Parametric FE-modeling of High-speed Craft Structures

Version 1.0

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2012 - 12 - 06

Abstract

The primary aim of the thesis was to investigate aluminum as building material for high speed craft, study the hull structure design processes of aluminum high speed craft and develop a parametric model to reduce the modeling time during finite element analysis. An additional aim of the thesis was to study the degree of validity of the idealizations and the assumptions of the semi-empirical design methods by using the parametric model.

For the aluminum survey, a large amount of scientific papers and books related to the application of aluminum in shipbuilding industry were reviewed while for the investigation of hull structure design, several designs of similar craft as well as all the classification rules for high speed craft were examined. The parametric model was developed on Abaqus finite element analysis software with the help of Python programming language. The study of the idealizations and the assumptions of the semi-empirical design methods was performed on a model derived by the parametric model with scanltings determined by the high speed craft classification rules of ABS.

The review on aluminum showed that only specific alloys can be applied on marine applications. It also showed that the effect of reduced mechanical properties due to welding could be decreased by introducing new welding and manufacturing techniques. The study regarding the hull structure design processes indicated that high speed craft are still designed according to semi-empirical classification rules but it also showed that there is tendency of transiting on direct calculation methods. The developed parametric model does decrease the modeling time since it is capable of modeling numerous structural arrangements. The analysis related to the idealizations and the assumptions of the semi-empirical design methods revealed that the structural hierarchy idealization and the method of defining boundary by handbook type formulas are applicable for the particular structure while the interaction effect among the structural members is only possible to be studied by detailed modeling techniques.

Keywords: high speed craft, aluminum, hull structure design, finite element analysis, parametric modeling

Acknowledgements

First and foremost I would like to express my deepest gratitude to my supervisor, Mike Razola, for his excellent guidance, patience and dedication during my master thesis project.

I would like also to thank Dr. Rosen, for his critical comments and interventions which kept be on the right track.

Finally, I would like to thank my family, for supporting and encouraging me with their best wishes during the whole period of my master's studies.

Contents

Chapter 1

Introduction

High speed craft is a particular category of ships which have as main characteristic the ability of achieving high speeds. The category is mainly comprised by patrol craft, special operation military vessels as well as fast passenger ferries. The principle of the category, apart from high engine power, requires a lightweight hull structure but with sufficient strength to withstand all the loads that are derived during the operation. Therefore, great emphasis is given to the choice of structural material as well as to the hull structural design.

Aluminum is one of the major structural materials that has been used extensively for more than half a century for building high speed craft. It offers similar production cost and manufacturing simplicity with steel but with significant less weight. Nevertheless, there are still concerns regarding the application of it on high speed craft due to the fact that it experiences reduced mechanical properties and performance after the welding process [1].

Hull structural design is a process where the hull structure arrangement as well as the scanltings of the craft are derived. Such a design process is conducted either by taking account similar craft, either according to semi-empirical classification rules or by more explicit design methods such as the direct calculation methods. The majority of high speed craft have their hull structure designed according to semi-empirical rules of a classification society. However, every classification society publishes its own rules based on different requirements. Hence, the structural outcome differs among the classification societies even for the same craft with the same structural arrangement [2]. The direct calculation methods provide the most explicit hull structure designs since they provide an opportunity to study the loads and the structural mechanics of the craft in detail. For instance, it is possible to study the interaction among the structural components of the craft on which the previous methods did not provide a clear picture. However, deriving the hull structure through the process of direct calculation methods is time consuming especially in the research field where numerous structural arrangements have to be modeled and tested.

The present thesis conducts an extensive literature survey regarding aluminum as structural material for high speed craft. The scope of the review is to report the marine aluminum alloys and their properties, to identify the causes that make aluminum experiencing reduced mechanical properties and performance after welding and to introduce new welding and manufacturing techniques which minimize the aluminum's drawback.

Regarding the hull structural design of high speed craft, the thesis maps three hull structure design processes. In the first process it introduces several designs of similar high speed craft. In the second process it identifies the differences among the hull structural requirements of all the classification rules while for the third design process, it collects relevant information regarding the direct calculation methods and develops a parametric model which reduces the modeling time during finite element analysis. In addition, within the thesis stand a finite element analysis which examines and comments which idealizations and assumptions of the semi-empirical design methods reflect the actual structural situation.

Chapter 2

Literature Survey Of Aluminum Alloys

2.1 Historical Review Of Aluminum

Sir Humphry Davy at the beginning of 19^{th} century was the first who identified as individual element the aluminum. Despite Davy's invention, aluminum was first subscribed to the science community as a unique element twenty years later from the research of Whoeler [3]. The production of aluminum started at the same century when Touissant Hrnoult and Charles Martin Hall individually but at the same time, managed to develop a production based on electrolytic process [3].

The aeronautical industry was the first industry where aluminum found applications. It substituted material such as wood and tissues for the construction of zeppelin frames [1]. Aluminum found applications in the marine industry during the last decade of 19^{th} century where it was used for the shell plating of sailing boats. One sailing boat of 19^{th} century that had aluminum as construction material was the famous "Defender" which won the American cup of fast ships at 1895 [4].

After the end of second world war, aluminum became more popular and found usage in various applications relevant to vehicle industry. The reasons of gaining such popularity were the drop of the production price compared to steel and the application of arc welding which replaced the old fashioned riveting as joining technique [1]. The increasing demand of lightweight materials and higher speed performance sparked the scientific society to conduct more research regarding aluminum alloys and their applications.The results of these researches were extraordinary. New aluminum alloys with enhanced mechanical properties such as corrosion resistance and improved strength at the heated affected zone were introduced. Production techniques such as extrusion emerged to reduce the number of welding seams. New joining techniques such as friction stir welding and adhesive bonding were invented so the join of two panels is possible without the heat affected zone drawback.

2.2 Types Of Aluminum Alloys For Marine Applications

The technological innovations during the last 70 years made aluminum a primary structural material for the shipbuilding industry [5]. In large merchant vessels, aluminum find applications on the design of the vessel's superstructures as well as on the design of cargo tanks in LPG vessels and on decks in RO-RO ships. On the high speed craft category where the structural weight is critical factor of the craft's performance, aluminum with its unique characteristics such as lightness, capability to form any kind of shape or profile and weldability, stand as the dominant material for the complete hull structure [5].

However, not all aluminum alloys are capable to fulfill the design and the operational needs of high speed vessels. Fundamentally, the suitable aluminum alloy must be able to withstand all the loads that the vessel will experience during its operation life. This means that it must have adequate strength for the loads and at the same time, adequate fatigue performance to last for the whole operation period. The alloy must be also processable to various shapes and advanced profiles in rational production time in order to fulfill the construction demands of the vessel. Furthermore, it must be weldable so panels and large sections can be manufactured. Since vessels operate in a marine environment, the aluminum alloy must also be corrosion resistant. Ultimately these demands, must be combined with reasonable production cost which is competitive to other building materials [1, 4]. The above requirements, are summed up to the following:

- Good corrosion resistance
- Adequate strength, stiffness and fatigue performance
- Functionality to manufacturing technologies such as welding
- Ability to form advanced profiles and diversity of shapes
- Competitive production and material cost

All aluminum alloys have an identification system so they can be distinguished from each other. The identification system contains a series of 4 digits followed by a string. The first digit of the 4 digit code reflects the main chemical composition of the alloy. The rest 3 digits represent a specific alloy composition. The string that follows is used to identify if the alloy can be strengthened from work hardening or if it is heat treatable. The heat treatable property is represented by the letter [T] while the work hardening is represented with the letter [H] [1].

The alloys that satisfy these requirements are the aluminum-magnesium alloys (series AA5-xxx) and aluminum-magnesium-silicon alloys (series AA6-xxx) [4]. The 5xxx-series alloys are not heat treatable, but they can gain additional strength via work hardening and their products are often sheets and rolls. The 6xxx-series are alloys on which thermal treatment can be applied. Usually, 6xxx-series alloys are used for extrusion products [4]. The products of 5-xxx series which are plates and stiffeners and the premade extrusion panels from 6-xxx series cover the major needs of construction material of high speed craft industry [1].

However, not all alloys with 5xxx and 6xxx composition satisfy the requirements and are suitable for usage in marine applications. There are only a certain number of the 5xxx series listed at ASTM B 928-04 that are accepted from classification societies as construction material for high speed craft. Regarding 6xxx series, the classification societies are more strict. They state that the alloys of 6xxx-series must not be directly in contact with sea water unless they are painted or anodes are mounted on the surface [1].

The table 2.1 illustrates in terms of percentage, the chemical composition of the most usual aluminum alloys for shipbuilding industry.

Table 2.1: Chemical composition of marine aluminum alloys [1]

Alloy	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**
5059	0.45	0.5	0.25	0.60-1.2	5.0-6.0	0.25	0.4-0.90	0.20
5083	0.40	0.4	0.1	0.4-1.0	4.0-4.9	0.05-0.25	0.25	0.15
5086	0.40	0.5	0.1	0.20-0.70	4.0-5.2	0.25	0.40	0.15
5383	0.25	0.25	0.20	0.7-1.0	4.0-5.2	0.25	0.40	0.15
5454	0.25	0.40	0.10	0.50-1.00	2.4-3.0	0.05-0.20	0.25	0.20
5456	0.25	0.40	0.10	0.50-1.00	4.7-5.5	0.05-0.20	0.25	0.20
6005A	0.50-0.90	0.35	0.30	0.50	0.40-0.70	0.30	0.20	0.10
6061	40- 80	0.7	0.15-0.40	0.15	0.80-1.20	0.04-0.35	0.25	0.15
6063	0.2- 0.6	0.35	0.10	0.10	0.45-0.90	0.10	0.10	0.10
6082	0.7-1.3	0.50	0.10	0.40-1.0	0.6-1.2	0.25	0.20	0.10

2.3 Mechanical Properties Of Aluminum Alloys

Aluminum is a metal with unique mechanical and technological properties. Compared to steel or wood, aluminum is considered as a new construction material in heavy industries. To make an impact into the heavy industry, a comparison between the major competitor, the steel, must be done in order to identify the conditions and the fields where aluminum is more efficient than steel [3]. Such a comparison must include all the mechanical and technological properties of both materials that have been gathered from various experiments and tests.

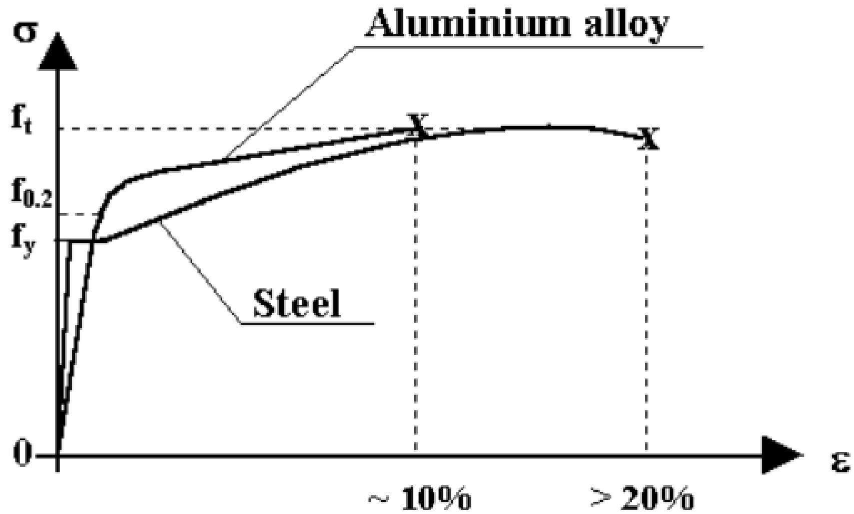
The table 2.2 depicts the comparison between some of the physical properties of aluminum and steel that extracted form the research conducted in [4]. The figure 2.1 which was created by the experiments held in [3], illustrates the stress-strain curves of a typical aluminum alloy and mild steel. The f_t, $f_{0.2}$ and f_y which depicted in the figure correspond to the ultimate strength, elastic limit and yield stress respectively. The comparison of [3] showed that both the curves of steel and aluminum had linear elastic slope until their elastic limit while the result of the ultimate deformation was close to 10% and 20% for aluminum and steel respectively. The research also showed that aluminum tends to be more sensitive in thermal variation where the thermal coefficient ranges from $19 * 10^{-6}$ to $25 * 10^{-6}$, twice as much of steel's. Furthermore, the results of [3] showed that the ultimate strength and the elastic limit ratio were lower in steel while the residual stress from thermal deformation was 30% larger in aluminum.

The tensile stress tests conducted in [1] and the stress-strain curves that derived from these tests showed an additional difference related to the mechanical behavior of the two metals. The aluminum does not have a specific yield point and it keeps deforming elastically instead of experiencing softening. Such mechanical behavior is justified due to the elastic module difference which is up to 70% between aluminum and steel [1].

Table 2.2: Comparison between physical properties of aluminum alloys and steel [4]

Physical property	**Aluminum alloys**	**Construction mild steel**
Density kg/m^3	2700	7850
Young Modulus Mpa	72000	205000
Thermal conductivity W/m $^\circ K$	235	79
Melting temperature $^\circ C$	$550 \div 650$	~1500
Oxides melting temperature $^\circ C$	2060 (Al_2O_3)	$800 \div 900$ (FeO, Fe_2O_3, Fe_3O_4)
Electrical resistivity Ohm cm	$\sim 2.65 * 10^{-6}$	$\sim 10 * 10^{-6}$
Relative magnetic permeability	< 1 (paramagnetic)	80-160 (ferromagnetic)
Crystalline structure (elementary cell)	single-phase CFC	two-phase CBC-CFC

Figure 2.1: Comparison between typical stress-strain curves of aluminum alloys and mild steel [3]



Experimental tests regarding the mechanical properties of aluminum and steel were conducted in [6] as well. The primary scope of the research was to identify the level of influence of the manufacturing processes on the mechanical properties of the two metals. The conclusion was that both the Young's Modulus [E] and Poisson's Ratio [v] were affected from the manufacturing process. More specifically the Young's Modulus [E] was increased with strain hardening for aluminum and decreased for steel. In research was also asserted that during the cold rolling process both aluminum and steel increased their strength while their ultimate elongation decreased.

A thorough investigation of the mechanical properties of 5xxx-series and 6xxx-series relevant to the marine applications was done in [1]. The table 2.3 summarize the extracted results of [1] including properties such as yield stress, ultimate strength, density and elastic modulus for various marine aluminum alloys at their base form.

The values in table 2.3 correspond to the base properties of the alloys and are relevant for joining techniques that do not include welding process. Aluminum mechanical properties alternate when the metal is subjected to welding processes. The mechanical properties of the welded aluminum products tend to be weaker than the base metal properties [1]. An endeavor to

Table 2.3: Mechanical properties of marine alloys [1]

Alloy and Temper	Thickness Range $[mm]$	Ultimate Strength $[Mpa]$	Yield strength $[Mpa]$	Elastic Modulus $[Mpa10^3]$	Density $[g/cm^3]$
5059-H111 (E)	3.0-50	329	160	-	2.66
5059-H116 (S & P)	3.0-20	438	270	-	2.66
5059-H116 (P)	20.1-50	359	259	-	-
5059-H321 (P)	3.0-20	369	270	-	-
5059-H321(S & P)	20.1-50	359	259	-	-
5083-H111 (E)	<=130	275	165	-	2.66
5083-H116 (S & P)	4.0-40	305	215	71.0	2.66
5083-H116 (P)	40-80	285	200	71.0	2.66
5083-H321 (S & P)	1.6-38	303	214	71.0	-
5083-H321 (P)	38.1-76.5	283	200	-	-
5086-H111 (E)	<=130	250	145	-	2.66
5086-H116 (S & P)	All	275	195	71.0	2.66
5383-H-112 (E)	-	310	190	71.0	2.66
5383-H116 (P)	<20	305	215	71.0	2.66
5454-H111 (E)	<=130	230	130	71.0	2.66
5454-H32 (S & P)	0.5-50	250	180	71.0	2.66
5456-H116 (S & P)	4.0-12.5	315	230	71.0	2.66
5456-H116 (P)	12.51-0.0	305	215	71.0	2.66
5456-H116 (P)	40.01-80	285	200	71.0	2.66
6005A-T61 (E)	-	260	240	68.9	2.70
6061-T6 (E)	All	260	240	68.9	2.70
6063-T6 (E)	All	205	170	68.9	2.70
6082-T6 (E)	All	310	262	-	2.70

define the differences between the pre-welding and post-welding properties was held in [7]. A graphical image of two stress-strain curves was created by tensile coupon tests of 5383-H116 alloy in an attempt to define the differences in yield stress, ultimate tensile stress and fracture strain between the post-welded and the pre-welded condition. However, in the experimental tests , the Elastic Modulus [E] of the 5383-H116 aluminum alloy was considered as 75 Gpa instead of 70 Gpa. Due to that variation, their base mechanical properties are different from the mechanical properties of [1]. The results that were published from the research are illustrated in table 2.4.

