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"Assessment on the design and production of a composite inland waterway vessel by means of Additive Manufacturing''

By

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Summary

Introduction

Additive Manufacturing (AM) offers potential to add value in terms of storage, localised production, production rate, weight reduction, customization and offers complexity for free. Within the Maritime Construction Sector (MCS) business models for AM are difficult to obtain due to its relatively large objects and the corresponding low building cost. In recent years, AM processes have developed significantly in terms of machine dimensions, building speed, material properties and production costs. It is concluded there is sufficient reason for further research on AM production within the MCS.

Large scale additive manufacturing, material extrusion, offers high deposit rates and thermoplastic composite material properties. Cheap thermoplastics in combination with fibre reinforcements provide the opportunity to reduce required mass, increase building time and cut building costs. Interest in composite cargo vessels is noticed mainly due to weight reduction and corrosion resistance. However, financial consequences due to mould making and expensive materials, and regulations obstruct widespread developments. To explore the possibilities resulting from additive manufacturing within the maritime construction sector a Class III inland waterway vessel is used as case study. For more in depth knowledge the bow section of the vessel is considered. To retrieve relevant information about the feasibility and requirements of a thermoplastic bow section the main question and resulting sub-questions are stated as follows:

<u>1: Can a thermoplastic composite Class III inland waterway vessel be produced competitively using Additive Manufacturing – Material Extrusion, compared to steel and what is the expected weight reduction?</u>

Following sub-questions are listed to help answering the main question.
<u>2: What are the vessel’s functional, market driven and regulatory requirements?</u>
<u>3: How does AM-ME comply with stated market driven, functional and regulatory requirements?</u>
<u>4: What AM-ME polymer and reinforcing material is best suited for inland waterway vessels?</u>
<u>5: What is the expected weight reduction using AM-ME and accompanied thermoplastic composite?</u>
<u>6: How is the required equipment within the vessel installed?</u>
<u>7: What will be the final weight reduction and cost price of the inland waterway vessel and can it become Class approved?</u>
By answering the stated sub-questions, the main question is answered.

Approach:

Functional requirements describe what a bow section should do and how it should fulfil its purpose. Market driven requirements state maximum allowable costs, building time and weight in order to be competitive over traditional manufacturing. Regulatory requirements are derived from Lloyds Register Rules & Regulation on special service craft, in which composite vessels are treated. Rules prescribe material requirements, composite laminate requirements, design pressures, fire safety, maximum allowable stresses and deflection and more.

AM ME offers advantages in terms of building dimensions, deposit rate and costs. Research on AM-ME results in a collection of technologies and developments required with respect to the production of large composite objects. Special attention is provided to multi-axis material deposition, material selection and cost price.

Based on required mechanical material properties and material durability a selection of polymers, reinforcing fibres and additives is derived. Using composite theory for anisotropic composites, final material properties are calculated required for further bow section analyses. Besides direct composite

characteristics some basic conclusions about creep and fatigue, and the use of recycled content, are derived.

To estimate the final weight of the bow section, and complete inland waterway vessel, a global and local design space is derived. First, adjustments on the section due to installation of components is discussed. Manual calculations applicable on main components with composite material properties offer first weight estimations. Optimizing for laminate thickness and fibre orientation offers additional weight reduction. Insight is provided in the way the bow section is produced using AM, including installation of components and post-processing the outer surface.

Besides being able to insert components and systems, these need to be connected to the bow section without causing extended assembly time, repair work, durability and leakage. Various methods of connection are proposed. To keep production costs low, weight reduction is a significant factor resulting from material costs and building time. Building time cannot exceed traditional building time especially during outfitting. In the final sub-question, final weight reduction, building time and costs are discussed. By answering the final sub-question, the main question can be answered.

Conclusions:
AM developments offer the possibility to comply with stated functional, market driven and regulatory requirements. Main challenge is keeping production costs low and offering cross-plied laminates. Uncertainties rising from AM production are material integrity, fatigue and classification. Keeping costs low is to be done by using cheap thermoplastic composites, increase deposit rates and reduce weight as much as possible, to keep machine time and material usage low.

Based on the global design space and a reference local layout of the bow section a final weight reduction of 36% is estimated, in which various known and underestimated safety factors are taken into account. The outcome is validated by analyses of individual components and the complete bow section using software Hyperworks. By optimizing laminates on thickness and orientation an additional 9% weight reduction seems achievable, depending on initial selections for thickness and orientation. Since midship section are subjected to higher bending moments, less weight reduction is achievable for the entire vessel.

It is concluded material costs can reach low values although it will be hard to prepare the required amount of materials for a cost price of in between 0.97 and 1.63 EUR/kg, to reach desired final production costs. Most favourable material compound is Polyethylene Terephthalate (40 wt%), Polycarbonate (5 wt%), E-glass direct roving (40 wt%) and E-glass short fibres (7 wt%) including a set of chosen additives (8 wt%). The selected material complies with stated regulations. The use of recycled polymers offers advantages since cost price is reduced. PET polymers show good recycling properties and allow for regeneration up to virgin quality. Although selected materials show promising fatigue properties, the effect resulting from AM deposition remains uncertain.

Machine rate, building time, material costs and optimised weight of the object have resulted in a total cost price reduction of in between 15% and -22% of traditional building cost. Building time of 3 to 5 days is calculated feasible in which a 22 to 25 tonnes weighing bow section is deposited, offering 36% weight reduction over traditional manufacturing. Weight and cost reduction extrapolated to a complete vessel is less due to higher bending moments in the midship section and requires further research.

Classification remains an issue although to direct rejections are expected. To comply with fire safety, fire resistant panels need to be installed. Most critical rules are respected but additional research is required on fire safety and process control during the manufacturing process, including standardization of machinery.

List of abbreviations

MCS	Maritime Construction Sector
AM	Additive Manufacturing
DED	Direct Energy Deposition
PBF	Powder Bed Fusion
ME	Material Extrusion
WAAM	Wire Arc Additive Manufacturing
MDR	Material Deposition Rate
DFM	Design for Manufacturing
DFA	Design for Assembly
CSM	Chopped Strand Mat
WR	Woven Roving
CP	Cross Plied
BV	Bureau Veritas
FDM	Fused Deposition Modelling
CNC	Computer Numerical Control
WHAM	Wide and High Additive Manufacturing
BAAM	Big Area Additive Manufacturing
LSAM	Large Scale Additive Manufacturing
HM	Hybrid Manufacturing
ATP	Automated Tape Placement
AFP	Automated Fibre Placement
CFAM	Continuous Fibre Additive Manufacturing
FRP	Fibre Reinforced Polymers
PET	Polyethylene terephthalate
PC	Polycarbonate
SF	Safety Factors
SIMP	Solid Isotropic Material Method
ESO	Evolutionary Structural Optimization Method
BESO	Bidirectional Structural Optimization Method
SOMP	Solid Orthotropic Material Penalization
CFAO	Continuous Fibre Angle Optimization
FMO	Free Material Optimization
DMO	Discrete Material Optimization

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1. Introduction

Leading factors in the MCS are production costs, delivery time and quality/performance which comprises, vessel weight, welding quality, finishing and more. Low margins in vessel production result in the need for efficient and affordable production methods. Lead-time, required man hours and steel price are key in keeping costs low. Various studies underline the aim to reduce costs in order to stay ahead of competition (Ecorys-scs, 2009; Gattorna, 2015; Sauerhoff, 2014).

Additive Manufacturing (AM) is a growing production process in a wide variety of industries. It affects existing market strategies in terms of storage, repair and localised production and it shows potential to add value in cost price, production rate, weight reduction and customization and offers complexity for free (Doubrovski, 2016). Within the (MCS) business models for AM are difficult to obtain due to its relatively large objects and the corresponding low building cost (Bergsma, van der Zalm, & Pruyn, 2016). Other challenges such as material integrity and a lack of classification are noted but opportunities, such as lower costs and sustainability, are also identified.

