Structural analysis of introducing high strength steel in light craft design

Master’s thesis in the International Master´s Programme Naval Architecture and Ocean Engineering

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Department of Shipping and Marine Technology
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Sister ship to Älvsnabben 5 in the fore front of Chalmers Lindholmen

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ABSTRACT

Light crafts are traditionally built in aluminium since this material has a high strength in relation to its weight. However, the industry is constantly searching for alternatives that could reduce weight. The use of composites is developing but it has proven to be challenging. Another alternative for a light construction is high strength steel, which is the focus of this thesis.

The analysis consists of three cases. The first and main case is to evaluate two smaller light crafts, one passenger ferry and one high speed vessel, with respect to the DNV light craft rules. The vessels are chosen due to their differences regarding speed and operating conditions. The comparison is made between aluminium NV5083 and high strength steel Weldox 700 E Offshore.

The second case is a comparison between aluminium NV5083 and high strength steel Weldox 700 E Offshore when introducing an ice-reinforcement to a light craft passenger vessel. This ice-reinforcement is based on the Finnish-Swedish ice class IC and applied to one of the vessels in the first case.

The third and last case regards larger vessels and is a simplified study comparing the high strength steel Weldox 700 E Offshore with a commonly used steel with a yield strength of 360 MPa. The purpose of this study is to give an indication if weight can be reduced using high strength steel, therefore it only includes bottom plating.

The results from the first case show that a light craft built in high strength steel is heavier than the same vessel built in aluminium. The second case shows that the ice-reinforcement is heavier for a vessel built in high strength steel. For larger vessels, the third case, the results indicate that weight can be reduced by using high strength steel compared to the commonly used steel.

The main conclusion from the study of the first case is that high strength steel is not an alternative to aluminium in terms of weight when using the DNV light craft rules as they are today. Due to uncertainties discovered during the work further investigations needs to be conducted before high strength steel is disregarded as an alternative to aluminium for light craft designs. The conclusion from the second case is that the ice class rules are not applicable to aluminium and therefore the weight estimation is not reliable. The conclusion from the study of the third case is that the weight can probably be reduced and a more holistic analysis needs to be conducted before a solid conclusion can be drawn.

Key words: aluminium, high strength steel, ice-reinforcement, light craft, weight reduction

Strukturanalys av att introducera höghållfasthetsstål i lätta fartygskonstruktioner
Examensarbete inom Naval Architecture and Ocean Engineering
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SAMMANFATTNING

Lättviktsfartyg byggs traditionellt i aluminium eftersom det är ett förhållandevis lätt material i relation till dess styrka. Industrin söker konstant efter alternativa material för att minska vikten av fartyg. Användningen av kompositer ökar men det har visat sig vara utmanande. Ett annat alternativt material för lättviktskonstruktioner är höghållfasthetsstål vilket detta examensarbete behandlar.

Studien består av tre fall. I det första, som är den huvudsakliga studien, utvärderas två mindre lättviktsfartyg (en passagerarfärja och ett höghastighetsfartyg) med avseende på DNV:s regler för lättviktskonstruktioner. Fartygen som behandlas är valda på grunda av sina olikheter med avseende på hastighet och opererarationsförhållanden. Materialen som jämförs är aluminiumet NV5083 och det höghållfasta stålet Weldox 700 E Offshore.

I studien av det andra fallet jämförs aluminiumet NV5083 och det höghållfasta stålet Weldox 700 E Offshore för ett is-förstärkt lättviktsfartyg, passagerarfärjan från första studien. Is-förstärkningen är baserad på den finsk-svenska isklassen IC och adderas till ett av fartygen från det första fallet.

Det tredje och sista fallet behandlar större fartyg. Studien är förenklad och jämför Weldox 700 E Offshore mot ett stål med en sträckgräns på 360 MPa, vilket är vanligt för stål som man bygger större fartyg av. Syftet med denna studie är att ge en indikation på om vikten kan reduceras genom att tillverka större fartyg i höghållfasthetsstål. Enbart bottenplåten analyseras.

Resultatet från studien av det första fallet visar att lättviktsfartyg som är byggda i höghållfasthetsstål väger mer än samma fartyg byggt i aluminium. Studien av det andra fallet visar att en is-förstärkning väger mer om fartyget är tillverkat i höghållfasthetsstål. Den tredje studien, som avser större fartyg, indikerar att vikten troligen kan reduceras om ett fartyg byggs i höghållfasthetsstål.

Den huvudsakliga slutsatsen från det första fallet är att höghållfasthetsstål inte är ett alternativ till aluminium med avseende på vikt om DNV:s regler för lättviktskonstruktioner tillämpas. Slutsatsen från det andra fallet är att isklassreglerna inte går att tillämpa på aluminium och därför är inte viktuppskattningen tillförlitlig för detta fall. Under arbetet med det första och det andra fallet upptäcktes att fler studier bör göras innan höghållfasthetsstål kan strykas som ett alternativ till aluminium för lättviktsfartyg. Slutsatsen från det tredje fallet är att den totala vikten troligen kan reduceras men att en mer övergripande studie behöver göras innan en definitiv slutsats kan dras.

Nyckelord: Aluminium, höghållfasthetsstål, isförstärkning, lättviktsfartyg, viktreducering

Contents

Preface

This thesis was conducted as a part of the Master of Science in Naval Architecture and Ocean Engineering at Chalmers University of Technology, Göteborg, Sweden. It has been carried out between January and June of 2015 at FKAB, Uddevalla and Göteborg.

We would like to acknowledge and express our gratitude to our examiner and supervisor, Per Hogström at the Department of Shipping and Marine Technology, for his excellent guidance and support.

We would also like to thank our corporate supervisor Stefan Johansson, Technical Manager at FKAB, for his support and inspiration during the work. Moreover, we would like to thank Pål Gjerum, Senior Structural Analysis Engineer at FKAB, for his theoretical and practical guidance.

Finally we would like to express our gratitude to all employees at FKAB, both in Uddevalla and Göteborg. Your knowledge and willingness to guide us has been highly appreciated.

Göteborg, June 2015

Christoffer Ahlström & Lisa Kilsmark

Abbreviations

AP	Aft Perpendicular
BL	Baseline
CAD	Computer-Aided Design
CL	Centreline
CG	Centre of Gravity
DNV	Det Norske Veritas
FKAB	Fartygskonstruktioner Aktiebolag
FP	Forward Perpendicular
GL	Germanischer Lloyd
GMAW	Gas Metal Arc Welding
LCG	Longitudinal Centre of Gravity
LIWL	Lower Ice Waterline
UIWL	Upper Ice Waterline
WL	Waterline
WT	Watertight

Notations

Roman upper case letters

A	Design load area [m^2]
B	Greatest moulded breath [m]
C_B	Block coefficient
C_W	Wave coefficient
D	Moulded depth [m]
E	Young's modulus [N/mm^2]
F	Excitation frequency [Hz]
I	Moment of inertia [cm^4]
L	Length between perpendiculars [m]
P_S	Engine output [kW]
T	Fully loaded draught when the vessel is floating at rest [m]
V	Maximum speed [knots]
Z	Section modulus [cm^3]

Roman lower case letters

a_{cg}	Vertical acceleration at CG [m/s^2]
a_v	Vertical acceleration [m/s^2]
f_1	Material factor based on yield strength
g_0	Standard acceleration of gravity [m/s^2]
h_0	Vertical distance from WL to the load point [m]
l	Stiffener span [m]
p	Pressure [kN/m^2]
p_{ice}	Pressure from ice load [kN/m^2]
p_{sea}	Sea pressure [kN/m^2]
p_{sl}	Pressure related to slamming [kN/m^2]
s	Stiffeners spacing [m]
t	Plate thickness [mm]

Greek lower case letters

σ_f	Yield stress [N/mm^2]

1 Introduction

This thesis is a study of the effects when introducing high strength steel to mainly light craft designs but also for ice-reinforcement and larger vessels. The study is initiated by Fartygskonstruktioner AB (FKAB) to investigate if the high strength steel Weldox 700 E Offshore could serve as an alternative material for their future vessel designs. In this section the purpose of the thesis is described as well as the methodology and the limitations.

1.1 Background

In the modern world of shipping factors such as efficiency, rate of emissions, fuel consumptions and payload have become more and more important for actors in the field. All these factors can be related to the weight of a vessel or more specifically its light ship displacement. By reducing weight the resistance of the vessel decreases and the energy consumption is therefore reduced (Jai and Ulfvarson, 2005).

Both economical and perhaps more importantly sustainable driving forces also points out the benefits with lighter vessel designs. Different materials have different impact on the environment during a products life cycle in terms of manufacturing, usage and disposal or recycling. Also, the amount of material used will impact the amount of pollution that is released during the life cycle.

Traditionally the most commonly used material for shipbuilding is steel. Other materials that can be used are aluminium and composites. The most common applications for aluminium and composite materials are smaller vessels such as fishing vessels, patrol boats, sea rescuers but also in high speed ferries and larger naval ships. An example of a larger naval ships built in aluminium is the 127 meter long littoral combat ship Independence (Austal, 2015). An example of a larger naval ship built in a composite material is the 73 m long Visby Classed Corvette, which is built in a sandwich material composing of carbon fibre reinforced plastic (SAAB, 2015).

Although the use of composite material is increasing, aluminium is still the most favoured material for smaller vessels. Composite has proven to be beneficial in order to reduce weight but could still have a disadvantage in terms of environmental impact during its life cycle (Duflou et al., 2012) as well as poor performance in fire (Mouritz and Gibbson, 2006). Even though aluminium is a rather light material compared to its material properties the construction and material cost is higher than for steel (Jai and Ulfvarson, 2005).

On the market today there are new high strength steels that have more beneficial mechanical properties than ordinary low carbon mild steel. These high strength steels are rarely used in ship design. An example of when it has been used is the conceptual motor boat M10.5, built by Swedish Steel Yachts AB (Utterström, 2014). This vessel is constructed in high strength steel from Sandvik and the plate thickness of the hull is decreased down to only 2 mm. Theoretically it could be built in thicknesses down to 1.6 mm according to the owner of Swedish steel yachts.

Other high strength steels such as the Weldox series by SSAB are used for marine application in offshore structures and by the Swedish navy for their submarines (SSAB, 2015). However for hull plating the Weldox steels have never been used. It is therefore interesting to investigate if it is beneficial, with respect to saving weight, to use these steels for hull structures.

Fartygskonstruktioner AB (FKAB) has many years of experience from vessel and marine design. This includes experience from designing smaller vessels and light crafts. The light crafts of FKAB are constructed in aluminium and want to investigate if high strength steel can be an alternative.

1.2 Objective

The objective of this thesis is to investigate if weight can be reduced using high strength steel instead of aluminium for small vessel designs. In the analysis aluminium NV5083 is compared with steel Weldox 700 E Offshore, see Appendix A for material specifics. NV5083 is a commonly used material for smaller light weight vessels. Weldox 700 E Offshore is classed by DNV GL (DNV-GL NVE690) and its high strength is taken in consideration in the calculations according to the DNV light craft rules. In this thesis the classification society will be referred to as DNV GL while rules will only be referred to as DNV. The later is because no common rules have been developed yet and the rules used belong to DNV only.

In the main study two light weight vessels are analysed, the first is a passenger ferry and the second is a high speed vessel. The original designs of the vessels are built in aluminium NV5083, for description and main particulars see Section 2. The vessels are chosen due to their differences in speed and service restriction which will affect the loads on the hull. Hypothetically, the high strength of the steel is more utilized for the high speed vessel. Thus, this investigation will establish under which conditions the high strength steel is beneficial.

The passenger ferry is ice-reinforced in its original design. Therefore a study is conducted in order to give an indication to whether or not high strength steel could be an alternative to aluminium for an ice-reinforced light craft. The passenger ferry is the basis of this study.

Since Weldox 700 E Offshore has not been used for hull plating before a simplified study is conducted of whether or not high strength steel could reduce the weight of larger vessels traditionally built in regular steel. This comparison regards Weldox 700 E Offshore and a more commonly used steel with yield strength of 360 MPa. This study is not the main task and is therefore simplified, it only includes the bottom plating.

1.3 Methodology

At the start of this thesis a literature study of the DNV rules is carried out in order to investigate which rules that applies for this project and how they can be adopted. To ensure that the rules are correctly interpreted there is a meeting with representatives from DNV GL whom are specialized in light craft design. The results from the study and the meeting are the base from which the method for the new dimensions is established.

In the study of the two light crafts appropriate sections for the analysis are chosen from studying the drawings of the vessels. The chosen sections are one close to 0.5L (the middle), one close to 0.9L (the fore body) and one watertight bulkhead. The sections include plating, stiffeners and web frames, except from the watertight bulkhead which only includes plating and stiffeners. The sections are dimensioned with respect to local strength, buckling and eigenfrequencies. The loads considered are the DNV design loads. The new designs of the sections are established for both materials, except from the stiffeners and plating in aluminium of the high speed vessel which are kept as the original design.

The major part of this thesis is solved analytically using beam theory and structural stability analysis. This regards calculations of design loads, dimension requirements of plating and stiffeners as well as the elastic buckling stress. The web frames are dimensioned using 3D-beam software (DNV, 2012a). The web frames, including the plating, are modelled as beam elements. The calculated design loads are applied and combined to give the worst total load case. Boundary conditions are applied to the model to represent the effects of girders and stiffening elements not considered in the analysis. The dimensions of the web frames are altered until the resulting stresses are below the allowed stresses. For more details regarding this analysis, see Section 4.

When designs are established for the sections and bulkheads their weight is estimated. The weight of the sections, apart from the stiffeners, is found using 3D-beam. The weight of the stiffeners is calculated analytically and added to the total weight of the section and then the weight is compared between the materials. The total weight is estimated by dividing the weight of each section with the length of the section. This is then multiplied with the length of the hull that corresponds to a similar type of structure. The weight of the bulkheads is multiplied with a number that represents the number of bulkheads and their size. The resulting designs are visualized using a CAD-software.

The passenger ferry is originally ice-reinforced and will therefore be analysed with respect to ice-class. The ice-class notation that is used is the Finnish-Swedish ice class IC, class notation ICE-1C. The ice belt region is determined for the sections and then the requirements for the plating, stiffeners and web frames of this region are found analytically.

Since FKAB is interested in weight saving measures a minor study of using Weldox 700 E Offshore for larger vessels is conducted. A simplified analysis is made only including plate thickness of the bottom with respect to vessel length. Weldox 700 E Offshore is compared with a steel that has a yield strength of $\sigma_f = 360\ MPa$. The ship length is varied between 100 and 300 m. This study only includes the equations for minimum thickness with regards to ship length and sea load.

1.4 Limitations

In order to define this thesis further, certain limitations are established to delimit the work. These are as follows:

- This thesis does not cover changes in hull shape or the positions and spacing of the web frames and girders.
- The study is only taking normal operation conditions of the vessels into consideration. Special loading or strength cases such as collisions are not included in this thesis. However loads and design aspects for ice class are included.
- Ship specific details such as doors, hatches and other irregularities normally placed in connection to specific web frames are not taken into consideration. This means that the web frames under consideration are simplified before being analysed.
- Since the dimensions for the longitudinal stiffeners are proposed to become rather small only flat bar profiles are evaluated. HP-profiles or L-profiles with too small dimensions are highly unrealistic to use or produce.
- The study will be conducted without any regards to fire regulations. Fire isolation and fire protection measures, such as stated in SOLAS chapter II-2, for the construction is not considered in this thesis.
- Methods for manufacturing will not be evaluated in this thesis.

1.5 Outline of the thesis

Section 2 describes the vessels that are analysed with regards to the light craft rules. The design loads that are used in the analysis of the light crafts are presented in Section 3. In Section 4 the dimension requirements are established based on the design loads. The evaluation method for the ice-reinforcement of the passenger vessel is described in Section 5. The results from the light craft analysis and the ice-reinforcement analysis are presented in Section 6.

Section 7 describes the analysis of the larger vessels and presents the results. The contents of Sections 3-7 are discussed in Section 8 and the conclusions from the discussion are stated in Section 9. The recommended future work is presented in Section 10.

2 Description of crafts

This thesis concerns two different light crafts with different parameters and operating conditions. The first is a passenger ferry called Älvsnabben 5 and the second one is a high speed vessel. Both are existing designs built in aluminium and they are used as the basis of the analysis. This section describes and presents the differences of these vessels and methods for manufacturing.

2.1 Passenger ferry

Älvsnabben 5 is a small passenger ferry, see Figure 2.1. It is designed for inshore traffic in the river inlet of Gothenburg and has been reinforced for ice impact. This vessel has not been assigned class by any classification society but it has been approved by the Swedish Maritime Administration.

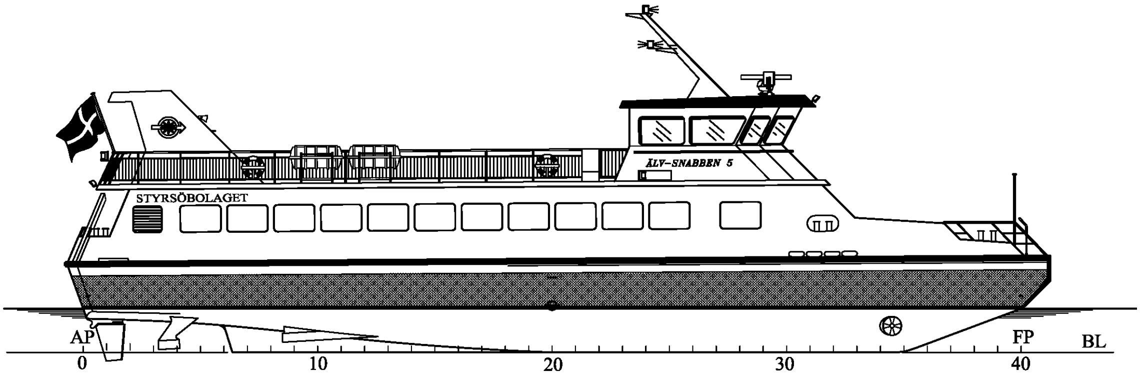

Figure 2.1 Älvsnabben 5. (With courtesy of FKAB)

It has a design speed of 12 knots and is allowed to carry 448 passengers (Styrsöbolaget, 2015). Its main particulars are presented in Table 2.1. For more specifics see Appendix B.

Table 2.1 Main particulars of Älvsnabben 5.

Length over all	31.6 m
Length between perpendiculars	30.0 m
Width over all	8.0 m
Draught	1.5 m
Maximum design speed	12 knots
Displacement	150 tonnes

The hull of the passenger ferry is of monotype and the plating is longitudinally stiffened. The chosen sections for the analysis of the passenger ferry are centred at the web frames situated at 0.5L and at 0.9L. The length of each section is the same as the frame spacing which is 750 mm at 0.5L and 1125 mm at 0.9L. The watertight bulkhead is positioned at 0.55L. The positions are visualised in Figure 2.2.