In an attempt to formally present the mechanical properties of the marine aluminum alloys that can be accepted as construction material, various organizations such as classification societies published results mentioning the yield stress after welding of several aluminum alloys. Nevertheless, the results were discouraging due to the large variations among the published

Table 2.4: Mechanical properties of 5383-H116 for welded and unwelded condition [7]

Mechanical Properties	Yield stress $[Mpa]$	Ultimate tensile stress $[Mpa]$	Fracture Strain %
Unwelded alloy of 5383-H116	262	356	15.04
Welded alloy of 5383-H116	160	306	15.94

values of each organization [1]. Part of the study of [1] was to gather the data of the most renowned organizations that conducted and published relevant research and formulate a database. The table 2.5 which is a reproduction of the table that stands in [1] depicts the yield stress values that the organizations published for various marine aluminum alloys in welded condition.

Table 2.5: Published yield stress results of welded aluminum [1]

Alloy	Type	ABS $[Mpa]$	DNV $[Mpa]$	Aluminum association $[Mpa]$	AWS Hull Welding $[Mpa]$	ALCAN $[Mpa]$	US NAVY $[Mpa]$
5086-H32	E	-	92	95	-	-	97
5086-H111	P	131	92	95	131	-	152
5086-H0	E	124	92	95	124	-	110
5086-H116	P	131	92	95	131	-	152
5083-H111	E	145	-	110	145	-	-
5083-H116	P	165	116	115	165	125	-
5383-H111	E	145	-	-	-	145	-
5383-H116	P	145	140	-	-	145	-
5454-H111	E	110	76	85	110	-	110
5454-H34	P	110	76	85	110	-	110
5454-H32	P	110	76	85	110	-	-
5456-H111	E	165	-	125	165	-	145
5456-H116	P	179	-	105	179	-	179
6061-T6	E,P	138	105	80	138	-	-

The main reason of these differences at the published results of the organizations, come from the different interpretation of the heat affected zone (HAZ). The heat affected zone is the joining area that suffers from microstructure change due to welding [8]. Some organizations consider as heat affected zone only the weld metal area, resulting in a 50 mm gage while others count an additional area of the base metal, resulting in a gage of 250 mm [5]. Another rational approach is the conceptualization of DNV which consider an area three times the average thickness of the welding materials. The most accurate procedure to approximate the heat affected zone is however by taking hardness measurements on the welded material. [7].

Notwithstanding, the actual reduction of the mechanical properties of aluminum alloys is still controversial. The scientific society claims that the approximation of the heat affected zone is a multi-parametric task where parameters such as thickness and alloy composition affect the outcome significantly. In [9] it is asserted that thicker plates have different range of heat affected zone and for a multi pass welding without limits in the temperature in a thick material, the heat affected zone can reach up to 75 mm. Moreover, in [9] an equation that approximates the heat affected zone in thick sheets was modeled. The equation had the following form of:

$$HAZ = \sqrt{\frac{A_w}{N}}$$

where $[A_w]$ is the total weld section area and $[N]$ is the number of heat flow paths [9].

Regarding the interaction between the composition of the alloy and the heat affected zone, the study in claimed [10] that due to an effect known as overageing, a welded 6xxx-series alloy will have significant reduction in its mechanical properties at the heat affected zone compared to 5xxx-series alloy which is strain hardened because the 6xxx-series include a different composition of Magnesium and Silicon than 5xxx-series alloys [10]. On the other hand, the welding process in strain hardened alloys such as 5xxx-series does not have such an impact in strength values. For instance, the AA5754-H32 alloy that used in [11] had 8% strength reduction in heat affected zone.

As rule of thumb it can be stated that the reduction magnitude of the strength of marine aluminum alloys is about 30% to 50% if the heat affected zone considered to be in a range of 10 to 30 mm and claim is supported in [5, 10].

2.4 Corrosion Performance

One of the characteristics of aluminum is that it has an oxide layer on its surface which acts as a natural corrosion protection. This characteristic makes aluminum favorable to marine structures where the environment is highly corrosive due to the contact of the structure with the sea water. The 5xxx-series and 6xxx-series aluminum alloys which are used for marine constructions, have additional corrosion resistance due to their element composition. The corrosion performance of these alloys is characterized as excellent and many aluminum ships that have been built from these series and operated for more than 30 years have no signs of corrosion [1].

When comparing the two marine series, it can be stated that the 5xxx-series excels the 6xxx-series in terms of corrosion resistance. Tests that conducted during the 1950s and 1960s, confirm that the maximum corrosion from pitting, localized corrosion which leads to small holes in the metal, was 0.18 mm and 0.86 mm for 5xxx-series while for 6xxx-series was 1.3 mm and 1.65 mm for 5 and 10 years of immersion respectively [5].

However, there are more corrosion types than pitting corrosion that affect the marine aluminum alloys. The exfoliation, intergranular and stress-corrosion cracking are three types of corrosion that significantly affect all the 5xxx-series with Magnesium percentage over 3% while the corrosion-erosion type affects most of 6xxx-series. Regarding cavitation corrosion, both series have poor resistance and are not recommended for areas or components such as propellers where the occurrence of the cavitation phenomenon is regular. Concerning the galvanic and crevice corrosion, both series are prone to these types of corrosion if another metal is mounted nearby and creates an anodic environment [1].

Concluding, aluminum has good corrosive properties by its nature and in combination with anti-fouling paints create a product which is unlikely to be affected from any type of corrosion.

2.5 Fatigue Performance

Fatigue is the structural failure that occurs under cyclic loading. In ships, there are two major sources of fatigue loading. The first one is due to the encounter of sea waves while the ship is sailing and the other is due to the vibrations that are created by the machinery during the operation of the craft [1].

In aluminum craft, many of the scantlings are determined based on the fatigue performance. For that reason, fatigue analysis must be conducted at the early stages of the design in order to identify the components that are prone to fatigue [5].

The fatigue analysis is conducted by resistance data that have a form of $[S - N]$ curve. The $[S]$ represents the stress range while $[N]$ represents the number of cycles before the failure of the component occurs. In an idealized case, the designer is able to define, in a stress range $[S]$, the number of load fluctuations $[n]$, that have been applied during the operation that did not exceed the number of cycles before the failure $[N]$. In reality though, fatigue analysis for ships is not that simple and most likely fatigue loading spectrums must be developed [12].

For aluminum structures, joints and especially weldings are the structural components that are most prone to fatigue failure due to heat affected zones that are created during the welding process. For that reason special interest was paid in these particular areas and various methods of assessing the fatigue life were developed from a number of renowned organizations related to the field [12].

Regarding ships and fatigue performance of marine aluminum alloys, DNV and Eurocode 9 developed assessment methods based on $[S-N]$ curves for welded joints with hot-spot stresses and in conjunction with nominal stress respectively [12].

Aluminum has poor fatigue performance compared to steel. The crack propagation in aluminum structures can be 8 times larger than steel if parameters such as residual stress and mean stress do not taken into account [13]. Tests conducted both in [1] and [5] strengthen this claim and reveled an even greater crack propagation growth rate, up to thirty time more, for the same time frame.

However, the aluminum's poor fatigue performance is not only because the material itself, it is because the problematic design and welding processes. The research of [14] showed that the samples that had been welded manually experienced significantly lower fatigue life compared to the samples that had been welded automatically by robots [14].

Improvement of welding process such as refine welding geometry with techniques like dressing, grinding and TIG remelting, introduction of new welding techniques such as friction stir welding (FSW) and building techniques such as extrusion could increase the fatigue life of aluminum structures significantly [14].

2.6 Joining Techniques

Welding is the joining of two metallic components via the unification of their attached edges. This unification can be achieved either by melting the two edges together, known as fusion welding, or by bonding the attached areas with the help of pressure and heat. The fusion welding is named autogenous when only the parent metals are melting and heterogeneous when additional filler of metals involved into the process [15]. The most usual welding processes for all metals are the gas metal welding arc (GMAW) or known as MIG and the gas tungsten arc welding (GTAW) or known as TIG.

The gas tungsten arc welding is characterized by the non-consumable tungsten electrode and the inert gas which is used to shield the electrode and the arc column, and to control the weld pool. The technique is mostly applied to thin components up to 6 mm thick because it provides excellent welding quality thanks to its ability to operate with low current [15]. For aluminum the TIG welding can operate both at direct and alternative current which is and the most common. For inert gas the TIG welding is using argon or helium or alternatively, a mixture of them which is by far the most efficient solution [15].

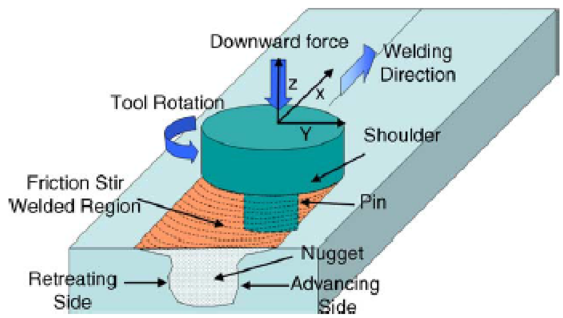
The gas metal arc welding (GMAW) or MIG is a welding process where the electrode is continuously consumed during the welding. A shield gas protects the arc and the weld pool from immediate contact to the atmosphere [15]. The gas metal arc welding functions with direct current when it is used for welding aluminum. Argon and helium are the gases used more often for the inert gas shield. Argon produces slower welding compared to helium and the best result both in terms of speed and on welding quality is achieved with a mixture of the gases. Furthermore, by creating a mixture of the gases, thicker welding can be achieved [15].

One advantage of the MIG over the TIG process is that the travel speed is greater, categorizing MIG technique as more cost effective. Furthermore, the welding penetration is deeper than TIG and for that reason is preferred for thicker plates and areas such as corners. The most critical advantage though, which is especially important for aluminum, is that the heat affected zone is smaller than the one produced with the TIG welding process. All the above advantages constitute the MIG as the most widely used welding process [15].

The gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) are dominating the welding processes of aluminum since the introduction of the material into the industry. However, a welding process that was invented at the early 1990s in United Kingdom by the The Welding Institute (TWI) brought revolution in the welding industry of aluminum [16]. The technique, named friction stir welding (FSW) and the idea behind, is relative simple but innovative.

The tool of the friction stir welding device consist two parts, a shoulder and a pin. A downward force presses the pin to fit between the two aluminum parts that will be welded and the shoulder to touch the welded surfaces. As seen in the figure of 2.2, the rotation of the device produces heat which softens the edges that are going to be welded and through the motility of the device towards the welding line, a flow propagates at the opposite direction creating a solid phase. During the process, no shielding gas or filler is used for the most welding materials [12].

Figure 2.2: Sketch of friction stir welding [FSW][16]



During the welding process the friction heat must maintained constant. The reason is that the friction heat has an effect on the plasticized state of the material constituting it crucial for a proper welding joint [17]. Apart from the friction heat constancy, the charactristics of the tool affect the welding process significantly. The geometry of the tool affects the width between the aluminum samples as well as the material flow while the rotation rate affects the mixing and the stirring of the material surrounding the pin [16]. Another important parameter is the welding speed of the tool which does not only affect the time of the process, but also the resulting tensile strength of the weld [16, 17].

The technique of friction stir welding offers a number of advantages compared to ordinary welding techniques both to the mechanical characteristics of the welded products and the environmental aspect of the process. Friction stir welding is considered as a green welding process because the emitted smoke is not harmful, it does not emit any light radiation, the process is free of sparkle and noise, and the energy consumption is significantly lower compared to ordinary welding processes [4, 16]. Concerning the mechanical characteristics of the friction stir welding products, it can be stated that because of the flat weld the fatigue performance is increased while the seam weight is decreased in a magnitude of 12% [4]. The side effect of distortion from the welding process is decreased up to 75% compared to ordinary fusion weldings while the collapse strength increased from 10% up to 20% [13].

Generally, the friction stir welding is regarded as a welding solid-state process, free of filler or metal gases, with small effect at the residual stress of the products and ability to weld a combination of metal and dissimilar alloys up to 35 mm with one pass [4, 16].

Adhesive bonding is an alternative joining technique which used for joining aluminum compartments with great efficiency. Properties such as high surface energy, formability and high strength to weight ratio make aluminum ideal material for applying this technique [18].

Adhesive bonding has a number of advantages compared to regular joining techniques like welding, and these advantages generate great potential of applying it in shipbuilding industry. The first advantage of the technique is that it provides the opportunity to use plates of any thickness and strength for joining, reducing the structural and scantling weight significantly. Another advantage of adhesive bonding is that it does not affect the mechanical properties of the joint like the welding process which decreases the mechanical properties of material in the welding area significantly. Furthermore, the technique does not need any heating process resulting in zero distortions and the joining area remains smooth so no grinding is required after the process. The panels can be painted first and then joined which gives great flexibility in the construction flow. All the above advantages limit the iterative working processes and minimize the construction time [4] [19].

Nevertheless, the technique has not been used extensively in shipbuilding industry because there is lack of information regarding its longterm behavior and there are no relevant guidance rules concerning the inspection, the application and the repair of any compartment joint by the technique [19]. Currently, the application of adhesive bonding in shipbuilding is limited in certain areas such as bonding large window areas and seat rails on ferry's decks [19].

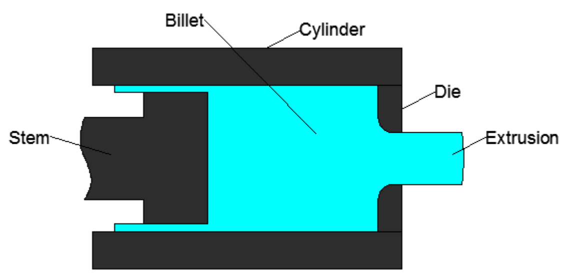
2.7 Extrusion

Extrusion is one of the production methods for creating prefabricated cross sections. The principle idea of the production method is the same as patented by Joseph Bramah at 1797. The patent that Bramah developed had as starting point the heating of the material into a specific temperature so it can maintain the solid shape but at the same time can be deformed relatively easy. The material was then pushed through a die that sets the desired cross section shape [20].

During the last decades the demand from the market for more specialized products forced the community that was dealing with extrusion methods to develop more advanced and more specialized variants of the basic method. The scientific community developed several methods of extrusion, but two of them are considered as the major methods, the direct extrusion and the indirect extrusion [20].

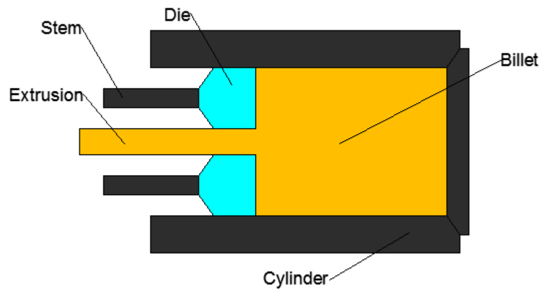
The principle of the direct extrusion as seen in figure 2.3 consist of a stem which pushes the billet through a die which gives the desired shape. The stem contains a pressure pad which is responsible for pushing the billet to the die. The direct extrusion have the option to function either with lubrication during the process or without. When lubrication is applied on the extrusion, a film stands between the die and the material and sprays the surface with lubricated liquid. The direct extrusion is the method that used more often since the end products are close to designed shape [20].

Figure 2.3: Direct extrusion schematic sketch



The indirect extrusion can be performed either as hot indirect extrusion where the billet is heated before loading it on the container or as cold indirect extrusion where the billet has the temperature of the room. As depicted in figure 2.4 the die is pushed to the billet by the hosting container which stands at the back [20].

Figure 2.4: Indirect extrusion schematic sketch



These extrusion methods are applicable to a vast range of materials. However, aluminum is the material that these methods are used more often thanks to its metallurgical properties. The annealing temperature of aluminum is lower than the one of steel which is the building material for the tools that comprise the device and that makes it capable to endure thermo-mechanical stresses that created when aluminum is processed. Moreover, the aluminum process via the extrusion method can generate products that are close to the final form, making the method cost effective and favorable in many industries [20].

The aluminum products from the extrusion methods vary from relative simple shapes, such as Tee bars, to very complex and advanced shapes such as ship panels, which no other hot working process can generate [3]. Additionally, the extrusion products does not require any grinding process resulting a signification reduction of the construction time [20].

The above advantages contribute to a final product with improved geometrical properties resulting less weight and high structure efficiency thanks to the ability of extrusion to form products in any shape, and minimum amount of welding seams because the only seams that are needed are the ones that join the extruded panels [3].

In particular to shipbuilding and hull structure design of high speed craft, these advantages can be translated as less consumption, higher speed and larger operation range for the sake of less structural weight, and less construction time with smaller chances of construction errors due to lower amount of welding seams [20].