In recent years AM processes have developed significantly in terms of machines, building speed, surface quality, mechanical properties and closed loop systems. The progress in these fields are expected to continue developing at a high rate (Doubrovski, 2016). According to (Berger, 2013) the adoption of AM will increase in the future since building speed, machine dimensions and material prices show potential. (Bergsma et al., 2016) have argued that there is sufficient stimulant for further research on AM production within the MCS. To be able to come to decisive conclusions, however, additional knowledge and a higher level of detail is required. Related to the challenges present within the MCS and the opportunities rising resulting from AM, this thesis proposes a research on the feasibility of AM within the MCS.

Since AM will significantly affect current production processes benefits resulting from AM need to be clarified. Within the MCS, costs, lead-time and/or quality have to be beneficial, in which cost price is the leading factor. Also (safety)regulations, structural characteristics and product acceptance must be taken into account. Given the challenges: costs, delivery time and quality, the adoption of AM might bring opportunities related to potential low building costs, predictive building time and repeatable/duplicatable object quality, without interference of human errors. When cheap materials are used and machine rate is kept low, AM, offering uninterrupted and almost unmanned production can have a big impact on these elements.

In §1.1 an AM process is selected based on being most beneficial in terms of costs, production time and building dimensions. §1.2 the reference case is introduced to be able to compare AM with traditional manufacturing. In §1.3 the main and secondary opportunities resulting from AM production are discussed. This paragraph is followed up by the expected challenges in §1.4, subdivided in production costs and class regulations. §1.5 discusses further research to be performed. Based on these paragraphs, the main question and accompanied sub-questions are listed in §1.6.

1.1. AM Process Selection

In this paragraph it is explained what AM process is further researched and what arguments underline this choice. In (Bergsma et al., 2016) it is described the three most relevant AM processes for the MCS are Direct Energy Deposition (DED), Powder Bed Fusion (PBF) and Material Extrusion (ME). A clear distinction is present between metal AM and polymer (composite) AM. For the MCS, the three most relevant parameters to be influenced by AM seem to be building envelope, AM process (including material), and costs. Based on above stated AM abilities the choice for most promising AM production method was assumed to be DED, a metal AM process, which is an obvious choice since the larger part of the MCS is using steel as building material. In (Buirma, Joon, Streng, & van Voorst tot Voorst, 2017) the focus in on Wire Arc Additive Manufacturing (WAAM) and (Pino, 2018) states DED and PBF show highest interest for the MCS based on building dimensions and deposit rate, retrieved from (Bergsma et al (year)). These choices depended on favourable building dimensions and deposit rate. It is concluded metal AM brings difficulties in competitiveness mainly related to cost price.

Developments within the AM-ME industry brings new preferences for possible adoption within the MSC, related to very high deposit rates, strong, lightweight thermoplastic composite materials and large building volumes. Additional benefits can be found in the use of recycled or sustainable, corrosion resistant and cheap materials. The ratio between machine dimensions and deposit rates for ME are more beneficial compared to DED and PBF based on the current AM status. (Thermwood, 2016; Yakubov & Uzan, 2015). Machines for AM – ME, such as LSAM from Thermwood have reached dimensions of over dozens of meters and Material Deposition Rate (MDR) can go up to 1000 kilo's per hour per machine. Building dimensions and deposit rates are continually increasing. Polymer material costs for ME match regular polymer bulk prices as can be found in the injection moulding industry. In (Bergsma et al., 2016) the above stated combination of data is not retrievable due to recent AM developments and outdated referenced AM – ME machines (Stratasys – Fortus 900mc) which has a small building envelope (0.9 x 0.6 x 0.9 m) and demands very expensive feedstock such as thermoplastic powder and filament based materials having significantly higher cost prices compared to polymer bulk prices.

Other opportunities resulting from AM applicable within the MCS are: production on location, reduced fuel consumption, weight reduction, corrosion resistance, complexity for free and vibration dampening, (Bergsma et al., 2016; Ecorys-scs, 2009; Sauerhoff, 2014; Thomas & Gilbert, 2014). Although a wider selection of advantages for the MCS is seen cost reduction and/or shorter lead time will be crucial for AM adoption while maintaining or increasing object quality (Ecorys-scs, 2009). The combination of building dimensions and deposit rate is currently most favourable in the AM-ME industry. The thermoplastic materials used offer low costs, low density, corrosion resistance and allow for recycling. Although the MCS usually uses steel materials, material extrusion and accompanied composite materials brings potential benefits in lower production costs, decreased vessel weight, corrosion resistant surfaces and a less demanding environmental impact. This combination of the AM-ME process and accompanied composite material characteristics, combined with the resulting benefits for the MCS, provide a sufficient base for further research.

1.2. Case Study

To explore the possibilities resulting from polymer extrusion based production within the MCS, a Class III inland waterway vessel is used as reference. There is interest noticed in composite inland waterway vessels (CompocaNord, InBat, FibreShip). Also, wave forces are limited compared to seagoing vessels, inland waterway vessel production is cheap, and an inland waterway vessel has realistic dimensions with respect to the current technological AM status. To offer in depth knowledge, the bow section is chosen for detailed research, since it offers a wider variety of technical challenges such as installed machinery, tanks, equipment and housing. Although the bow section is more complicated (double curved plating) and is subjected to lower bending moments compared to a midship section, it offers sufficient knowledge on the feasibility of an AM-ME produced inland waterway vessel.

The bow section of the reference Class III inland waterway vessel has dimensions of approximately 9 x 9 x 4 meters and weighs about 40 tonnes. A diesel or diesel electric propulsor is installed to propel the bow thruster and auxiliary equipment. In front of the watertight bulkhead there is a ballast tank, and on the sides, there are fresh water, fuel and oil tanks, divided by cofferdams. An emergency generator is installed above the waterline, and in the middle, housing for crew is located. Various auxiliary systems, electrical supplies and pipes are installed throughout the section. An example of a simplified reference bow section presented in figure 1

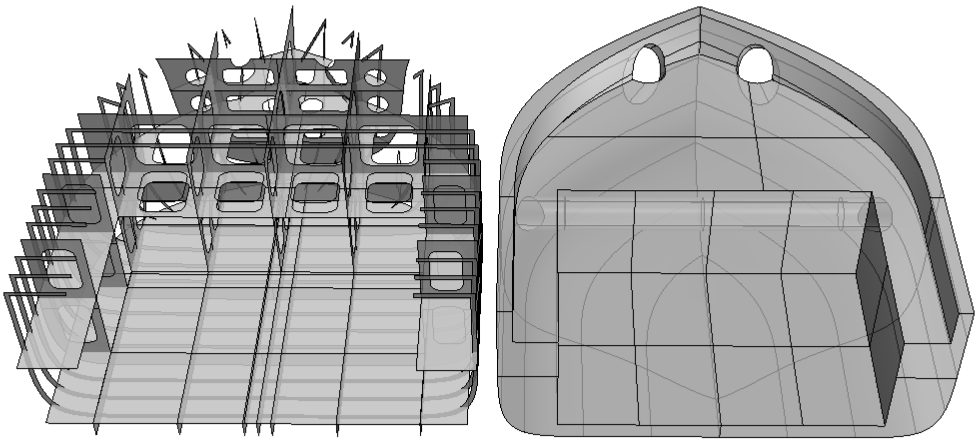


Figure 1 Reference bow section

The reference bow section is used for further calculations on building time, weight and production costs. Functional, market driven and regulatory requirements are collected to be able to compare the AM-ME bow section with a traditional bow section. Rules applicable on the traditional bow section are derived from (Lloyds.Register, 2008) inland waterway vessels and rules applicable on the (composite) AM-ME bow section are derived from (Lloyds.Register, 2017a) offering regulations for composite crafts.