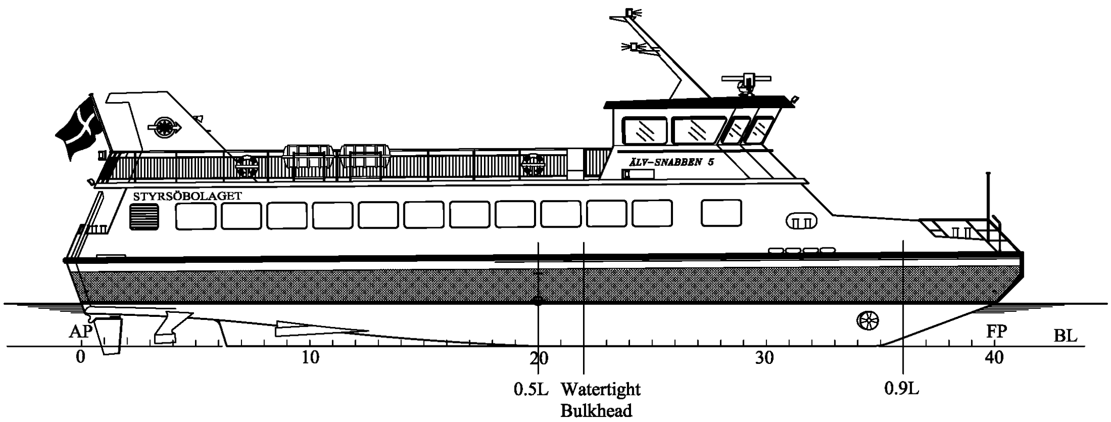

Figure 2.2 The high speed vessel with chosen sections indicated.

The hull shape and original design of each chosen section is presented in Figures 2.3 and 2.4. The figures show the original design of the vessel. The section at 0.5L has a round hull shape compared to the section at 0.9L which has a shape that is very sharp. The bottom of the section at 0.5L, see Figure 2.3, is considered as the area from the keel to the chine. The sides start at the chine and extend to the deck. The section at 0.9L, see Figure 2.4, is considered not to have any bottom, only sides, due to the pointy shape. As can be seen in Figure 2.4 the fore body has a wide deck since this is where passengers will board the vessel. In Figures 2.3 and 2.4 tanks, strengthened attachments for the engines, supports etc are presented. These details are neglected.

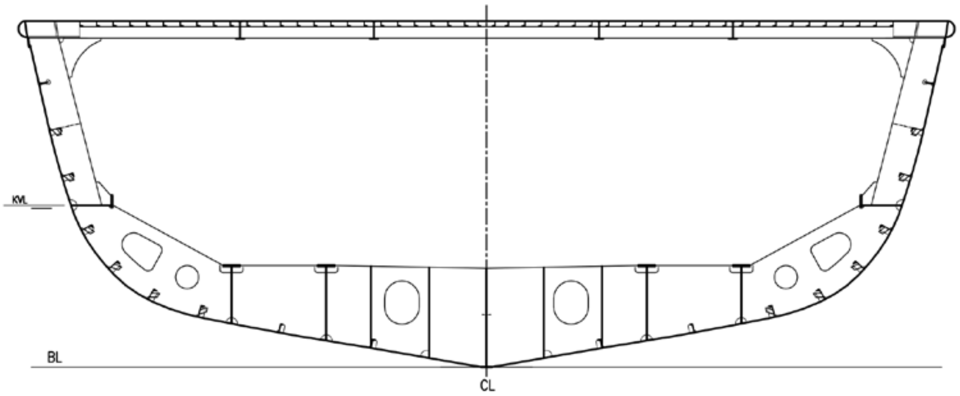

Figure 2.3 The hull shape and original design of the web frame at 0.5L of the passenger ferry.

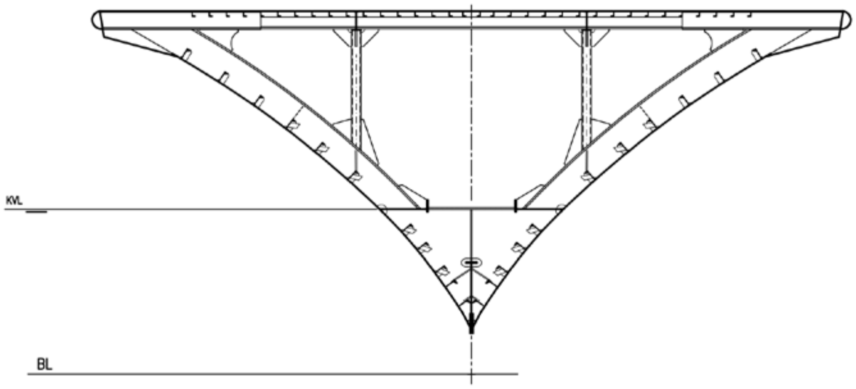

Figure 2.4 The hull shape and original design of the web frame at 0.9L of the passenger ferry.

2.1.1 Adoption of rules with regards to classification

The passenger ferry has not been assigned a class, but is approved by the Swedish Maritime Administration. To determine which rules that can be applied is essential for the analysis. Based on the size and characteristics it is assumed to fulfil the requirement for a light craft with additional notation passenger craft (DNV, 2012b). Before using these rules a validation of this assumption is made. In order to achieve class notation light craft the following displacement requirement has to be fulfilled (DNV, 2014):

$$\Delta \leq (0.13LB)^{1.5} = 174.3\ tonnes \tag{2.1}$$

This criterion is fulfilled for the passenger ferry since it has a displacement of 150 tonnes. In order to be classed as a high speed light craft two additional criteria must be fulfilled. The first is that the vessel must have a maximum speed of not less than 25 knots. Since the passenger ferry does not fulfil the first criterion it cannot be considered as a high speed light craft. The notation passenger is applicable and required since the vessel is designed to take more than 12 passengers (DNV, 2012b).

The vessel must have a service area restriction notation according to Table 2.2. The table presents the maximum distances in nautical miles that a vessel is allowed to have to the nearest harbour or safe anchoring with respect to each service notation. The notation R0 and the option to not have any service restriction notation are applicable for a passenger ferry. Älvsnabben 5 is designed for inshore conditions always operating close to shore, this corresponds to notation R4 (DNV, 2014). The notation will affect the calculated design loads.

Table 2.2 Service restrictions, the distances are presented in nautical miles (DNV, 2014).

Condition	Notation	Winter	Summer	Tropical
Ocean	None	-	-	-
Ocean	R0	300	-	-
Ocean	R1	100	300	300
Offshore	R2	50	100	250
Coastal	R3	20	50	100
Inshore	R4	5	10	20
Inland	R5	1	2	5
Sheltered	R6	0.2	0.3	0.5

2.2 High speed vessel

The second vessel is slightly smaller than the passenger ferry, see Figure 2.5. It is a high speed vessel designed to operate in the North Sea. It has been assigned the high speed light craft class with additional notation patrol boat (DNV, 2012c). It is intended to operate offshore and therefore has service notation R2 (DNV, 2014). The vessel has no reinforcement due to ice impact.

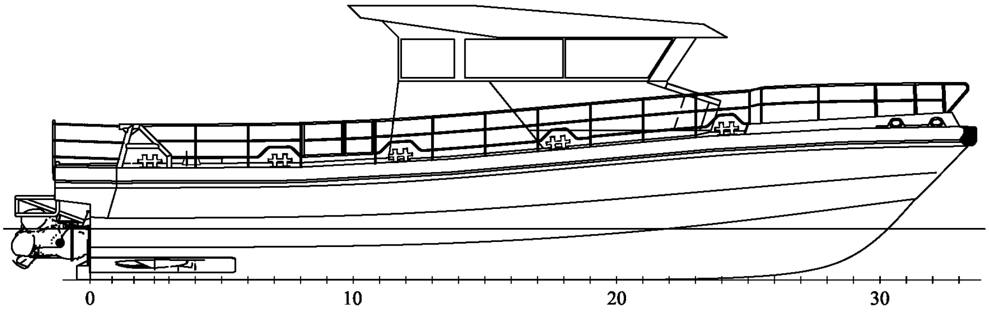

Figure 2.5 High speed vessel. (With courtesy of FKAB)

The designed maximum speed is 38 knots, which in comparison to the passenger ferry will cause larger accelerations and loads on the vessel. The main particulars of the vessel are presented in Table 2.3. For more specifics see Appendix B.

Table 2.3 Main particulars of the high speed vessel.

Length over all	22.00 m
Length between perpendiculars	18.2 m
Width over all	6.26 m
Draught	1.10 m
Maximum design speed	38 knots
Displacement	62.8 tonnes

The hull is of monotype and the plating is longitudinally stiffened. The chosen sections for the analysis of the high speed vessel are centred at the web frames situated at 0.56L and at 0.89L. The length of each section is the same as the frame spacing which is 600 mm for both sections considered. The watertight bulkhead is positioned at 0.5L. The positions are visualised in Figure 2.6.

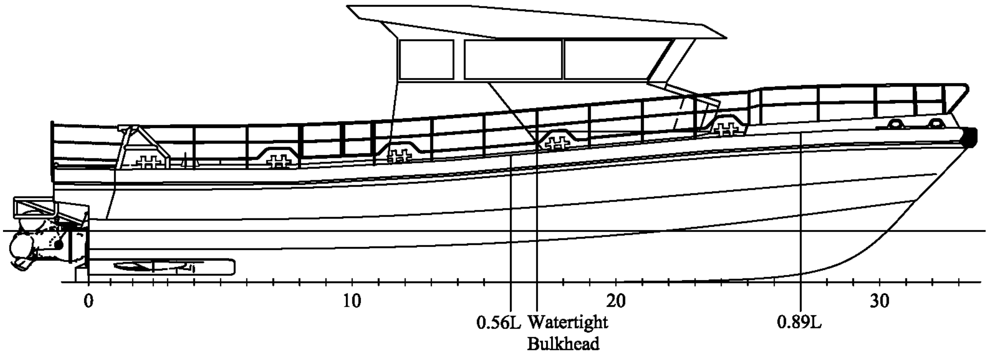

Figure 2.6 The high speed vessel with chosen sections indicated.

The hull shape and original design of each chosen section is presented in Figures 2.7 and 2.8. As can be seen in the figures both sections have spray rails and a sharp shape of the bottom. The two holes at the bottom of both sections are tanks, since they are such large part of the structure their profiles are kept but loads form the tanks are disregarded in the analysis. For the section at 0.56L, see Figure 2.7, the bottom is considered as the area from the keel to the first spray rail. The figure shows a hatch at the deck, this is neglected as well as the irregular shape of the deck which is considered to be flat in the analysis. The section at 0.89L, see Figure 2.8, is considered to have a bottom from the keel to the first spray rails.

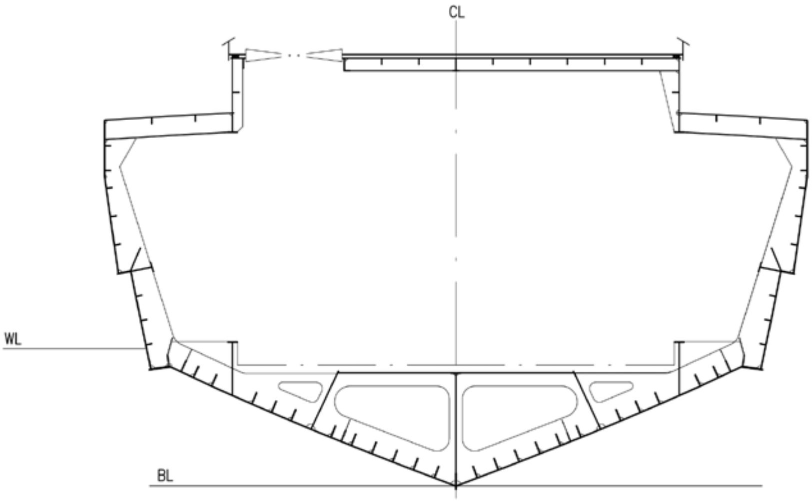

Figure 2.7 The hull shape and original design of the web frame at 0.56L of the high speed vessel.

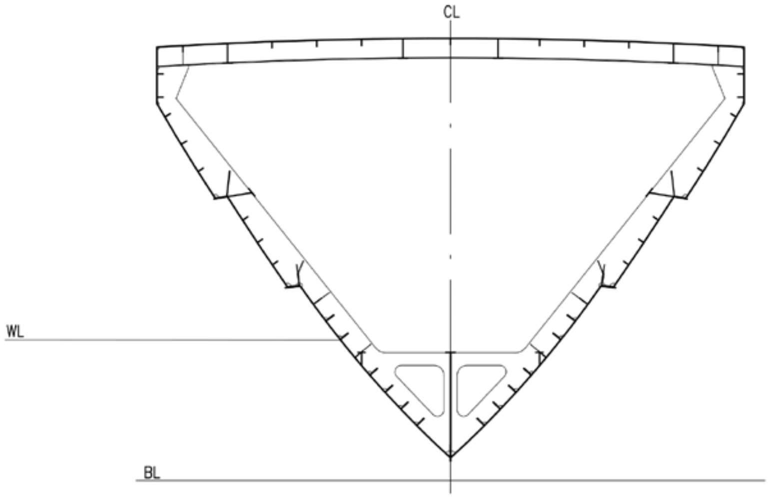

Figure 2.8 The hull shape and original design of the web frame at 0.89L of the high speed vessel.

2.3 Principles of manufacturing

The manufacturing method of vessels made in aluminium is today a well tested and used method. Some parts are extruded and others are cut and the parts are joined by gas metal arc welding (GMAW). The dimensions that will be used in this thesis for the aluminium designs are verified with Andersson[1]. This thesis will not consider extruded parts.

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[1] Morgan Andersson (project manager, Swede Ship Marine AB) interviewed by the authors 2015-02-16.

To build light weight vessels in high strength steel is uncommon. The shipyards that FKAB has been working with have little experience of building light crafts in steel. In general it is uncommon for shipyards to work with dimensions of steel that are as small as the dimension considered in this thesis. There is one example of when it has been done, not connected to FKAB, and it is mentioned in Section 1.1. The steel used for that vessel has a yield strength of 640 MPa (Sandvik, 2015). The steel yacht has been manufactured of plates as thin as 2 mm (von Schultz, 2015). The parts were cut by laser and joined with a special developed welding method. Therefore it is assumed that this thesis can regard plates with a thickness down to 2 mm.

3 Design loads

This section describes the design loads that are considered in the dimensioning of the vessels (DNV, 2012d). The design loads can be divided into local and global loads and they are further described in this section. This section will only regard static loads that are presented in the regulations.

3.1 Global loads

Normally global strength needs to be taken into consideration when defining scantlings requirements. However, due to the particular hull dimension of the two vessels the global strength could be unnecessary to consider in this case. If a vessel has a length that is less than 50 m and fulfil Equation (3.1) the global strength can be neglected (DNV, 2012d).

$$\frac{L}{D} < 12 \tag{3.1}$$

L = Length between perpendiculars

D = Moulded depth

Since none of the two vessels have a length over 50 m and L/D is 10 for the passenger ferry and 7.1 for the high speed vessel, global strength is not considered in this thesis.

3.2 Local loads

This section covers the local loads that are applicable to the vessels analysed in this thesis. The loads that will be considered are (DNV, 2012d):

- Slamming pressure
- Pitch slamming pressure
- Fore body side and bow impact pressure
- Sea pressure
- Deck pressure
- Sea pressure on watertight bulkheads

The load point on which a design load is considered to act, is for plating at the middle of the considered element and for stiffeners at the midpoint of the span. For girders it is at the centre of the load area.

In addition to the loads the vertical acceleration is calculated since slamming pressure and the deck pressure are depending on it. The vertical acceleration at LCG is calculated according to Equation (3.2).

$$a_{cg} = \frac{V}{\sqrt{L}} \frac{3.2}{L^{0.76}} f_g g_0 \tag{3.2}$$

f_g = acceleration factor (3 for high speed vessel, 1 for passenger ferry)

For the passenger ferry service restriction R2 and the high speed vessel service restriction R4 the vertical acceleration is not to be taken less than g_0. The ratio $\frac{V}{\sqrt{L}}$ is not to be taken greater than 3.0. The acceleration at different positions along the length of the vessel is calculated according to Equation (3.3).

$$a_v = k_v a_{cg} \tag{3.3}$$

The longitudinal distribution factor, k_v, is chosen according to Figure 3.1. The figure shows how the vertical acceleration increases forward of midship and reaches its maximum at the forward perpendicular.

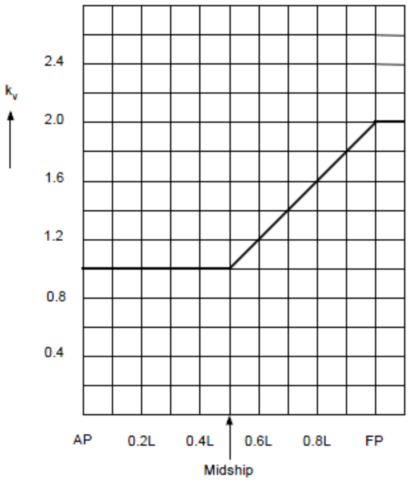

Figure 3.1 The figure shows the longitudinal distribution factor, k_v, for the vertical acceleration (DNV, 2012d).

3.2.1 Slamming pressure

Slamming occurs due to waves and the impact increases with speed. The resulting pressure affects the bottom (DNV, 2012d). The slamming pressure design load should be regarded when $V/\sqrt{L} \geq 3$. This is valid for the high speed vessel but not for the passenger ferry. The slamming pressure is calculated according to Equation (3.4).

$$p_{sl,1} = 1.3 k_l \left(\frac{\Delta}{nA}\right)^{0.3} T_O^{0.7} \frac{50-\beta_x}{50-\beta_{cg}} a_{cg} \tag{3.4}$$

k_l = 1, for sections considered in this thesis

n = 1, number of hulls

A = load area of the considered element

T_O = draught considered at 0.5L during normal operation

β_x = dead rise angle of the considered element, minimum 10° and maximum 30°

β_{cg} = dead rise angle at LCG

Since the high speed vessel has a rather flat bottom the dead rise angle is measured as the angle between the bottom and the baseline.

3.2.2 Pitch slamming pressure

The pitch slamming pressure, which affects the bottom, is calculated according to the equation below (DNV, 2012d).

$$p_{sl,2} = \frac{21}{\tan(\beta_x)} k_a k_b C_W \left(1 - \frac{20T_L}{L}\right)\left(\frac{0.3}{A}\right)^{0.3} \tag{3.5}$$

k_a = 1 for plating, minimum 0.35 and maximum 1.0 for stiffeners and girders

k_b = 1 for plating, stiffeners and girders

T_L = draft at FP for the lowest service speed

Since $\left(1 - \frac{20T_L}{L}\right)$ is 0.07 for the passenger ferry and -0.2 for the high speed vessel this pressure is neglected.