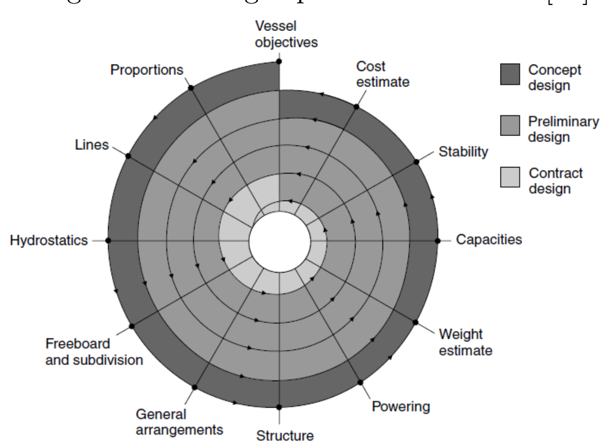
Chapter 3

Hull Structure Design Levels

3.1 Hull Structure Design And Design Requirements

The design process of a ship is described in the design spiral of J.H. Evans which was formed at 1959 [21]. As the initial point of the design spiral which is illustrated at the figure 3.1, stand the vessel's objectives or the design requirements set by the owner. The design requirements have direct impact on the design principle of the craft since they define the type of the ship, the speed, the range and the operational area and ultimately, formulate the operational envelop of the craft [21, 22].

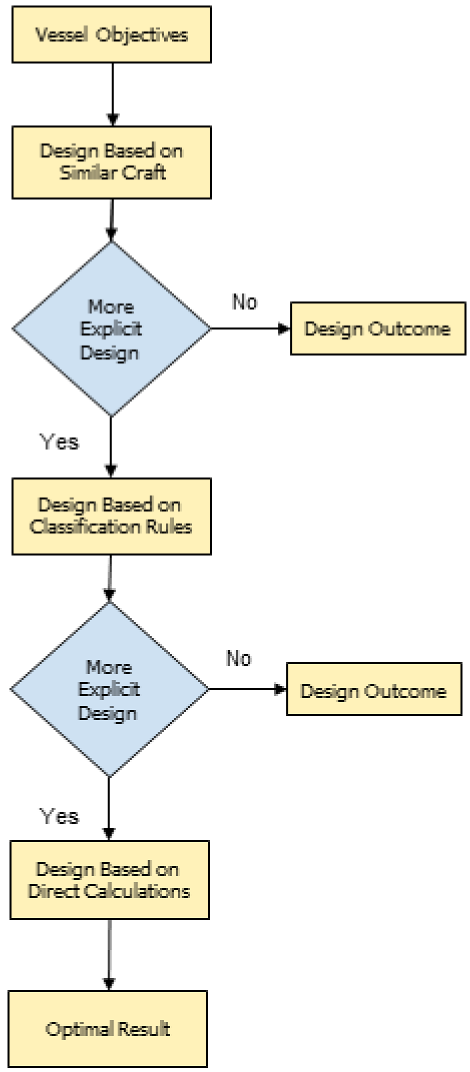
Figure 3.1: Design spiral of J.H. Evans [23]



The design requirements are also influence the hull structure design process of the craft due to the fact that they determine fundamental structural properties. The design requirements of speed and operational area affect significantly the choice of the engine which in return directs the dimensions and the orientation of the scantlings of the bottom compartment of the craft [24, 25]. The operational range prerequisite stipulates the dimensions of the fuel and oil tanks of the vessel which in the overwhelming majority stand in the double bottom area and usually, act as a guide of defining the exact location of the transverse bulkheads. The interaction among the design requirements and hull structure design process expand to the deck section too. The structural design of the deck compartment depends on the type of the craft or more specific, on the operational mission that the craft serves. For instance, some special operation craft, are required to carry heavy units and smaller boats on their decks. Hence, additional conditions related to the operational mission of the craft influence the deck structural design [26].

The design requirements set a number of fundamental structural properties in the hull structure design process. However, to provide a structural outcome which withstands all the loads that derived during the operation of the craft requires a lot more structural conditions. The number of the structural conditions depends on the level of design. Typically and as seen in figure 3.2, the hull structure design process can be divided into three design levels where every design level can release a hull structure that fulfills the vessel's objectives and simultaneously, act as a stepping stone to the next design level. The difference among the levels is identified in the level of the design detail and the amount of time spent. The first level requires a small amount of man-hours but the design outcome cannot be considered in any way as idealized or optimal. On the other hand, the last design level provides an idealized and thorough design with the cost of significant more man-hours.

Figure 3.2: Sketch of hull structure deign levels



3.2 Hull Structure Design Based On Similar Vessels

High speed craft have been designed and operated for more than half a century. During this time, vast amount of experience has been gathered resulting qualitatively craft design practices. Therefore, a study in order to identify similar vessels works both as an inspiration and as a guidance to the new design concept [21]. From such an investigation, it is possible to extract information regarding the main particulars, the hull lines, the seakeeping and stability behavior as well as the hull structural orientation and scantlings dimensions of the craft [21, 26].

The scantlings provided by similar craft may fit to the needs of the current vessel if the operational envelopes of both craft are similar and the craft does not need certification from a classification society. However, choosing the scantlings of a similar vessel may require little design effort and relatively small amount of man-hours but the design outcome would be coarsely and inefficient.

Two similar high speed craft concepts are identified in [27]. The first craft is a comparative design of a 42.67 m high speed craft built from 5083-H116 and 5083-H111 aluminum alloys. The principal dimensions of the craft are found in the table 3.1. The hull structure of the craft is longitudinally stiffened. The primary longitudinal members are Tee shaped girders which oriented across the bottom and deck section. The secondary longitudinal members are rounded Tee shaped stiffeners with stiffener space [s] set at 302 mm, 304 mm and 381 mm for the bottom, side and deck sections respectively. To stiffen the structure transversely, webframes are introduced with the frame space [s_t] set at 1219 mm [27]. The exact dimensions of the scantlings as well as the thicknesses of the plates for all the three sections are presented in figure 3.3 and in table 3.2.

Table 3.1: Main particulars of the 42.67 m high speed craft [27]

Principle Dimensions	
WaterLine Length [L_{wl}]	42.67 m
WaterLine Beam [B_{wl}]	7.27 m
Draft at MidShip [T]	2.05 m
Speed [V]	32 kn
Displacement [$\triangle$]	416.6 m^3

Figure 3.3: Cross section of the 42.67 meter high speed craft [27]

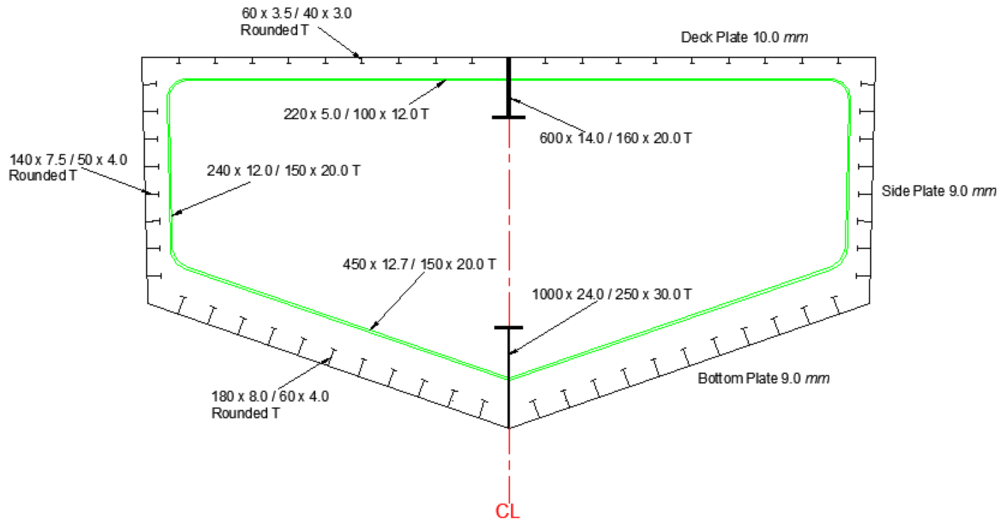


Table 3.2: Scantlings of the 42.67 m high speed craft [27]

Scantlings / Sections	Bottom	Side	Deck
Plating [mm]	9.0	9.0	10.0
Girders [mm]	1000 x 24.0 /250 x 30.0	-	600 x 14.0 / 160 x 20.0
Lon. Stiffeners [mm]	180 x 8.0 / 60 x 4.0	140 x 7.5 / 50 x 4.0	60 x 3.5 / 40 x 3.0
Tranv. WebFrames [mm]	450 x 12.7 / 150 x 20.0	240 x 12.0 / 150 x 20.0	220 x 5.0 /100 x12.0

The second concept is a design of a larger and faster high speed craft. The building material is again 5083-H116 aluminum alloy for the plating but not for the stiffeners. All the stiffener members are extrusions of 6061-T6 aluminum alloy. The main particulars of the vessel are outlined in table 3.3. Similar to the first comparative design, the hull structure of the 61 meter high speed craft is longitudinally stiffened but with no longitudinal primary members like girders or keelsons. Instead it is stiffened with rounded Tee shaped stiffeners with space [s] equal to 260 mm for the bottom and 400 mm for the side section. Transversely, the craft is stiffened by integrated Tee shaped webframes [27]. The dimensions of all the scantlings and plating are illustrated in the cross section figure 3.4 of the craft as well as in table 3.4.

Table 3.3: Main particulars of the 61 m high speed craft [27]

Principle Dimensions	
WaterLine Length $[L_{wl}]$	61 m
WaterLine Beam $[B_{wl}]$	11.7 m
Draft at MidShip $[T]$	2.87 m
Speed $[V]$	50 kn
Displacement $[\triangle]$	950 m^3

Figure 3.4: Cross section of the 61 meter high speed craft [27]

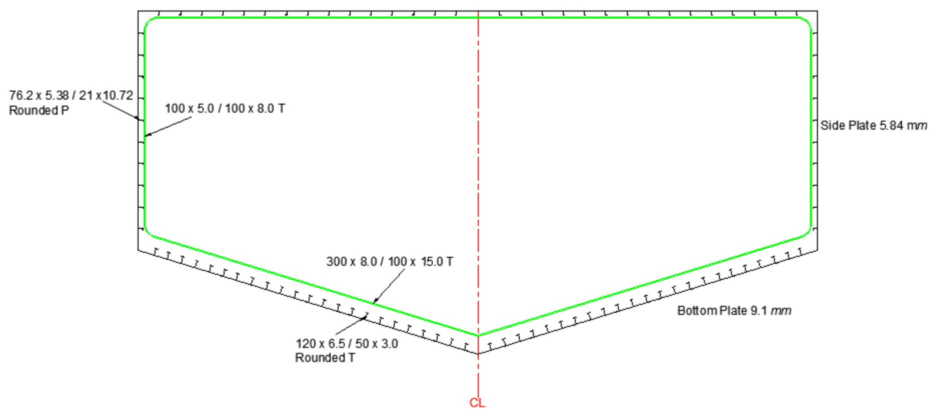


Table 3.4: Scantlings of 61 m high speed craft [27]

Scantlings / Sections	Bottom	Side
Plating $[mm]$	9.1	5.84
Girders $[mm]$	-	-
Lon. Stiffeners $[mm]$	120 x 6.5 / 50 x 3.0	76.2 x 5.38 / 21 x 10.72
Tranv. WebFrames $[mm]$	300 x 8.0 / 100 x 15.0	100 x 5.0 / 100 x 8.0

Two more similar design concepts of aluminum high speed craft were published as master thesis projects from the department of Naval Architecture and Marine Engineering of the Technical University of Athens (NTUA) [26, 28]. The first concept is a small high speed craft made from 5083-H111 and 6082-T5 aluminum alloys. The 5083-H111 alloy is used for the plating and for the build up stiffeners while the 6082-T5 alloy is used for the extrusion stiffeners. The vessel which main particulars are presented in the table 3.5, is designed according to the rules of Lloyds Register of Shipping for high speed craft with service notation registered in group 3 (G3). The vessel's structure is primarily longitudinally stiffened with Tee shaped girders as primary members and flat bar stiffeners as secondary members. The longitudinal stiffeners have stiffener space [s] equal to 300 mm for the bottom and side section and 375 mm for the deck section. Concerning the traversal stiffness of the craft, Tee shaped webframes abeam the whole cross section with a spacing [s_t] set at 700 mm are introduced [28]. The figure 3.5 and the table 3.6 depict all the corresponding scantlings as well as the thicknesses of the shell plating of the three sections [28].

Table 3.5: Main particulars of the 15.7 m patrol high speed craft [28]

Principle Dimensions	
WaterLine Length [L_{wl}]	15.7 m
WaterLine Beam [B_{wl}]	4.45 m
Draft at MidShip [T]	0.9 m
Speed [V]	>25 kn
Displacement [$\triangle$]	24 $tons$

Figure 3.5: Cross section of the 15.7 meter high speed craft [28]

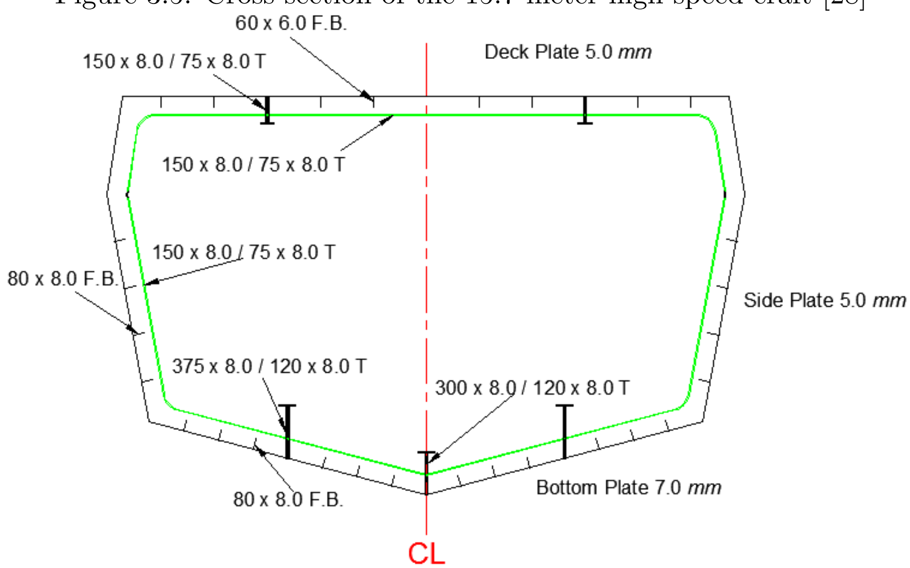


Table 3.6: Scantlings of the 15.7m patrol high speed craft [28]

Scantlings / Sections	Bottom	Side	Deck
Plating [mm]	7.0	5.0	5.0
Center Girder [mm]	300 x 8.0 / 120 x 8.0	-	-
Side Girders [mm]	375 x 8.0 / 120 x 8.0	-	150 x 8.0 / 75 x 8.0
Lon. Stiffeners [mm]	80 x 8.0	60 x 6.0 (Aft) | 80 x 8.0 (Fore)	60 x 6.0
Tranv. WebFrames [mm]	150 x 8.0 / 75 x 8.0	150 x 8.0 / 75 x 8.0	150 x 8.0 / 75 x 8.0

The second concept of the two thesis projects of NTUA is related to a special operation high speed craft. The craft's name is "Hermes" and the design material is 5083-O/H111 aluminum alloy. As the previous concept, "Hermes" is designed according to the rules of Lloyd's Register of Shipping with service notation registered in group 3 (G3). The principal dimensions of the craft are shown in the table 3.7. The craft is stiffened longitudinally by Tee shaped stiffeners of stiffener space [s] equal to 315 mm, 331 mm and 341 mm for the bottom, side and deck sections respectively. At the bottom section, where the effect of slamming occurs, apart from longitudinal stiffeners the vessel has seven additional Tee shaped keelsons where six of them are side girders and one is center line girder. The three sections are stiffened transversely by webframes with frame space [s_t] equal to one meter [26]. The cross section of the craft in figure 3.6 as well as the table 3.8 depict the dimensions of all the stiffener members including the plating of the craft sections [26].