1.3. Opportunities

This paragraph discusses expected opportunities resulting from the use of AM-ME and accompanied thermoplastic composite materials within the MCS. The paragraph is subdivided in weight reduction and secondary opportunities

1.3.1. Weight reduction

This sub-paragraph discusses the use of (thermoplastic) composite material for cargo vessels. Several articles underline the interest, although limited, in composite cargo vessels (Fibreship, InBat, CompocaNord). Stated advantages such as weight reduction, vibration damping and resistance to corrosion show highest interests (Job, 2015). The advantages of composite vessels are clear but the financial consequences are less favourable due to mould making, the use of expensive thermoset composites, comprehensive labour and unfamiliar regulations, which seem to obstruct widespread developments (Guesnet 2005, Leerink 2008, García-Espinosa 2017). With the use of AM, no mould making is required, the amount of workforce is decreased significantly and commodity thermoplastic material prices are low (CES.EduPack, 2018). Opposite, expensive and complicated machines are required which demand high initial investments.

The use of lightweight thermoplastic composite materials in combination with AM provide the possibility to make more accessible use of topology optimization (A. T. Gaynor & Guest, 2016; Komi, 2016; Larsson, 2016) and offers complexity for free. Weight reduction results in performance improvement and/or lower fuel consumption. In (Hekkenberg, 2012) it is stated a 50% hull steel weight decrease results in the possibility of taking in 7% to 10% additional cargo. Although the extra amount of cargo and/or lower fuel consumption is limited, reduction in weight is advantageous in directly reducing building cost and building time since raw material costs and building time (machine rate) are direct cost items within AM (Thomas & Gilbert, 2014). Stated in (Pino, 2018) topology optimization for large objects requires devious computational power and time, which is currently, and within the scope of this master thesis, irrelevant regarding the questions of this master thesis. In (Buirma et al., 2017), various options for weight reduction related to stiffener configurations are proposed resulting in significantly increased profit margins.

Polymers can be divided into plastics and elastomers. Plastics are divided in thermoset and thermoplastic polymers. This research focusses on the deposition of thermoplastic materials using material extrusion. To gain a composite material, a second component is to be added. For composite vessels this is usually glass fibre due to its cost and strength. A polymer-glass composite shows improved specific strength (kN·m/kg) due to its high tensile strength and low density compared to steel. The increase in raw material price compared to steel price (950,- EUR/ton, (Buirma et al., 2017) is compensated with improved strength-to-weight ratio of fibre reinforced thermoplastic resin.

Based on claims resulting from reference composite vessels (Fibreship, InBat, CompocaNord) in between 30% and 50% weight reduction over steel is achievable. Thermoset composite vessels are produced using thermoset resin and glass fibre fabrics. Thermoplastic resins are available with comparable mechanical properties (strength and stiffness) as thermoset resins offer. Resulting composite properties, based on composite theory, are comparable. In thermoset composite production woven or cross-plied fabrics are impregnated using vacuum injection. In AM, impregnated glass fibres are deposited. Due to the layer-wise production process it will be a challenge to deposit impregnated fibres in multiple directions to reach the required strength.

In table 1 a comparison is provided between steel and composite, based on material properties used in composite shipbuilding (CompocaNord). Based on specific strength, using composite materials, in between 80% to 90% weight can be reduced. Reduced specific stiffness requires additional material of in between 40% and 70% but can be compensated by adjusting geometry in terms of increasing the amount of stiffeners, decreasing span widths or by relocating material.

Material	Density Kg/m^3	Yield strength (MPa)	Specific strength	Young's modulus (GPa)	Specific stiffness
Steel	7.85	250	31.8	205	26.8
Composite	1.5 - 1.9	280 - 350	147.4 – 233.3	15 - 24	7.9 – 16

*Table **1** Specific strength and stiffness retrieved from (CES.EduPack, 2018)*

Due to the relatively new AM production process losses in mechanical properties are seen. Layer adhesion is less optimal compared to mechanical properties as provided in material datasheets. Comparisons show about 70% reduction of the unreinforced resin strength at best (Stratasys). The layer-wise AM effect and corresponding rounded edges cause excessive material usage of about 10%. Fibres might not be as uniformly distributed compared to thermoset woven fabrics. Additional safety factors are requested due to unknown fatigue properties and reduced material integrity. Taking these issues into account, an initial resulting 30% to 50% weight reduction is assumed achievable, offering a 23 tonnes bow section, supplemented in *Appendix 1.1. Theoretical weight reduction.*

1.3.2. Secondary opportunities

Secondary opportunities resulting from the ME process, as discussed before, strengthening the choice for polymer AM, are elaborated in this sub-paragraph.
Thermoplastic composite materials are corrosion resistant, offering the possibility to avoid conservation directly after production but also during the years of service of the vessel. Although at this point the questions remains whether composite materials are more durable in terms of fatigue, micro-cracks and

degradation of the material, failure will not be caused by corrosion. No coating or painting required offers, although limited, reduced finishing time and reduced finishing costs.

For well-coordinated shipyard productivity, all individual activities such as sectional construction, conservation and assembly need to be adjusted onto each other. An implemented AM production process affects other processes and thus a clear production strategy is required. Recently developed AM-ME machines are equipped with material extruding systems which are able to deposit over 1000kg/hr (Sloan, 2016; Thermwood, 2016). Depending on the final extruding volume, a 40 tonnes bow section (Class III) would be produced within days instead of several weeks, a reduction in section building time of in between 40% and 70%. Within shipbuilding, however, sections are often produced simultaneously and erecting the vessel on the slipway is more time consuming. Therefore, not only individual sectional building time, but in particular outfitting of AM sections should be beneficial in order to decrease costs and building time.

Since short sectional production is not a direct opportunity, this topic is not evaluated within this master thesis. A clear benefit of decreased sectional building time is the fact that machine costs due to reduced machine hours is decreased and building risks due to failures are reduced. Other secondary advantages considering building time when using AM as production method can be, which are relevant to mention, found in the concept Design for Manufacturing (DFM) and Design for Assembly (DFA), related to the power of complexity for free, which might influence the ease and speed of installation procedures.

Another opportunity shortly discussed is the accessible use of recycled and/or recyclable material. In recent years, additional attention was on the environmental footprint of the shipping sector. Thermoplastics can be re-used multiple times and current technologies offer recycled thermoplastics with the quality of virgin material. Although research on the specific business case for recycled thermoplastic inland waterway vessels is not within this master thesis, the use of recycled content lowers material cost price, offering additional competitiveness.

Above stated secondary advantages are shortly addressed within this master thesis since they offer potential cost reduction, directly or indirectly. Main advantage is weight reduction, offering direct costs reduction in the AM production process and indirect cost reductions in terms of profit, related to the increased amount of cargo to be taken in, increased sailing speed and/or lower fuel consumption.

1.4. Challenges

In this paragraph the expected challenges for adoption of AM-ME within the MCS are discussed subdivided in production costs, and being able to comply with stated rules and regulations.

1.4.1. Costs

In this subparagraph the challenge of production costs are discussed. Since building costs in low waged countries for the hull of a simple inland waterway vessel are low (in between 2.50,- and 3,- EUR/kg) (Hekkenberg, 2014) a major challenge will be keeping AM costs low. Steel used for shipbuilding is purchased at about 950,- EUR/tonnes. This includes purchasing, cutting and conservation (Hekkenberg, 2012) retrieved from (Aalbers, n.d.; Buirma et al., 2017) Since most thermoplastic polymers are more expensive than 0.95 EUR/kg, the selection of available polymers is strongly reduced. Reinforcing glass fibres are more expensive than 0.95 EUR/kg as well but due to beneficial specific strength, less weight material is required for equal strength.

