	Section 3 (3.5 m)	6	6	7	7	7	7
Hold 2	Section 1 (3.5 m)	6	6	7	7	7	7
	Section 2 (3.5 m)	6	6	7	7	7	7
	Section 3 (3.5 m)	6	6	7	7	7	7
Hold 3	Section 1 (3.5 m)	6	6	7	7	7	7
	Section 2 (3.5 m)	6	6	7	7	7	7
	Section 3 (3.5 m)	6	6	7	7	7	7
	Section 4 (3.5 m)	6	6	7	7	7	7
Hold 4	Section 1 (3.5 m)	6	6	7	7	7	7
	Section 2 (3.5 m)	6	6	7	7	7	7
	Section 3 (3.5 m)	6	6	7	7	7	7
Hold 5	Section 1 (3.5 m)	6	6	7	7	7	7
	Section 2 (3.5 m)	6	6	7	7	7	7
	Section 3 (3.5 m)	6	6	7	7	7	7
	Parts ∑	96	96	112	112	112	112
	Parts ∑	192		224		224	

Block dimensions

	Bottom	Chine	Side
Length [m]	3.49	0.46	2.47
Width [m]	0.60	-	0.46
Height [m]	0.22	-	0.22
Volume [m³]	0.46	0.10	0.25

Mass

		Bottom	Chine	Side
Polystyrene	Density [kg/m³]	28	28	28
	∑ [kg]	2500	600	1600

Panels		Bottom		Chine		Side		Total
		Starboard	Port	Starboard	Port	Starboard	Port	
Length [mm]		3500		3500		2720		
Width [mm]		645		400		500		
Area [m^2]		2.26		1.40		1.36		
Total area [m^2]		430		40		300		770
Composite	Per unit area [kg/m^2]	10.3		10.3		8.1		
	∑ [kg]	4500		500		2500		7500
Steel	Per unit area [kg/m^2]	33.5		33.5		33.5		
	∑ [kg]	14500		1500		10200		26200
Aluminium	Per unit area [kg/m^2]	6.8		6.8		6.5		
	∑ [kg]	2900		300		2000		5200

Blocks		Bottom		Chine		Side		Total
		Starboard	Port	Starboard	Port	Starboard	Port	
Length [m]		3.49		0.46		2.47		
Width [m]		0.60		-		0.46		
Height [m]		0.22		-		0.22		
Volume [m^3]		0.46		0.10		0.25		0.81
Polystyrene	Density [kg/m^3]	28		28		28		
	∑ [kg]	2500		600		1600		4700

11.1.3 Weight calculation

ADN Double Hull

Part	Weight		Quantity	Total weight	
	Plate	Stiffener			
	[kg]	[kg]	[-]	[kg]	[kg]
Inner bottom	19904		1	19904	33440
Inner side	6768		2	13536	
Inner bottom longitudinal		837	10	8370	17786
Inner side frame		44	214	9416	
			∑	51226	

Foam/steel Double Hull

Part	Weight		Quantity	Total weight	
	Plate	Stiffener			
	[kg]	[kg]	[-]	[kg]	[kg]
Inner bottom	19904		1	19904	43308
Inner side	11702		2	23404	
Inner bottom longitudinal		837	10	8370	8370
Foam blocks side		47.5	224	10640	10640
			∑	62318	

λ-Shape Double Hull

Part	Weight		Quantity	Total weight	
	Plate	Stiffener			
	[kg]	[kg]	[-]	[kg]	[kg]
Inner bottom	19904		1	19904	33440
Inner side	6768		2	13536	
Inner bottom longitudinal		837	10	8370	26248
Corrugated side		8939.0	2	17878	
			∑	59688	

Rubber Bags

Part	Weight		Quantity	Total weight	
	Plate	Stiffener			
	[kg]	[kg]	[-]	[kg]	[kg]
Rubber bag (10.5 m length)	500		8	4000	5000
Rubber bag (14.0 m length)	500		2	1000	
Supports				4700	9700
Fittings/attachments				5000	
			∑	14700	

11.2 Composite lengthening

Table 38: Detailed mass of structure in glass variants

		Single skin laminates	Sandwich
		Mass	Mass
Outer parts	bottom	2.71	2.89
	inner bottom	3.06	1.99
	chine radius	0.57	0.31
	side shell plating	2.00	1.17
	inner side plating	3.42	1.07
	sheer strake	0.70	0.23
	longitudinal girders	0.37	0.10
	deck & stringer plate	1.52	0.22
	coaming	2.28	0.84
	coaming stiffener top 1 (horiz.)	0.74	0.14
	coaming stiffener top 2 (vert.)	0.33	0.06
	coaming stiffener sec.	0.30	0.08
Inner parts	floor	1.62	1.31
	bulkhead	0.16	0.04
	bulkhead vertical stiffeners	0.03	0.01
	side frame trans.	0.62	0.49
	inner side frame trans.	0.66	0.52
	deck beam	0.24	0.18
	coaming vertical stiffener	0.37	0.18
	brackets	0.20	0.15
Total		**21.90**	**11.79**