Table 3.7: Main particulars of the special operation high speed craft "Hermes" [26]

Principle Dimensions	
WaterLine Length [L_{wl}]	18.659 m
WaterLine Beam [B_{wl}]	5.047 m
Draft at MidShip [T]	1.09 m
Speed [V]	30 kn
Displacement [$\triangle$]	50.5 $tons$

Figure 3.6: Cross section of the high speed craft "Hermes" [26]

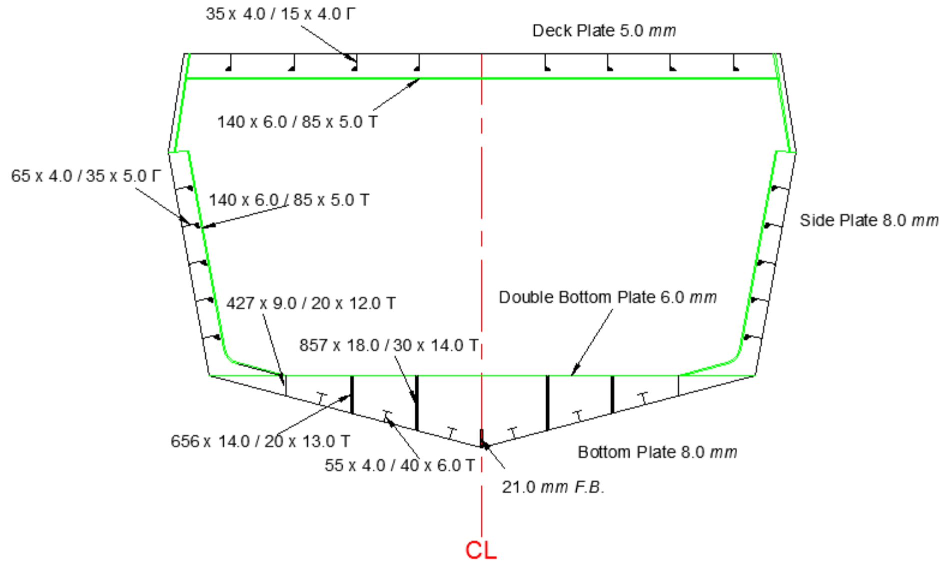


Table 3.8: Scantlings of the special operation high speed craft "Hermes" [26]

Scantlings / Sections	Bottom	Side	Deck
Plating [*mm*]	8.0	8.0	5.0
Center Line Girder[*mm*]	21.0	-	-
Side Girder 1* [*mm*]	857x18.0/30x14.	-	-
Side Girder 2* [*mm*]	656x14.0/20x13.0	-	-
Side Girder 3* [*mm*]	427x9.0/20x12.0	-	-
Lon. Stiffeners [*mm*]	55x4.0/40x6.0	65x4.0/35x5.0	35x4.0/15x4.0
Tranv. WebFrames [*mm*]	-	140x6.0/85x5.0	140x6.0/85x5.0

* The side girders count from the center line and end at the chine of the craft

From the similar craft study it can be concluded that aluminum covers a large range of design concepts and craft dimensions. Also, the aluminum alloys of 5xxx-series seems to dominate the shipbuilding aluminum market. Regarding the hull structure design, it can been noted that the structural components that are used in all four comparative designs are longitudinal girders, transverse webframes and longitudinal stiffeners. In all craft that were studied the primary members had Tee shape while the secondary members, the longitudinal stiffeners, were design with various shapes such as, flat bars, Tee shapes and rounded Tee shapes. Based on these data, a first picture of what kind of structural components and shapes are usually required for designing an aluminum high speed craft can be formed. Also, these data are considered as the fundamental criteria of the modeling philosophy of the parametric model which presented on chapter 4.

3.3 Hull Structure Design According To Classification Rules

The hull structure design of the majority of high speed craft is based on rules of classification societies. Such a design process, according to figure 3.2, is regarded as the second design level. The classification rules are semi-empirical with various simplifications and generalizations especially in the way of interpreting the design loads and the boundary conditions. On the one hand, their semi-empirical nature together with the various generalizations and simplifications, have significant impact on the design detail and optimization of the structure but on the other hand, the simplicity and the guidance they offer even in design stages with great level of uncertainty, reduces the amount of man-hours in such a level that constitutes them as a really competitive design choice [22, 2].

Currently, there are four classification societies that have released rules for high speed craft while three more, have been united and formulated an expansion guide of the primitive structural requirements that IMO high speed craft code introduced. The four individual classification societies that have published rules are the American Bureau of Shipping (A.B.S), the Nippon Kaiji Kyokai (N.K.K), the Det Norske Veritas (D.N.V) and the Lloyd's Register of shipping (L.R.). The classification societies Registro Italiano di Navale (R.I.NA), Germanisher Lloyd (G.L) and Bureau Veritas (B.V) united and formulated the group UNITAS [25].

All classification societies have a certain design flow in their rules but different requirements and evaluation criteria within their design processes. The design flow of every classification society which publishes rules for high speed craft is described extensively in appendix A. Descriptively, the hull structure design flow of all classification rules can be presented as a process of four steps. In the first step all classification societies postulate at least one condition regarding which craft can be registered in the category of high speed craft. This criterion is related with the speed that the craft can achieve. However, some classes publish an additional criterion related to the maximum displacement that the craft can have. The table 3.9 depicts the required criteria of every classification society in order to register a craft in the category of high speed craft [29, 30, 31, 32, 33].

Table 3.9: Requirements of every classification society in order to register a craft into the high speed craft category [29, 30, 31, 32, 33]

Class Society	High speed definition	Light craft definition
A.B.S.	$2.36 * \sqrt{L}$	-
D.N.V.	$7.16 * \Delta^{0.1667}$	$\Delta = (0.13 * L * B)^{1.5}$
L.R.	$7.16 * \Delta^{0.1667}$	$\Delta = 0.04 * (L * B)^{1.5}$
N.K.K.	$7.1922 * \Delta^{0.1667}$	-
UNITAS	$7.16 * \Delta^{0.1667}$	$(V/\sqrt{L}) > 10$

L and B correspond to the length and the breadth of the craft in $[m]$ respectively, Δ account for the craft's displacement in $[tons]$ or $[m^3]$ and V stands for the craft's speed in $[kn]$.

In the second step of the design flow, every classification society delimits which high speed craft can be designed by the semi-empirical rules or there is need for a more explicit design method such as the direct calculation method. The constrains which are depicted in 3.10 are related to the maximum length and the maximum speed that a craft can have in order to be designed according to the semi-empirical rules.

Table 3.10: Constrains of speed and length dimensions among the structural design processes [29, 30, 31, 32, 33]

Class Society	Direct Calculations
A.B.S.	> 61 $[m]$ or 50 $[kn]$
D.N.V.	> 50 $[m]$
L.R.	> 60 $[kn]$
N.K.K.	$-$
UNITAS	> 65 $[m]$ or 45 $[kn]$

In the third step, the design loads of the craft are formulated either by semi-empirical rules if the craft is under the conditions of table 3.10 or by direct calculations methods if the craft exceeds the corresponding conditions. The design loads that are extracted by semi-empirical rules, are divided into two principal categories. The first category consists the global loads which for some classification rules are taken into account only when the craft exceeds a certain length. The second category concentrates the hydrostatic pressure loads and the slamming and impact pressure loads which are generated while craft is planning over the water surface. These loads interact primarily with the bottom and the side sections of the craft. The loads of both categories are formulated as static and uniformly distributed across the sections of the craft and are directly influenced by principal parameters such as speed, craft type and dimensions, and operational area. The table 3.11 depicts the various interpretations of the loads of the second category as well as the assignment of the corresponding loads to the craft sections according to all classification societies.

Table 3.11: Summary of design loads for every section according to the rules of the classification societies [29, 30, 31, 32, 33]

Classification Society	Bottom Section	Side Section	Deck Section	Fore End - Side Section
A.B.S	P_{sl} , P_{Hyd}	P_{sl} , P_{Hyd} , P_{imp}	P_{hyd}	P_{imp}
D.N.V	P_{sl} , P_{Hyd} , P_{pitch}	P_{hyd}	P_{hyd}	P_{imp}
L.R	P_{imp}	P_{imp}	P_{hyd}	P_{imp}
N.K.K	P_{imp}	P_{hyd}	P_{hyd}	-
UNITAS	P_{imp}	P_{hyd}	P_{hyd}	-

P_{sl} corresponds to slamming pressure, P_{Hyd} account for hydrostatic pressure, P_{pitch} stands for pitching slamming pressure and P_{imp} tally to impact pressure.

The last step of the design flow for all classification societies comes along with the scantling prerequisites. The scantlings requirements of all classification rules, which are presented on table 3.12, are related to the strength and stiffness capabilities of the stiffener members and the allowable bending of the plates. The requirements of all classification rules are based on simple beam and plate theory and due to that fact there are not many variations among the formulas of the rule requirements. However, some classification societies include to their rules more mannered requirements for specific cases.

Table 3.12: Summary of scantling requirements for structural component according to classification societies [29, 30, 31, 32, 33]

Classification Society	Girders	Webframes	Stiffeners	Plates
A.B.S	SM, I, Web_{ratio}	SM, I, Web_{ratio}	SM, I, Web_{ratio}	t_{min}
D.N.V	SM, AW, t_{min}	SM, AW, t_{min}	SM, $AW_{bottomstiffeners}$	t_{min}, t_{slam}, t_{ben}
L.R	SM, I, AW	SM, I, AW	SM, I, AW	t_{min},t_{keel}
N.K.K	SM, AW	SM, AW	SM	t_{min}
UNITAS	SM, A_t	SM, A_t	SM, A_t	t_{min}

SM corresponds to Section Modulus in $[cm^3]$, I accounts for Moment of Inertia in $[cm^4]$, A_W and A_t correspond to effective web area and shear area both in $[cm^2]$, Web_{ratio} stands for web depth-thickness ratio, t_{min} tally for minimum thickness in $[mm]$ and t_{slam} , t_{bend} corresponds to minimum thickness due to slamming and bending respectively in $[mm]$.

Summing up, it can be asserted that neither into the first or the second step of the design flow are issued large differences among the classification rule requirements and evaluation criteria. On the third step of the design flow though, it can be concluded that there is a number of differences in the evaluation criteria and requirements among the classification rules. These differences stem primarily from the different operation notations that every classification introduces to the design process and secondarily, due to the different methods of dividing the hull structure into sections. Concerning the fourth step of the design flow, it can be concluded that there are not differences on the requirements and on the evaluation criteria of the classification rules since all stem from the same beam and plate theory. However, differences do occur on the design outcomes due to the fact that every classification introduces its own coefficient system and minimum thickness requirements. The conclusion is also clarified by the researches of [25] and [2] where a comparison of several classification rule guides took place on the same craft, and conclude to different results among the dimensions of the scanltings as well as the structural weights of the cross sections.

3.4 Hull Structure Design By Direct Calculations

As discussed in sub-chapter 3.3, the majority of high speed craft designs are conducted according to semi-empirical rules of classification societies. However, during the last twenty years and notably in the field of high speed craft, the introduction of new design methods and materials brought new capabilities of achieving high speeds in such levels that there are no records or formulas that the semi-empirical rules can rely on [22, 34].

Hence, the development and the adoption of one more design level with a more explicit design method like the direct calculation method was more than welcome from the design community of high speed craft. Principally, the direct calculation methods have applications on two fields of the high speed craft design. The first field is related to the determination of the design loads while the second field is connected with the structural mechanics of the craft.

The determination of the design loads through direct calculations is the simulation of the ship motions and the dominant hydrodynamic loads that interact with the craft during its operation and under the conditions that have been defined in its operational envelop. Such simulations are conducted either by computational fluid dynamics (CFD) or by extensions of typical 2D strip theory and $2\frac{1}{2}$D high speed strip theory [35].

The structural mechanic problem of the craft is typically solved with the help of finite element methods. The loads that are assigned to the craft in order to calculate the structure's response can be derived either from statistical data in a process similar to [36], either from the process of classification rules as presented in sub-chapter 3.3 or by simulation models created by direct calculation methods similar to [35]. The resulting structural response is used to assess whether or not the design have adequate properties to fulfill the safety requirements of stiffness, strength and fatigue [37].

The direct calculation methods enable detailed studies in relation to the design loads and the structural mechanics of high speed craft. Such studies contribute to the comprehension of the interaction among the derived loads and the structural response and hence, to the development of idealized and optimal designs [34]. However, detailed studies based on direct calculation methods require a significant amount of working hours. The process becomes extremely time consuming in research studies where a large amount of structural arrangements has to be modeled and investigated.

The time spent on modeling these structural arrangements could be decreased by developing a model which produces structural arrangements by introducing the structural components parametrically. In particular, if the model could control the number, the location, the shape and the dimensions of all the structural components and introduced them into the designed structure with respect to the hull line coordinates, then such a model could be extremely useful since it would give the chance to rapidly establish numerous structural arrangements for testing reducing the working hours significantly [38]. Such a parametric model conduce also to the development of unconventional designs and promote the state of art of hull structure design.

A parametric model with the capabilities cited above has been developed in the current thesis and presented in chapter 4. More specific, chapter 4 outlines the modeling philosophy and architecture of the model as well as the constrains of such an attempt.

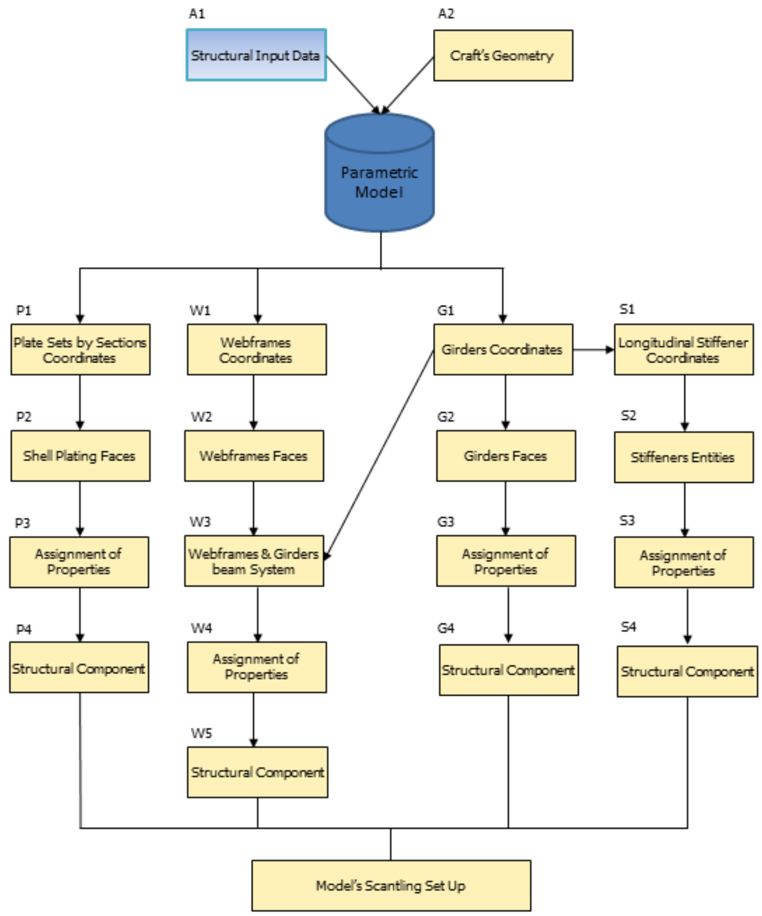
Chapter 4

Parametric Hull Structure Modeling

4.1 Modeling Philosophy And Architecture Of The Parametric Model

The design philosophy of the parametric model is based on data that extracted from the study of sub-chapter 3.2. The major outcome of the study, in relation to hull structure components, is that the hull structure design philosophy of high speed craft is principally based on longitudinal stiffeners, girders and transverse webframes. These three types of structural components together with the shell plating set the foundation of the modeling architecture of the parametric model which is represented from the scheme of figure 4.1

Figure 4.1: Scheme of the architecture of the parametric model



As seen in the figure 4.1 the model requires two basic categories of inputs before starts modeling. The first category which is represented by the box A1, consist all the required data for modeling every structural component. These data are introduced by the user and control the material, the number, the location and the structural properties of all the structural components that can be modeled by the parametric model.

Due to the large number of structural components within the model, a syntax based on the type of the component and the section they are located is formulated. The detailed nomenclature is found in the main sheet of the software where all the data are imported. Within the thesis paper stands only a reference example of the formulating philosophy of the actual nomenclature.

The primary members of the structure, the girders and the webframes, are introduced in the parametric model either by five variables if they are comprised only by a web or by nine variables if they are comprised by a web and a flange . Table 4.1 depicts the required variables in order to model a primary member by using a girder primary member as reference.

Table 4.1: Primary member nomenclature of the parametric model

Structural Component	Bottom Section	Side Section	Deck Section
Material Of Girders	Aluminum 5083-H116	Aluminum 5083-H116	Aluminum 5083-H116
Name Of Girder	Bottom Girder N	Side Girder N	Deck Girder N
Location Of Girder	[Y] coordinate	[Z] coordinate	[Y] coordinate
Web Height Of Girder	Dimension in [m]	Dimension in [m]	Dimension in [m]
Web Thickness Of Girder	Dimension in [m]	Dimension in [m]	Dimension in [m]
Name Of Girder's Flange	Bottom Girder Flange N	Side Girder Flange N	Deck Girder Flange N
Name of Girder's Flange Profile	B. Girder's Flange Profile N	S. Girder's Flange Profile N	D. Girder's Flange Profile N
Width of Girder's Flange	Dimension in [m]	Dimension in [m]	Dimension in [m]
Thickness of Girder's Flange	Dimension in [m]	Dimension in [m]	Dimension in [m]

As discussed in sub-chapter 3.2 the longitudinal stiffeners can have various cross section shapes. Hence, to cover all possible cross section arrangements, their cross section have to be modeled arbitrarily. Therefore, the number of variables that are required for introducing a longitudinal stiffener into the parametric model cannot be regarded as constant. Indicatively, as seen in table 4.2, the longitudinal stiffeners with cross section of Tee or L require one variable for defining their structural material, six variables for modeling their shape and four variables for determining their location. In contrast to primary members, the location of the longitudinal stiffeners is not introduced by one variable but it is derived by the location and the number of the girders, the sub-sections that are created from the corresponding girders as well as the number of stiffeners that are introduced in every sub-section.