For the bow section of a Class III inland waterway vessel having a steel weight of about 40 tonnes, approximately 2100 man-hours are required for steelwork, using steel of EUR 950,- per ton and 45

EUR/hr man-hour rate. According to (Aalbers, n.d.) and (Coenen, 2008) resulting production costs are roughly EUR 111.500,- depending on an optimistic and pessimistic scenario based on the country of production, weight and hourly rate and material price (1), substantiated in *Appendix 1.5.1. Calculated building costs.*

$$C_{(object\ cost)} = (C_{(raw\ material\ cost)} \cdot M_{(mass\ object)}) + (C_{(cost\ manhour)} \cdot T_{(manhours)}) \tag{1}$$

	Material (€/ton)	Mass (tonnes)	Manhour costs (€)	Manhours (hr.)	Total:
Optimistic	900,-	35	25,-	1900	79.000,-
Average	950,-	40	35,-	2100	111.500,-
Pessimistic	1000,-	45	45,-	2300	148.500,-

General AM costs are calculated according to machine rate, material price and building time (Thomas & Gilbert, 2014). For this calculation cheap polymers and cheap fibre reinforcements are assumed. The height of machine rate is comparable to multiple AM machines as discussed in (Thomas and Gilbert 2014) taking into account a 25 tonnes thermoplastic composite bow section, based on an approximated weight reduction of 30% a 50%.

$$C_{(object\ cost)} = C_{(raw\ material\ cost)} \cdot M_{(mass\ object)} + C_{(machine\ cost\ rate)} \cdot T_{(total\ build\ time)} \tag{1}$$

	Material (€/ton)	Mass (tonnes)	Machinehour costs (€)	Machinehours (hr.)	Total:
Optimistic	800,-	20	500,-	60	46.000,-
Average	1200,-	25	800,-	90	102.000,-
Pessimistic	1600,-	30	1100,-	120	180.000,-

Concluded from the divergent cost expenses AM offers the potential to be cost efficient but solely when all cost factors can be kept low. Since small variation in one of the items results in a significant change in final costs, optimistic and pessimistic scenarios are provided. Costs for general object include all additional expenses such as transportation and overhead and are stated equal in both scenario's. It is important, however, to take into account additional expenses related to the AM production process including the use of fire prevention systems and possible additional expenses related to outfitting.

1.4.2. Rules & Regulations

Inland waterway vessels are subjected to a series of strict rules and regulations drafted by various class societies such as Lloyds Register, Bureau Veritas and IMO. Regarding composite inland waterway vessels, (Lloyds.Register, 2017a) is applicable.

Beside the bow section is to fit its purpose in terms of functional and market driven requirements, (Lloyds.Register, 2017a) prescribes rules about composite material components, structural laminate requirements such as thickness and span widths and mechanical laminate properties. A multi-directional, cross-plied or woven, fibre reinforcement orientation is required for all laminates. This is a challenge using layer-wise AM production and accompanied anisotropic composite properties since the strength in layer deposition direction is significantly weaker. The bow section needs to be strong and stiff enough to maintain maximum allowed deflections and material stresses.

Regulations for thermoset composite inland waterway vessels are relatively new and the use of thermoplastic materials for hull parts is unknown. No direct restrictions are retrieved for the use of AM – ME technology and corresponding thermoplastic materials but being able to comply with 'Class A' fire safety will be difficult. Not only will the bow section be subjected to direct rules for heat-resistance, it should also maintain its strength and stiffness during a regular fire-test (Lloyds.Register, 2017a) (*Pt 17, Ch 1, 2.2 Fire test 2.2.1.*). Although this thesis does not include whether a fire test will be passed, expectations about the feasibility of a fire test are expressed. Flame retardant additives and fire resistant panels provide opportunities but these precautions affect cost price and assembly time in a negative manner.

In previous paragraph it was discussed keeping costs at the level of steel manufacturing will be a challenge. AM is in most examples still a relatively expensive production method resulting from material prices and machine rates. thermoplastic resin is combustible and is to be protected using fire safety provisions. The composite bow section needs to comply with structural requirements as stated by the rules.

1.5. Further Research

Above paragraphs explain weight reduction is the leading opportunity to perform research on inland waterway vessels consisting out of thermoplastic composites and produced via AM. Secondary advantages are corrosion resistance and the use of environmentally friendly materials. Main challenges are keeping costs at level, and being able to comply with structural and fire safety regulations as prescribed by the rules.

To evaluate the opportunities and challenges, a set of main questions is listed in order to estimate the appearance and construction of an AM inland waterway vessel's bow section and the expected advantages and disadvantages.

1.6. Research Objectives

To be able to produce maritime structural components with the use of AM-ME, under associated advantages stated in previous paragraphs, the bow section of a Class III inland waterway vessel is used as reference case. The main question of this Master Thesis is as follows:

<u>1: Can a thermoplastic composite Class III inland waterway vessel be produced competitively using Additive Manufacturing – Material Extrusion, compared to steel and what is the expected weight reduction?</u>
To be able to answer the main question a number of six sub-questions are listed below. The focus is on thermoplastic composites using AM-ME, since this process offers high deposit rates, and large building volumes. Thermoplastic fibre reinforced composites are lightweight, strong and durable. Based on specific strength and stiffness it is assumed significant weight reduction over a steel vessel is possible. For a feasible business case, the vessel will need to be competitive in terms of costs, weight and building time and should comply with stated regulations.

Following sub-questions are listed to help answering the main question.

<u>2: What are the inland waterway vessel's functional, market driven and regulatory requirements?</u>
This sub question is divided in market driven, functional and regulatory requirements. Depending on the type of requirements these can serve as final checklist, feasibility check, or input for further calculations or comparisons, as for example design pressures, allowable stresses/deflection and material properties.

<u>3: How does AM-ME comply with stated market driven, functional and regulatory requirements?</u>
In this sub-question it is discussed at what extend AM-ME allows to comply with stated requirements. AM-ME production needs to be at least competitive. Secondly, an AM vessel is deployed with the same purpose as a traditional steel vessel and thirdly, the vessel should comply with stated regulatory requirements.

4: What AM-ME polymer and reinforcing material is best suited for inland waterway vessels?
In case of AM-ME, used material consists of polymer and reinforcing fibres. Additives can be applied to be able to comply with UV radiation, microbials and to help in offering fire resistance. Material should meet stated material properties by the rules and need to be feasible in terms of strength, fatigue and durability.

5: What is the expected weight reduction using AM-ME and accompanied thermoplastic composite?
The combination of the vessel's arrangement, material selection, applicable regulations and AM strategy results in a structural arrangement. Combined with design pressures, material properties and maximum allowable stresses and deflection a bow section construction is derived on weight, strength and production strategy. By optimizing composite strategy weight is to be significantly reduced.

6: How is the required equipment within the vessel installed?
Within the vessel's bow section, machinery, equipment's, tanks, electricity and housing are present which require attention in terms of instalment, access space and maintenance. The location and installation of components might influence the AM strategy and design of the vessel while the overall layout should maintain its original requirements.

7: What will be the final weight reduction and cost price of the inland waterway vessel and can it become Class approved?
Since the final AM strategy, used AM-ME material and installation time influences cost and building time, a validation is needed with regards to the competitiveness of an AM inland waterway vessel. Within AM, weight reduction directly influences costs. Calculated weight reduction and derived production costs answers the main question stated.

To elaborate on these sub-questions each consecutive chapter deals with these topics in order to find reasonable insight in the main question.

2. Functional, market driven and regulatory requirements bow section

This chapter discusses the sub-question 2. In this chapter, functional requirements, market driven requirements and regulatory rules applicable on a Class III inland waterway vessel's bow section are discussed. Functional requirements are applicable on the purpose of a bow section in general in comparison with a traditional steel bow section. Market driven requirements refer to its competitiveness while regulatory requirements prescribe guidelines for material selection, laminate requirements and strength and stiffness on global and local level. A selection of the relevant regulatory requirements is retrieved from (Lloyds.Register, 2017a), treating composite cargo vessels. For comparison with steel vessels (DNV-GL, 2015; Lloyds.Register, 2017b) is consulted.

Functional requirements applicable on a general bow section are listed in §2.1 serving as final checklist to show whether an AM bow section is able to fit it's specified purpose in comparison with a steel bow section. In §2.2 market driven requirements are provided subdivided in building time, allowable weight, durability and costs. structural regulatory requirements on a composite bow section are discussed §2.3 subdivided in laminate build-up, design pressures, allowable deflection and rules applicable on critical components. Data is used to be able to perform calculations on strength and stiffness. To be able to select an appropriate thermoplastic composite, material requirements are discussed in §2.4 , subdivided in raw materials, laminate strength, allowable stresses and material handling requirements. Allowable stresses are provided to be able to see whether the thermoplastic material and geometry is strong and stiff enough. Finally, §2.5 discusses requirements on fire safety, since a thermoplastic composite material in combustible and tends to melt when heat is added.