Table 39: Detailed mass and cost of structure in carbon variants

		Single skin laminates	Sandwich
		Mass	Mass
Outer parts	bottom	2.15	1.81
	inner bottom	2.43	1.39
	chine radius	0.45	0.19
	side shell plating	0.98	0.75
	inner side plating	1.30	0.75
	sheer strake	0.25	0.15
	longitudinal girders	0.29	0.06
	deck & stringer plate	0.60	0.15
	coaming	0.72	0.50
	coaming stiffener top 1 (horiz.)	0.24	0.07
	coaming stiffener top 2 (vert.)	0.11	0.03
	coaming stiffener sec.	0.09	0.04
Inner parts	floor	1.28	1.18
	bulkhead	0.05	0.02
	bulkhead vertical stiffeners	0.02	0.003
	side frame trans.	0.32	0.17
	inner side frame trans.	0.37	0.20
	deck beam	0.14	0.07
	coaming vertical stiffener	0.30	0.13
	brackets	0.13	0.06
Total		**12.21**	**7.71**

Table 40: Scantlings & moment of inertia single skin glass variants

	t [mm]	z-position [m]	length [m]	A[m²]	z*A[m³]	VCG-z	I [m^4]	Steiner	I + Steiner
bottom	10.00	0.00	8.90	0.09	0.00	1.30	7.42E-07	0.00E+00	7.42E-07
inner bottom	12.00	0.40	8.39	0.10	0.04	0.90	1.21E-06	1.61E-02	1.61E-02
chine radius	20.00	0.15	0.47	0.01	0.00	1.15	2.07E-02	2.12E-04	4.19E-02
side shell plating	2070.00	1.50	0.0146	0.03	0.05	0.20	5.37E-07	3.71E-02	7.43E-02
inner side plating	2500.00	1.50	0.0250	0.06	0.09	0.20	3.26E-06	7.68E-02	1.54E-01
sheer strake	440.00	3.00	0.0254	0.01	0.03	1.70	6.01E-07	3.21E-02	6.43E-02
longitudinal girder (centre)	400.00	0.20	0.0100	0.00	0.00	1.10	3.33E-08	1.60E-04	1.60E-04
longitudinal girder (side)	400.00	0.20	0.0100	0.00	0.00	1.10	3.33E-08	1.60E-04	1.60E-04
longitudinal girder (side)	400.00	0.20	0.0100	0.00	0.00	1.10	3.33E-08	1.60E-04	1.60E-04
deck & stringer plate	25.00	2.90	1.00	0.03	0.07	1.60	2.08E-03	6.37E-02	1.31E-01
coaming	1500.00	3.65	0.0250	0.04	0.14	2.35	1.95E-06	2.06E-01	4.13E-01
coaming stiffener top 1 (horiz.)	30.50	4.4	0.40	0.01220	0.05	3.10	1.63E-04	1.17E-01	2.34E-01
coaming stiffener top 2 (vert)	180.00	4.38475	0.0305	0.00549	0.02	3.08	4.26E-07	5.21E-02	1.04E-01
coaming stiffener sec.	20.50	3.65	0.24	0.00492	0.02	2.35	2.36E-05	2.71E-02	5.42E-02
			SUM:	0.40	0.52			**Iy [m^4)**	**1.2874**
			VCG[m]	**1.30**				**W [m³]**	**0.4158**

Table 41: Main stresses single skin glass variants

Position	Hatch coaming			Deck			Stiffener coaming		
Type of stress		**Hogging**	**Sagging**		**Hogging**	**Sagging**		**Hogging**	**Sagging**
	Lower edge S1U [N/mm²]	**46.39**	**31.17**	S 1	**46.39**	**31.17**	Upper stiffener S1 [N/mm²]	**90.00**	**60.47**
	Upper edge S1L [N/mm²]	**90.00**	**60.47**				Lower stiffener S1 [N/mm²]	**68.20**	**45.82**