Table 4.2: Longitudinal stiffener nomenclature of the parametric model

Structural Component	Bottom Section	Side Section	Deck Section
Material Of Longitudinal Stiffeners	Aluminum 5083-H116	Aluminum 5083-H116	Aluminum 5083-H116
Location Of Girder	[Y] coordinate	[Z] coordinate	[Y] coordinate
Number Of Girders	1	0	1
Number Of Created Sections	2	1	2
Number Of Stiffeners in each Section	1,1	1	1,1
Name Of Stiffener	Bottom Stiffener 1, Bottom Stiffener 2	Side Stiffener 1	Deck Stiffener 1, Deck Stiffener 2
Name Of Stiffener's Profile	B. Profile Stiffener 1, B. Profile Stiffener 2	S. Profile Stiffener 1	D. Stiffener Profile 1, D. Stiffener Profile 2
Web Height Of Stiffener	Dimension in [m]	Dimension in [m]	Dimension in [m]
Web Thickness Of Stiffener	Dimension in [m]	Dimension in [m]	Dimension in [m]
Width Of Stiffener's Flange	Dimension in [m]	Dimension in [m]	Dimension in [m]
Thickness Of Stiffener's Flange	Dimension in [m]	Dimension in [m]	Dimension in [m]

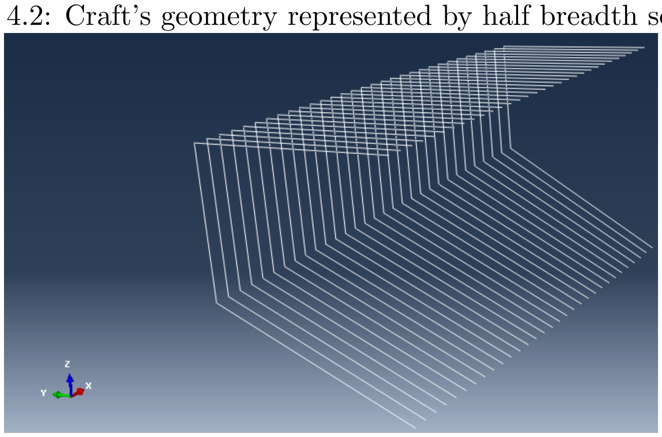
The shell plating components are sorted into three groups where every group represents the shell plating of one of the three compartments of the craft. The reason of formulating groups stems from the need of assigning the same properties in all the shell plating components that comprise a plate section. As depicted in table 4.3 every plate section requires three variables in order to be modeled by the parametric model.

Table 4.3: Shell plating nomenclature of the parametric model

Structural Component	Bottom section	Side section	Deck section
Material Of Plate Section	Aluminum 5083-H116	Aluminum 5083-H116	Aluminum 5083-H116
Name Of Plate Section	Bottom Section N	Side Section N	Deck Section N
Thickness Of Plate Section	Dimension in [m]	Dimension in [m]	Dimension in [m]

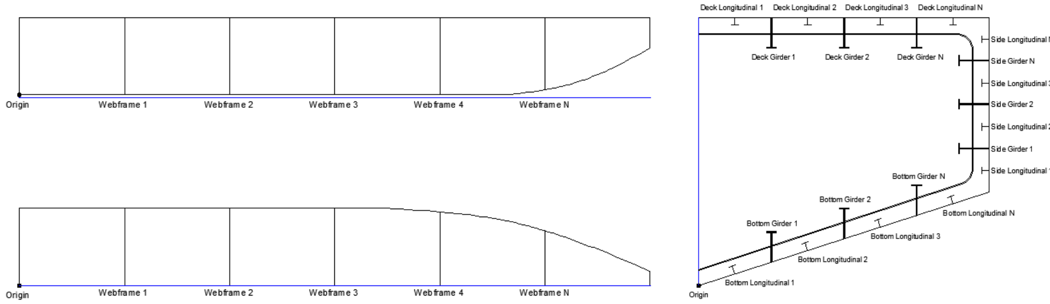
The geometry of the craft, which is represented by the box A2 correspond to the second category of required inputs. The geometry of the craft is imported to the model, as depicted in figure 4.4, in a format of half breadth sections of four points connected by three straight lines.

Figure 4.2: Craft's geometry represented by half breadth sections



In order to harmonize the parametrization of the structural components with the coordinate system of the craft's half breadth sections, an origin point as well as a numbering system is introduced to the model. As origin point of the model is set the intersection point between the first half breadth section and the imaginary Center Line while the parametrization of the structural components is conducted according to the numbering system of figure 4.3

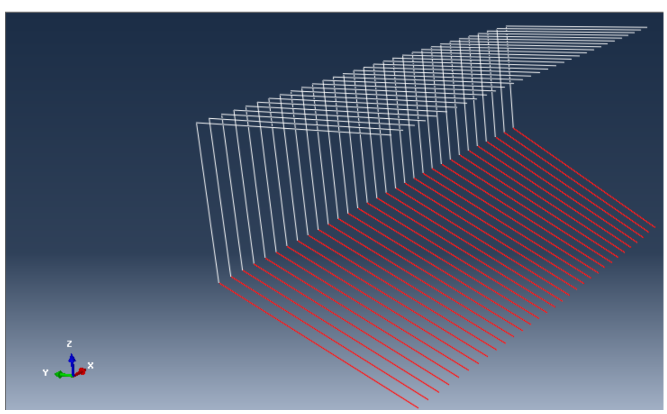
Figure 4.3: Numbering philosophy of the parametric model



According to figure 4.1 the modeling process of every structural component is comprised by a series of steps. Each step represents a module or a process that is conducted in order to model the structural component.

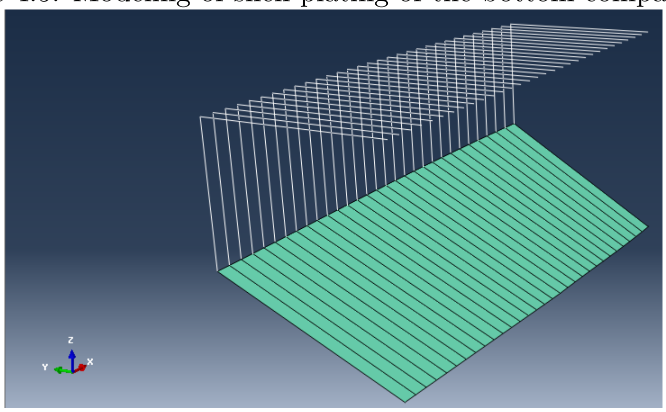
The shell plating of the craft is modeled separately for every compartment in a process of three steps. In the first step, the P1 of figure 4.1, the half breadth section lines of every compartment are grouped together as depicted in figure 4.4. The reason is to provide boundary conditions for the faces that are going to be modeled in the next step.

Figure 4.4: Grouping of half breadth section lines of the bottom compartment



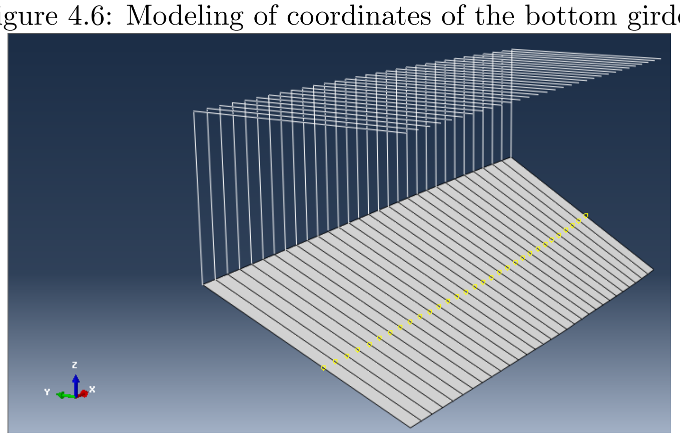
In step P2, faces on each area that had been created by the grouped lines of step P1 are modeled and grouped so they can represent the compartment as one unit. In step P3, a shell section is created based on the variables presented in table 4.3 and is assigned to the united shell plate area that had been modeled in step 2. The figure 4.5 illustrates the modeled shell plating outcome of the bottom compartment of the craft.

Figure 4.5: Modeling of shell plating of the bottom compartment



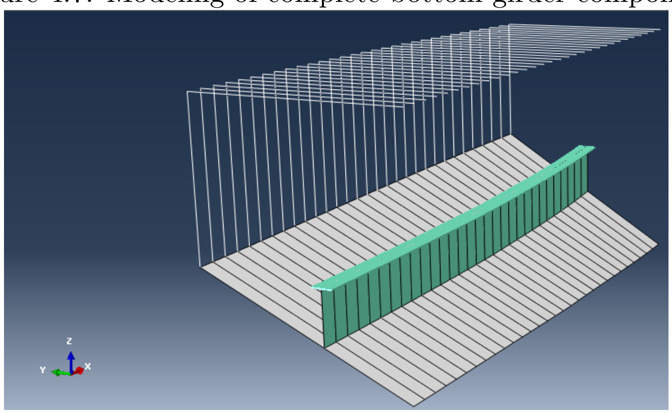
The modeling process of every girder structural component is conducted in three steps. In the first step, depicted as G1 in 4.1, the exact location of the girder is determined by introducing one coordinate. This coordinate is represented by the location variable of table 4.1. The rest two coordinates are determined by linear interpolation based on the introduced coordinate and the coordinates of the corresponding the half breadth section points. The outcome of the process, as seen in figure 4.6, is a series of points over the half breadth sections lines that represent the exact location of the girder.

Figure 4.6: Modeling of coordinates of the bottom girder



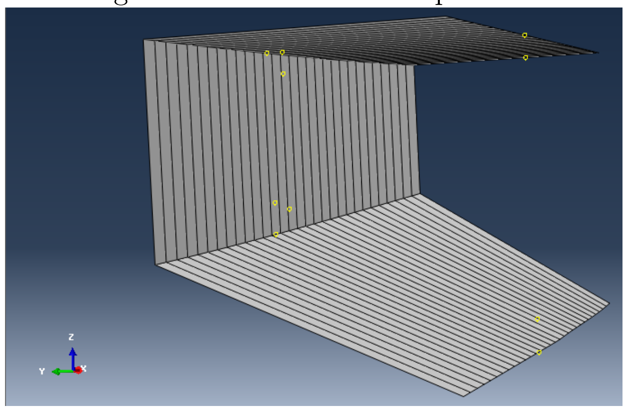
In the next step, the web faces of the girder component are modeled as shell elements based on the web height variable of table 4.1. In step G3, two processes are conducted. In the first process the girder flange is modeled as beam element over the upper edge of the girder's web while in the second process, properties based on the remaining variables of table 4.1 are assigned on the girder's parts. As soon as the step G3 is completed the girder component has its final form as illustrated in figure 4.7

Figure 4.7: Modeling of complete bottom girder component



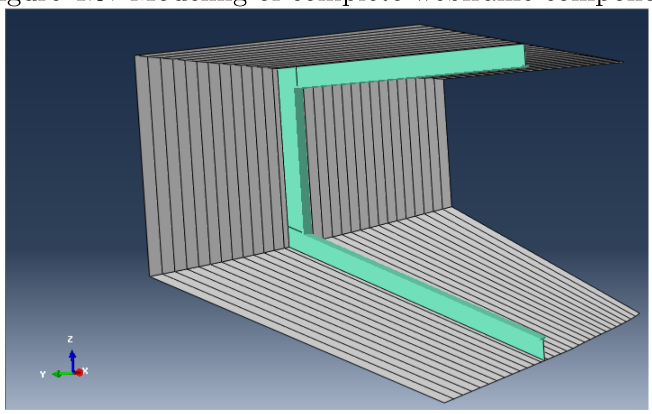
According to the scheme of figure 4.1, a webframe is modeled in a process of four steps. Similar to the first step of the girder's modeling flow, the step W1 corresponds to the process of determining the location of each webframe by introducing one coordinate. As illustrated in figure 4.10, a webframe is modeled separately in each compartment, by two points and across the length of the craft. Hence, the introduced coordinate can only be the [X] coordinate for all webframes regardless the compartment they are modeled. The remaining coordinates are approximated on two different ways for the side and for the bottom and deck webframes. For the bottom and deck webframes, the [Y] and [Z] coordinates are determined by linear interpolation based on the introduced coordinate and the coordinates of the corresponding half breadth section points. The [Y] and [Z] coordinates of the side webframe are derived by the coordinates of the points that stand on the edges that connect the bottom and the deck compartment with side compartment.

Figure 4.8: Modeling of coordinates of a complete webframe component



In step W2, the web faces of the webframe component are modeled in a process similar to G2. Specifically, the web part of the webframe is modeled by shell elements and with respect to the related "web height" variable of table 4.1. In W3, a system which finds the coordinates of the intersection points among the primary members is established. The need of such a system stems from the fact that the girders interrupt the continuity of the webframes resulting individual sub-webframes which make the process of assigning properties problematic. The system, through the coordinates of the intersection points, track the number and the location of the individual sub-webframes and grouped them into one system-matrix which can be utilized in the process where the properties are assigned on the components. In step W4, the processes that are conducted are identical to the ones of step G3 of the girder's modeling flow. In other words, flanges are modeled over the upper edges of the webframe webs as well as properties are assigned on the webframe parts according to the reference example of table 4.1. The figure 4.11 depicts the form of a webframe after completing all four steps of the webframe's modeling flow.

Figure 4.9: Modeling of complete webframe component



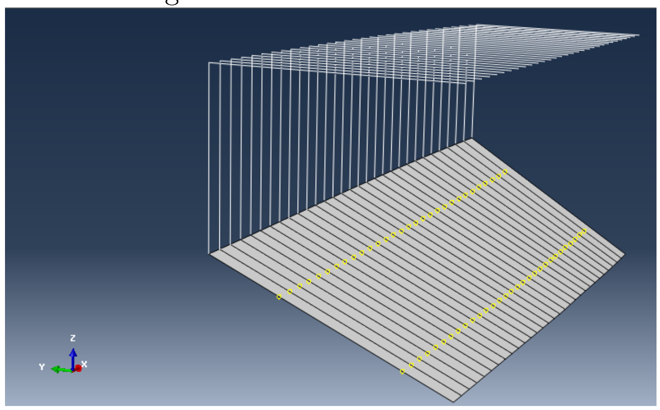
The longitudinal stiffeners are modeled as a group of components for every structural compartment of the craft in a process of three steps. In the first step, the S1 of figure 4.1, the location of the stiffener components is defined. In contrast to the modeling process of primary members, no location variable is introduced to the modeling process of stiffeners. Hence, all three coordinates must be defined by the parametric model. Since, the stiffener components are modeled on the longitudinal of the craft, their [X] coordinate is defined by the respective [X] coordinate of the half breadth sections. The [Y] coordinate of the stiffener members is determined by a mathematical formula which utillizes the location variables of table 4.2. The formula behind the process is illustrated below.

$$Y_{stif} = \frac{s}{N+1} * n_i + GR_m \tag{1}$$

[Y_{stif}] is the [Y] coordinate of each stiffener that is modeled, [s] is the width of the subsection, [N] is the number of stiffeners in every subsection, [n_i] is the relevant number of each stiffener (e.g. $n_i = 2$ stands for the second stiffener) and [GR_m] is the distance of the stiffener from the closest girder.

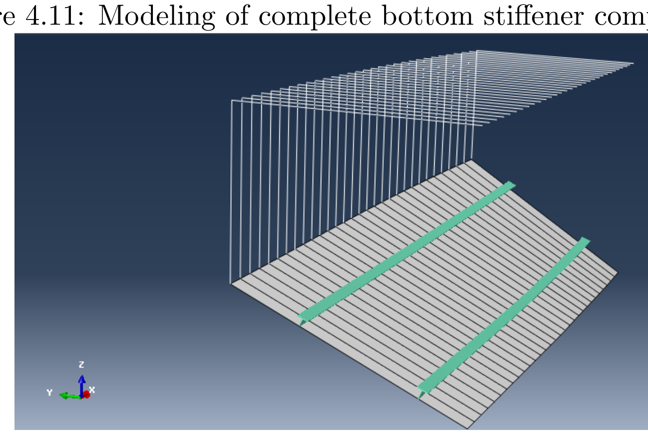
The [Z] coordinate of the longitudinal stiffeners is defined by linear interpolation based on their [Y] coordinate and the coordinates of the corresponding points of the half breadth sections. The series of points depicted in figure 4.10, represent the exact location of two bottom stiffener components and stand as the result of the process that conducted in step S1.

Figure 4.10: Modeling of coordinates of bottom stiffener components



In step S2, the coordinate points that have been modeled on step S1 are connected by wire lines and defined as new entities by using the "name of stiffener" variable of table 4.2. In step S3 of the stiffeners modeling flow, two processes are taking place. In the first process the stiffener components are modeled by beam elements while in the second process, properties based on the remaining shape variables of table 4.2 are assigned on the stiffener components. By completing all three steps of the stiffener's modeling flow, the stiffener components haver their final form which is presented in figure 4.11

Figure 4.11: Modeling of complete bottom stiffener components



The outcome of the parametric model, after the modeling completion of the introduced components by the corresponding modeling flows, is a structural arrangement where all the scantlings have been derived by the structural input data of A1 and appended on the craft geometry of A2 of figure 4.1.