3.2.3 Fore body side and bow impact pressure

The impact pressure on the fore body side and bow is calculated according to (DNV, 2012d):

$$p_{sl,3} = \frac{0.7LC_LC_H}{A^{0.3}}\left(0.6 + 0.4\frac{V}{\sqrt{L}}\sin\gamma\cos(90° - \alpha) + \frac{2.1a_0}{C_B}\sqrt{0.4\frac{V}{\sqrt{L}} + 0.6\sin(90° + \alpha)\left(\frac{x}{L} - 0.4\right)}\right)^2 \tag{3.6}$$

α = flare angle, see Figure 3.2

h_0 = vertical distance from the water line to the load point

γ = water line angle, measured according to Figure 3.3

x = longitudinal distance from AP to the position in consideration

Figure 3.2 shows the hull shape of a transverse section. The flare angle is the angle between the side plating and the horizontal line.

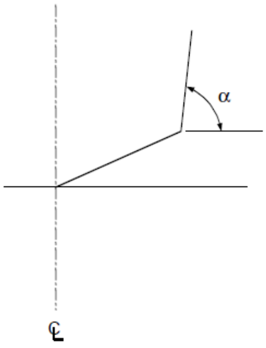

Figure 3.2 The figure shows how the flare angle, α, should be measured (DNV, 2012d).

Figure 3.3 shows the bow of a longitudinal section at the water plane. The waterline angle is the angle between the waterline and a longitudinal line measured at the section considered.

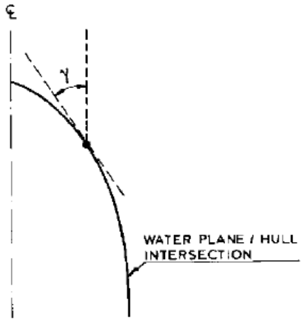

Figure 3.3 The figure shows how the waterline angle, γ, should be measured (DNV, 2012d).

In Equation (3.6) the ratio $\frac{V}{\sqrt{L}}$ is not to be taken greater than 3.0. The coefficients C_L and C_H are calculated according to Equation (3.7) and (3.8) respectively.

$$C_L = \frac{250L - L^2}{15000} \tag{3.7}$$

$$C_H = 1 - \frac{0.5}{C_W} h_0 \tag{3.8}$$

The wave coefficient is calculated according to Equation (3.9).

$$C_W = 0.08L \tag{3.9}$$

The wave coefficient is reduced due to service restriction with 40% for R4 (the passenger ferry) but no reduction is made for R2 (the high speed vessel). The resulting wave coefficient for the passenger ferry is 1.44 and for the patrol vessel it is 1.46. A higher wave coefficient gives a higher pressure on the vessel.

The block coefficient, C_B, is calculated according to Equation (3.10).

$$C_B = \frac{\Delta}{1.025 L B_{WL} T} \tag{3.10}$$

The resulting block coefficient for the passenger ferry is 0.43 and for the patrol vessel it is 0.49. The coefficient is fairly similar for the two vessels. A higher coefficient gives a lower pressure.

The acceleration, a_0, is calculated according to Equation (3.11).

$$a_0 = \frac{3C_W}{L} + C_V \frac{V}{\sqrt{L}} \tag{3.11}$$

Where:

$$C_V = \frac{\sqrt{L}}{50}, \qquad C_V \leq 0.2 \tag{3.12}$$

The pressure should not be taken less than 5 kPa for the passenger ferry due to service restriction R4. For the high speed vessel the pressure should not be less than 6.5 kPa due to service restriction R2. This pressure acts on an area from 0.4L forward of AP to the bow. For the vessels in this analysis this means that the fore body side and impact pressure affects all sections. The vertical extension of the pressure is from bottom chine or upper turn of bilge to the main deck. The lower margin of the load area should not be above the waterline. If the vessel has a V-shaped hull the pressure should be assumed to act on the entire hull. For the passenger ferry the load extends from the water line and up to the deck of the midship section and all over the hull of the forward section, since it has a V-shape. The load extent on the high speed vessel is from the lowest spray rails and up to the deck of the midship section and all over the hull of the forward section since this has a V-shape.

3.2.4 Sea pressure

A vessel is subjected to a pressure from the sea on the bottom, sides and weather decks (DNV, 2012d). The pressure acting below the design water line is calculated according to Equation (3.13).

$$p_{sea} = a\left(10h_0 + \left(k_s - \frac{1.5h_0}{T}\right)C_W\right) \tag{3.13}$$

The sea pressure acting above the design water line is calculated according to Equation (3.14).

$$p_{sea} = ak_s(C_W - 0.67h_0) \tag{3.14}$$

h_0 = the distance from the waterline at draught T to the load point

k_s = sea load distribution factor, see Figure 3.4

a = for passenger ferry, 1.0 for side and bottom, 0.8 for weather deck

= for high speed vessel, 1.25 aft of L/2, 2.0 forward of FP (DNV, 2012c)

Figure 3.4 shows how the sea load distribution factor increases forward of midship. The increase is determined by the block coefficient calculated according to Equation (3.10).

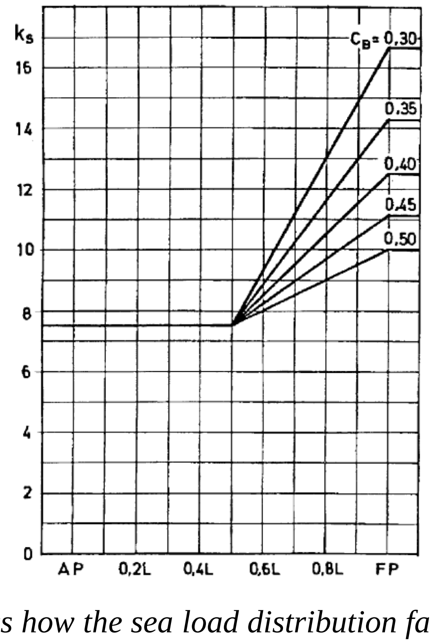

Figure 3.4 The figure shows how the sea load distribution factor changes over the length of the vessel (DNV, 2012d).

The sea pressure is not to be taken less than the given values in Table 3.1. These values are related to each vessel service restriction. As can be seen in the table this results in higher minimum pressures for the high speed vessel.

Table 3.1 Minimum sea pressure due to service restriction [kPa].

	Passenger ferry	**High speed vessel**
Side	5	10
Weather deck	4	5.0

3.2.5 Deck pressure

The deck should be dimensioned for loads likely to occur according to the equation below (DNV, 2012d).

$$p = \rho H(g_0 + 0.5a_v) \tag{3.15}$$

The load, ρH, corresponds to a water pillar of height H and density ρ. For the passenger ferry $\rho H = 0.5\ t/m^2$ for the whole deck, this represents 6 passengers per square metre. For the high speed vessel ρH is 1.0 t/m^2 at the fore body where there is a weather deck and 0.35 t/m^2 at the midship where the deck is an accommodation deck. The values for the high speed vessel are taken from Table 2C in Pt.3, Ch.1, Sec.2 (DNV, 2012d).

3.2.6 Sea pressure on watertight bulkheads

Sea pressure on watertight bulkheads only appears during flooded conditions (DNV, 2012d). The design pressure on the watertight bulkheads is calculated according to the equation below:

$$p = 10h_b \tag{3.16}$$

Where h_b is the vertical distance from the load point to the top of the bulkhead.

3.3 Summary of loads

The loads that will be considered in the dimensioning of the vessels are static and local. The loads considered are:

- Slamming pressure
- Fore body side and bow impact pressure
- Sea pressure
- Deck pressure
- Sea pressure on watertight bulkheads

The slamming and the fore body side and bow impact pressures both occur when the hull encounters the water surface. The resulting pressures are related to the speed of the vessels as well as the angle of the impact surface in relation to the water surface. The length, draught and the additional class (passenger vessel and patrol boat) of the vessels govern the resulting pressure from the sea. In the case of slamming the section in consideration is not submerged in water and the hull is only subjected to slamming pressure and no sea pressure. When there is fore body side and bow impact pressure on the sides of the hull there is also sea pressure on the bottom. The impact pressure is not to be considered when the sea pressure on the sides is larger. The vessels are dimensioned against the worst loading conditions.

The deck load is related to what kind of deck that is considered and if there are any particular requirements for the vessel. The resulting pressure is then related to the vessel speed trough the vertical acceleration.

The sea pressure from a flooded condition is the only pressure that the watertight bulkheads are subjected to. The watertight bulkheads are isolated from the loads that are acting on the outside of the hull. The pressure on the watertight bulkhead is only related to the height of the bulkhead.

The following sections describe the loads that should be considered for each vessel. The loads are compared and combined in order to find which load cases that will govern the dimensions. For calculated results of the design loads see Appendix C.

3.3.1 Passenger ferry

The loads considered for the passenger ferry are:

- Fore body side and bow impact pressure
- Sea pressure
- Deck pressure
- Sea pressure on watertight bulkheads

The pressure acting on the section at 0.5L is presented in Table 3.2. The pressure that is the largest is written in bold letters. The bottom and sides are both subjected to the sea pressure. The sides are also subjected by fore body side and bow impact pressure. Since the deck of this section is in an enclosed environment the load from the passengers is the only load that subjects the deck. For this section only one combined load case is evaluated, it consists of the deck pressure and the sea pressure on the bottom and sides of the hull.

Table 3.2 Pressures that subjects the section at 0.5L of the passenger ferry.

Part	**Loads**	
Hull bottom	**Sea pressure**	-
Hull side	**Sea pressure**	Fore body side and bow impact pressure
Deck	**Deck pressure**	-

The pressure acting on the section at 0.9L is presented in Table 3.3. The pressure that is the largest is written in bold letters. This section is considered to not have a bottom. Due to the narrow shape of the hull the section is considered to consist of sides. The deck of this section is not in an enclosed compartment and sea pressure on the deck is evaluated. For this section only one combined load case is evaluated, consisting of deck pressure and fore body side and bow impact pressure on the bottom and sides.

Table 3.3 Pressures that subjects the section at 0.9L of passenger ferry.

Part	Loads	
Hull	Sea pressure	**Fore body side and bow impact pressure**
Deck	Sea pressure	**Deck Pressure**

The watertight bulkhead is only analysed with respect to the sea pressure from a flooded condition.

3.3.2 High speed vessel

The loads considered for the high speed vessel are:

- Slamming pressure
- Fore body side and bow impact pressure
- Sea pressure
- Deck pressure
- Sea pressure on watertight bulkheads

The considered pressures of the section at 0.56L are presented in Table 3.4. The pressure that is the largest is written in bold letters. The bottom and sides are subjected to the sea pressure. Due to the high speed of the vessel the slamming pressure on the bottom has to be considered. In addition to the sea pressure the sides are subjected to the fore body side and bow impact pressure. The deck of this section is enclosed in the accommodation and therefore the pressure from the accommodation governs the dimensions of this deck.

For this section two load combinations are evaluated. The first is when there is slamming pressure on bottom, no pressure on the sides and the deck pressure. The second is when there is deck pressure and sea pressure on the bottom and the sides.

Table 3.4 Pressures considered for the section at 0.56L of the high speed vessel.

Part	Loads	
Hull bottom	Sea pressure	**Slamming pressure**
Hull side	**Sea pressure**	Fore body side and bow impact pressure
Deck	**Deck pressure**	-

The pressure considered for the section at 0.89L is presented in Table 3.5. The pressure that is the largest is written in bold letters. The sea pressure affects the whole section, including the deck. The bottom is subjected to slamming pressure and the sides are subjected by the fore body side and bow impact pressure. Apart from the sea pressure on deck the deck load is also evaluated.

For this section two load combinations are evaluated. The first is when there is slamming pressure on bottom, no pressure on the sides and deck pressure. The second is when there is sea pressure on bottom, impact pressure on the sides and deck pressure.

Table 3.5 Pressures considered for the section at 0.89L of the high speed vessel.

Part	**Loads**	
Hull bottom	Sea pressure	**Slamming pressure**
Hull side	Sea pressure	**Fore body side and bow impact pressure**
Deck	Sea pressure	**Deck pressure**

The watertight bulkhead is dimensioned for the sea pressure on watertight bulkheads from a flooded condition.

4 Dimensioning

This section describes the method used to establish dimensions for the passenger ferry and the high speed vessel. The design loads used in Sections 4.2 and 4.3 are described in Section 3. The analysis considers two sections and one watertight bulkhead of each vessel. The sections consist of plating, stiffeners and web frame girders. The bulkhead consists of plating and stiffeners.

The chosen sections of the passenger ferry are centred at the web frames situated at 0.5L and at 0.9L. The length of each section is the same as the frame spacing. The watertight bulkhead is positioned at 0.55L. The positions are visualised in Figure 4.1. The vessel and the sections are further described in Section 2.1.

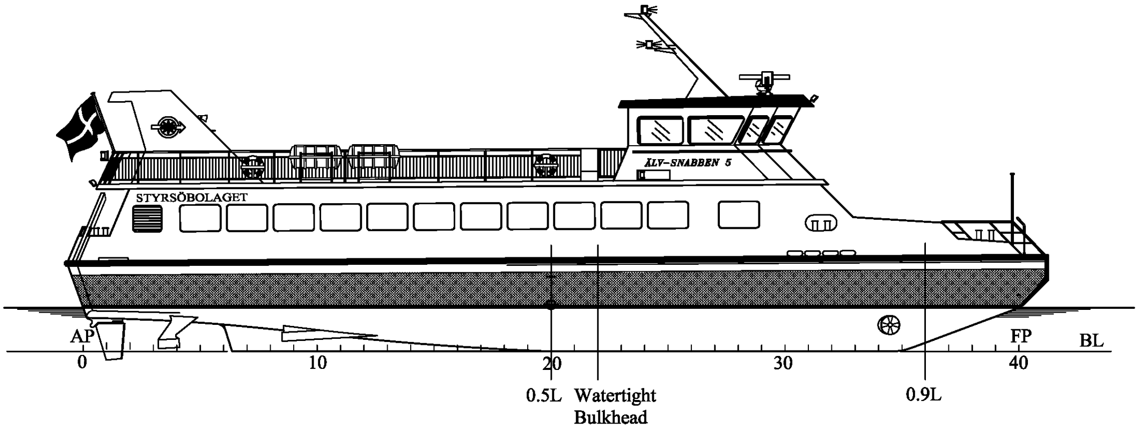

Figure 4.1 The passenger ferry with chosen sections indicated.

The chosen sections of the high speed vessel are centred at the web frames situated at 0.56L and at 0.89L. The length of each section is the same as the frame spacing. The watertight bulkhead is positioned at 0.5L. The positions are visualised in Figure 4.2. The vessel and the sections are further described in Section 2.2.

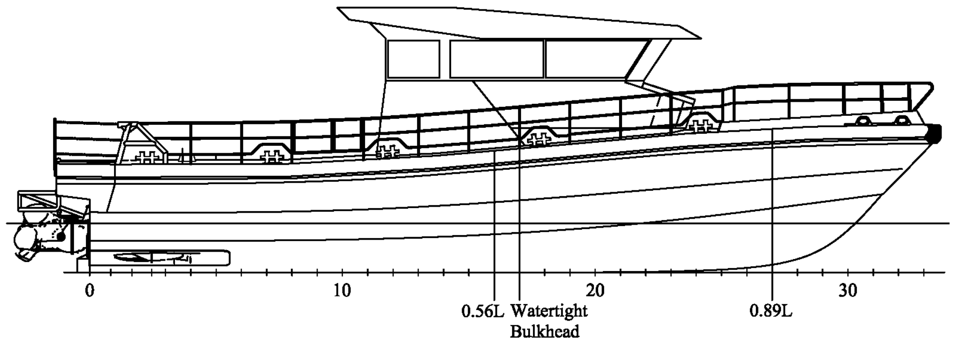

Figure 4.2 The high speed vessel with chosen sections indicated.

4.1 Plating

There are two requirements for each material that the plating must fulfil in terms of minimum thickness. The first requirement regards the length of the vessel in consideration and how this is calculated for each material is described in Sections 4.1.1 and 4.1.2 respectively. The second requirement is based on the design load pressures. For this case the requirement with regards to length will be the governing one.

4.1.1 Steel

The minimum allowed thickness of the plating is governed by Equation (4.1) for steel (DNV, 2012e).

$$t = (t_0 + kL)\frac{s}{s_r} \tag{4.1}$$

Where:

$$s_r = 2(249 + L) \tag{4.2}$$

For the watertight bulkheads $s_r = 760$ mm. The parameters t_0 and k in Equation (4.1) are presented in Table 4.1.

Table 4.1 The parameters for calculating the minimum thickness.

	t_0	k
Bottom and side	5.0	0.04
Deck	4.5	0.025
Watertight bulkhead	5.0	0.025

The ratio $\frac{s}{s_r}$ is restricted according to Equation (4.3).

$$0.5 \leq \frac{s}{s_r} \leq 1 \tag{4.3}$$

The lowest ratio will give the lowest minimum thickness, which is when $\frac{s}{s_r} = 0.5$. The spacing that gives this ratio for longitudinal hull stiffeners is 270 mm for the passenger ferry and 260 mm for the high speed vessel. For the watertight bulkhead it is 380 mm for both vessels.

4.1.2 Aluminium

The thickness of the plating is governed by Equation (4.4) for aluminium (DNV, 2012f).

$$t = \frac{t_0 + kL}{\sqrt{\frac{\sigma_f}{240}}}\frac{s}{s_r} \tag{4.4}$$

Where:

$$s_r = \frac{2(100 + L)}{1000} \tag{4.5}$$

The parameters t_0 and k in Equation (4.4) are presented in Table 4.2.

Table 4.2 The parameters for calculating the minimum thickness.

	t_0	k
Bottom and side below waterline	4.0	0.03
Side above waterline	3.5	0.02
Deck	3.0	0.03
Watertight bulkhead	3.0	0.02

The ratio $\frac{s}{s_r}$ is restricted according to Equation (4.6).

$$0.5 \leq \frac{s}{s_r} \leq 1 \tag{4.6}$$

The spacing between the stiffeners of the passenger ferry is chosen to be the same as for the steel, i.e. 270 mm and 380 mm, this gives a ratio of 1. For the high speed vessel the plating and the stiffener spacing are considered to be the same as the original design.

4.2 Stiffeners

The requirement of stiffeners according to the steel rules (DNV, 2012e) and the aluminium rules (DNV, 2012f) is calculated according to the same method. Therefore the same procedure is used for the two materials.