Table 42: Scantlings & moment of inertia glass sandwich variants

	t [mm]	z-position [m]	length [m]	A[m^2]	z*A[m^3]	VCG-z	I [m^4]	Steiner	I + Steiner
bottom	45.00	0.00	8.90	0.40	0.00	0.75	6.76E-05	0.00E+00	6.76E-05
inner bottom	33.00	0.40	8.39	0.28	0.11	0.35	2.51E-05	4.43E-02	4.43E-02
chine radius	45.00	0.15	0.47	0.02	0.00	0.60	4.67E-02	4.77E-04	9.43E-02
side shell plating	2070.00	1.50	0.0360	0.07	0.11	0.75	8.05E-06	4.14E-08	1.62E-05
inner side plating	2500.00	1.50	0.0330	0.08	0.12	0.75	7.49E-06	4.59E-08	1.51E-05
sheer strake	440.00	3.00	0.0360	0.02	0.05	2.25	1.71E-06	8.02E-02	1.60E-01
longitudinal girder (centre)	400.00	0.20	0.0120	0.00	0.00	0.55	5.76E-08	1.92E-04	1.92E-04
longitudinal girder (side)	400.00	0.20	0.0120	0.00	0.00	0.55	5.76E-08	1.92E-04	1.92E-04
longitudinal girder (side)	400.00	0.20	0.0120	0.00	0.00	0.55	5.76E-08	1.92E-04	1.92E-04
deck & stringer plate	15.000	2.90	1.00	0.02	0.04	2.15	1.25E-03	6.93E-02	1.41E-01
coaming	1500.00	3.65	0.0390	0.06	0.21	2.90	7.41E-06	4.92E-01	9.84E-01
coaming stiffener top 1 (horiz.)	24.000	4.4	0.40	0.00960	0.04	3.65	1.28E-04	1.28E-01	2.56E-01
coaming stiffener top 2 (vert.)	180.00	4.388	0.0240	0.00432	0.02	3.64	2.07E-07	5.72E-02	1.14E-01
coaming stiffener sec.	24.00	3.65	0.18	0.00420	0.02	2.90	1.07E-05	3.53E-02	7.06E-02
			SUM:	0.98	0.73			**Iy [m^4)**	**1.8654**
			VCG[m]	**0.75**				**W [m^3]**	**0.5111**

Table 43: Main stresses glass sandwich variants

Position	Hatch coaming			Deck			Stiffener coaming		
Type of stress		**Hogging**	**Sagging**		**Hogging**	**Sagging**		**Hogging**	**Sagging**
	Lower edge S1U [N/mm^2]	**43.13**	**28.98**	S 1	**43.13**	**28.98**	Upper stiffener S1 [N/mm^2]	**73.23**	**49.19**
	Upper edge S1L [N/mm^2]	**73.23**	**49.19**				Lower stiffener S1 [N/mm^2]	**58.18**	**39.08**

Table 44: Scantlings & moment of inertia single skin carbon variants

	t [mm]	z-position [m]	length [m]	A[m^2]	z*A[m^3]	VCG-z	I [m^4]	Steiner	I + Steiner
bottom	10.00	0.00	8.90	0.09	0.00	0.87	7.42E-07	0.00E+00	7.42E-07
inner bottom	12.00	0.40	8.39	0.10	0.04	0.47	1.21E-06	1.61E-02	1.61E-02
chine radius	20.00	0.15	0.47	0.01	0.00	0.72	2.07E-02	2.12E-04	4.19E-02
side shell plating	2070.00	1.50	0.0085	0.02	0.03	0.63	1.06E-07	9.69E-04	1.94E-03
inner side plating	2500.00	1.50	0.0120	0.03	0.05	0.63	3.60E-07	1.65E-03	3.31E-03
sheer strake	440.00	3.00	0.0115	0.01	0.02	2.13	5.58E-08	2.30E-02	4.60E-02
longitudinal girder (centre)	400.00	0.20	0.0100	0.00	0.00	0.67	3.33E-08	1.60E-04	1.60E-04
longitudinal girder (side)	400.00	0.20	0.0100	0.00	0.00	0.67	3.33E-08	1.60E-04	1.60E-04
longitudinal girder (side)	400.00	0.20	0.0100	0.00	0.00	0.67	3.33E-08	1.60E-04	1.60E-04
deck & stringer plate	12.50	2.90	1.00	0.01	0.04	2.03	1.04E-03	5.16E-02	1.05E-01
coaming	1500.00	3.65	0.0100	0.02	0.05	2.78	1.25E-07	1.16E-01	2.32E-01
coaming stiffener top 1 (horiz.)	12.50	4.4	0.40	0.00500	0.02	3.53	6.67E-05	6.24E-02	1.25E-01
coaming stiffener top 2 (vert.)	180.00	4.39375	0.0125	0.00225	0.01	3.53	2.93E-08	2.80E-02	5.60E-02
coaming stiffener sec.	8.00	3.65	0.24	0.00192	0.01	2.78	9.22E-06	1.49E-02	2.98E-02
			SUM:	0.30	0.26			**Iy [m^4)**	**0.6581**
			VCG[m]	**0.87**				**W [m^3]**	**0.1863**