4.2 Assumptions, Simplifications And Limitations Of the Parametric Model

The parametric model is a primitive attempt of achieving the function of parametrization in a finite element software. Therefore, a number of initial assumptions and simplifications are mandatory not only to bound the problem but to achieve a result in certain period of time. Apart from the various simplifications and assumptions that are known and accepted from the beginning of the modeling process, there are always limitations in the final model which come into the surface during the modeling phase. These limitations is something inescapable that all the models have to face. The critical point is to avoid the limitations which deviate the model of the initial objectives and area of applicability. In the case of the parametric model, none of the limitations that occurred during the modeling phase influence the initial objectives that had been set from before.

One major simplification and one significant assumption of the parametric model are found in the geometry formulation of the half breadth sections. The half breadth sections have been simplified to be represented by four points connected by straight lines. In addition, the side compartment of craft is assumed to be always vertical to the Center Line. Nevertheless, the majority of the simplifications and assumptions, and most of the limitations are found in the process of modeling the structural components.

More specific, the structural components of girders are assumed to be always parallel to the center line. Also, it is assumed that their continuity extents all over the model but at the same time, follows the curvature of the compartment they stiffen. The limitation of the girder components is that they can only be assigned either with Tee shaped flange or with no flange at all. The webframes are assumed of being always parallel to the half breadth sections and similar to the girder components, their limitation is that they can only be assigned with Tee shape flange or with no flange at all. The longitudinal stiffeners are modeled by taking into account two limitations. The first limitation is related to the lack of individuality of the components. The stiffeners that are modeled on the same compartment are limited to have the same cross section shape. The other limitation is related to the dependency of the longitudinal stiffeners from the girder primary members. All the longitudinal stiffeners are bind to follow the curvature of the girder primary members with the result of risking the feasibility of such a design in reality. Finally, the plate components of the same compartment are assumed to have the same thickness.

Chapter 5

Application Of The Model

5.1 Set-Up Of The Finite Element Analysis

As discussed in subchapters 3.3 and 3.4, the hull structure designs which are derived by semi-empirical methods contain various idealizations and assumptions.

A critical idealization of the corresponding design processes is related to the development of a system of structural hierarchy. Such a system has been developed by the designers in order to enable the application of handbook type deformation and stress formulas into the classification rules. The principle behind the system of structural hierarchy is that the loads acting on the shell plates are distributed to the secondary members which in return, transfer them on the primary members. Such an idealization gives the opportunity to study every structural member individually with boundary conditions and span determined by the accounted boundary conditions. The design idealization of the structural hierarchy may produce feasible structural designs with certain arrangement but it does not provide a clear picture of the interaction effect among the structural members. On the other hand, the introduction of the finite element analysis into the hull structure design process provide the opportunity to model the structure as one unit and hence, the possibility to study the interaction among the structural components in detail.

The present analysis is an attempt to examine and comment to what extent the idealizations and the assumptions that have been applied by semi-empirical methods on the hull structure designs reflect the actual structural situation by using more detailed modeling techniques such as the finite element methods. More specific, the analysis examines the idealization of hierarchy among the structural members and whether or not the loads are distributed from the secondary members to the primary members, it investigates the interaction between the members in a beam-girder system and finally evaluates the validity of setting boundary conditions according to the principle of the handbook type formulas.

The analysis is conducted on the tentative study of the 42.67 meter high speed craft presented in the sub-chapter 3.2. The cross section of the craft as well as its main particulars and scantling dimensions are depicted in figure 3.3 and in tables 3.1 and 3.2 respectively. Moreover, the design pressure that is used for the determination of the scantlings of every structural component is illustrated in table 5.1. As discussed in 3.2 sub-chapter, the craft is designed by two aluminum alloys where their mechanical properties are shown in table 2.5.

Table 5.1: The design pressures of the tentative structural design of the 42.67 meter high speed craft

Structural component	**Pressure** $[KN/m^2]$
Bottom Plate	261.5
Bottom Lon. Stiffeners	261.5
Bottom transverse webframes	261
Side Plate	261
Side Lon. Stiffeners	260
Side transverse webframes	234.9
Deck Plate	15.88
Deck Lon. Stiffeners	15.88
Deck transverse webframes	15.88

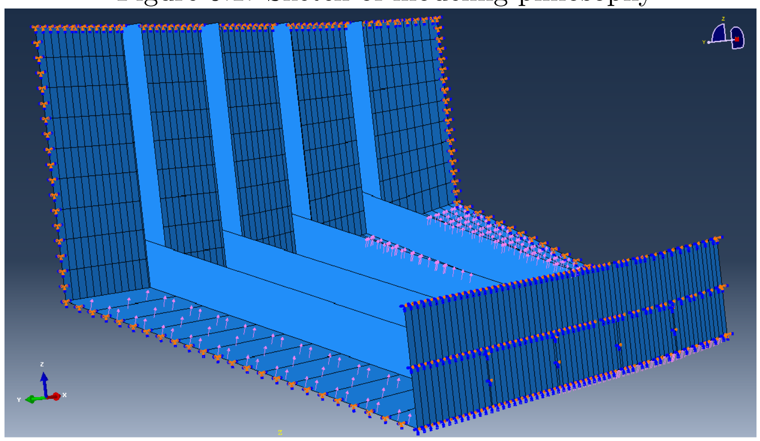
The first step of the analysis is to implement the design of the craft into the Abaqus finite element software [39]. This step is carried out by the parametric model as soon as the scantlings of the craft have been derived and there is a geometry file which contains the craft's hull lines. In the case of the 42.67 meter high speed craft, the scanltings of the craft have been derived by [25] but no geometry file is included to the study. The alternative is to modify the geometry file of another craft and try to create similar hull lines as the ones of the original craft. For this purpose the hull lines of the craft presented in [35] are used.

Despite the modification in the hull lines, a number of minor simplifications must take place in the original cross section of the craft in order to make it processable by the parametric model. The first is related to the side section of the craft. The side section of the craft is modeled as vertical instead of inclined. The second simplification is related to the modeling of the webframes. The craft's webframes are designed with radiused connections while the parametric model can only model straight connections. Hence, the connections of the webframes are modeled as straight. The last simplification is related to the rounded Tee shape longitudinal stiffeners which on the parametric model are modeled as standard Tee shape stiffeners.

Due to the need of greater detail, the analysis does not include the whole craft but a section of it close to the longitudinal center of gravity [LCG]. The chosen section does represent the whole craft accurately firstly because it is located between two bulkheads which can be considered as fixed boundary conditions and secondly, because all the structure components are fully deployed across and abeam the section. However, the deck section has been neglected from the analysis. The reason stems from the fact that the dominated loads are located on the bottom part of the craft where the deck section participate inasmuch as having fixed boundary conditions in the upper edge of the side section. The length of the section is equal to the distance of the bulkheads or the length of five webframes. The breadth of the section is taken as the breadth in the water line. In the parametric model though, since only the port side of the craft is modeled, boundary conditions due to symmetry are assumed at the center line.

The load that is applied in the analysis is the bottom load derived from the tentative analysis of [27] according to the high speed craft rules of ABS. The load is applied in the whole area of the bottom section as static and uniformly distributed [29]. The figure 5.1 portraits the chosen section after being scaled and modified by the parametric model at the step where the pressure loads and the boundary conditions have been applied.

Figure 5.1: Sketch of modeling philosophy



Before starting the analysis process the whole model must be meshed. The number of the mesh elements as well as the mesh element type affect the result of the analysis significantly. The direct calculation rules of ABS does not state any prerequisite regarding the number of minimum mesh elements and it accepts any mesh density as long as the size of the mesh elements is smaller than the stiffener space and the stress distribution is possible to be observed [29]. The direct calculation rules of DNV publishes similar conditions with the an additional requirement regarding the number of the elements in the primary members. More specific, they stipulate that all the primary members that are modeled by shell elements must have at least three mesh elements if the members are formulated by four node element (S4R) and two mesh elements if they are formulated by eight node elements (S8R) [33].

In the present analysis, due to the need of great accuracy and detail, a mesh density equal to 0.08 is chosen. With a seed density set to 0.08, the section is meshed by 12562 mesh elements. The shell elements of the plates and of the webs of the primary members, are meshed by eight node quadratic elements (S8R) while the beam elements of the longitudinal stiffeners and of the flanges of the primary members are meshed by three node quadratic elements (B32). By applying the above mesh density and element type all the requirements of all classification societies are fulfilled. As reference, the web of the girder and webframes are comprised by fourteen and seven shell elements respectively while the stiffener spacing is consisted by three mesh elements.

5.2 Results Of The Finite Element Analysis

In order to interpret the results effectively, three paths corresponding to three structural elements are created. The first path represents the girder of the section, the second path represents the second webframe of the section and the third path represents the sixth bottom stiffener of the section. The reason of selecting the second webframe and the sixth stiffener stem from the fact that since they are located in the center of the section and stand away from the boundary conditions, their responses should reflect the interaction among the structural member objectively.

The finite element analysis extract results related to the deflection, the stress and the rotation response of the structure. The results of the deflection response can be divided with respect to the coordinates that the components are deflecting. Therefore, three types of deflection related to the three coordinates are extracted from the structure response with the deflection of the [Z] coordinate to be the dominant. The outcomes of the deflection over the [X] and [Y] coordinates of the three members are portrayed in appendix B while the result of the deflection over the [Z] coordinate as well as an illustrative figure of the whole section's response are depicted in figures 5.2 and 5.3 respectively.

Figure 5.2: Deflection of the complete structure in [Z] direction

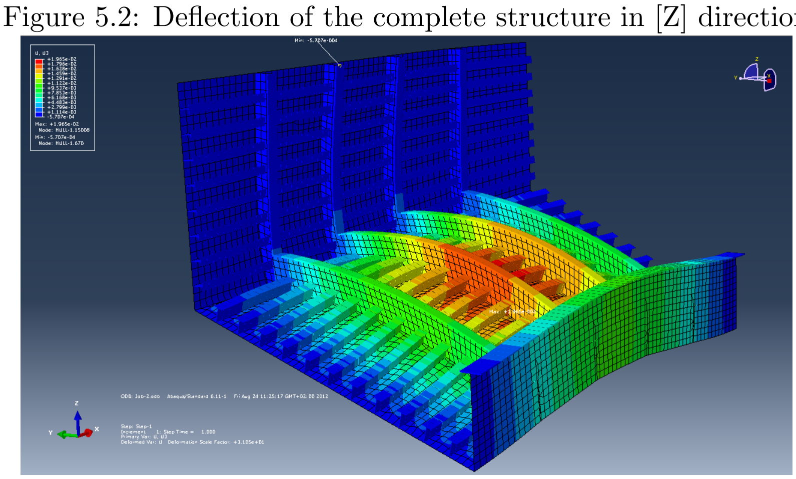
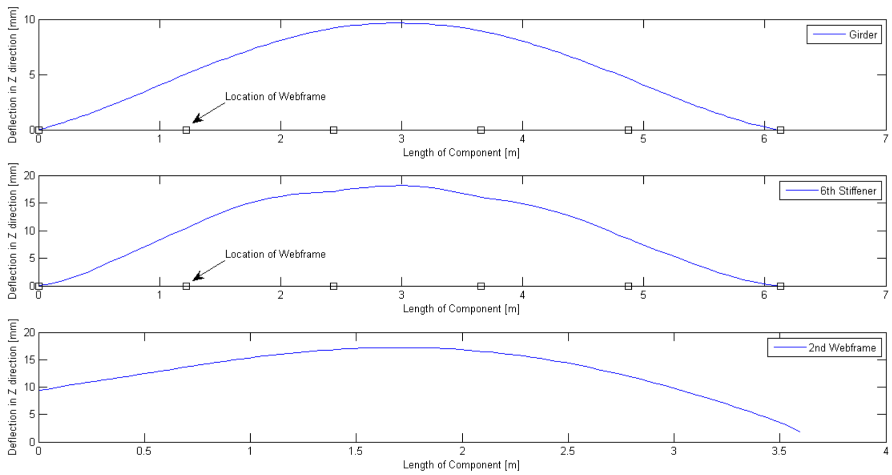


Figure 5.3: Deflection plot of the girder, the 6^{th} stiffener and the 2^{nd} webframe in [Z] direction



As seen in figure 5.3 the maximum deflection of the girder is 9.64 mm. The maximum global deflection of the stiffener member is 18.12 mm whilst for the same point, the maximum local deflection is 2.05 mm. Similar to the stiffener member, the plating has maximum global deflection of 19.64 mm and maximum local deflection of 3.4 mm. The webframe has completely different deflection curvature from the ones of the girder and stiffener. In the keel side, where it is connected with the girder, the webframe has an initial deflection of 9.3 mm while its maximum deflection appears on the midspan with a value of 17.21 mm.

The stiffness of a structure is directly linked with its deflection magnitude under loading. In other words, the smaller the deflection values are, the stiffer the structure it is. Nevertheless, there are no regulations in any of the classification society regarding the maximum deflection that a panel or a stiffener should tolerate. A rule of thumb though, expressed by [40] states that the ratio between the panel's smaller span or the stiffener's span and the corresponding deflection value shall be within 75 to 100 and 150 to 200+ for panel and stiffeners respectively. In the case of the section of the 42.67 high speed craft the ratios of the panel and the stiffener elements are 87.79 for the panel, 632.26 for the girder, 459.54 for the webframe and 594.6 for the stiffener severally. The above values indicate that the choice of the plating thickness in combination with the frame spacing produce a plating stiffness ratio which is on the recommended limits while, they also confirm that the girder is the dominant structural component since it has the greater relative stiffness.

From the deflection response of the structure, a number of critical outcomes regarding the structural hierarchy and the interaction among the structural components can be formulated. More specific and as seen in figure 5.3, the idealization of structural hierarchy seems to be relevant for the current section since the girder, which is above all in the structural hierarchy, supports the webframes and carries most of the bottom load. The interaction effect among the structural components is confirmed at the webframe plot where the deflection of the girder influences the deflection level of the webframe at their connection edge. This interaction however, denotes that the design principle of the semi-empirical methods which states that the primary members shall considered as rigid components does not reflect the actual situation and hence can be quesitoned.

The direct calculation classification guides may not publish conditions regarding maximum deflection that a structure should tolerate but they do publish requirements regarding the magnitude of the allowable stresses. In particular, ABS set requirements regarding the maximum allowable Von Mises, shear and bending stress that the structure shall experience. According to the rules, the maximum allowable Von Mises stress for aluminum alloys shall not exceed the 85% of the alloy's yield strength while for shear and bending stress is 59.88% and 40% respectively [29]. By taking the above into account the maximum allowable values for the alloys of 5083-H116 and 5083-H111 that are used in the section of the 42.67 meter craft are calculated and presented in table 5.2

Table 5.2: Maximum allowable values of Von Mises, shear and bending stresses for the aluminum alloys of 5083-H111 and 5083-H116 according to ABS

Stress Type	5083-H111 aluminum alloy	5083-H116 aluminum alloy
Von Mises Stress	123.25 $[Mpa]$	140.25 $[Mpa]$
Bending Stress	86.82 $[Mpa]$	98.80 $[Mpa]$
Shear Stress	58.00 $[Mpa]$	66.00 $[Mpa]$

The Von mises stress response of the whole section is depicted in figure 5.4, while the graph of figure 5.5, illustrates the Von Misses stress of three structural components. As seen in figures 5.4 and 5.5 the larger values of the Von Mises stress are concentrated at the connection edges of the bottom and side webframes and at the connection of all the longitudinal members with the bulkheads. The stress concentration at the webframes connections was expected due to the assumption of modeling the webframe edges as straight instead of radiused. The high stress levels at the connection of the longitudinal members with the bulkheads were also expected since the bulkheads were stated as fixed boundary conditions. Apart from the connection areas that highlighted above, it is worth noticing that the flange of the webframes appear to have stress levels above the allowable limit and hence a redesign of the structural components may be required. Concerning the rest of the structural components including the plating with maximum Von Mises stress value of 58.51 [Mpa], they appear to be below the allowable stress limits.