Depending on the position of the stiffeners their dimensions will vary along the hull side. In order to make the production less complex the stiffeners are arranged to have the same dimensions in groups of minimum 5 stiffeners. The height of the stiffeners is chosen with intervals of 5 mm and the thickness in intervals of 1 mm. The stiffener dimensions for the high speed vessel in aluminium are kept as the original design.

The required section modulus of the stiffeners is calculated according to Equation (4.7).

$$z_{req} = \frac{ml^2sp}{\sigma} \tag{4.7}$$

p = the maximum design load pressure acting on the stiffener in consideration, see Section 3 for design loads

σ = allowed bending stress, see Table 4.3

m = 85 for all longitudinal stiffeners, 125 for vertical bulkhead stiffeners

The allowable stresses are based on the yield strength which is considered through the material parameter f_1. For Weldox 700 E Offshore it is 2.88 and for NV5083 it is 0.6, for material parameters see Appendix A. The values of the allowable stress are multiplied with 1.1 for the high speed vessel (DNV, 2012c). The reason why the allowable stress differs for different items in Table 4.3 is that some items are more often subjected to a load than others. For example the watertight bulkhead is rarely subjected to a load, since this means that the vessel is flooded, and the allowable stress is therefore higher. The same reason is behind the increased allowable stresses for the high speed vessel, which is classed as a patrol boat. The differences between the materials in Table 4.3 are discussed in Section 8.1.

Table 4.3 Allowable bending stresses [N/mm²].

Item	Steel	Aluminium
Bottom, slamming loads	$150f_1$	$180f_1$
Bottom, sea load	$160f_1$	$160f_1$
Side, slamming load	$160f_1$	$160f_1$
Side, sea load	$160f_1$	$160f_1$
Deck	$160f_1$	$160f_1$
Watertight bulkhead	$220f_1$	$200f_1$

The dimensions of the steel stiffeners are also governed by Equation (4.8).

$$t \geq \frac{1}{15} h \tag{4.8}$$

t = web thickness of stiffener

h = web height of stiffener

The resulting required sectional modulus is presented in Appendix D.

4.3 Web frames

The requirement of web frames according to the steel rules (DNV, 2012e) and the aluminium rules (DNV, 2012f) are the same. Therefore the same procedure is used for the two materials. The maximum allowed bending stress for web frames due to static loads is determined according to Equation (4.9).

$$\sigma_{max} = 160f_1 \tag{4.9}$$

The resulting allowed stresses are presented in Table 4.4. The maximum allowed bending stress is multiplied with 1.1 for the high speed vessel (DNV, 2012c).

Table 4.4 Maximum allowed bending stress in web frames [MPa].

	Passenger ferry	High speed vessel
Steel	460.8	506.9
Aluminium	96	105

The web frame dimensions for aluminium are at first based on the original design of the vessel. The steel web frames scantlings are initially dimensioned using minimum plate thickness together with the relationships in Equation (4.10) and (4.11). In 3D-beam (DNV, 2012a) this is conducted by adding an I-profiled beam to the outer hull line of the web frame of the chosen sections. This profile is representative for the T-profile of the web girder attached to the hull plating. Then the hull plating for both materials is kept to minimum while the dimensions for the web girder at first is increased relationally and then varied until satisfying bending stresses occurs in the structure.

The relationships for the dimensions of steel stiffeners in shape of T-profiles (DNV, 2012e) are presented in Equations (4.10) and (4.11).

$$t_f \geq \frac{1}{15} w_f \tag{4.10}$$

t_f = flange thickness of stiffener

w_f = flange width of stiffener

$$t_w \geq \frac{1}{50} h_w \tag{4.11}$$

t_w = web thickness of stiffener

h_w = web height of stiffener

Since there are no similar relations for aluminium these are also used for the dimensioning in aluminium. The dimensions of web heights and flange width are chosen with an interval of 1 mm. The profile thickness is chosen with an interval of 0.5 mm.

4.4 Buckling

The dimensions of plating and stiffeners are controlled against buckling. Since the global strength is neglected for the two vessels the stiffeners will not be affected of buckling. The thickness of the plating is investigated with regards to buckling. The formula for calculating the ideal elastic buckling stress according to the steel rules (DNV, 2012e) and the aluminium rules (DNV, 2012f) are the same. The same procedure is therefore used for the two materials.

The following formula is used to calculate the ideal elastic buckling stress:

$$\sigma_{el} = 0.9kE\left(\frac{t}{1000s}\right)^2 \tag{4.12}$$

Since the plating is longitudinally stiffened:

$$k = \frac{8.4}{\Psi + 1.1} \tag{4.13}$$

Where $\Psi = 1$. The stresses in the web frame are found using 3D-beam. But the software only gives the stresses for the web frame flange. The bending moment is constant over the web frame cross-section and it is calculated as (KTH, 2010):

$$M = \sigma Z \tag{4.14}$$

The stress in the plate is then calculated as:

$$\sigma_{plate} = \frac{\sigma_{flange} Z_{flange}}{Z_{plate}} \tag{4.15}$$

4.5 Eigenfrequencies

The web frame and the stiffener dimensions are verified against eigenfrequency criterion (DNV, 1982). The moment of inertia of each cross-section should not be less than according to Equation (4.16).

$$I = \frac{10ta + An + c_2 a^2 k_3}{k_1 n} k_2 l^4 \left(\frac{F}{250}\right)^2 \tag{4.16}$$

The parameter t is the thickness of the plating, when analysing the deck t is increased to give the same weight in steel as the passenger load. When analysing the web frame at the deck the thickness is increased to include the weight of the stiffeners. The parameter a is the width of the plate field and n is the number of stiffeners. For simplicity n is taken as one which gives the plate width, a, as the span between stiffeners.

The area, A, is the cross-sectional area of the stiffener or web frame considered. The parameter c_2 considers the damping effect of water on the plating. For the hull that has water one side $c_2 = 400$ and for the deck that is normally not subjected to water pressure $c_2 = 0$. The factor k_1 considers the shape of the stiffeners and it is 1 since the profiles are symmetric. The parameter l is the length of the plate field. Figure 4.1 gives the factor k_2, the maximum value of k_2 is chosen since this gives the highest moment of inertia requirement.

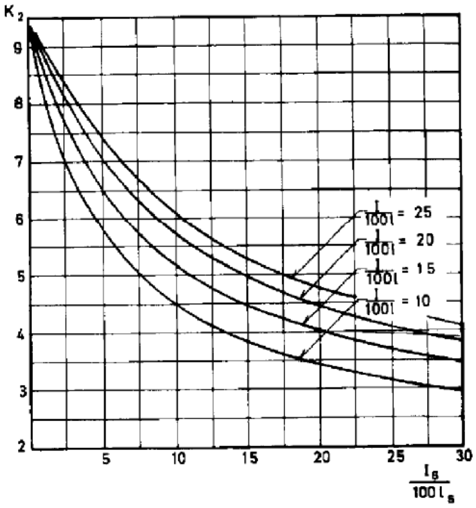

Figure 4.1 The figure shows how k_2 should be estimated (DNV, 1982).

The factor k_3 is calculated according Equation (4.17).

$$k_3 = \frac{2}{3}\left[1 + \frac{1}{2\sqrt{1 + \left(\frac{2a}{l}\right)^2}}\right] \tag{4.17}$$

The parameter F represents the exciting frequency. For the passenger ferry, the frequency is induced by the engines and propellers. It is calculated as:

$$F = \frac{1.1 N_p Z_p}{60} \tag{4.18}$$

The maximum rotation of the propeller, N_p, is calculated according to Equation (4.19).

$$N_p = \frac{1800}{3.091} = 582\, rpm \tag{4.19}$$

The number of propeller blades, Z_p, is 3 for the passenger ferry.

Since the high speed vessel has water jet propulsion the engines will have a high number of revolutions and the vibrations from the engines will not affect the dimensions. Due to the high speed the wave encounter excitation frequency has to be considered. It is calculated as (Lewis, 1989):

$$F = \frac{\omega_e}{2\pi} = \left(\omega - \frac{\omega^2}{g_0} V \cos(\mu)\right) / 2\pi \tag{4.20}$$

The wave encounter excitation frequency depends on the heading angle, μ. For head sea the heading angle is $\mu = 180°$, which gives the largest encounter frequency. The wave frequency, ω, is given by Equation (4.21).

$$\omega = \frac{2\pi}{T_w} \tag{4.21}$$

Where T_w is the wave period.

The excitation frequency due to waves is not high enough to affect the dimensions. The required moment of inertia is already fulfilled.

5 ICE-IC

The passenger ferry travels in conditions where there is a risk of ice during winter, similar to the conditions regarded in the Finnish-Swedish ice class IC (ICE-1C) (DNV, 2013). The passenger ferry is today reinforced with respect to ice impact but it has not been assigned class. A new reinforcement is therefore added for both materials to the passenger ferry in order to further evaluate the high strength steel. The analysis follows a similar method as for the dimensioning in Section 4 with an adaption of the ICE-1C rules. Since this is a reinforcement previous rules for light craft must be fulfilled as well.

Design loads and pressure from an ice impact is calculated with regards to existing engine effect on the passenger ferry. A criterion according to ice-class says that 1000 kW is required but the passenger ferry has an effect of 2x280 kW. This rule is therefore neglected since the purpose is to compare the materials with regards to the ice-reinforced passenger ferry rather than to achieve a proper ice-class notation.

When introducing an ice-reinforcement to a vessel transverse framing is commonly used. However, for the original design of the passenger ferry there are longitudinal framing, i.e. the stiffeners. This thesis will therefore consider longitudinal frames by reinforcing the stiffeners from the previous sections.

5.1 Defining ice belt region

The reinforcement is not necessary for the whole hull and therefore an ice region has to be defined. The ice strengthening is determined from the Upper Ice Water Line (UIWL) and the Lower Ice Water Line (LIWL). The UIWL is the draught at fully loaded condition and the LIWL is the draught at light ship. These are presented in Table 5.1.

Table 5.1 Ice water lines draught and minimum ice belt extensions in meter for the passenger vessel.

	UIWL	**LIWL**
Forward section	1.48	1.04
Midship section	1.45	1.17

The ice belt margins are vertically extended from the upper and lower ice water lines. The extension differs for plating and stiffeners. They are governed by the ice class notation (DNV, 2013). The minimum extensions for ICE-1C are presented in Table 5.2.

Table 5.2 Minimum vertical extension for plating and stiffeners in meter.

	Plating upper extension	**Plating lower extension**	**Stiffeners upper extension**	**Stiffeners lower extension**
Forward section	0.40	0.70	1.00	1.6
Midship section	0.40	0.60	1.00	1.3

The upper extensions are added to UIWL and the lower extensions subtracted from LIWL. The resulting margins are presented in Table 5.3.

Table 5.3 Ice region outer margins for plating and stiffeners in meter.

	Forward section	**Midship section**
Upper region end for stiffeners	2.48	2.45
Upper region end for plating	1.88	1.85
Lower region end for plating	0.34	0.57
Lower region end for stiffeners	-0.56 (below baseline)	-0.13 (below baseline)

In Figure 5.1 the outer margin for every region can be seen in accordance with Table 5.3. The left side shows the midship web frame with the ice belt region indicated. The right side shows the ice belt region for the forward section. As can be seen in the figure the lower stiffener region is below the baseline.

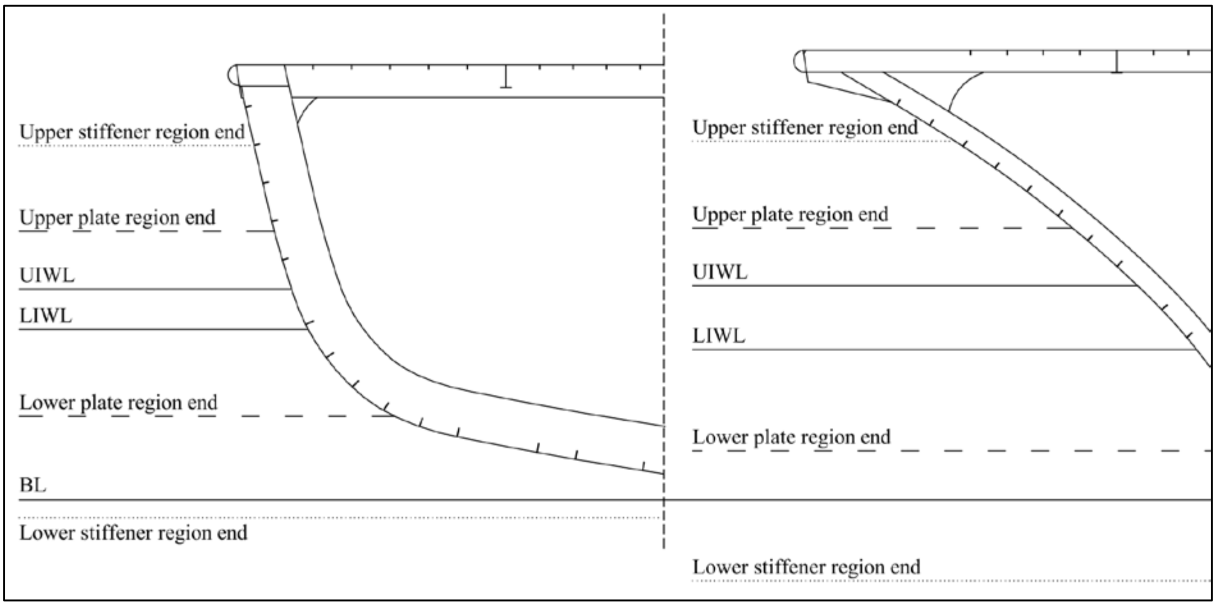

Figure 5.1 The ice belt regions of the passenger ferry for the section at 0.5L to the left and 0.9L to the right.

5.2 Design loads

An ice impact will give rise to a pressure on the hull (DNV, 2013). The design ice height is $h_{ice} = 0.22\ m$ and the ice level should not exceed $h_0 = 0.4\ m$ for ice-class IC. Ice pressure is calculated according to Equation (5.1)

$$p_{ice} = 5600 c_d c_1 c_a \tag{5.1}$$

c_1 = 0.50 for midship section, 1.0 for forward section

The coefficient c_d is calculated as:

$$c_d = \frac{ak + b}{1000}, c_d \leq 1 \tag{5.2}$$

a = 8 for midship section, 30 for forward section

b = 214 for midship section, 230 for forward section

Where k is:

$$k = \frac{\sqrt{\Delta_f P_s}}{1000} \tag{5.3}$$

P_s = Engine effect, $2 \cdot 280\ kW$

Δ_f = displacement of the ship on the maximum ice class draught which for this case is the maximum displacement

The coefficient c_a is calculated as:

$$c_a = \sqrt{\frac{l_0}{l_a}} \tag{5.4}$$

l_0 = 0.6 m

l_a = see Table 5.4

The coefficient, c_a, is restricted according to Equation (5.5).

$$0.35 \leq c_a \leq 1.0 \tag{5.5}$$

Table 5.4 presents the values of the distance l_a that are used in this thesis. The distance differs depending on what kind of element that is considered and in what direction the stiffeners are positioned. Since this thesis only concerns longitudinal stiffeners and therefore only values concerning this are presented in the table. The resulting ice loads are presented in Appendix C.

Table 5.4 Definition of l_a for the structures considered.

Structure	l_a
Plating	$1.7s$
Longitudinal stiffeners	l
Web frames	$2l$

5.3 Ice belt plating

The minimum thickness of the plating is determined by Equation (5.6) (DNV, 2013).

$$t = 21.1s\sqrt{\frac{p_{ice}}{f_2\sigma_f}} + t_c \tag{5.6}$$

How the coefficient $f_2$is calculated is determined by the following ratio:

$$\frac{h_{ice}}{s} = \frac{0.22}{0.27} = 0.84 \tag{5.7}$$

Since $h_{ice}/s \leq 1$:

$$f_2 = 0.6 + \frac{0.4}{h_{ice}/s} \tag{5.8}$$

In Equation (5.6) an abrasion and corrosion margin, t_c, is added of 2 mm for steel and 4 mm for aluminium. The margin for steel is given in the rules but there are no guidelines for aluminium since vessels in this material are hardly ever assigned any ice class. The aluminium is a more soft material and the abrasion and corrosion margin is therefore assumed as twice the steel margin. The dimensions of the plating are chosen with intervals of 0.5 mm.

5.4 Stiffeners

For the midship section the ice region is extended from the keel up to 2.45 m above the base line. This means that at the midship section 16 of 17 stiffeners on each side of the hull lies within the stiffeners ice region. For the forward section the distance is 2.48. At the forward section 10 of 12 stiffeners on each side of the hull are within the ice region. Equation (5.9) gives the required section modulus for the ice belt stiffeners (DNV, 2013).

$$Z = \frac{f_4 p_{ice} h_{ice} l^2}{m_1 \sigma_F} 10^3 \tag{5.9}$$

The required cross sectional area:

$$A = \frac{8.7 f_4 f_5 p_{ice} h_{ice} l}{\sigma_F} \tag{5.10}$$

Where:

$$f_4 = 1 - 0.2 \frac{h_{ice}}{s} \tag{5.11}$$

f_5 = 2.16
m_1 = 13.3

The bow region has an additional requirement regarding web thickness for the longitudinal stiffeners. The thickness must fulfil every of the following requirements.

- $t_w \geq$ 9 mm.
- $t_w \geq$ one half of the shell plate thickness
- $t_w \geq \frac{h_w \sqrt{\sigma_f}}{282}$, where h_w is the web height

The dimensions are chosen with an interval of 1 mm for heights and 0.5 mm for thicknesses. The resulting requirements of sectional modulus and cross sectional area are presented in Appendix D.

5.5 Web frames

The dimensions of the web frame shall meet the requirement of the section modulus given by the equation below (DNV, 2013):

$$Z = \frac{M}{\sigma_{\mathrm{f}}} \sqrt{\frac{1}{1 - \left(\gamma \frac{A}{A_a}\right)^2}} 10^3 \tag{5.12}$$

The required area A (actual shear area) is calculated according to:

$$A = \frac{17.3\alpha f_{33} Q}{\sigma_f} \tag{5.13}$$

A_a = A_f + A_w, actual cross sectional area of web frame

A_f = cross sectional area of free flange

A_w = actual effective cross sectional area of web plate

f_{13} = 1.1, factor that takes into account the shear force distribution

α = 1.5

γ = 0

Q = F, Q is the maximum shear force under the load F which for this case is Q=F

The bending moment M is calculated according to:

$$M = 0.193Fl \tag{5.14}$$

In order to calculate the bending moment and dimension the web frames the load transferred to it from the longitudinal framing must be calculated. The load is governed by Equation (5.12).

$$F = f_{12} p_{ice} h_{ice} s \tag{5.15}$$

f_{12} = factor of web frames, to be taken as 1.8

The resulting requirement of the web frame profiles are presented in Appendix D. The design of the web frames without ice-reinforcement is strong enough when the plating is increased. Therefore the design of the web frames is not changed.