Table 45: Main stresses single skin carbon variants

Position	Hatch coaming			Deck			Stiffener coaming		
		Hogging	**Sagging**		**Hogging**	**Sagging**		**Hogging**	**Sagging**
Type of stress	Lower edge S1U [N/mm²]	**115.61**	**77.67**	S 1	**115.61**	**77.67**	Upper stiffener S1 [N/mm²]	**200.92**	**134.98**
	Upper edge S1L [N/mm²]	**200.92**	**134.98**				Lower stiffener S1 [N/mm²]	**158.26**	**106.32**

Table 46: Scantlings & moment of inertia carbon sandwich variants

	t [mm]	z-position [m]	length [m]	A[m^2]	z*A[m^3]	VCG-z	I [m^4]	Steiner	I + Steiner
bottom	33.00	0.00	8.90	0.29	0.00	0.73	2.67E-05	0.00E+00	2.67E-05
inner bottom	21.00	0.40	8.39	0.18	0.07	0.33	6.47E-06	2.82E-02	2.82E-02
chine radius	33.00	0.15	0.47	0.02	0.00	0.58	3.42E-02	3.50E-04	6.91E-02
side shell plating	2070.00	1.50	0.0270	0.06	0.08	0.77	3.40E-06	9.15E-05	1.90E-04
inner side plating	2500.00	1.50	0.0210	0.05	0.08	0.77	1.93E-06	8.60E-05	1.76E-04
sheer strake	440.00	3.00	0.0270	0.01	0.04	2.27	7.22E-07	6.12E-02	1.22E-01
longitudinal girder (centre)	400.00	0.20	0.0084	0.00	0.00	0.53	1.98E-08	1.34E-04	1.34E-04
longitudinal girder (side)	400.00	0.20	0.0084	0.00	0.00	0.53	1.98E-08	1.34E-04	1.34E-04
longitudinal girder (side)	400.00	0.20	0.0084	0.00	0.00	0.53	1.98E-08	1.34E-04	1.34E-04
deck & stringer plate	12.00	2.90	1.00	0.01	0.03	2.17	1.00E-03	5.65E-02	1.15E-01
coaming	1500.00	3.65	0.0270	0.04	0.15	2.92	2.46E-06	3.45E-01	6.91E-01
coaming stiffener top 1 (horiz.)	14.40	4.4	0.40	0.00576	0.03	3.67	7.68E-05	7.76E-02	1.55E-01
coaming stiffener top 2 (vert.)	14.40	4.3928	0.0144	0.00021	0.00	3.66	3.58E-09	2.78E-03	5.56E-03
coaming stiffener sec.	14.40	3.65	0.24	0.00346	0.01	2.92	1.66E-05	2.95E-02	5.90E-02
			SUM:	0.68	0.49			**Iy [m^4)**	**1.2462**
			VCG[m]	**0.73**				**W [m^3]**	**0.3396**

Table 47: Main stresses carbon sandwich variants

Position	Hatch coaming			Deck			Stiffener coaming		
Type of stress		**Hogging**	**Sagging**		**Hogging**	**Sagging**		**Hogging**	**Sagging**
	Lower edge S1U [N/mm^2]	**65.18**	**43.79**	S 1	**65.18**	**43.79**	Upper stiffener S1 [N/mm^2]	**110.22**	**74.05**
	Upper edge S1L [N/mm^2]	**110.22**	**74.05**				Lower stiffener S1 [N/mm^2]	**87.70**	**58.92**