Figure 5.4: Von Mises stress contour plot of the whole section

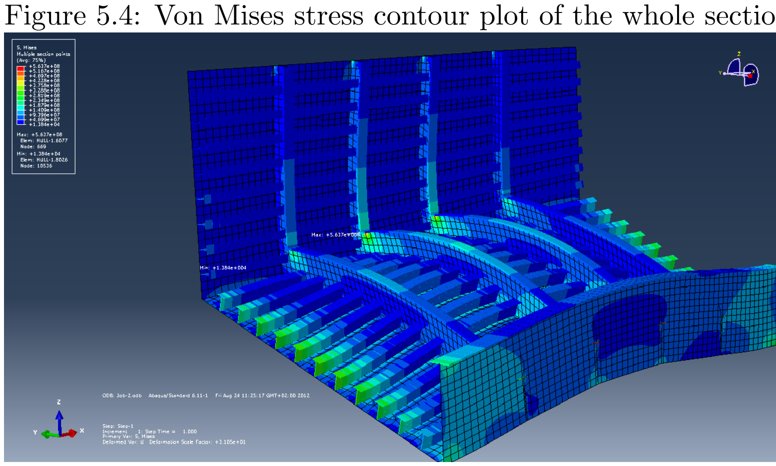
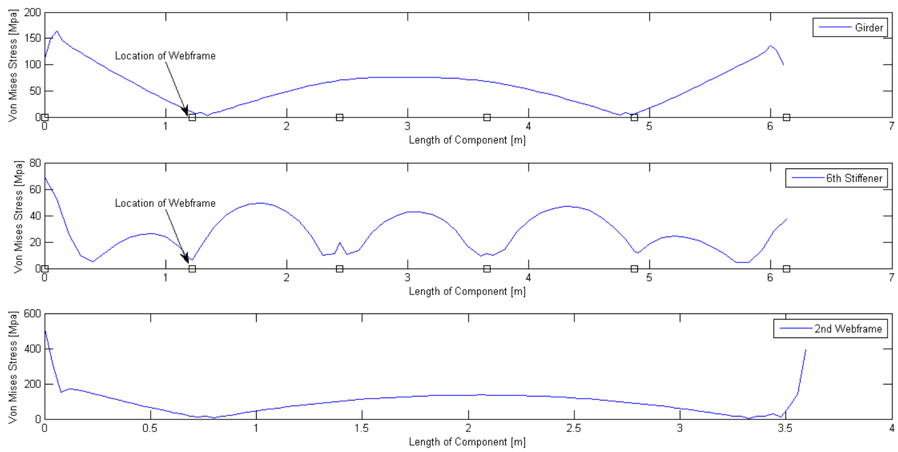


Figure 5.5: Von Mises stress plot of the girder, the 6^{th} stiffener and the 2^{nd} webframe



The figures 5.6 and 5.7 depict the bending stress response of the whole section as well as the bending stress values of three structural components respectively. As seen in figures 5.6 and 5.7, the largest bending stress values are found at the connections of the longitudinal members with the bulkheads and at the connections of the bottom webframes with the rest of the primary members. The high bending stress levels at the webframes edges are products of the simplification of modeling the webframe edges as straight. In reality, most likely, all the connection edges will be designed with stress relief tripping brackets which not only reduce the concentration levels but they contribute to a smoother stress slope. Regardless the connection edges, only the flanges of the bottom webframes seem to have bending stress levels over the allowable limits.

Figure 5.6: Bending stress contour plot of the whole section

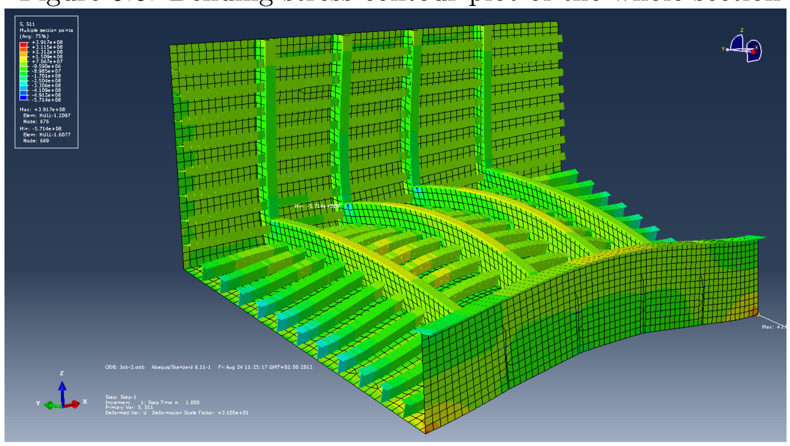
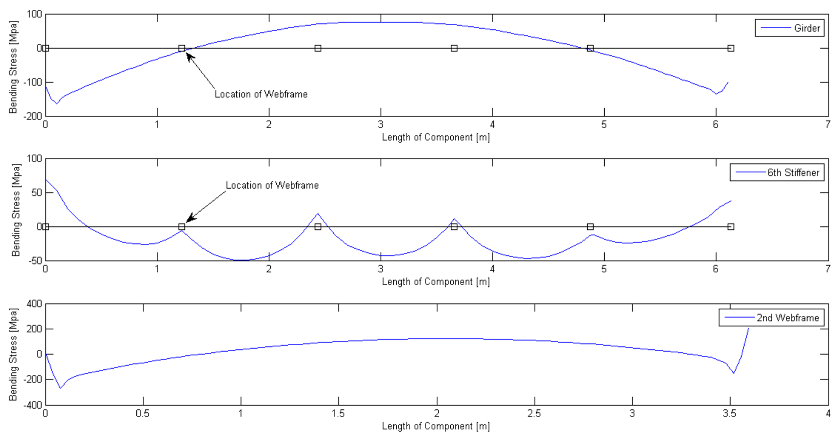


Figure 5.7: Bending stress plot of the girder, the 6^{th} stiffener and the 2^{nd} webframe



From the Von Mises and bending stress responses several conclusions related to the interaction among the stiffeners and the webframes, the corresponding structural hierarchy, and regarding the boundary conditions of the stiffener members can be deduced. As seen in the plots of figures 5.5 and 5.7, the stress of the stiffener is transfered to the webframes which act as stress relief components signifying clear interaction between the structural members. Furthermore, in the stiffener plot, it is observed that the webframes do act as boundary conditions for the longitudinal stiffener validating part of the semi-empirical design methods which state that the primary members shall act as boundary conditions on the secondary members.

Similar to the Von Mises and bending stress, the higher shear stress levels are found at the connection edges between the bottom webframes with the side webframes and the girder. The maximum shear stress values of the webframes reach the 139.9 [Mpa] which is far above the allowable limit. The connection edges of the girder with the bulkheads produce shear stress levels up to 73.53 [Mpa] which are above allowable limit as well. The bottom longitudinal stiffeners on the other hand, with a shear stress average of 10.27 [Mpa] are below the allowable limits.

The finite element analysis of Abaqus software provide rotation responses on the three axises. The largest rotation value is -1.14 degrees and it is found at the connection edge between the bottom and the side webframe during the rotation around [X] axis. The [X] axis rotation graph is depicted in appendix B. Regarding the interaction among the components and the applied boundary conditions, the plots of the rotations around the [Y] and [Z] axis contribute to the formulation of several outcomes. As seen in figure 5.8, both the girder and the stiffener appear to have symmetry around their midpoint which is the center of rotation of the [Y] axis as well. However, it can be noticed that the rotation of the stiffener is prevented by the webframes compared to the girder's which follows a constant slope. This prevention which appears greater at the rotation around [Z] axis in figure 5.9 indicates that the webframes interact with the stiffener by setting boundaries to the rotation of the stiffener.

Figure 5.8: Rotation plot of the girder, the 6th stiffener and the 2nd webframe over the [Y] axis

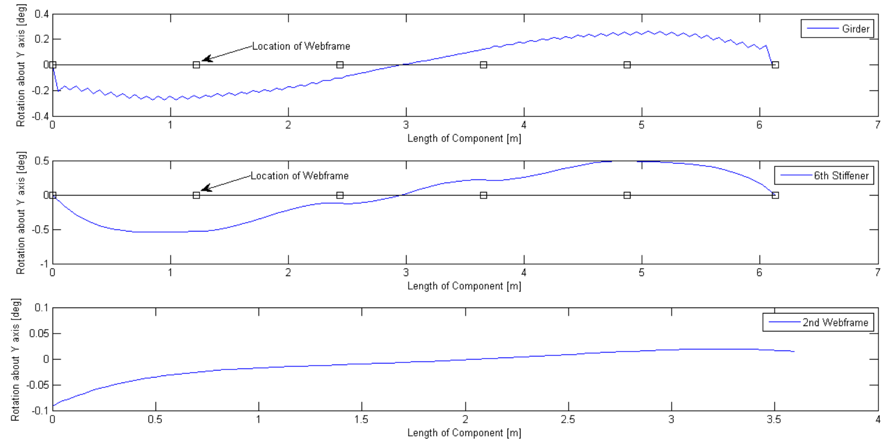
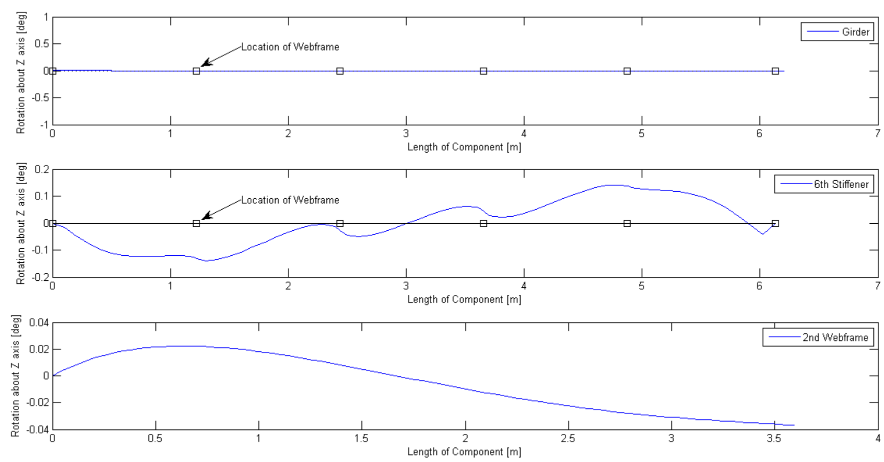


Figure 5.9: Rotation plot of the girder, the 6th stiffener and the 2nd webframe over the [Z] axis



Chapter 6

Conclusions

The conclusions part is divided into two sections where the first section reflects on the hull structure design of high speed craft and the aluminum as building material while the second section is related to the development of the parametric model and the analysis of the structural hierarchy and the boundary conditions of the secondary members.

6.1 Aluminum And Hull Structure Design Of High Speed Craft

From the thesis review it can be stated that aluminum is considered the dominant design material from middle and large size high speed craft. The reason of this preference comes from the fact that aluminum is harmonized perfectly with the design principle of the high speed category since it combines the manufacturing simplicity and production cost of a metal with the weight advantage of a plastic material. The drawback of reduced mechanical properties and fatigue performance due to welding which in certain alloys reached the 50%, seems to be overcome with the introduction of enhanced alloys such as the AA5754-H32 with only 8% welding reduction on its properties, and manufacturing and welding techniques such as the extrusion and friction stir welding (FSW). The friction stir welding technique does, apart from the contribution to the HAZ effect, increase the collapse strength of the welded material by 20% and it reduces the welding distortion and seem weight by 75% and 12% respectively. The manufacturing technique of extrusion on the other hand, conduce both to the reduction of the structural weight since it creates idealized cross sections, and to the structural reliability because it reduces the amount of welding seems which are sources of imperfections.

Concerning the hull structure design of high speed craft, the review issues three design levels which vary both in complexity and design time. The majority of the new design concepts are still conducted with the second design level which is according to semi-empirical classification rules. Nevertheless, there is tendency of transiting to the third design level where the design concepts are conducted by direct calculation methods which provide more explicit design outcomes and this claim is clarified by the attempt of classification societies to introduce conditions of verifying analysis based on direct calculation methods.

6.2 Parametric Model And Application Analysis

The parametric model that has been developed in the present thesis project controls the number, the type, the location and the properties of the major structural components that are required for the hull structure design of high speed craft. It is applicable for modeling numerous structural design arrangements and hence, it does reduce the computational time of the finite element analysis in a great level. The applicability of the model is additionally clarified by demonstrating its capabilities on the analysis of chapter 5.

The analysis that is conducted within the thesis project had as primary scope to study the degree of validity of the idealizations and the assumptions that are stated by the handbook type formulas in the semi-empirical design methods and as secondary scope, to verify if the chosen section fulfills requirements of the finite element classification rules of ABS.

Concerning the secondary scope, it can be stated that the section responses in relation to the Von Mises and bending stress exceed the allowable limits at the flanges of the webframes and at the connection areas of the webframes along with the other primary members. However, these increased stress concentrations are result of the modeling simplifications and hence an analysis with radiused webframes edges is recommended before redesigning the components.

The results of the analysis in relation to the primary scope denote that the idealizations and part of the assumptions that are stated by the handbook type formulas in the semi-empirical design methods, are applicable on this particular structure. More specific, the structure can be idealized according to the structural hierarchy principle since the girder carry most of the bottom load and support the webframes which in return act as stress relief components for the longitudinal stiffeners. The method of defining the boundary condition of the structural members according to the principle of handbook type formulas is validated from the stress and rotation responses. Particularly, the assumption that the primary members shall act as boundary conditions for the secondary members is validated from the Von Mises, bending stress responses as well as from the [Z] and [Y] rotation responses. Regarding the investigation of the interaction effect among the structural components it can be concluded that all the structural components do interact among them with obvious influence of each one to the others. This influence however, cannot be approximated by the handbook type formulas due to the fact that are based on simple mechanics where they isolate every structural component in order to derive its structural response. Therefore, the semi-empirical design methods do not provide an explicit picture of the actual interaction among the components which can only be studied by more detailed modeling techniques like the finite element methods.

Appendix A

Classification Rules

The ABS formulates two classification rule guides for high speed craft. The first was formed during 1990 and named "Guide of building and classifying high speed craft" while the second published during 2003 and it is known as "Guide for Building and Classing High Speed Naval Craft". Both guides include calculation procedures for all three types of building materials, steel, aluminum and fibre reinforced plastic [25].

The High Speed Craft guide includes all the types of high speed vessels with different applicable length for each category. The High speed Naval Craft guide follows the same principle, but it includes four additional vessel types the High Speed Craft, the Naval Craft, the Coastal Naval Craft and the Riverine Naval Craft [25]. Both classification guides have similar requirement regarding the characterization of a vessel as high speed craft. The requirement is related to the operational speed of the craft and is defined by the following formula [22]:

$$V > 2.36 * \triangle/\sqrt{L}$$

where V is the operational speed at m/s, $\triangle$ is the craft's displacement in m^3 and L is the craft's length in m.

To cover even the unusual design cases, both classification guides introduce a direct analysis process when the vessel exceeds some specific main particulars such as length or operational speed. For vessels that are going to be designed according to High speed craft guide, direct analysis is required for length over 61 meters for aluminum and steel hull, or if the operating speed is over 50 knots regardless length. On the other hand, for vessel that are going to be designed with High Speed Naval Craft guide, the criteria for direct analysis are related to vessel type [25].

The main difference between the two guides though, is the way of interpreting the design acceleration. The design acceleration formula is directly dependable from the speed [V], the water line breadth [B_w], the displacement [$\triangle$] and the significant wave height coefficient [$H_{1/3}$] which is the actual parameter that varies among the guides. The High Speed Naval Craft guide calls for calculation of the vertical acceleration in two cases, the design condition and the survival condition while the High Speed Craft postulates only the first case. The High Speed Craft requires the approximation of the design acceleration in a wave height of $L/12$ and not more than 4 meters while the High Speed Naval Craft requires the design acceleration in a wave height of 4 meters as design condition and in 6 meters with a speed of 10 knots as survival condition [25].

Concerning the approximation of the design loads both rule guides publish the same calculation flow and the same formulas [25]. The design pressure of the bottom part should be the larger value between the hydrostatic pressure and bottom slamming pressure. The bottom slamming pressure is calculated at the area of longitudinal center of gravity for vessels smaller than 61 meters and both at the longitudinal center of gravity and at an area clear from the longitudinal center of gravity for vessels larger than 61 meters. The value is primarily depended on the vertical acceleration [n_{cg}] and craft's particulars such as length [L_w], breadth [B_w] and displacement [$\triangle$]. The hydrostatic pressure is based on the wave parameter [H] and the stationary draft [d]. The design pressure of the side part is defined via the larger value between the hydrostatic pressure in the side part, the slamming pressure which is the same as in the bottom part and the fore end side design pressure. The hydrostatic pressure in the side part is approximated with respect to the distance of the side part from the water line [y]. The fore end side design pressure is applicable in certain areas of the side part and mainly depends on the length [L_w] of the craft. The design pressure on deck is defined by a formula based on the length [L_w] of the craft [29].

The aluminum scantling formulas for all structural components of both ABS rule guides are identical. The calculation of the minimum plate thickness is similar to the bottom, side and strength deck sections and the outcome depends on the frame spacing [s], the craft's length [L_w] and the design stress coefficient [σ_a] which varies among the sections.

The primary and secondary member dimensions are defined from the Section Modulus [SM], Moment of Inertia [I] and web-depth thickness ratio [$\frac{d_w}{t_w}$]. The strength and stiffness requirements are affected significantly from a coefficient which alternate with respect to the position of the stiffener (deck - bottom - side) and the type of it (primary-secondary, longitudinaltransversal) as well as from the span [l] of the member since it is defined in a power of two and three for Section Modulus and Moment of Inertia respectively. The web-depth thickness ratio varies among the slamming area and other areas and depends on the material properties [29].

The Det Norske Veritas (DNV) was the first classification society that introduced rule guides for high speed craft. The first guide was named "Construction and Classification of light craft" and published at 1972 [22]. The current DNV rules for high speed and light crafts set criteria for high speed craft, light craft and naval surface ships for all building materials. The interpretation of what is considered as high speed craft is slightly different than the one of ABS. More specific to register a vessel into the DNV's class it must be capable to reach a speed of 25 knots regardless its size and also, the maximum speed of it to be greater than the following formula [25]:

$$V \geq 7.16 * \triangle^{0.1667}$$

where V is the craft's speed in knots and $\triangle$ is the displacement of the craft in *tons* at sea water.