6 Results

This section describes the resulting dimensions and designs of the considered sections for each vessel and material as well as the ice-reinforcement dimensions of the passenger ferry. The estimated weights are also described in this section. The results have been divided into four subsections. Section 6.1 covers the results for the final design of the passenger ferry. In Section 6.2 the design is presented and described for the high speed vessel.

During the analysis of web frames of the high speed vessel it was discovered that the stress in the aluminium web frames was not satisfying when the design loads were applied. The web frames had to be strengthened in order to give a fair comparison. The plating and stiffener dimensions are kept as the original since they are assumed to fulfil the requirements considered in this thesis.

Section 6.3 describes and presents the designs with regards to ice-reinforcement. In the final Section 6.4 the weight estimations based on the previous results are presented. This part presents the following results:

- Estimated weight of the passenger ferry for each material and the sections under consideration.
- Estimated weight of the high speed vessel for each material and the sections under consideration.
- Estimated weight of the passenger ferry for each material and the sections under consideration and ice-reinforcement.
- Total weight estimation for both materials regarding the passenger ferry, the high speed ferry and the passenger ferry with ice-reinforcement.

6.1 Passenger ferry

Hull plate thicknesses and stiffener dimensions are presented in the following section along with cross-sections of the sections under considerations. The dimensions of the web frames are presented in Appendix E. The plating thickness of the passenger ferry is presented in Table 6.1.

Table 6.1 Plating thicknesses of the hull of the passenger ferry [mm].

	Weldox 700 E Offshore	**NV5083**
Below the waterline	3	5.5
Above the waterline	3	4.5
Deck	3	4.5

Figures 6.1 and 6.2 show the midship web frame and stiffeners. In both figures longitudinal girders can be seen between the longitudinal stiffeners. These have not been a part of the analysis but are kept in the figures in order to visualize their positions. The radius in the deck corners represents rigid reinforcements based on the original design. For the high strength steel design, Figure 6.1, the web frame girder height around the bilge area of the hull is greater than for the rest of the hull. This is due to higher strength requirement around this area. For the side and bottom a lower height of the web frame girder is enough to fulfil the strength requirement. The web frame girder for the aluminium midship section has the same

height along the whole hull side as can be seen in Figure 6.2. The two figures are also visualizing the differences in girder height of the two designs. As can be seen the overall girder height for Weldox 700 E Offshore is lower than for NV5083.

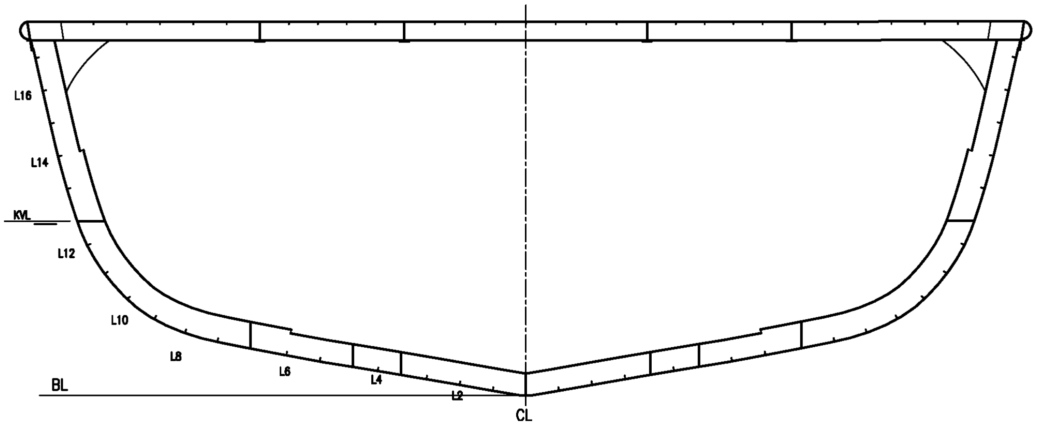

Figure 6.1 Web frame at 0.5L of the passenger ferry in Weldox 700 E Offshore.

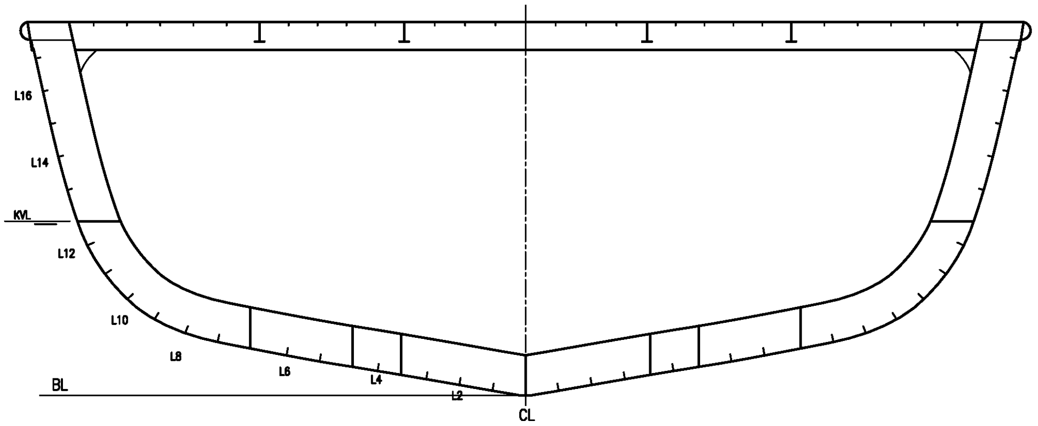

Figure 6.2 Web frame at 0.5L of the passenger ferry in NV5083.

The dimensions for longitudinal stiffeners in Weldox 700 E Offshore and NV5083 at 0.5L of the passenger ferry are shown in Table 6.2. The deck stiffeners are considerably smaller since the deck load on the section is lower than the loads on the hull.

Table 6.2 Dimension of stiffeners at 0.5L of passenger ferry [mm].

	Weldox 700 E Offshore		**NV5083**	
	Thickness	Height	Thickness	Height
L1-12	3	30	3	60
L13-17	3	30	3	40
Deck stiffeners	2	25	3	35

The designs of the bow section at 0.9L are presented in Figures 6.3 and 6.4. These designs have the same reinforcement in the corners as the midship sections have. In both figures longitudinal girders can be seen between the longitudinal stiffeners. These have not been a part of the analysis but are kept in the figures in order to visualize their positions.

Figure 6.4 shows that the web frame girder height varies along the hull of the aluminium design. The bottom is reinforced due to the high loads acting on it. The figure shows that the height of stiffeners L6 and L17 could cause problems for the manufacturing process since their height might interfere with the girders, how this can be solved is further discussed in Section 8.1. The two figures are also visualizing the differences in girders height for the two designs. As can be seen the overall girder height for Weldox 700 E Offshore is lower than for NV5083.

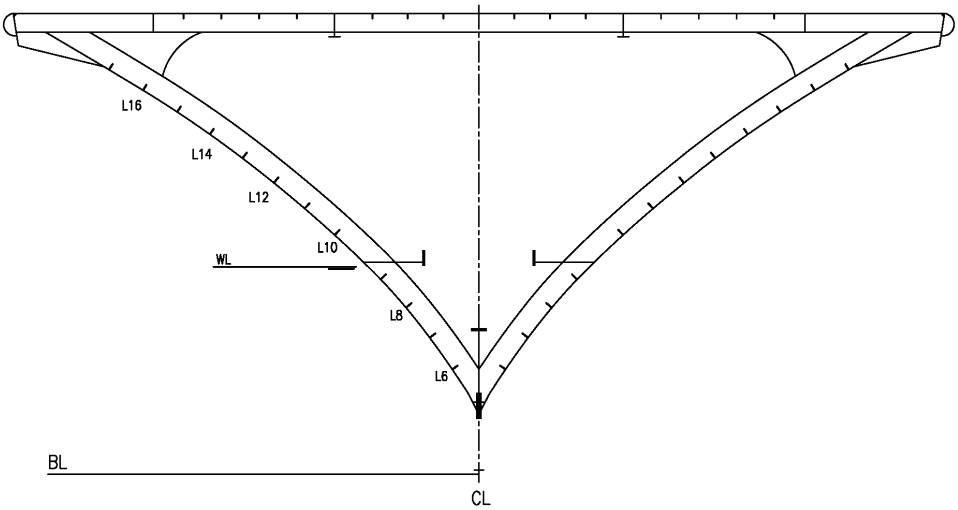

Figure 6.3 Web frame at 0.9L of the passenger ferry in Weldox 700 E Offshore.

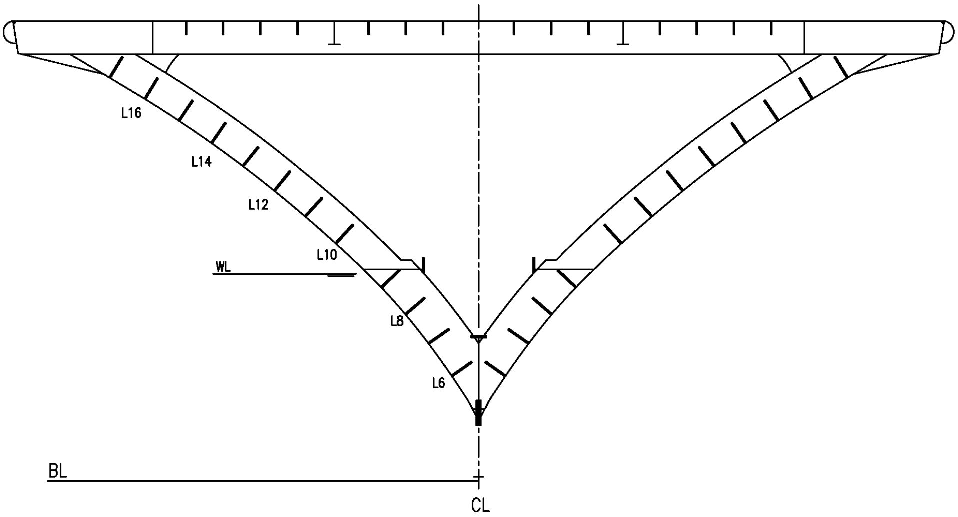

Figure 6.4 Web frame at 0.9L of the passenger ferry in NV5083.

The dimensions of the longitudinal stiffeners in Weldox 700 E Offshore and NV5083 at 0.9L of the passenger ferry are shown in Table 6.3. The deck stiffeners are considerably smaller since the deck load on the section is lower than the loads on the hull.

Table 6.3 Dimension of stiffeners at 0.9L of passenger ferry [mm].

	Weldox 700 E Offshore		**NV5083**	
	Thickness	Height	Thickness	Height
L6-7&13-17	4	45	10	165
L8-12	4	50	10	170
Deck stiffeners	2	35	6	90

The plating of the watertight bulkhead is 3 mm in Weldox 700 E Offshore and 4 mm in NV5083. There are 17 stiffeners on the watertight bulkheads with dimensions 2x25 mm in Weldox 700 E Offshore and 3x50 mm in NV5083. The difference in plate thickness between the materials is considerably low and this is further discussed in Section 8.1.

6.2 High speed vessel

Hull plate thicknesses and stiffeners dimensions are presented in the following section along with cross-sections from the sections under considerations. The dimensions of the web frames are presented in Appendix E. The plating thicknesses of the hull of the high speed vessel are presented in Table 6.4.

Table 6.4 Plating thicknesses of the hull of the passenger ferry [mm].

	Weldox 700 E Offshore	**NV5083**
Below the waterline	3	7
Above the waterline	3	5
Deck	2.5/3[*]	4

Figures 6.5 and 6.6 show the midship web frame and stiffeners. Girders and bottom tank are also present in the figures below. The girders have not been a part of the analysis and are therefore only included in the figures to show their positions.

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[*] The deck in Weldox 700 E Offshore is 2.5 mm at 0.56L and 3 mm at 0.89L.

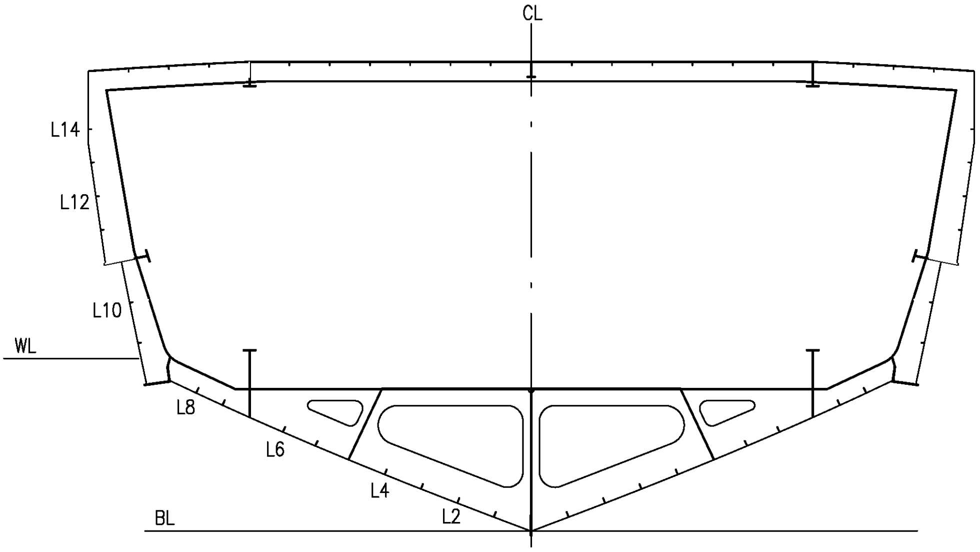

Figure 6.5 Web frame at 0.56L of the high speed vessel in Weldox 700 E Offshore.

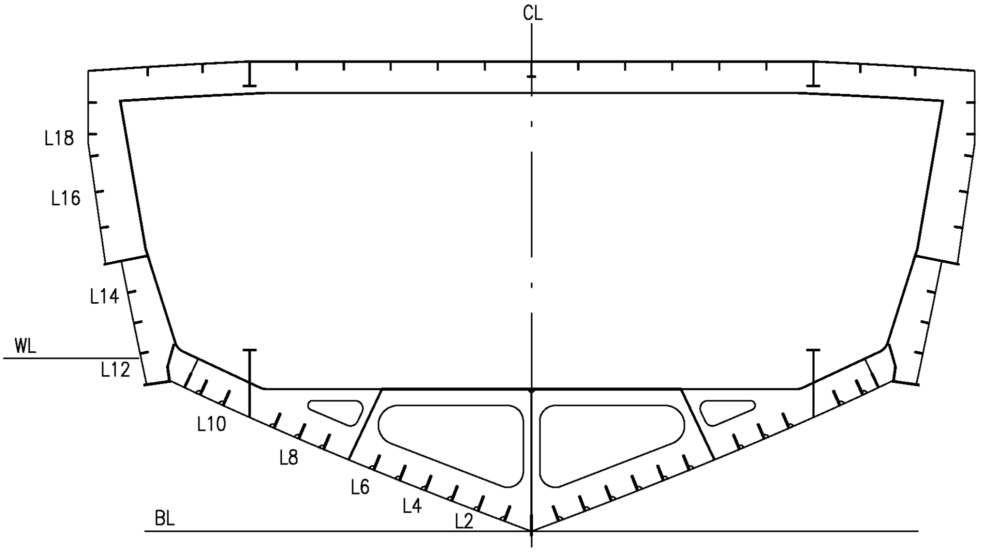

Figure 6.6 Web frame at 0.56L of the high speed vessel in NV5083.

The dimensions for longitudinal stiffeners in Weldox 700 E Offshore and NV5083 at 0.56L of the high speed vessel are shown in Table 6.3. As can be seen the deck stiffeners for the high speed vessel have to be bigger in size since the vessel is subjected to bigger loads. Therefore, unlike the passenger ferry, the deck stiffeners of the high speed vessel have similar dimensions to the hull stiffeners.

Table 6.3 Dimension of stiffeners at 0.56L of the high speed vessel [mm].

Weldox 700 E Offshore			**NV5083**		
	Thickness	Height		Thickness	Height
L1-8	3	35	L1-11	8	100
L9-14	2	20	L12-19	8	50
Deck stiffeners	2	20	Deck stiffeners	8	50

Figures 6.7 and 6.8 show the web frame and stiffeners at 0.89L. Girders and bottom tank is also present in the all the figures below. The girders have not been a part of the analysis and are therefore only included in the figures to show their positions.

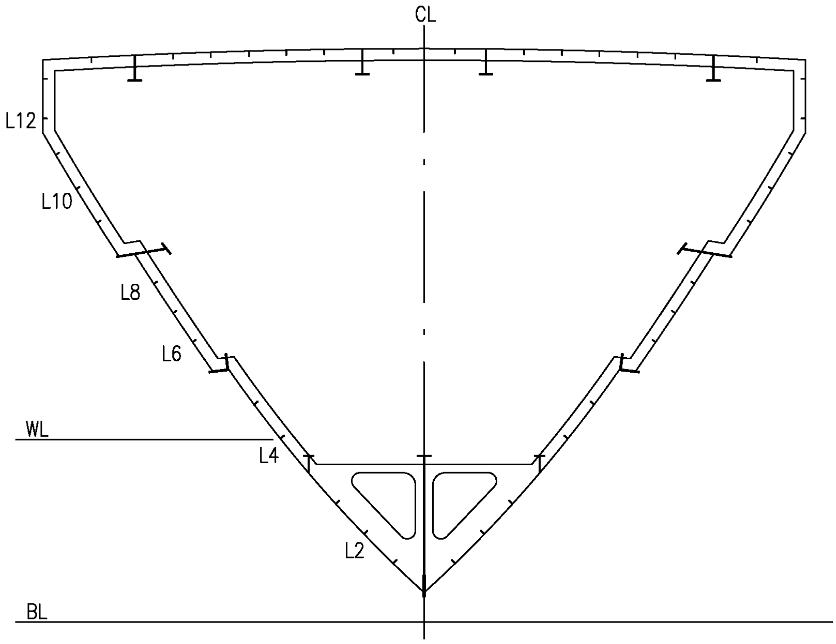

Figure 6.7 Web frame at 0.89L of the high speed vessel in Weldox 700 E Offshore.