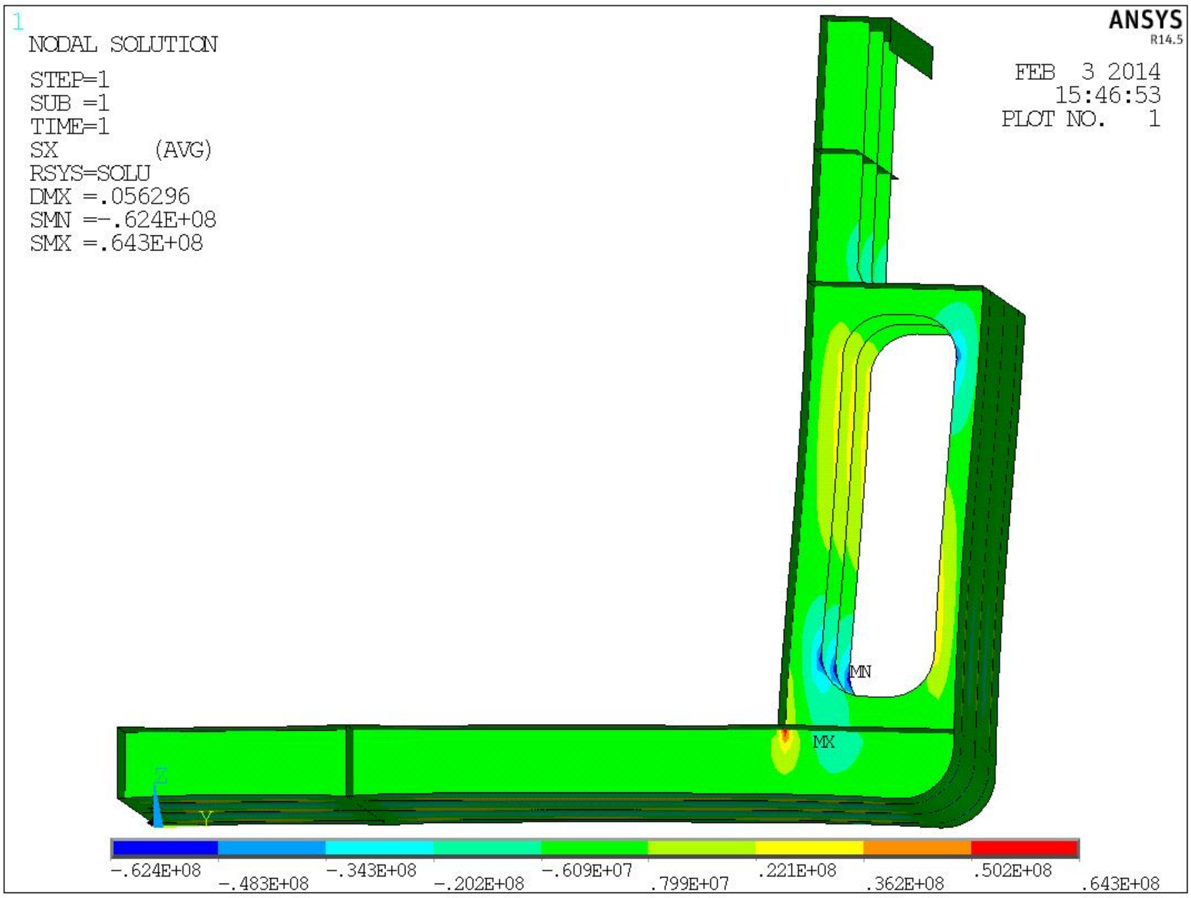


Figure 34: Stress along local X-axis in glass single skin variant

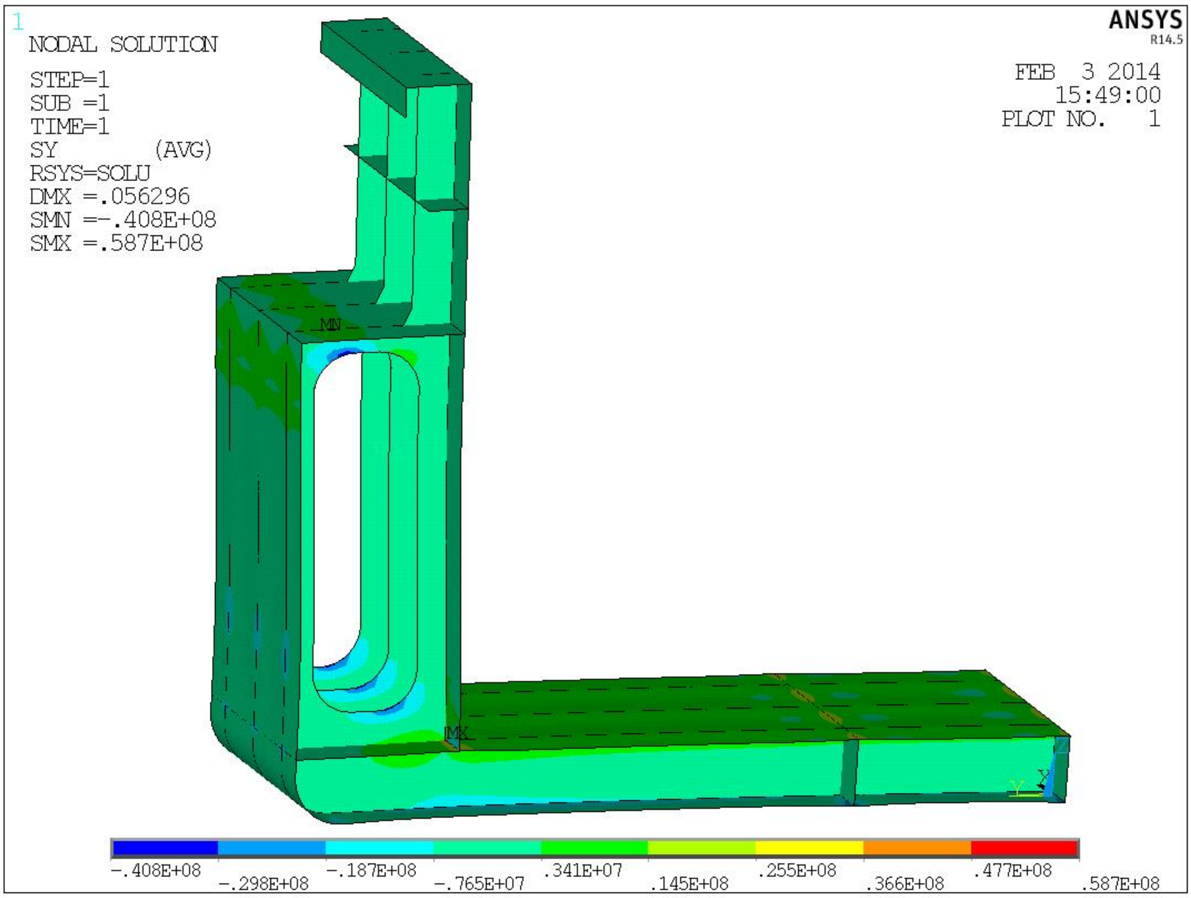