The conditions of DNV to categorize a vessel as high speed craft extent to the displacement of the vessel as well. The rules state that the high speed craft must not have full load displacement larger than [25]:

$$\triangle = (0.13 * L * B)^{1.5}$$

where L and B are the length and the breadth of the craft in m and $\triangle$ is the displacement of the craft in *tons* at sea water.

Similar to the IMO code of High Speed Craft, each vessel that is classified by DNV is also categorized to a particular service classification related to the service area and operational mission. This characterization affects the structural design in a great level since it is factor for setting the design acceleration of the craft [25]. Other variables that impact the value of the design acceleration are the speed [V], the length [L] and the water line breadth [B_{wl}] of the craft [33]. As an antipode to the direct analysis of ABS for vessels that exceed some certain criteria, DNV postulates a global finite element analysis for vessel with length greater than 50 meters [25].

For steel or aluminum hull, the DNV divides the structure into four sections, the bottom section, the deck section, the side section and the fore-body side and bow section. In every section, DNV sets the design pressure load as the largest load among all the loads that interact with the section [33].

For the bottom section there are three loads that interact with the structure, the slamming pressure load, the pitching slamming pressure and the sea pressure load. The slamming pressure load is mainly dependable from the vertical acceleration [a_{cg}] and the draft [T_O] in normal operation condition. The pitching slamming pressure which is applicable only in a certain area of the bottom is mainly influenced from wave coefficient [C_w] which is defined from the service notation and the deadrise angle [β_x]. The sea pressure load which typically is the smallest value of the three depends on the vertical distance from the water line [h_0] and the wave coefficient [C_w]. For the side and deck section, DNV publishes only one design pressure load, the sea pressure load. However, apart from the sea pressure load, the deck section is checked for an additional pressure load if is designed to carry heavy units. The additional pressure load is calculated as a function of the mass of the unit [M] and the design acceleration [a_v]. Concerning the fore-body side and bow section DNV publishes an impact pressure which is calculated as a function of length [L], speed [V] and block coefficient [C_B] [33].

The shell plating thickness of a metal craft is defined by the largest value of the minimum thickness requirements that the rules publish. These requirements are defined as the general minimum plate thickness, the bending minimum plate thickness and for the bottom section the slamming minimum plate thickness. All three prerequisites depend on the frame space [s], the design pressure load and the yield stress coefficient [σ] which defines the section that the plate covers [33].

The strength and stiffness conditions for the stiffeners are defined via the calculation of the Section Modulus [Z]. The value of the Section Modulus is mainly affected by the span of the member [S] which stands in a power of two. Concerning the bottom stiffeners there is an additional regulation regarding the Shear Area [Aw]. The outcome of the Shear Area [Aw] is affected by the frame space [s] and the span [S] of the member. The primary members of the craft, the girders and the webframes, have minimum thickness prerequisites as well as strength and stiffness requirements which approximated via the Section Modulus [Z] and the Shear Area [A_w] like the bottom stiffeners but with different coefficients. The minimum thickness prerequisite is defined with respect to parameters like the length of the craft [L], the frame space [s] and a coefficient [k] that states the location off the member among the sections. The Section Modulus [Z] is defined in the same manner as the bottom stiffeners but now the coefficient of the formula [σ] alternate with respect to the location of the member. The Shear Area [A_w] is calculated as a function of the span [S], the load area [b] and the number of secondary stiffeners [a] between the section and the nearest support [33].

As a leading classification society Lloyd's register of shipping could not neglect the demand for classification guides related to high speed craft. Lloyd's register introduced the first guide during 1996 which was applicable in vessels with length greater than 24 meters [22].

The Lloyd's rule guides, as the DNV and ABS, correspond to all building materials and to various types of craft such as high speed craft, light craft, multi-hull vessels and craft with draft to depth ration less or equal to 0.55. Concerning the criteria to characterize a vessel as a high speed craft, the guide of Lloyd's register of shipping acts in the same wavelength as the guide of DNV. It states an identical formula regarding the craft's speed and a similar formula for the maximum displacement of the craft. The formula that Lloyd's register of shipping set regarding the displacement criterion is illustrated below [25]:

$$\triangle = 0.04 * (L * B)^{1.5}$$

where $\triangle$ is the craft's displacement in *tons* and L, B are the Length and the Breadth of the craft in m respectively.

For unusual hull designs and for vessels with operational speed larger than 60 knots, Lloyd's Register of Shipping publishes a direct calculation process which accredit the design according to the classification demands. Similar to ABS and DNV, Lloyds register of shipping has introduced notations and restrictions in relation to the service area and operating mission of the craft [25]. The restrictions from the notations have indirect effect on the design acceleration of the craft since they affect the significant wave height coefficient $[H_{1/3}]$. Apart from the significant wave height coefficient $[H_{1/3}]$ the design acceleration variable is also affected from the main particulars of the craft. In contrast to the other classification rule guides, Lloyd's register of shipping publishes an additional vertical acceleration condition based on the displacement operation mode of the craft. The corresponding formula publish results as a function of the speed $[V]$ and the length $[L_w]$ of the craft without taking into account the significant wave height coefficient $[H_{1/3}]$ [31].

The Lloyd's register of shipping demands design pressure loads for four sections in the same way as DNV. For the weather deck and interior decks section, the design load should be the larger value between the hydrostatic pressure for displacement mode and hydrostatic pressure for non-displacement mode. The hydrostatic pressure for the displacement mode varies across the length of the craft and depends on the speed $[V]$ and on main particulars of the vessel such as length $[L_w]$, draft $[T]$ and depth $[D]$. The value of hydrostatic pressure for the non-displacement mode varies also across the length of the craft and counts on the vertical acceleration $[a_v]$ and the length of the craft $[L_w]$. The design load of the bottom section is defined as the largest value among the impact design pressure due to slamming for the displacement and non-displacement mode. The impact load for the displacement mode varies across the length of the craft and depends on the draft $[T]$, the length $[L_w]$ and the speed $[V]$ of the craft. The impact pressure load for the non-displacement mode differs across the length as well and it is function of the vertical acceleration $[a_v]$, the length $[L_w]$ and the displacement $[\triangle]$ of the vessel. Considering the side part of the craft, the design load that is registered in the section is the product of the impact pressure load due to slamming for non-displacement mode with the ratio of the dearise angles of bottom $[\theta_B]$ and side part $[\theta_S]$. The last section that Lloyd's register of shipping publishes requirements is the forebody section. In this section, the design pressure load is defined either from the forebody impact pressure for displacement mode or from the non-displacement mode. Both impact pressure loads vary across the length of the ship and are dependable from the main particulars of the craft [31].

The process of determining scantlings for aluminum hull structure via the rule guides of Lloyd's register of shipping is based on a number of general requirements related to minimum thickness requirements for plating, and minimum stiffness and strength requisites for the stiffeners. Concerning the shell plating, the thickness requirement of each plate on every section is based on the corresponding design pressure, the frame space $[s]$, the panel aspect ratio $[\beta]$ and a factor $[f_\sigma]$ which varies with respect to the location of the plate. In addition to the general formula, Lloyd's publishes two more minimum thickness requirements for two particular areas, the stem area and the keel area. At the keel area the rule guide set conditions for the breadth of keel as well as the minimum thickness. Both formulas are functions of the length $[L_w]$ of the craft. At the stem area the guide states a minimum thickness requirement based only on the length $[L_w]$ of the craft [31].

The strength and stiffness requirements of Lloyd's register of shipping are similar to ABS since all the stiffeners, primary and secondary, postulate conditions for Section Modulus $[SM]$, Moment of Inertia $[I]$ and Web Area $[A_w]$. The Section Modulus $[SM]$ and Moment of Inertia $[I]$ are defined identically in Lloyd's and ABS. The only difference appears on the coefficients which are interpreted from another perspective on both classes. The Web Area $[A_w]$ is similar requirement to the web-depth thickness ratio of ABS and it primary dependable on the space framing $[s]$, the span $[l_e]$ and on coefficients similar to Section Modulus and Moment of Inertia [31].

The last of the individual classes that formulate classification rules for high speed craft is the Nippon Kaiji Kyokai (NKK). The rules for high speed craft of NKK are applicable to all building materials. The registration of a vessel as high speed craft comes from the same criterion as the one from the IMO code of high speed craft [30].

$$V = 3.70 * \triangle^{0.1667}$$

where $\triangle$ is the displacement of the craft in m^3. The NKK has specific notations and restrictions identical to Lloyd's [25]. However, the notations of the NKK affect only the significant wave height coefficient [$H_{1/3}$] and not the vertical acceleration [A_f] [30].

The NKK publishes design loads for three sections which correspond to the bottom section, the side section and the deck section of the craft. The design load of the bottom section is defined through the impact pressure load. The impact pressure load is a function of the second power of the impact velocity [V_i] and the compensating factor [K_{PW}]. The design load of the side section is defined through a pressure load that is similar to the hydrostatic pressure. This load pressure is a function of some particulars of the craft such as the breadth [B] and the draft [d], and factors such as significant wave height [$H_{1/3}$] and vertical distance [h']. The design load of the deck section comes from a pressure load which is dependable on the scantling length of the craft [L_s] for exposed decks and on vertical acceleration [A_f] for other deck constructions [30].

The NKK rule guide determines the scantlings based on the material of the hull structure. For aluminum hull structures the conditions are related to minimum thickness requirements for plating and strength and stiffness requirements for stiffeners. The scantling determination of the plating is dependable on the spacing [s] of the longitudinal stiffeners as well as the square root of the allowable stress [σ_{all}] and the corresponding design pressure load. The strength of the longitudinal stiffeners is defined through the calculation of the section modulus [SM] in equal way to the other classification rule guides. The primary members of the structure are defined from the conditions of the Section Modulus [SM] and the Web Sectional Area [W_A]. Both conditions are approached in the same as in DNV rule guide [30].

The classification societies Registro Italiano Navale (RINA), Germanischer Lloyd (GL) and Bureau Veritas (BV), found the classification union for high speed craft UNITAS. The classification guide for high speed craft of UNITAS published at 1997 and is considered as an expansion of the primitive guide that IMO code of high speed craft introduced [22]. According to UNITAS a vessel can be accredited as high speed craft if its operational speed is larger than the speed requirement of IMO code of high speed craft and at the same time, it fulfills an additional requirement regarding the speed-length ratio of the craft. The additional requirement is illustrated in the following formula [22]:

$$(V/\sqrt{L}) > 10$$

where V is speed at m/s and L at m.

Likewise the other classification rule guides the UNITAS rule guide is applicable to all building materials. Moreover, for hull structure orientations that cannot be assessed realistically or for vessels with length larger than 65 meters or operation speed larger than 45 knots the rule guides of UNITAS propose direct calculation process. Concerning the operation issues of the craft, it publishes notations as well as area constrains in similar manner to the other four classification societies [32]. The operation notations and the area constrains have direct impact on the calculation of the vertical acceleration $[a_{cg}]$ since they are products that are taken into account when it is calculated. Other factors that affect the vertical acceleration $[a_{cg}]$ are the speed $[V]$ and the length $[L]$ of the craft [32].

In analogous way to NKK, UNITAS have published three sections where specific design pressure loads are assigned to act on them. At the bottom section, UNITAS claim that two types of loads interact with the section, the sea pressure load and the impact pressure load. The impact pressure load is expected whenever the slamming effect occurs and is dependable on the displacement $[\triangle]$ and the vertical acceleration $[a_{cg}]$. On the other hand, the sea pressure is a function of the distance $[x]$ of the aft perpendicular to the load point, the length $[L]$ and the draft $[T]$ of the craft. The design load that acts on the bottom part should be the larger value among the impact pressure load and the sea pressure load. At the side part of the craft, the rule guide of UNITAS state that the design load stems from the sea pressure load but only for areas that have a vertical distance $[z]$ larger than the draft $[T]$. The design load for the side part is dependable on the vertical distance $[z]$ and the draft $[T]$ of the craft. At the deck section, the designed load pressure is defined based on the distance of the deck from the water line. If the deck is supposed to carry vehicles or objects, an additional regulation based on the concentrated force coming from that object is to be approximated [32].

Re the shell plating requisites of aluminum hull structure, the UNITAS rule guides publish a minimum thickness requirement based on the stiffener framing $[s]$ and permissible stress $[\sigma_{am}]$ which is determined from the location of the plate. The stiffeners are defined through the conditions of Section Modulus [SM] and Shear Area [A_t] alike the NKK rule guide. The only differences are identified on the coefficient that two rule guides introduce. The primary members have the same requirements as the stiffeners and defined by the same process. However, the dependency of their values is slightly different since they depend on the width of the larger side of the plate [b] and not at the frame spacing [s] [32].

Appendix B

Results Of The Finite Element Analysis

Figure B.1: Deflection of the Girder, the 6^{th} Stiffener and the 2^{nd} webframe over [X] axis

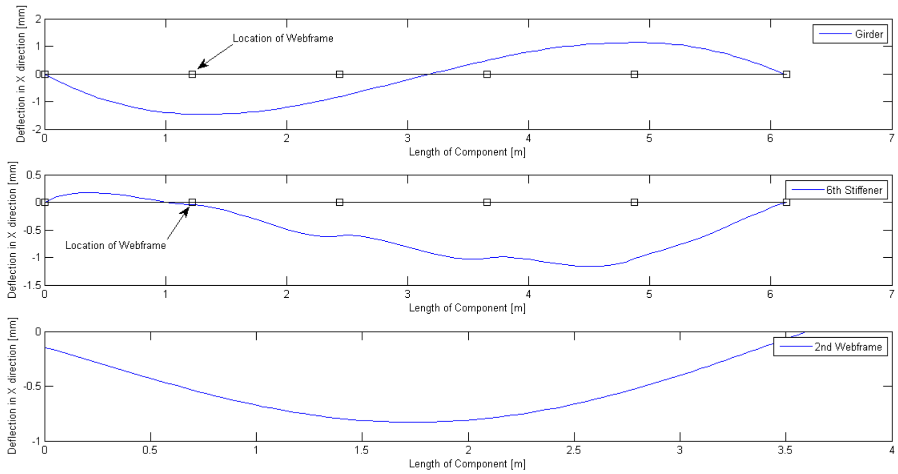


Figure B.2: Deflection of the Girder, the 6^{th} Stiffener and the 2^{nd} webframe over [Y] axis

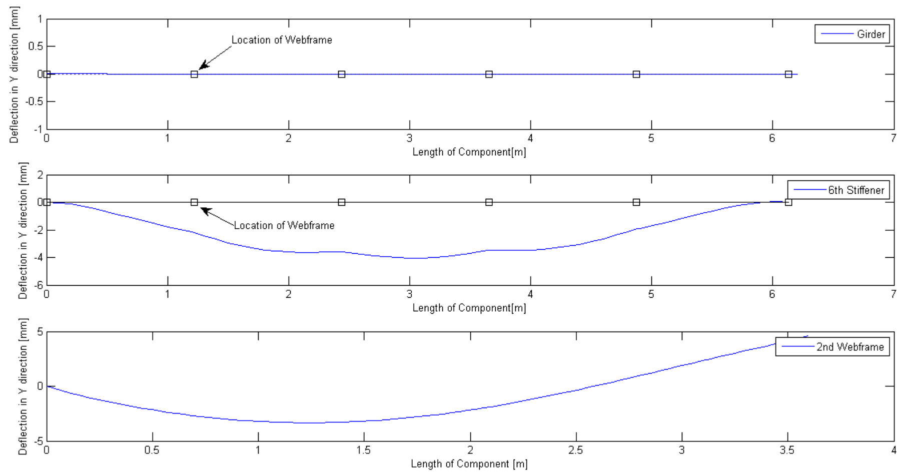
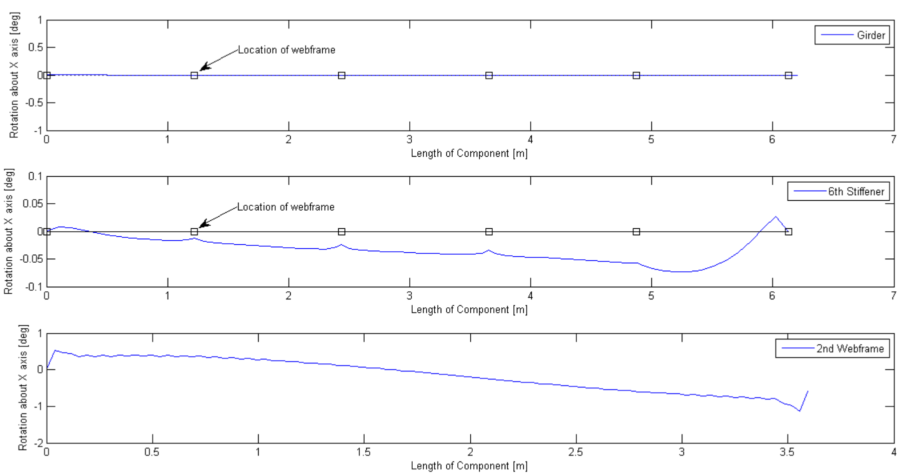


Figure B.3: Rotation of the Girder, the 6^{th} Stiffener and the 2^{nd} webframe over [X] axis



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