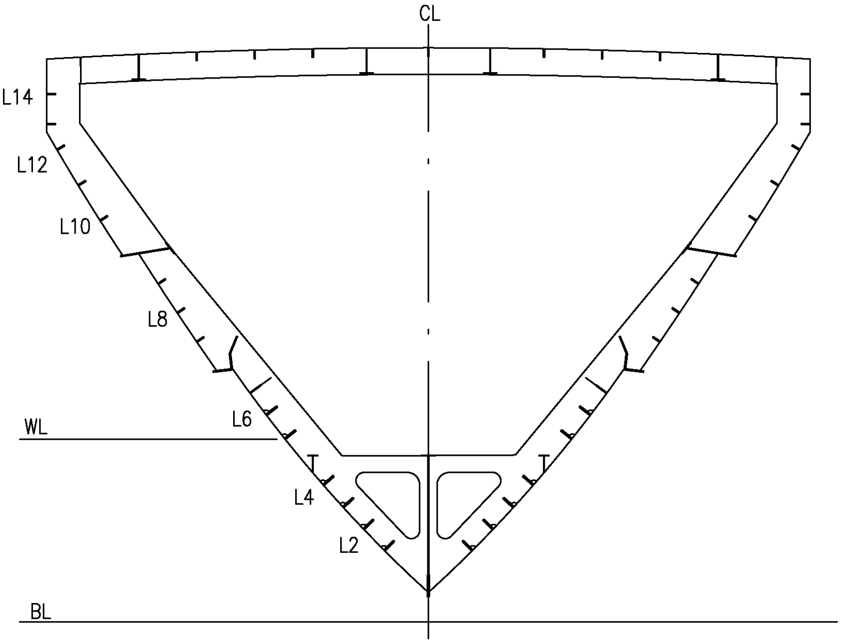

Figure 6.8 Web frame at 0.89L of the high speed vessel in NV5083.

The dimensions of longitudinal stiffeners in Weldox 700 E Offshore and NV5083 at 0.89L of the high speed vessel are presented in Table 6.4. As can be seen the deck stiffeners for the high speed vessel have to be bigger in size since the vessel is subjected to bigger loads. Therefore, unlike the passenger ferry, the deck stiffeners of the high speed vessel have similar dimensions to the hull stiffeners.

Table 6.4 Dimension of stiffeners at 0.89L of high speed vessel [mm].

Weldox 700 E Offshore			**NV5083**		
	Thickness	Height		Thickness	Height
L1-5	3	30	L1-6	8	80
L6-13	2	25	L7-14	5	50
Deck stiffeners	2	30	Deck stiffeners	5	50

The plating of the watertight bulkhead is 3 mm for Weldox 700 E Offshore and 3.5 mm for NV5083. There are 13 stiffeners on the watertight bulkheads in steel with dimensions 2x25 mm for the steel and 17 stiffeners in aluminium with dimensions 3x45 mm for the aluminium. As for the passengers ferry the difference in plating thickness is considerably small, this is discussed in Section 8.1.

6.3 Ice belt

The differences between the designs of the passenger ferry with and without the ice-reinforcement are the plating and the stiffeners. The dimensions of the web frames have not changed from the designs in Section 6.1 since the increased plating is enough to strengthen the web frame structure. The plating in the ice-reinforced belt of the section at 0.5L is 7 mm in Weldox 700 E Offshore and 13 mm in NV5083. For the rest of the hull, unaffected by the ice belt region, the plate thickness is the same as in Section 6.1. The stiffeners are presented in Figures 6.9 and 6.10 and specific stiffener dimensions are presented in Table 6.5.

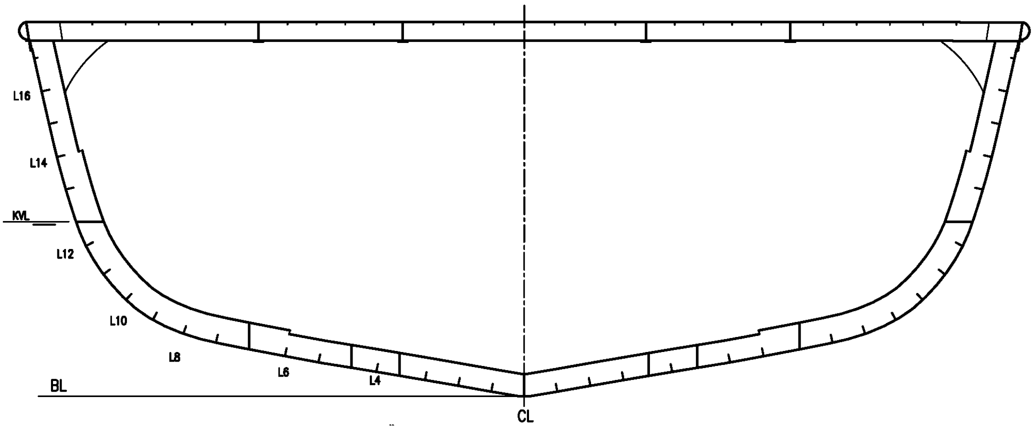

Figure 6.9 Web frame at 0.5L of the passenger ferry in Weldox 700 E Offshore with ice-reinforcement.

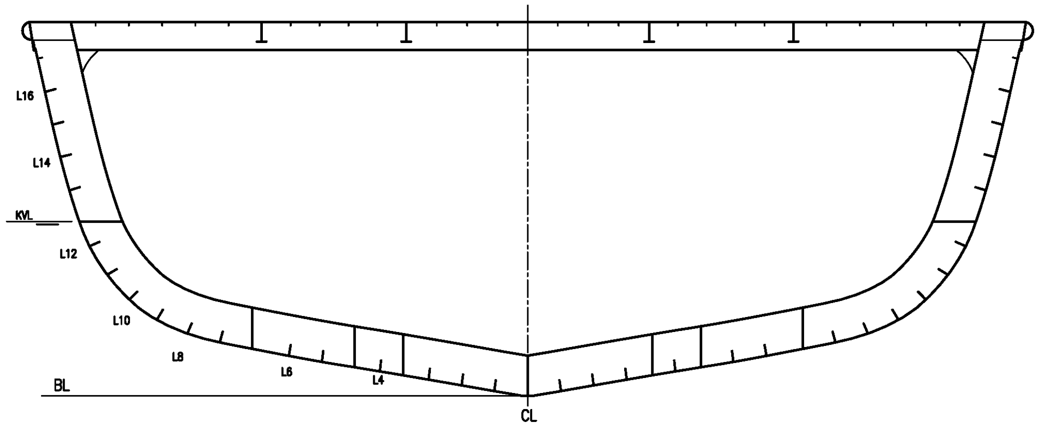

Figure 6.10 Web frame at 0.5L of the passenger ferry in NV5083 with ice-reinforcement.

The plating in the ice-reinforced belt of the section at 0.9L is 9.5 mm in Weldox 700 E Offshore and 17 mm in NV5083. For the rest of the hull, unaffected by the ice belt region, the plate thickness is the same as in Section 6.1. The stiffeners are shown in Figures 6.11 and 6.12. Specific stiffener dimensions are presented in Table 6.5. The dimensions of the stiffener of this section in aluminum are not changed from the design in Section 6.1 since these dimensions fulfil the requirement of the ice belt when the plate thickness is increased.

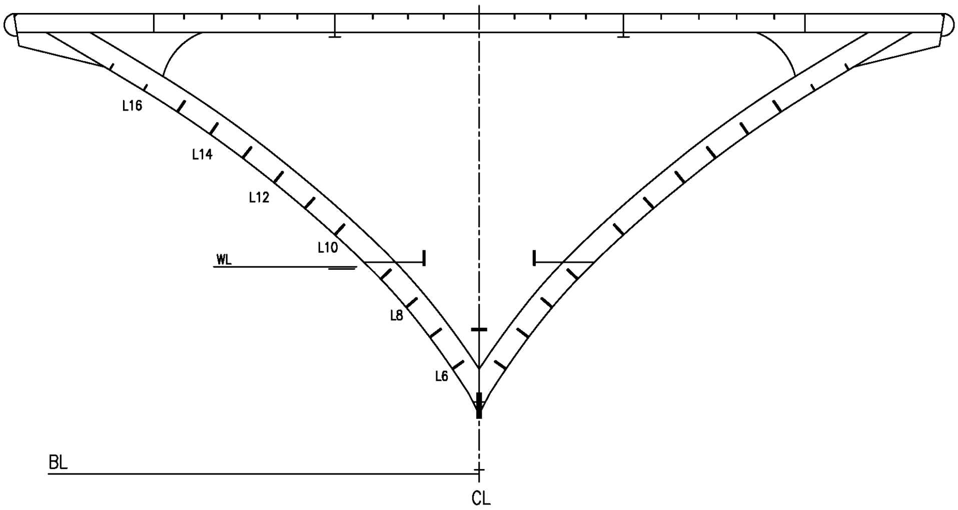

Figure 6.11 Web frame at 0.9L of the passenger ferry in Weldox 700 E Offshore with ice-reinforcement.

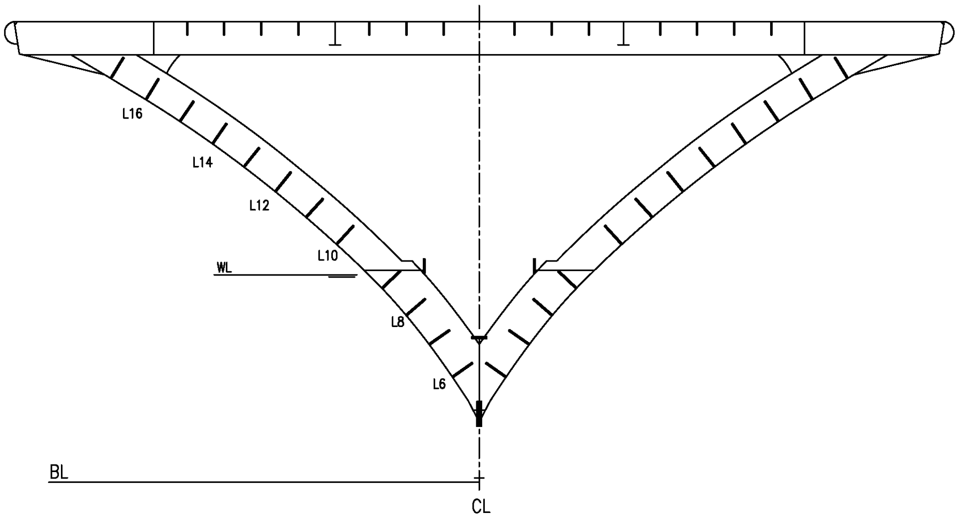

Figure 6.12 Web frame at 0.9L of the passenger ferry in NV5083 with ice-reinforcement.

The number of stiffeners is the same as the design in Section 6.1. The dimensions have been increased in order for the vessel to fulfil the ice class requirements, except for the aluminium stiffeners at section 0.9L. This is due to the fact that the stiffeners fulfil the requirements when the thickness of the plating is increased. The stiffener dimensions are the same for the whole ice belt since all stiffeners should withstand an ice impact.

Table 6.5 Dimensions of stiffeners for ice-reinforcement [mm].

	Weldox 700 E Offshore		**NV5083**	
	Thickness	Height	Thickness	Height
0.5L	5	65	7	90
0.9L	9	90	10	170

6.4 Weight estimation

The results from the weight estimation are presented by graphs where the bars with dotted horizontal lines denot the reference material NV5083. Sections constructed in Weldox 700 E Offshore are presented by the bars with diagonal lines. The weight estimation of each section of the passenger ferry is presented in Figure 6.13. As shown in the graph there is an increase in weight for Weldox 700 E Offshore compared to NV5083. The increase for the midship section is 35% and for the section at 0.9L it is 6%. This means that the strength of the steel is more utilised at the bow. The increase of weight of the watertight bulkhead is 116%. This was expected since the plating thickness of the bulkheads is similar for the materials but the density of steel is higher.

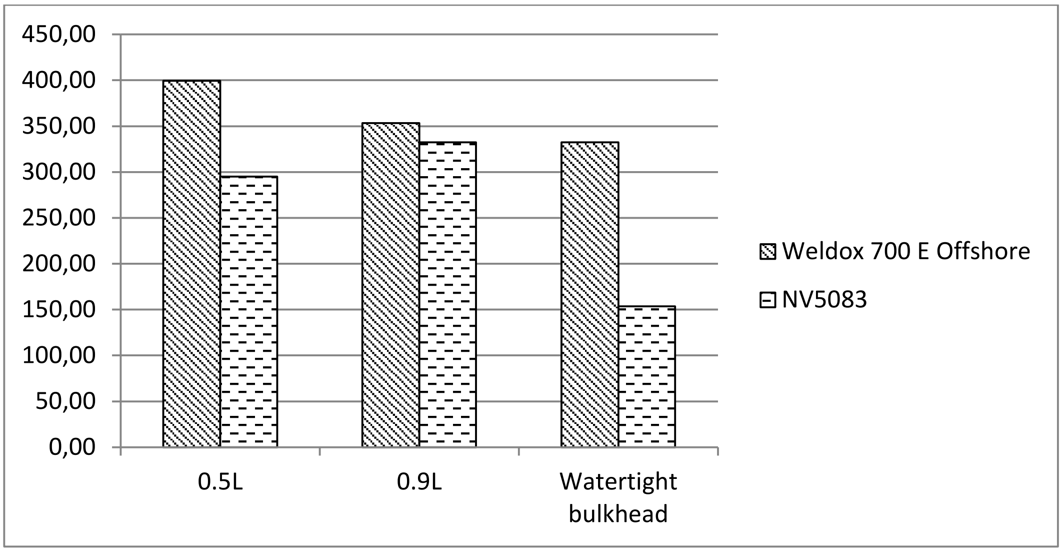

Figure 6.13 Estimated weight in kg of the sections of the passenger vessel.

The estimated weight of each section of the passenger ferry is presented in Figure 6.14. The graph shows that there is an increase in weight when using Weldox 700 E Offshore instead of NV5083. The increase of the section at 0.56L is 22% and for the section at 0.89L it is 28%. The increase is more similar between the sections for this vessel compared to the passenger ferry. The watertight bulkhead has an increased weight of 133%. This was expected since the plating thickness of the bulkheads is similar for the materials.

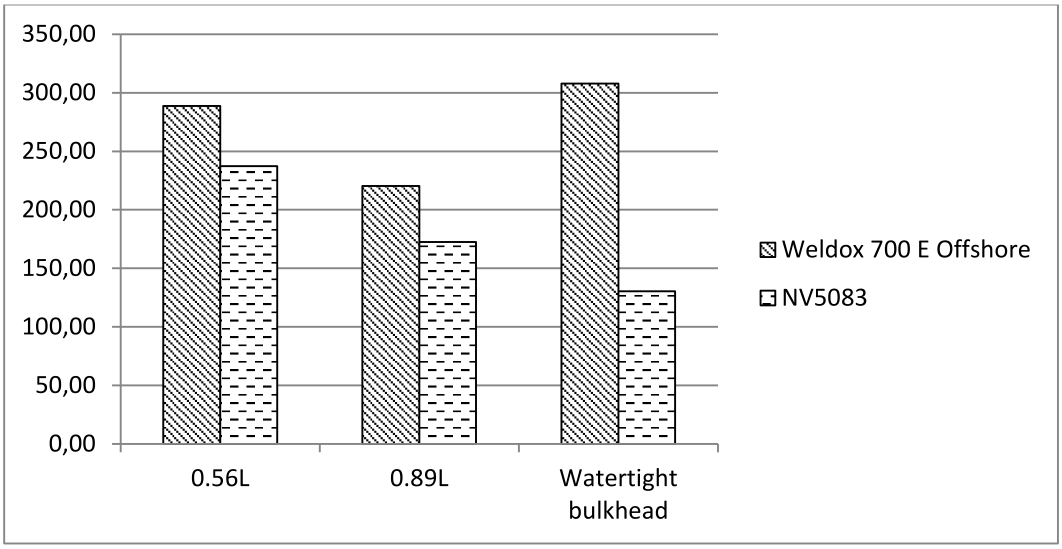

Figure 6.14 Estimated weight in kg of the sections of the high speed vessel.

The estimated weight of each section with ice-reinforcement of the passenger ferry is presented in Figure 6.15. The weight of the watertight bulkhead is not presented since it is not affected by the reinforcement. The weight of the section at 0.5L is 56% higher for Weldox 700 E Offshore and 46% higher for the section at 0.9L.

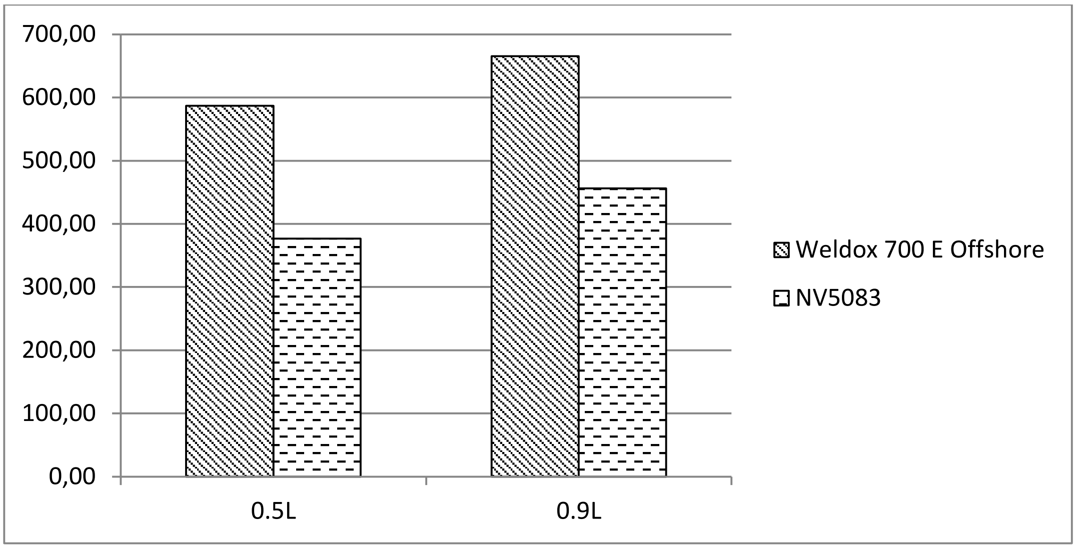

Figure 6.15 Estimated weight in kg of the sections of the passenger ferry with an ice belt.

The total weight of the hulls has been estimated and is presented in Figure 6.16. For both vessels there is an increase in weight, 35% for the passenger ferry and 31% for the high speed vessel. The ice-reinforcement is increasing the weight of the passenger ferry in both aluminium and steel. The increase is larger for steel which gives a weight that is 57% higher than for aluminium.