Figure 35: Stress along local Y-axis in glass single skin variant

Figure 36: Stress along local X-axis in carbon single skin variant

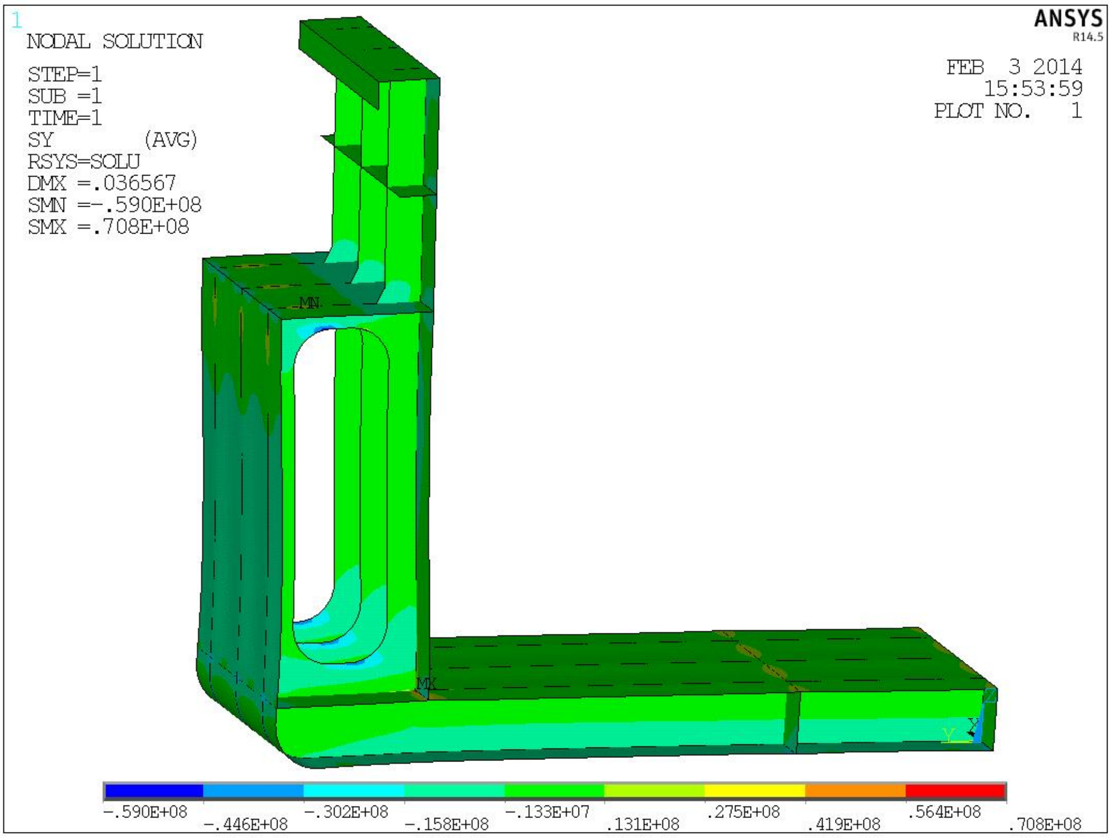


Figure 37: Stress along local