2.1. Functional requirements

This paragraph discusses functional requirements of a bow section in general. These are used as leading comparisons for the design and production proposals and serve as final checklist to see whether the AM bow section fits its specified purpose. A distinction is provided between steel and composite manufacturing.

A bow section's primarily purpose is to keep water out of its inner structure and redirect it away from its centreline to reduce wave and water resistance. The bow section is located in front of the midship section and holds various components such as tanks, power supply, housing and auxiliary equipment. In case of a collision, the bow section it so protect the components behind to prohibit the vessel from sinking. Besides obvious purposes it is to be strong and stiff enough during operational use, and offers protection for crew and auxiliary equipment within the subdivisions. There are various ways of assigning purpose requirements, based on what the object should do, but also based on safety, economic and performance perspective. In *Appendix 1.2. Functional requirements bow section* a more complete list of these requirements is provided, which will be compared to the final AM design to see whether the AM bow section is able to meet these requirements.

In comparison with a traditional steel bow section, the composite vessel is subjected to its own classification, being (Lloyds.Register, 2017a) applicable on composite inland waterway vessels. different from regulations applicable on a steel bow section in terms of pressures, material stresses and geometrical aspects such as span width and division thicknesses. For steel vessels, (Lloyds.Register, 2008) is applicable. Guidelines for steel construction relies on other requirements on plate thicknesses, stiffener distances, design pressures and maximum allowed stresses compared to composite vessels. A steel bow section is calculated for minimum required layout based on plate thicknesses and subdivision distances, presented in §2.2, substantiated in *Appendix 1.4. minimum required weight from regulations*.

2.2. Market driven requirements

This paragraph discusses market driven requirements to compare weight reduction, delivery time durability and costs. Based on previously stated these aspects are assumed to be most important for an AM bow section in order to be competitive.

Weight

This section discusses minimum stated requirements on potential weight reduction to become competitive over traditional manufacturing. Based on calculations from a steel reference vessel, provided in *Appendix 1.3 calculated weight bow section* , the weight of the bow section is approximated at 40 tonnes of steel weight. Based on (Lloyds.Register, 2008) and a reference bow section the minimum required weight is calculated to be around 35 tonnes, partly included in *Appendix 1.4. minimum required weight from regulations* and translated towards the reference geometry. Related to welding requirements and practical issue's plate thicknesses of inland waterway vessels are often thicker than required. Based on the reference steel bow section weighing in between 35 and 45 tonnes, the weight of the composite section should be at max in between 25 and 32 tonnes, offering a weight reduction of in between 30% and 50% retrieved from specific strength, assumed safety factors and reference composite vessels (CompocaNord, InBat, Fibreship). Reducing weight in the AM building process has the advantage of directly reducing building costs. From operational perspective, weight reduction offers increased profits due to additional cargo, increased sailing speed and/or less fuel consumption.

Building time

The reference bow section takes several weeks to produce, depending on the amount of shifts, manpower and the efficiency of the shipyard. Usually, multiple sections are produced simultaneously in order to start assembly and outfitting as soon as possible, since this makes up for the largest parts of vessel production. Traditional building time is based on calculation for manhours required stated by Kerlen, retrieved from (Aalbers, n.d.) supplemented with additional factors such as amount of workforce and simultaneously erected sections. An overview of calculated building time is presented in *Appendix 1.5 Calculated building time*

AM sectional production cannot take longer than traditional sectional building since multiple machines will be required and/or outfitting is delayed. Also, in case of failure of a printed part, the effect of an extensive production process is disastrous. Shorter AM production time directly lowers machine time and thus production costs. However, machines able to produce faster are usually more expensive. Shorter production time requires less machines operating simultaneously and thus requires less machines. However, additional research on shipyard logistics is required in order to come to conclusions. Primarily based on production costs resulting from machine time, faster production is beneficial, taking into consideration increased machine rate following from higher deposit rate. Since outfitting of the entire vessel usually takes the longest, a composite vessel cannot cause extensively more outfitting time.

Durability

Based on the reference bow section, which has an average depreciation time of about 30 years, the AM bow section is to withstand user and weathering conditions for a comparable period of time. Throughout these years the bow section cannot show significant structural decline and the geometry as produced is to maintain its shape and is to stay within boundaries on deflection. Materials cannot degrade or show abrasion such that the bow section is not able to perform its operational duty. In case of damage, repair work or maintenance, the bow section should be able to be fixed within a reasonable amount of time and effort.

Compared to steel, the following aspects are assumed crucial in terms of durability: corrosion resistance, fatigue, creep and damage & repair. Compared to steelwork, thermoplastic composites show beneficial corrosion resistance and fatigue properties. In contrast, the material is more sensitive to abrasion, impact loads (locally) and high temperatures. An important aspect to take into consideration is the ability to weld steel, offering a well-established method of repair, in case of a collision. Repairing thermoplastic composite parts and surfaces, besides yet unknown methods, requires additional attention.

Costs

Unless significant weight reduction is achievable or clear other benefits arise, an equally priced or slightly cheaper composite vessel will be difficult to sell since cost price is a leading factor. Reducing costs is one of the challenges although the most optimistic scenario shows reduced costs by approximately 40%. In contrast, a pessimistic scenario shows a cost increase of 20% compared to a pessimistic scenario for traditional production. Due to the uncertainties and theoretical input, cost calculations are still divergent at this point.

Discussed in previous paragraph an AM bow section does not bring significant benefits regarding sectional building time. In order to be competitive in terms of delivery time, the combination of hull production and outfitting cannot take longer than is seen in traditional manufacturing. To keep AM costs low, weight is to be reduced since this reduces manufacturing costs due to decreased machine time and material usage and secondly, offers the vessel to be able to take in additional cargo, sail at higher speeds or reduce fuel consumption. The use of thermoplastic composite offers corrosion resistance but the bow section needs to be competitive in terms of strength, stiffness and fatigue aver a lifetime comparable with traditional manufacturing. To be competitive, final building costs are not to exceed traditional building costs calculated to be around EUR 115.000,-.

2.3. Structural regulatory requirements composite bow section

This paragraph discusses structural requirements on a composite bow section in general, subdivided in composite laminate requirements, design pressures, resulting allowable deflections on global and local level and structural requirements for relevant components within the bow section.

2.3.1. Material structure

In this paragraph additional requirements on composite laminates are discussed. In (Lloyds.Register, 2017a) *(Pt 8, Ch3, S2, 2.1.)* it is stated *''structural laminates, used for both single skin and sandwich construction are, in general, to incorporate not less than 40 per cent, by weight, of woven or cross-ply reinforcement''*. The fact the reinforcing fibres should be **woven** or **cross-plied** is crucial considering the unidirectional layer-wise AM material deposition process. In §3.2. it will be discussed to what extend cross ply deposition is possible using AM. No solutions for an AM woven material structure is found except examples retrieved from (Quan et al., 2015) but this is not applicable on large scale FDM material deposition. Figure 2 presents an example of woven and cross-plied composite fabric.

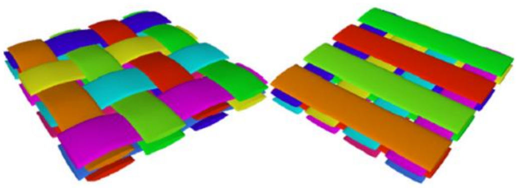


Figure 2 *Woven (left) and cross-plied (right) laminate* (T. Liu, Zhang, He, & Jia, 2017)

In (Lloyds.Register, 2017a) *(Pt 8, Ch3, S1, 1.13)* single skin plate laminates are subjected to a rule for minimum thickness (3), in which b = unsupported panel breath in mm, p = design pressure in kN/m^2 and E_{tp} = tensile modulus of the plate laminate in N/mm^2. Minimum thickness for a single skin laminate *(Pt 8, Ch3, S2, 2.4)* is based on the minimum required plate thickness multiplied by a factor ω for craft type (4) being 1.1 for an inland waterway vessel.

$$t_{min} = 0.146\, b^3 \sqrt{\frac{p}{E_{tp}}}\, mm \tag{2}$$

$$t_T = \omega t_{min} \tag{3}$$

Minimum laminate thickness is dependent on the mechanical laminate properties and span width. Mechanical laminate properties for cross-plied laminates are calculated in §3.2.2. using composite theory and span width is dependent on the geometry and stiffener configuration.