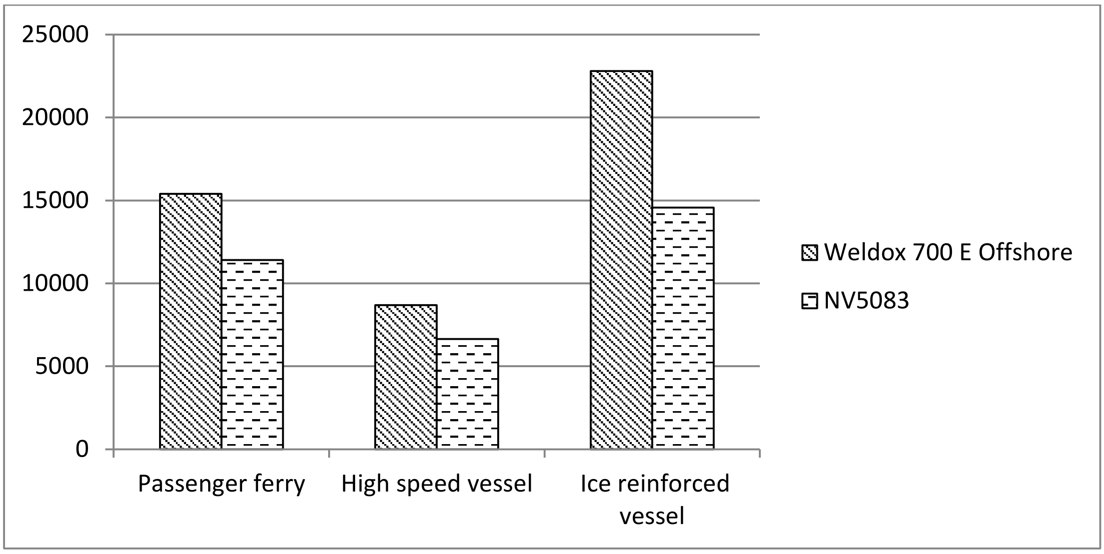

Figure 6.16 Total weight estimation.

Since the bulkheads are such large part of the weight increase the total weight without the bulkheads have been estimated and it is presented in Figure 6.17. Translating the figure into numbers gives that the passenger ferry weighs 31% more in high strength steel, the high speed vessel 23% and the ice-reinforced vessel 54%. By disregarding the watertight bulkheads the weight difference between the high strength steel and the aluminium is lower.

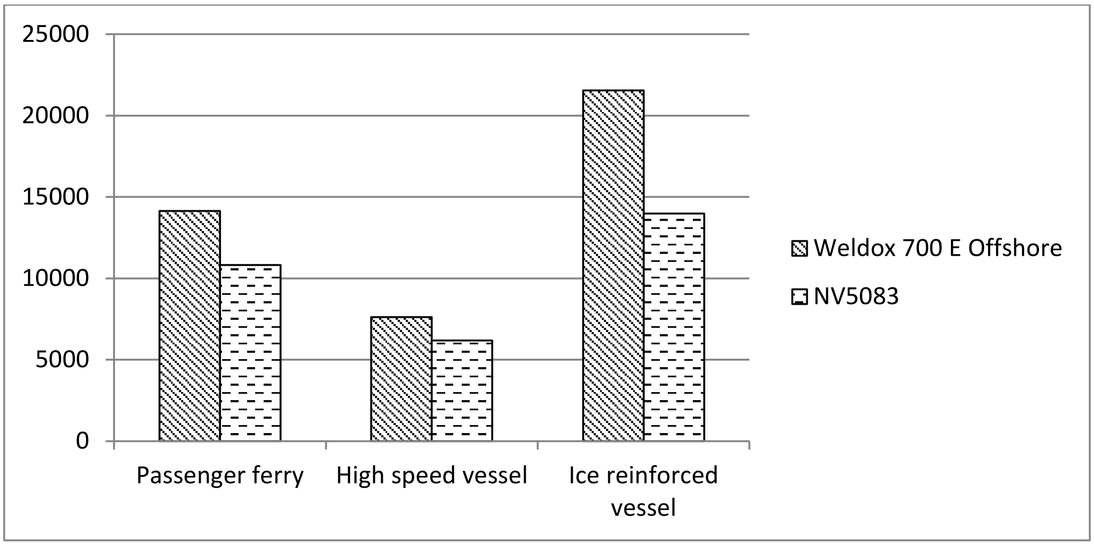

Figure 6.17 Total weight estimation without the watertight bulkheads

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7 Larger vessels

An investigation is made to see if there is an indication that weight can be saved for using high strength steel with $\sigma_f = 690\ MPa$ compared to regular steel with $\sigma_f = 360\ MPa$ for regular steel ships. Only the bottom plating is chosen to be analyzed. The minimum plate thickness should not be less than (DNV, 2015):

$$t_{min} = 5.0 + \frac{0.04L}{\sqrt{f_1}} + t_k \tag{7.1}$$

The corrosion factor, t_k, is chosen as 2 mm. The length is varied between 100 m and 300 m. The resulting thicknesses are presented in Table 7.1, the thicknesses are chosen with regards to intervals of 0.5 mm. Material parameter f_1 in these rules does not account for yield strength above 390 MPa. Therefore the parameter for Weldox 700 E Offshore is taken from the light craft rules (DNV, 2012e).

Figure 7.1 Bottom plate thicknesses for steel ships [mm].

Length of vessel, L [m]	**Weldox 700 E Offshore** ($\boldsymbol{f_1 = 2.88}$)	**Regular steel** ($\boldsymbol{f_1 = 1.39}$)	**Thickness reduction**
100	9.5	10.5	9.5%
150	10.5	12	12.5%
200	12	14	14.3%
250	13	15.5	16.1%
300	14	17	17.7%

However, it is rarely the minimum thickness with regards to length that determines the thickness of bottom plating of larger vessels. Normally the sea load is the determining factor of the bottom plating. The minimum thickness of bottom plating with regards to pressure is calculated according to Equation (7.2).

$$t_{min} = \frac{15.8 k_a \sqrt{p}}{\sqrt{\sigma}} + t_k \tag{7.2}$$

k_a = correction factor,

σ = allowable stress, $120 f_1$ for plating within 0.4L from midship or $160 f_1$ for plating within 0.1L from the aft and forward perpendicular.

If the corrosion margin, t_k, is disregarded in Equation (7.2) the thickness can be reduced with 30.5% when using the high strength steel compared to the regular steel. The actual reduction will be smaller when the corrosion margin is considered.

The density of steel does not vary that much between the different types and the weight reduction of the plating is therefore the same as the thickness reduction. From this result it is not possible to say how much weight that could be saved for an entire vessel but the result indicates that it should be possible to reduce the total weight.

8 Discussion

This section discusses the methodology used for the analysis, compares the results and discusses the differences between them. The discussion has been divided into three parts. Section 8.1 covers the light craft designs as well as the parameters and characteristics of the vessels and the materials used for the light craft analysis. In Section 8.2 the ice-reinforcement is discussed and in Section 8.3 the analysis of the larger vessels and the results are discussed.

8.1 Light crafts

The ratio between strength and density is 9% higher for Weldox 700 E Offshore than for NV5083. Therefore it should be possible to reduce the weight by up to 9%. Considering the ratio between the Young’s modulus and the density the ratio is only 1% higher for the steel. Since this thesis investigates light crafts for which the plating is relatively thin, buckling is a critical dimensioning parameter. Based on this a light craft should be about 1-9% lighter in Weldox 700 E Offshore than in NV5083. However, the vessels considered in this thesis are 31-42% heavier when built in Weldox 700 E Offshore. The reason for this unexpected weight increase is discussed further in this section.

The equations that are used for calculating the minimum thickness of the plating are different between steel and aluminium. In Equation (4.4) for aluminium the strength of the material is considered which is not the case in Equation (4.1) for steel. The fact that the material parameter is not considered in Equation (4.1) means that all steels will give the same minimum thickness. If the material factor was to be considered for the high strength steel, the minimum thickness would probably be thinner than what is calculated in this thesis. The basic stiffener spacing is calculated in different ways according to Equations (4.2) and (4.5) for steel and aluminium. The reason why the rules are different is that materials have different characteristics and the equations have been developed from different backgrounds and with different presumptions.

Another factor is the division of parameters in Tables 4.1 and 4.2, which has an effect on the resulting thicknesses. Particularly the watertight bulkheads are not in favour of the differences. Regarding steel the t_0 parameter is the same for bottom and watertight bulkhead but for aluminium the parameter is less for the watertight bulkhead than for the bottom. This result in thicknesses of 3 mm for both vessels in steel and 3.5 mm and 4 mm respectively for aluminium. It is not reasonable that the plating is only 0.5-1 mm thicker for aluminium. The main dimensioning parameter should be the yield strength since the watertight bulkhead should be allowed to buckle as long as the bulkhead remains watertight. A corrosion and abrasion margin should not give an impact on the result of this magnitude.

The allowable bending stresses of the stiffeners in Table 4.4 are generally the same for steel and aluminium but there are two that differ. When it comes to slamming on bottom the allowable stress parameter is much higher for aluminium than for steel. For the watertight bulkhead the parameter for steel is higher than for aluminium. It would be more logical if the parameters were either the same for both materials or if all parameters would be consistently higher for one of the materials.

The watertight bulkheads are the least favourable to build in high strength steel. Comparing Figures 6.16 and 6.17 it is possible to see that the watertight bulkheads have a big impact of the total weight, especially for the high speed vessel. Thus, a beneficial design would be a vessel with a steel hull and aluminium bulkheads. For the passenger ferry this would result in a decrease of 4% compared to a design completely in steel or 36% more than the design in aluminium. For the high speed vessel a steel hull and aluminium bulkheads would mean a decrease of 7.2% compared to the steel design or 21.5% more than the design completely in aluminium. This estimation is simplified and in reality there could be issues concerning manufacturing which could affect the weight.

The web frame spacing is not changed for any of the vessels in this thesis. The passenger ferry has different spacing for the two sections. The section at 0.9L has a spacing that is 50% longer than the section at 0.5L. For the passenger ferry the increase in weight is considerably lower at the forward section. This is not the case for the high speed vessel for which the increase is higher for the forward section. This could be an indication that the frame spacing has an impact on the result. It could also mean that larger frame spacing is in favour of Weldox 700 E Offshore.

If the frame spacing has a large impact on the results this could also be the case for the stiffener spacing. For the passenger ferry the same spacing is used for both materials but for the high speed vessel different spacing is used. The total weigh estimation of the high speed vessel shows a lower increase than the passenger ferry. The reason could be the stiffener spacing.

The spacing of the longitudinal stiffeners could be varied in order to affect the result. The spacing is affecting the stiffeners size, the minimum plate thickness and the elastic buckling stress of the plating. However, the web frame is not affected by variations of the spacing. An increased spacing would lead to a higher minimum thickness for steel only. The aluminium plate would be unaffected. The stiffeners would have to be bigger in size for both materials. It would also decrease the elastic buckling stress of the plating.

Decreasing the spacing would lead to an adverse effect of elastic buckling stress and stiffener size. For this case, the aluminium plate thickness would decrease but leave the steel plate thickness unaffected. The reason for why this happens with the minimum thicknesses is because of the different rule definitions regarding the spacing of each material. A suggestion would be to investigate and find a more optimized spacing for each material in order to refine the results.

The total weight increase of the high speed vessel is lower than for the passenger ferry. The reason for this could be that the speed and the service restriction of the high speed vessel give rise to higher loads. If the loads are higher it means that the yield strength will be a stronger factor for the dimension requirements. However, the total weight difference does not differ enough between the vessels in order to draw such conclusion only from this study.

The stiffeners of the section at 0.9L of the passenger ferry in aluminium are too high, see Figure 6.4. Particularly L6 and L17 will cause problems for the shipyard. The height can be reduced by using other profiles than flat bars. It is common to used bulb profiles for these types of vessels and Älvsnabben 5 is today built with bulb profiles. They give a smaller area for the same section modulus. The reason why only flat bars are considered in this thesis is that the dimensions of the steel profiles became a lot smaller than the standard profiles existing today and some of the profiles would be smaller than practically feasible. The reduced area of using bulb profiles instead of flat bars will give a weight reduction. Even though the weight can be reduced this will not be by much since the stiffeners are for most sections only a small part of the total weight.

Today Weldox 700 E Offshore is only available in sheets of 4 mm and above. If there will be a demand of Weldox 700 E Offshore for light craft design then it should be possible for SSAB to deliver thicknesses below 4 mm since this is possible for other steels, an example is the high strength stainless steel mentioned in Section 2.3. The question is how big the demand must be and what the cost will be. Bulb profiles with small dimensions should be possible to find on the market if the demand for them increases.

What has not been taken into consideration in this thesis is how alternative manufacturing methods could affect the result. For aluminium extruded profiles could be used that includes both plating and stiffeners, which could probably reduce the weight. The manufacturing methods used for steel vessels today limits the minimum scantlings. Smaller scantlings and further weight reduction is indeed possible by using other types of welding methods and different construction layout for the hull. This is achieved by Swedish Steel Yachts with their concept boat M10.5, mentioned in 1.1. On the downside these changes in manufacturing would require new set of manufacture machinery, upgrades of existing ship yards working with these vessels today and probably new knowledge for the staff. In the end this would generate higher costs in the quest to save weight, but it all depends on the number of vessel that there will be a demand for.

8.2 Ice-reinforcement

The result from adding an ice belt to the passenger ferry in Figure 6.16 shows that there is a great setback for using high strength steel. This could be explained by the fact that the rules that are applied for this is analysis are proven to be made with respect to steel. These rules are not specific for light craft design and are taken from the rules regarding ordinary vessels in steel. The analysis and method could therefore be considered as uncertain since there is a contradictory of using heavy ice-reinforcement on light crafts.

Another uncertainty is the abrasion and corrosion marginal t_c. It is clearly stated for steel but since the rules do not cover aluminium an assumption regarding this marginal is made in that case. Aluminium possesses greater corrosion properties than steel which could imply that the marginal could be kept the same. However abrasion is taken into consideration as well in this marginal and since steel is harder than aluminium some addition in thickness is necessary. This assumption has a great affect on the resulting plate thickness and should therefore be more investigated in the future, if there will be a demand for ice-reinforcement of an aluminium light craft.

The ice-reinforcement was established with regards to the existing engine effect, which was lower than what was required by the rules. This gives a lower ice pressure which in the end leads to a “weaker” structure than if the engine effect required by the rules would have been used. This adaption is used for both materials which is assumed to lead to a fair comparison.

8.3 Larger vessels

For larger vessels the weight can probably be reduced since the plating thickness is a main contributor to the total hull weight. The result from the analysis of the bottom plating should be a good indication to if using high strength steel compared to steels commonly used today can reduce the total weight of the hull. The yield strength of Weldox 700 E Offshore is almost twice as high as for the regular steel but still the weight reduction for the bottom plating is only about 10-20%. The reason why not more material can be reduced is that in Equation (7.1) the term that considers the yield strength is only a small part of the total minimum thickness. Without that term the thickness requirement is 7 mm for both steels. The reason for this is that the steels have similar abrasion and corrosion characteristics.

The simplified analysis of the steel ships does not include buckling. If buckling would be the dimensioning factor for a component in a steel ship the regular steel would be preferred instead of Weldox 700 E Offshore. They have the same strength against buckling and the same density but the regular steel costs less. If this only regards a small part of the vessel it could still be better to use the same material for the entire hull.

9 Conclusions

The main objective of this thesis is to analyze and estimate differences in weight between using aluminium and high strength steel in light craft design. This is conducted by analysing two different vessels, a passenger ferry and a high speed craft, with similar size. The passenger ferry is analyzed with and without ice-reinforcement. This analysis resulted in 3 different light craft designs from which the differences in weight between the aluminium and high strength steel could be studied. The two materials under consideration are Weldox 700 E Offshore with a yield stress of 690 MPa and NV5083 with a yield stress of 215 MPa. Two sections, placed at the midship and forward region, and one watertight bulkhead is considered. In addition to the light craft study a simplified analysis regarding larger vessels was conducted. This analysis compared Weldox 700 E Offshore with steel that has yield strength of 360 MPa. The structural analysis and design loads are based on regulations from DNV.

The conclusions drawn from the analysis are as follows:

- Weight reduction by using high strength steel is not successful for any of the three different light craft designs according to the method used. For every vessel aluminium is proven to give a lighter design.
- The high speed vessel shows best results in terms of total weight. As mentioned in Section 8.1 this could be due to the higher loads acting on the vessel. If this is true then this means that a higher speed and tougher service conditions makes high strength steel more beneficial.
- The DNV light craft rules for aluminium and steel are originated from different backgrounds. Their different origin and development give rise to inconsistency when comparing them. This provides uncertainties for the analysis and results.
- Figure 6.16 shows that using high strength steel, compared to aluminium, for the passenger ferry with additional ice-reinforcement is the worst case. However, the results for the ice-reinforced passenger ferry are not reliable. One of the reasons is that ice-reinforcement for a light craft design is considered to be contradictory. Another reason is that the ice class rules are not applicable to aluminium which gives unreliable result.
- For large vessels the minimum thickness reduction is enough to create an interest for further investigations.
- Methods for manufacturing high strength steel vessel are limited which then limit the minimum dimensions of stiffeners, hull plates, etc.

The final conclusion is that this thesis can be considered as a pre-study of introducing and evaluating high strength steel for mainly light crafts but also for larger vessels. A full assessment would require a more extensive analyze with different studies in other segments of light craft construction and design. These additional studies are summarized and presented in Section 10.

10 Future work

This thesis is the first step in analysing if high strength steel such as Weldox 700 E Offshore is a reasonable alternative to aluminium for light crafts. In order to make fair comparisons additional studies are recommended. The first step is to conduct the following studies:

- Make direct calculations in order to investigate if exceptions can be made from the light craft rules.
- The watertight bulkheads should be further investigated to see if the steel thickness can be reduced or if the aluminium thickness should be increased.
- Since the spacing of the web frames in this thesis are the same as the original designs the impact of having different spacing for steel and aluminium should be investigated in order to see how this would affect the total weight.
- Study the effect of using different stiffener spacing for the different materials.
- A study of how other profiles for stiffeners would affect the weight of the vessels.

If the results from the studies above conclude that high strength steel is interesting for light crafts the following studies could be conducted:

- Investigate what market demand for Weldox 700 E Offshore that is required for the supplier, SSAB, to manufacture sheets thinner than 4 mm and also compare the purchase price with aluminium.
- If there is an interest in using both high strength steel and aluminium for different parts of the hull a study of how they can be joined and if there are other difficulties should be conducted.
- Investigate the effects of the dimensions with regards to fire since this was not a part of this thesis.
- Study how well the ice class rules apply to aluminium and what a reasonable abrasion and corrosion margin for aluminium would be.
- A study of welding of Weldox 700 E Offshore with regards to smaller dimensions to estimate the manufacturing cost and also to find which dimensions that are reasonable to work with.

The thesis also included a study of high strength steel as an alternative to regular steel for large vessels. The following studies should be made before drawing conclusion if it is reasonable to use Weldox 700 E Offshore instead of the today commonly used steels:

- A more extensive study of the dimension requirements for one or two sections of a large ship.
- The purchase price for the steels should be compared.
- The manufacturing parameters should be investigated to find the manufacturing costs of a vessel in both materials.

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Appendix A Material specifics

This appendix contains material parameters used in the thesis.