Y-axis in carbon single skin variant

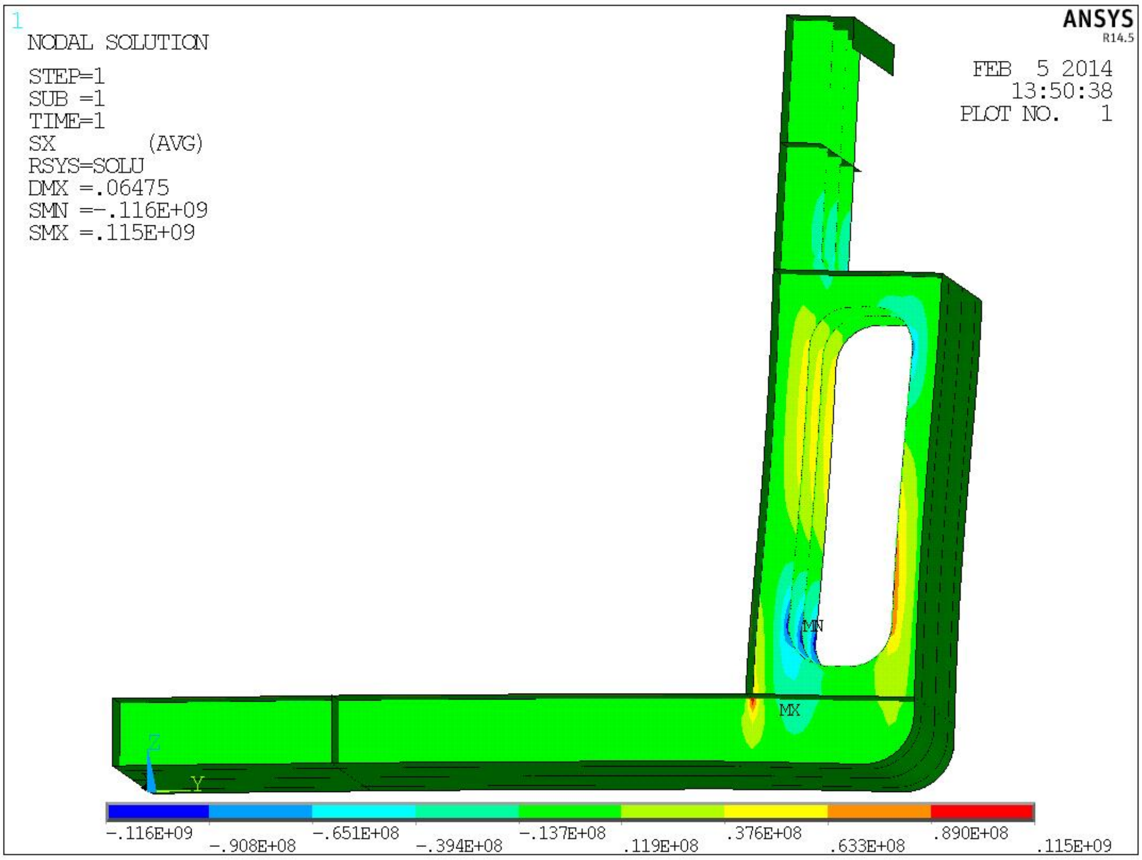


Figure 38: Stress along local X-axis in carbon sandwich variant

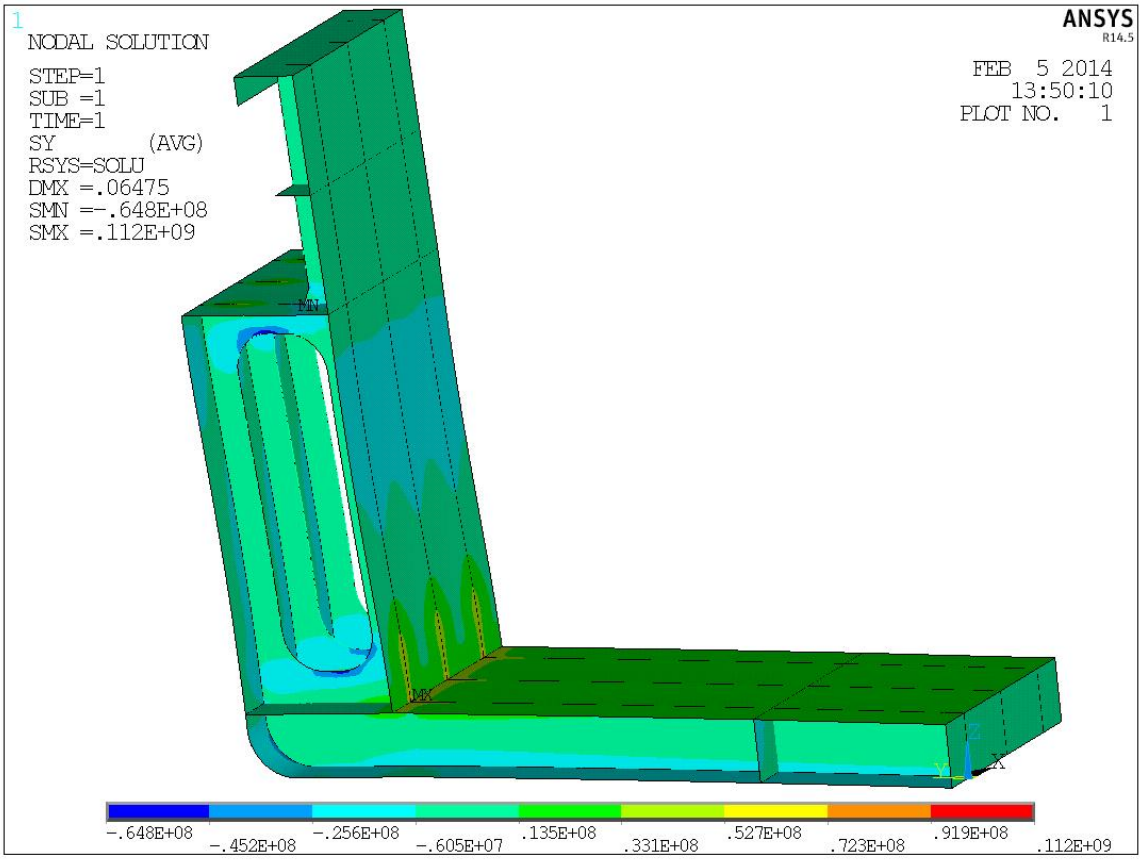