2.3.2. Design pressures

In this paragraph insight is provided in design pressures resulting from outside forces applicable on various components of a composite inland waterway vessel's bow section as stated by the rules. Design pressures serve as input for further strength and stiffness calculations.

To design a feasible bow section which will be strong and stiff enough in (Lloyds.Register, 2017a) *(Pt 5, Ch 2, St 2) to (Pt 5, Ch2, St 5)* a set of design pressures, loads and moments is provided applicable on a composite service craft. To estimate the values of design pressures the vessel is categorised and relevant input is used for design pressure calculations, retrieved from chapters (Ch 1, Ch 3, Ch 5) from (Lloyds.Register, 2017a). Categorization, and calculations are listed in *Appendix 1.6 Categorization and design pressure.* The resulting overview of design pressures is collected in table 2

Item	Ref.	Pt, Ch, Sc	Outcome	Unit
Combined pressure distribution, P_S	$P_H + P_W$	5.2.4.		
Hydrostatic pressure shell plating P_H	Eq (2) (P_H)	5.2.4.	0,..25	kN/m^2
Hydrodynamic wave pressure P_W	Eq (3) (P_W)	5.2.4.	39.65	kN/m^2
Pressure weather and interior decks	Eq (4)	5.2.5.	7.18	kN/m^2
Impact pressure displacement mode	Eq (5)	5.2.5.	78.13	kN/m^2
Design pressure deckhouse and bulwark	Eq (8)	5.2.7.	8.975	kN/m^2
Design press. Watertight /deep tank bulkhead	Eq (9)	5.2.7.	161.28	kN/m^2
Design load pillar	Eq (10)	5.2.7.	29.88	kN/m^2

Table 2 design pressures applicable on the Class III bow section (Lloyds.Register, 2017a)

To calculate bending moments the vessel is categorized according to its shape and function. Based on the categorization still water bending moment and vertical wave bending moments are calculated, presented in *Appendix 1.6 categorization, bending moments* and listed in table 3:

Item	Ref.	Pt, Ch, Sc	Outcome	
Still water bending moment	Eq (…)	5.5.2.	3178	kNm
Vertical wave bending moments	Eq (13)	5.5.2.	16897	kNm

Table 3 design pressures applicable on the Class III bow section (Lloyds.Register, 2017a)

Design pressures serve as input for strength and stiffness calculations in which the bow section should maintain maximum allowable deflections.

2.3.3. Allowable deflection

To evaluate whether the structural geometry of the bow design is strong and stiff enough maximum global and local deflections are indicated in (Lloyds.Register, 2017a) *(Pt 8, Ch 3, St 1-3).* In (Lloyds.Register, 2017a)*(Pt 8, Ch 3, St 6)* requirements for keels, centreline girders, side girders, inner bottom laminates and more are treated. In this paragraph a list of limiting span/deflection ratio's is provided, necessary to estimate whether the bow section will be strong and stiff enough. According to the rules, deflection of structural components within the composite hull is stated not to exceed the maximum allowable calculated deflection ratio (5):

$$Span\ deflection\ ratio\ f_{\delta} = \frac{span}{deflection} \tag{4}$$

In (Lloyds.Register, 2017a) *(Pt 8, Ch 7, St 1, 7.2.1)* a set of span-deflection ratio's is shown applicable on various components within the vessel. Since the span-deflection ratio for 'Primary girders and web frames' is highest, (f_d = 250) it means these components have the smallest deflection freedom. Since primary girders spread across the entire vessel it is assumed the global maximum deflection is dependent of this value. Based on a nine meter bow section, the maximum allowable deflection is 9000/250 = 36 mm. A complete list of span deflection ratios of residual components is provided in *Appendix 1.7 span deflection ratio's.*

2.3.4. Regulations on components and attachments

This paragraph discusses relevant regulations on components installed within the bow section. Loads resulting from components, required spaces and foundations influence the composition of divisions and thickness of the plating. In *Appendix 1.8 relevant components regulations* a list of relevant regulations applicable on components in provided. Most influencing regulation apply on:

-securing of propulsive machinery and corresponding forces
-resulting bow thruster forces
-resulting forces due to anchoring equipment, mooring lines and bollards
-prescribed manholes and corresponding dimensions
-prescribed access spaces
-fittings and attachments

The requirements influence the subdivision layout of the bow section in terms of dimensions, laminate thicknesses and access spaces and are therefore relevant to mention. Calculated values are taken into account in structural calculations and required access spaces are considered in the design of the subdivision layout.

2.4. Material regulatory requirements composite bow section

In this paragraph regulatory requirements applicable on the composite material are listed retrieved from (Lloyds.Register, 2017a).

2.4.1. Minimum required properties composite material

Germanischer Lloyd, an international organization consisting from Det Norske Veritas (Norway) and Germanischer Lloyd (Germany) and in (Lloyds.Register, 2017a)information is prescribed concerning ‘Composite Materials’ and their corresponding properties. (DNV-GL, 2015, 2016) *(Pt 2, Ch3, St 2, 1 General)* Section *1.2.2.* states: ‘’Fibre reinforcements other than glass fibre, carbon fibre and aramid fibre, resins other than polyester, vinyl ester and epoxy, and coatings other than gelcoat and topcoat, may be accepted based upon testing and approval in each individual case’’. This assumes no prohibiting regulation is determined considering the use of thermoplastic polymers. In (Lloyds.Register, 2017a) *(Pt 8, Ch3, St1)* minimum raw material properties of fibre reinforced composites and minimum laminate properties are discussed. Properties of resin including impregnated direct roving are also discussed in these paragraphs.

In (Lloyds.Register, 2017a) (*Pt8, Ch3, St 1, 1.2.7)* typical minimum thermoset resin properties are provided. Both resin types, thermoplastic and thermoset, need to comply with minimum required mechanical material properties. Thermoplastic resin types are available showing comparable mechanical properties as thermoset resin. To calculate laminate properties, identical composite theory calculations are used. For thermoset composite vessels, polyester, epoxy and vinyl ester are commonly used as resin. As for the type of reinforcing fibre, for a composite inland waterway vessel, the only suitable fibre type is E-glass, primarily due to cost price and mechanical properties. For thermoplastic composites the type of resin should meet minimum required resin properties, in combination with E-glass direct roving. In *Appendix 1.9 minimum required thermoset material properties* minimum required thermoset material properties or the resin as well as E-glass fibres are listed. In (Lloyds.Register, 2017a) (*(Pt 8, Ch 3, St 1)* It is prescribed a minimum of 40% glass-fibre reinforcement is required in all divisions.

Besides mechanical requirements, there are cost factors and weathering factors prescribed. Based on previously made estimation initial calculations material cost price needs to be low, under 3 EUR/kg to be able to produce a lighter bow section cost effectively. Above discussed shows no direct prohibitions are present for the use of thermoplastic materials.

2.4.2. Laminate strength

In this subparagraph it is discussed what minimum required laminate strength is prescribed based on comparable thermoset composites. In AM, short fibres, long fibres and continuous reinforcing fibres (direct roving) can be used to reinforce polymer resin. Therefore, minimum mechanical properties for Chopped Strand Mat (CSM), Woven Roving (WR) and Cross Plied (CP) glass reinforced laminates are calculated for 30%, 40%, 50% and 60% fibre weight content as comparison, provided by (Lloyds.Register, 2017a) *(Pt 8, Ch 3, St 1)*, and listed in *Appendix 1.10 minimum required laminate properties* In §3.2.2. AM composite properties are calculated and compared with the minimum required laminate properties as prescribed by the rules.