A1. High strength steel (Weldox 700 E Offshore)

Young's modulus: $E = 210\ GPa$

Density: $\rho = 7860\ \ kg/m^3$

Yield stress: $\sigma = 690\ MPa$

Ultimate strength: $\sigma = 770\ MPa$

Material factor: $f_1 = 2.88$

A2. Aluminium (NV5083)

Young's modulus: $E = 71\ GPa$

Density: $\rho = 2660\ \ kg/m^3$

Yield stress: $\sigma = 215\ MPa$

Ultimate strength: $\sigma = 305\ MPa$

Material factor: $f_1 = 0.60$

Appendix B Vessel specifics

This section describes the data used for the vessels.

B1. The passenger ferry

The vessel is designed for inshore conditions and can totally carry about 450 passengers. It is ice-reinforced. The vessel is not approved by any classification society, but the Swedish Maritime Administration has approved it.

Length between perpendiculars: $L = 30\ m$

Moulded breath: $B = 8\ m$

Moulded depth: $D = 3\ m$

Fully loaded draft: $T = 1.4\ m$

Fully loaded displacement: $\Delta = 150\ t$

Block coefficient: $C_B = \frac{\Delta}{1.025\mathrm{LBT}} = 0.43$

Maximum speed: $V = 12\ knots$

Engine output: $P_s = 2 * 280\ kW$

Wave coefficient: $C_W = 0.08L = 2.4$

Wave coefficient due to service restriction R4: $C_{W,rest} = C_W(1 - 0.4) = 1.44$

Frame spacing for web frame at 0.5L: $s = 750\ mm$

Frame spacing for web frame at 0.9L: $s = 1125\ mm$

B2. The high speed vessel

This vessel is designed for offshore conditions and is classed as a high speed light craft with additional class as patrol boat.

Length between perpendiculars: $L = 18.2\ m$

Moulded breath: $B = 5.66\ m$

Moulded depth: $D = 2.55\ m$

Fully loaded draft: $T = 1.1\ m$

Fully loaded displacement: $\Delta = 62.8\ t$

Block coefficient: $C_B = \frac{\Delta}{1.025\mathrm{LBT}} = 0.49$

Maximum speed: $V = 38\ knots$

Wave coefficient: $C_W = 0.08L = 1.46$

Frame spacing for both web frames considered: $s = 600\ mm$

Appendix C Design loads

This appendix contains calculated design loads for the stiffeners used in this thesis. The loads of the plating are of the same magnitude at the loads of the stiffeners.

Table C1 Slamming pressure [kPa].

	Section at midship	**Section at forward**
Passenger ferry	-	-
High speed vessel	76.61	55.92

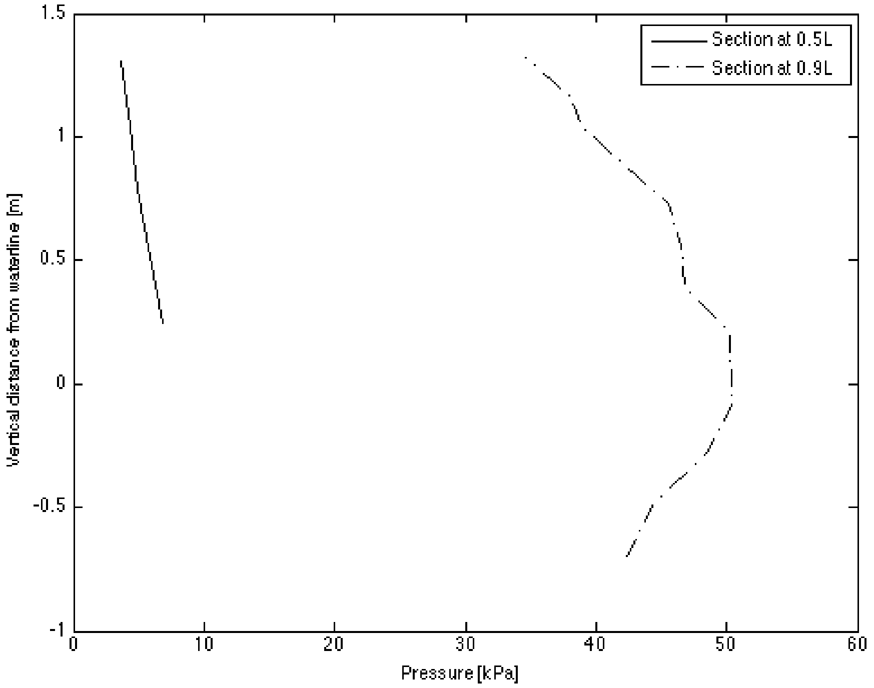

Figure C1 Fore body side and bow impact pressure on the passenger vessel.

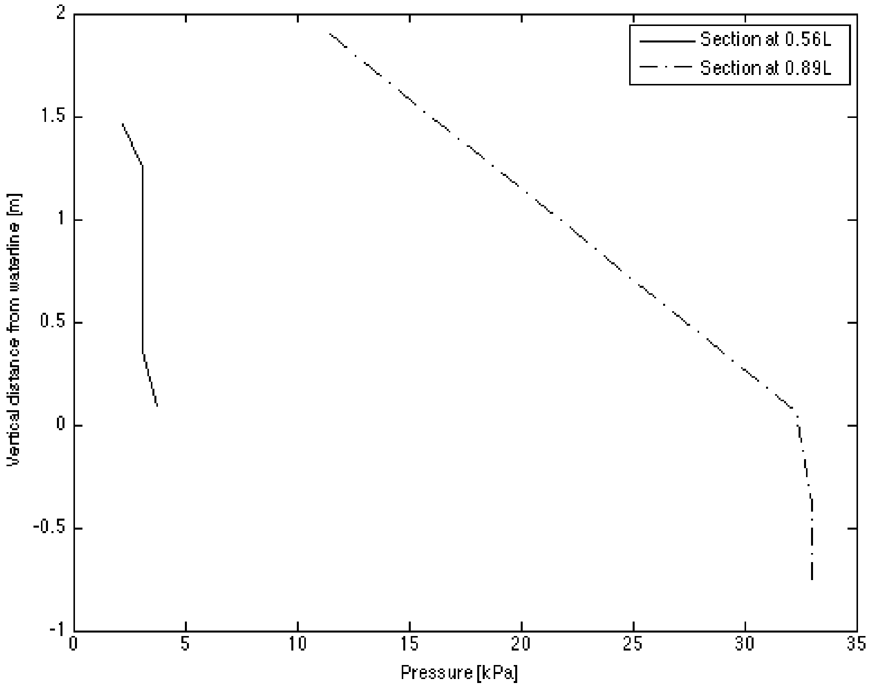

Figure C2 Fore body side and bow impact pressure on the high speed vessel.

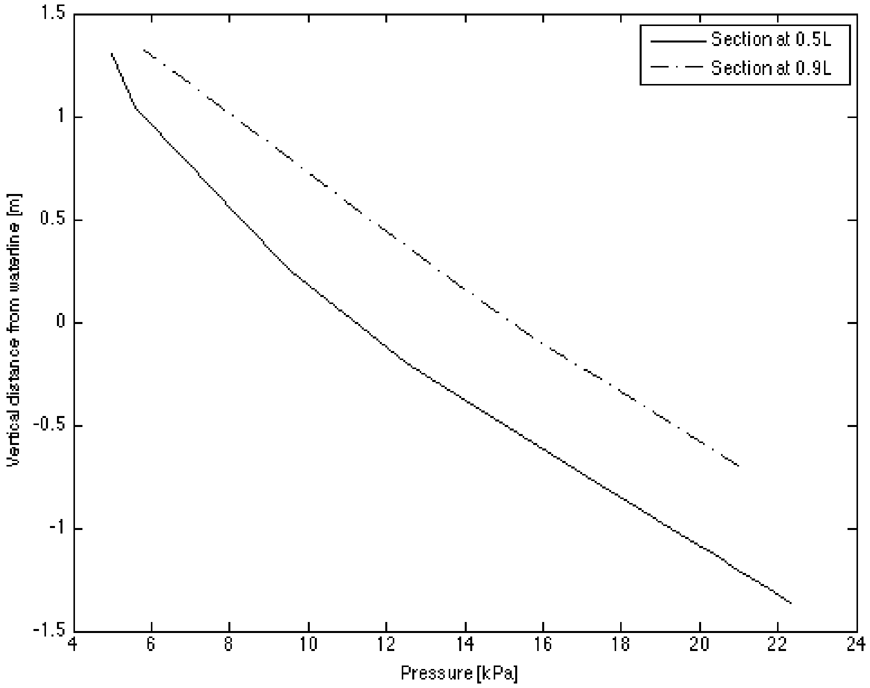

Figure C3 Calculated sea pressure acting from the top to the bottom of the hull for the passenger vessel.

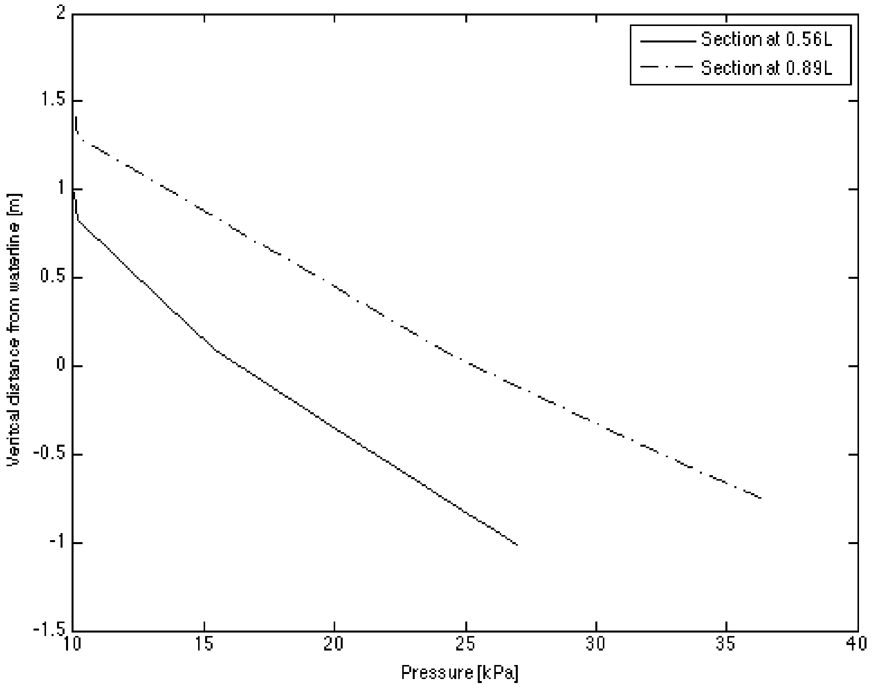

Figure C4 *Calculated sea pressure acting from the top to the bottom of the hull for the high speed vessel.*

Table C2 *Calculated deck pressure acting on passenger ferry and high speed vessel [kPa].*

	Section at midship	**Section at forward**
Passenger ferry	7.36	9.32
High speed vessel	9.54	37.53

Table C3 *Calculated sea pressure acting on the watertight bulkhead. Pressures are presented from the top to the bottom of the bulkhead [kPa].*

Passenger ferry	**High speed vessel**
4.25	7.50
7.65	8.70
10.85	9.35
10.30	12.70
	13.35
	13.90
	14.95
	15.00
	15.55

Table C4 *Calculated sea pressure of the ice-reinforced area of the passenger vessel [kPa].*

Structure	**Section at 0.5L**	**Section at 0.9L**
Plating	605.7	1 336.6
Longitudinal stiffeners	541.8	976.1
Web frames	383.1	690.2

Appendix D Stiffener requirements

This appendix presents the required sectional modulus for the passenger ferry, the high speed vessel and the ice-reinforced passenger ferry as well as the required area of the stiffeners of the ice-reinforced passenger ferry.

D1. The passenger ferry

The hull stiffeners at section 0.5L are subjected to sea pressure and fore body side and bow impact pressure. For the section at 0.9L both the sea pressure and the fore body side and bow impact pressure are considered. Since the fore body side and bow impact pressure is higher, this is the pressure that determines the requirement. The required sectional modulus of the hull stiffeners is presented in Table D1. The stiffeners are numbered from the bottom to the top.

Table D1 Required sectional modulus of the hull stiffeners of the passenger vessel [cm^3].

	Weldox 700 E Offhore		**NV5083**	
Stiffener	Section at 0.5L	section at 0.9L	Section at 0.5L	Section at 0.9L
1	0.6	-	3.8	-
2	0.6	-	3.7	-
3	0.6	-	3.6	-
4	0.6	-	3.5	-
5	0.6	-	3.4	-
6	0.6	2.7	3.4	66.8
7	0.5	2.8	3.2	70.0
8	0.5	3.1	3.1	76.4
9	0.5	3.2	2.9	79.5
10	0.5	3.2	2.7	79.2
11	0.4	3.0	2.4	73.8
12	0.3	2.9	2.1	73.3
13	0.3	2.9	1.6	71.7
14	0.2	2.7	1.4	66.4
15	0.2	2.5	1.2	61.4
16	0.2	2.4	0.9	60.1
17	0.1	2.2	0.8	54.5

The required sectional modulus of the deck stiffeners on the deck plating is determined by the pressure from the passengers. The required sectional modulus is presented in Table D2.

Table D2 The required sectional modulus of the deck stiffeners of the passenger vessel [cm^3].

	Weldox 700 E Offshore	**NV5083**
0.5L	0.2	1.2
0.9L	0.6	14.7

The load of the stiffeners on watertight bulkhead is varying with regards to the length of each stiffener. The highest load is chosen to dimension all the stiffeners so that they have the same size. The required sectional modulus of the bulkhead stiffeners are presented in Table D3.

Table D3 The required sectional modulus of the stiffeners on the watertight bulkhead of the passenger vessel [cm^3].

NV 5083	2.4
Weldox 700 E Offshore	0.5

D2. The high speed vessel

The stiffeners of the high speed vessel in the original design in aluminium are assumed to fulfil the DNV requirements. The required sectional modulus of stiffeners is only investigated with regards to the high strength steel for this vessel.

Two loads dimension the stiffeners on the hull of the section at 0.56L. The bottom is dimensioned by the slamming pressure and the sides are dimensioned by the sea pressure. The hull of the section at 0.56L can be subjected to two loading cases. The first is fore body side and bow impact pressure and the second is the sea pressure, both pressures are acting on the entire hull. The fore body side and bow impact pressure is higher than the sea pressure for stiffeners number 2-4.The required sectional modulus of the hull stiffeners is presented in Table D4. The stiffeners are numbered from the bottom to the top.

Table D4 The required sectional modulus of the hull stiffeners of the high speed vessel in Weldox 700 E Offshore [cm^3].

Stiffener	**0.56L**	**0.89L**
1	1.3	-
2	1.3	0.6
3	1.3	0.5
4	1.3	0.5
5	1.3	0.5
6	1.3	0.4
7	1.3	0.4
8	1.3	0.4
9	0.2	0.3
10	0.2	0.3
11	0.2	0.2
12	0.2	0.2
13	0.2	0.2
14	0.2	0.2

The required sectional modulus of the deck stiffeners on the deck plating is determined by the pressure on deck which is higher for the section at 0.89L. The required sectional modulus is presented in Table D5.

Table D5 The required sectional modulus of the deck stiffeners of the high speed vessel in Weldox 700 E Offshore [cm^3].

	Sectional modulus
0.56L	0.2
0.89L	0.6

The load of the stiffeners on watertight bulkhead is varying with regards to the length of each stiffener. The highest load is chosen to dimension all the stiffeners so that they have the same size. The required sectional modulus of the bulkhead stiffeners is 0.4 cm^3.

D3. The ice-reinforced passenger ferry

The requirements of the stiffeners in the ice-reinforced area are presented in Table D6.

Table D5 The required sectional modulus [cm^3] and cross-section area [cm^2] of the ice-reinforced stiffeners of the passenger ferry.

		Required cross-section area	**Required sectional modulus**
NV 5083	0.5L	19.6	6.5
	0.9L	79.6	17.7
Weldox 700 E Offshore	0.5L	6.1	2.0
	0.9L	24.8	5.5

The required sectional modulus and cross-sectional are of the web frames in the ice-reinforced area are presented in Table D6.

Table D5 The required sectional modulus [cm^3] and cross-section area [cm^2] of the ice-reinforced web frames of the passenger ferry.

		Required cross-section area	**Required sectional modulus**
NV 5083	0.5L	15.1	27.6
	0.9L	40.8	74.5
Weldox 700 E Offshore	0.5L	4.7	8.6
	0.9L	12.7	23.2

Appendix E Web frame dimensions

This appendix describes the specific dimensions of the vessel designs that have not been presented in Sections 6.1 and 6.2.

E1. Passenger ferry

This section presents the dimensions of the web frames for the passenger ferry.

Table E1 The dimensions of the web frame profile of the section at 0.5L of the passenger ferry.

		Weldox 700 E Offshore	**NV5083**
Bottom and side	Flange breath	60	98
	Web height	200	325
	Profile thickness	4	6.5
Deck	Flange breath	45	75
	Web height	150	250
	Profile thickness	3	5

Table E2 The dimensions of the web frame profile of the section at 0.9L of the passenger ferry.

		Weldox 700 E Offshore	**NV5083**
Bottom	Flange breath	45	83
	Web height	150	275
	Profile thickness	3	5.5
Side	Flange breath	45	68
	Web height	150	225
	Profile thickness	3	5
Deck	Flange breath	38	68
	Web height	125	225
	Profile thickness	3.5	4.5

E2. High speed vessel

This section presents the dimensions of the web frames for the high speed vessel.

Table E3 The dimensions of the web frame profile of the section at 0.56L [mm].

		Weldox 700 E Offshore	**NV5083**
Bottom (not at the tank)	Flange breath	38	80
	Web height	120	200
	Profile thickness	2.5	8
Side	Flange breath	38	85
	Web height	115	200
	Profile thickness	2.5	5
Deck	Flange breath	38	85
	Web height	115	200
	Profile thickness	2.5	5
Deck and side at the corner	Flange breath	45	-
	Web height	150	-
	Profile thickness	3	-
Over tank	Flange breath	38	60
	Web height	125	100
	Profile thickness	2.5	5
Below tank	Web height	125	200
	Profile thickness	2.5	8

Table E3 The dimensions of the web frame profile of the section at 0.89L [mm].

		Weldox 700 E Offshore	**NV5083**
Bottom (by the tank)	Flange breath	25	50
	Web height	70	200
	Profile thickness	3	7
Side	Flange breath	20	50
	Web height	70	200
	Profile thickness	3	5
Deck	Flange breath	15	80
	Web height	70	150
	Profile thickness	3	5
Over tank	Flange breath	15	50
	Web height	50	100
	Profile thickness	3	7
Below tank	Web height	100	150
	Profile thickness	3	7