Figure 39: Stress along local Y-axis in carbon sandwich variant

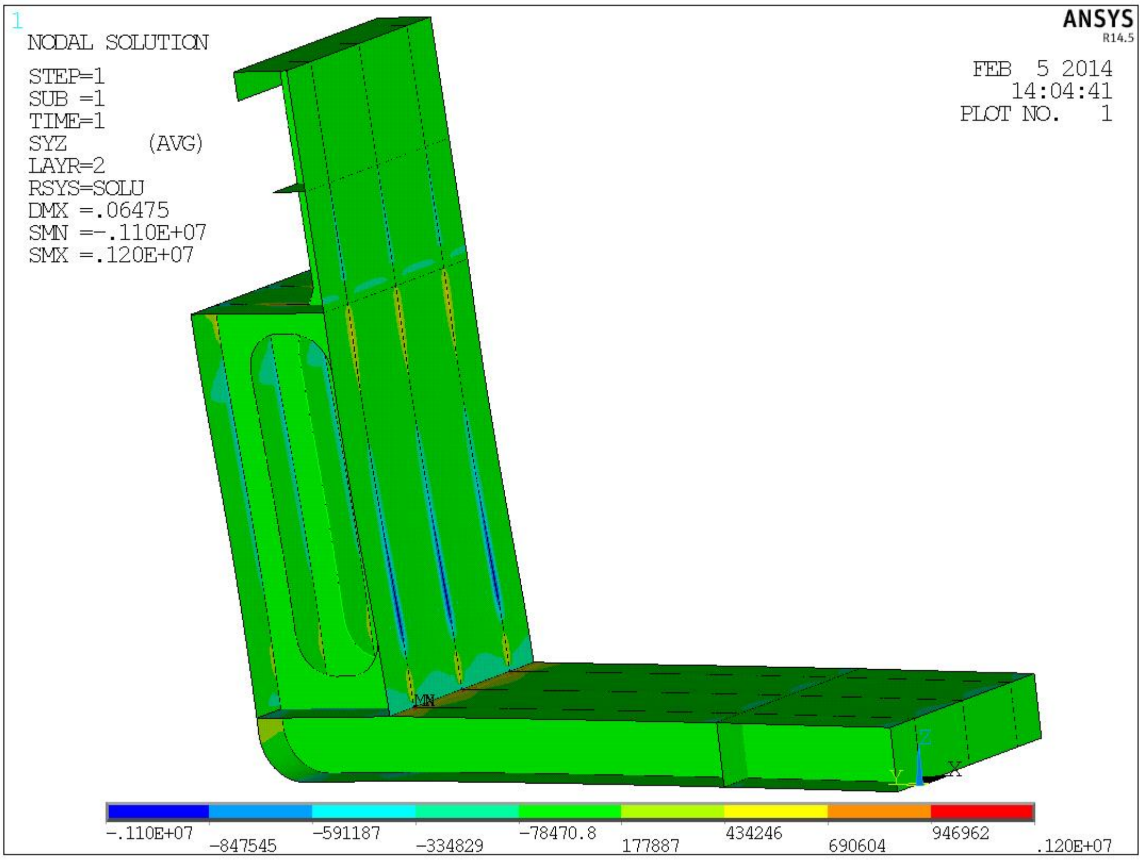


Figure 40: Shear stress in in core of carbon sandwich variant