2.4.3. Allowable material stresses

In this subparagraph allowable material stresses on global and local level within the bow section are discussed. In (Lloyds.Register, 2017a) *(Pt 8, Ch 7, St 3, 3.4)* it is stated interlaminar shear strength of the laminate is not to be less than **13.8 N/mm^2**. This is an important rule since this is applicable on the layer adhesion within AM.

Additional stresses are prescribed in (Lloyds.Register, 2017a) *(Pt 8, Ch 7, St 3, 7.3.1)* in which limiting stress criteria as a fraction of the ultimate shear strength of the laminate for local loading is prescribed. These are provided in *Appendix 1.11 limiting stress criteria*. The list includes values of in between 0.25 and 0.40. For example, a watertight bulkhead is allowed to reach a 0.40 fraction of the ultimate shear strength of the laminate. In (Lloyds.Register, 2017a) *(Pt 8, Ch 7, St, 3, 7.3.2),* limiting stress criteria for global loading is prescribed. For a reference Class III inland waterway vessel, a fraction of 0.33 of the ultimate shear strength is applicable.

For the stress and strength analyses not all individual components will be referenced but some critical examples are provided taking into account the most influencing values, which is 0.33 and 0.4 for local stresses and 0.33 for global stresses. For this, material properties such as ultimate shear strength and structural geometry, such as maximum span widths, need to be known.

2.4.4. Material handling

Additional requirements applicable on fibre reinforced polymers (FRP) can be found in (Lloyds.Register, 2017a) *(Pt 8, Ch 2, St, 2).* These include regulations for storage *(2.4)*, colouring pigments *(2.8)*, fillers *(2.9)*, additives *(2.10)*, fibre reinforcements *(2.11)*, surfacing materials *(2.12)* and adhesives *(2.15)*. Regulations by definition applicable on thermoset composites are neglected. (Lloyds.Register, 2017a) *(Pt 8, Ch 2, St 3)* provides additional regulations applicable on construction procedures mainly applicable for thermoset composite construction. To be able to classify and regulate the building process and produced object it is important to know whether all deposited layers are fused together. Stated in (Bergsma et al., 2016) material integrity is one of the main challenges of AM. Layer adhesion should be known and guaranteed at every location. Within AM, in recent years, methods are established to be able to classify AM parts, both metal and polymer and thus resulting in class-approved objects by the rules. Resulting from this paragraph relevant thermoplastic composite material requirements are listed which serve as checklist to compare with calculated composite properties.

2.5. Fire resistance regulatory requirements composite bow section

This paragraph discusses regulations applicable on fire resistance. Inland waterway vessels are subjected to rules on fire safety to keep crew and surroundings safe. Since most thermoplastic composites are combustible and thermoplastics melt when heat is added, fire safety provisions are required. This paragraph is subdivided in the use of combustible thermoplastic composites and an explanation fire class-division requirements.

2.5.1. Non-combustible or equivalent material requirement

This subparagraph discusses the use of combustible thermoplastic composites. Fire class divisions within inland waterway vessels in Europe need to be constructed out of non-combustible materials or equivalent materials (DNV-GL, 2015; Lloyds.Register, 2017b). Bureau Veritas (BV) (BureauVeritas, 2015) prescribes structural materials need to comply with the requirements of ‘’NR216 – Material and Welding’’ (BureauVeritas, 2017) (*Pt B, Ch2, St 3, 1.1).* Materials having different characteristics may be accepted, provided their specification *(manufacturing, chemical composition, mechanical properties, welding, et*c.) are submitted to the Society for approval. In NR216 *(Pt B, Ch 2, St 3)* no rules on fibre reinforced thermoplastic polymers are stated. The use of plastics, wood or other special materials not covered by these Rules is to be considered by the Society on a case by case basis. In such a case, the Society states the requirements for the acceptance of the materials concerned *(Pt B, Ch 2, St 3).*

An approved bow section needs to comply with fire safety regulations. With the usage of thermoplastic composite materials it will be hard to gain approval due to lack of research and combustible materials. Not all divisions within an inland waterway vessel are subjected to fire safety regulations. Class divisions constructed out of other materials than steel will have to pass a fire test. Previously discussed, there are no explicit rules prohibiting the use of thermoplastic materials if requirements on fire safety can be met. This is to be done by a fire test which is not within the scope of this master thesis. However, initial understanding is required to show the use of thermoplastic materials is no impossible option in terms of fire safety.

IMO (IMO, 2017) prescribes (Regulation 2) vessels need to be produced from steel (or equivalent material). To prevent a blockage on innovation 'Regulation 17' is approved. In principle every design can be submitted made out of every material if can be demonstrated the safety on board is guaranteed. Although IMO does not prescribe inland navigation vessels it is a useful directive.

According to rules and regulations for the classification of inland waterway vessels (Lloyds.Register, 2008, 2017b), apart from the rules stated about fire protection resulting from equipment such as sprinklers, fire resistant doors, materials used for valves and machinery (Pt 1-5), there are no written rules applied for structural materials but is directed to EC Directive (2006/87/EC), DIRECTIVE of the EUROPEAN PARLIAMENT (GEMEENSCHAPPEN, 2002) *(Pt 6, Ch 3 St 1)*

When implementing the provisions of *(Pt 6, Ch 3 St 1)* General 1.1.1. (b) LR will apply as appropriate either: *''The fire safety measures required by EC Directive (2006/87/EC), DIRECTIVE of the EUROPEAN PARLIAMENT and of the COUNCIL of 12 December 2006 laying down technical requirements for Inland Waterway vessels; or the fire safety measures required by European Agreement concerning the international carriage of dangerous goods by Inland Waterways (ADN)''*. However, *''due consideration will be given to arrangements deemed to provide an equivalent level of fire safety, taking due cognisance of the circumstances of the intended service of the vessel''* (Lloyds.Register, 2008).

(BureauVeritas, 2015) (*Pt B, Ch2, St 3)* prescribes a wide variety of material requirements and regulations prescribing regulations for additional fire safety based on general provisions and precautionary measures (*Pt D, Ch 2, St 7).* BV also subdivides divisions within an inland waterway vessel into 'A-class' or 'B-class' divisions.

Regarding above stated, no rules are present directly prohibiting the use of thermoplastic materials for fire-class divisions within inland waterway vessels. The following paragraph shortly addresses the specific fire regulations applicable on fire class divisions.

2.5.2. Fire-Class divisions

This paragraph discusses the criteria on fire resistance fire-class divisions needs to comply with. According to (BureauVeritas, 2015; Lloyds.Register, 2017a) inland waterway vessels in Europe are categorised in ''A-Class'' divisions which subjects a variety of divisions (bulkheads, walls) into class fire divisions. BV *(Pt D, Ch2, St 7)* and LR *(Pt 17, Ch 1, St 2)* provide input about A-Class divisions presented in *Appendix 1.12 A-Class divisions*. It is concluded most critical divisions are subjected to the following requirements:

In *(Pt C, Ch 3, St 1-2) A Class divisions:* 'A-class' divisions are those divisions formed by bulkheads and decks which comply with the following criteria:

a. they are constructed of steel or other equivalent material

b. they are suitably stiffened
c. they are insulated with approved non-combustible materials such that the average temperature of the unexposed side will not rise more than 140 °C above the original temperature, nor will the temperature, at any point, including any joint, rise more than 180 °C above the original temperature, within the time listed below:
-Class ''A-6o''..............60 minutes
-Class ''A-3o''..............30 minutes
-Class ''A-15''..............15 minutes
-Class ''A-o'' .... 0 minutes
d. they are so constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test
e. the Society required a test of a prototype bulkhead or deck in accordance with the Fire Test Procedures Code

As becomes clear from the paragraph above the bow section of an inland waterway vessel is subjected to the A-Class fire regulations stated. It includes a wide variety of subdivisions which are all individually annotated and need to be able to withstand the corresponding temperatures under the stated time durations.

2.6. Conclusions

In previous chapter relevant functional, market driven and regulatory requirements are discussed providing sufficient input for further elaboration on the material choice, local layout, choices of instalment and a comparison on the competitiveness of an AM-ME bow section. The chapter provides requirements on material structure, design pressures, allowable deflections and requirements on critical components. Value's for material properties, laminate properties and allowable stresses are prescribed including measures for material handling. Finally, fire safety and regulations are stated. To summarize, table 4, including most relevant regulations is provided underneath:

Requirements	§	Item	Goal
Functional	§2.1.	Purpose requirements	Functions/purpose
	§2.1.	Class-notation composite vessels	Lloyds 2017
Market driven	§2.2.	Weight	< 30 tonnes
	§2.2.	Building time < traditional	< traditional
	§2.2.	Durability	25 years of service
	§2.2.	Production costs	< 115.000,-
Structural	§2.3.1.	Material structure	Cross-plied
	§2.3.2.	Design pressures	Prescribed
	§2.3.3.	Maximum allowable global and local deflection	Prescribed
	§2.3.4.	Regulations on components	Prescribed
Material	§2.4.1.	Minimum required raw material properties	Resin, fibre
	§2.4.2.	Mechanical laminate properties	Laminate/cross plied
	§2.4.3.	Maximum allowable material stresses	Prescribed
	§2.4.4.	Class-approved material handling	Material integrity
Fire resistance	§2.5.1.	Non-combustible or equivalent material	Materials
	§2.5.2.	Class A-30 fire resistance	Fire-duration

Table 4 Summary requirements bow section inland waterway vessel

In following chapters, input from this chapter is used. First it is discussed how AM-ME is able to comply with functional, market driven and regulatory requirements stated. Chapter 4 calculates composite material strength using composite theory to compare with laminate properties stated. Design pressures in combination with allowable stresses and deflection are used in chapter 5 serving as direct input and reference values for strength and stiffness calculations. Chapter 6 discusses the effect of regulations on components and the final chapter, chapter 7, discusses final cost price and weight reduction to determine the bow section's competitiveness.

3. How does AM-ME comply with stated requirements

In this chapter it is discussed how AM-ME is able to comply with the stated requirements, corresponding to sub-question 3. Whether ME will be beneficial in terms of building dimensions, production rate and costs is discussed in paragraph §3.1 . In §3.2 it is determined whether AM will be able to deposit material in the prescribed directions offering cross-plied laminates. Achievable AM-ME material composite properties are shortly evaluated in §3.3, Finally, in §3.4, fire resistance of thermoplastic composite materials is discussed and methods to protect the material from direct and indirect heat are evaluated. Each discussed point of interest resulting from regulations is substantiated with available and potential AM technologies and processes.

3.1. Market driven AM-ME

In this paragraph, first, estimations are derived whether AM-ME will be able to produce a bow section competitively compared to traditional building. The paragraph is subdivided in the AM-ME process, building dimensions, deposit rate, surface finishing and production costs.

3.1.1. AM – Material Extrusion process

The AM process ME, also called Fused Deposition Modelling (FDM) is based on the process of deposition of molten material in layers onto each other. A wide variety of AM machine configurations is available and still expanding. For large scale FDM, the use of pellets or granules provides a cheaper and more obvious solution compared to filaments and powders. This is because pellets/granules is the material form used in the widely used injection moulding industry, and hence the cheapest form or polymer available. Material Deposition Rate (MDR) is determined by machine speed, layer height, material throughput and material cooling. Machines are able to move with high speed and extruding systems are seen having a throughput of over 1000 kg/hr. The time for thermoplastic material to cool sufficiently before a new layer is deposited is often a critical factor for MDR. Since a bow section consists of a lot of stiffeners, divisions and frames, a sufficient layer length should be found in order to offer optimal material cooling time.

3.1.2. Dimensions

In recent years the building dimensions of AM-ME machines have increased rapidly. Although, it is possible to produce objects out of multiple parts, a higher amount of accuracy and extra labour is required to assemble parts. Manual or machinal post-processing and assembly will be the consequence of making segments watertight. Besides practical reasons every new object, although limited, requires extra costs resulting from removal of the objects and preparing the machine (Thomas & Gilbert, 2014). Additionally, a mechanical connection produced in one piece is in most cases stronger than when multiple separate parts need to be connected. Because of this, it is assumed an AM bow section produced in one piece is practical beneficial.

For the bow section of a Class III inland waterway vessel an AM machine is required having inside building dimensions of at least 10 x 10 x 5 meters. The main difference between AM an Computer

Numerical Control (CNC) cutting machines, is the tool which deposits material compared to subtractive cutting tools. In figure 3 examples are provided of CNC cutting- and AM machines having extremely large building volumes. Additionally, robotic machines including robots on a track are seen.

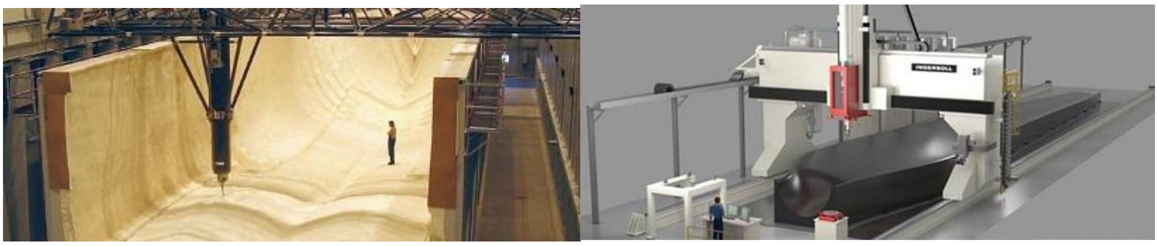


Figure 3 largest CNC subtracting machines in the world (Benchoff, 2012) and WHAM (Wide and High Additive Manufacturing (Sloan, 2016)

Based on above it is concluded an AM machine being able to produce the bow section in one piece is favourable and machines offering such building dimensions are present.

3.1.3. Deposit rate

Discussed in the introduction, shipbuilding does not necessarily benefit from shorter sectional building time. Shorter building time does however reduce building costs since machine time is reduced. Increased deposit rate increases machine rate from a certain point since additional or more advanced equipment is required.

In figure 4 a graph is presented retrieved from (Buirma et al., 2017) in which Wire Arc Additive Manufacturing (WAAM) deposition rate (kg/hr) is plotted against indirect costs (€/kg). As can be seen, increased deposit rate reduces costs significant up to a certain point. A comparable graph shape is expected regarding FDM though with different value's.

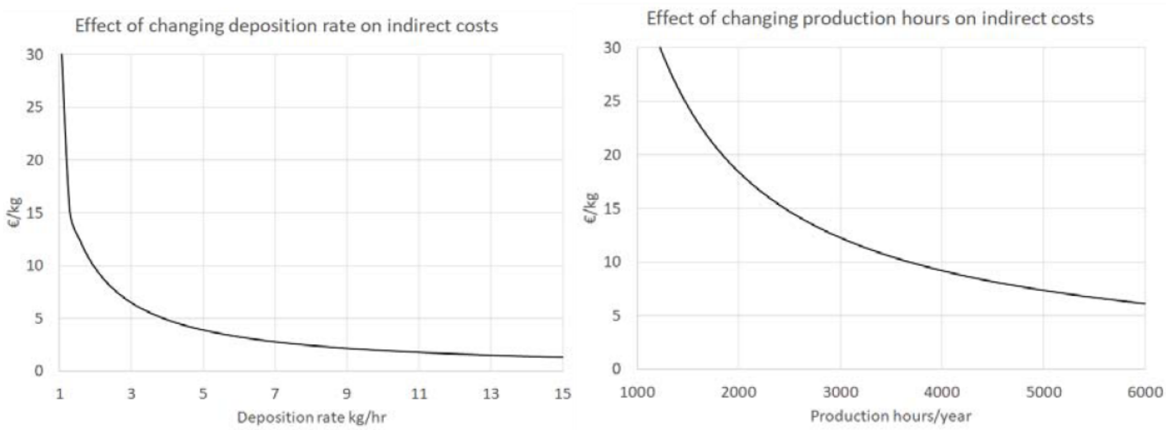


Figure 3 Deposition rate and production hours on EUR/kg (Buirma et al., 2017)

For an AM bow section to be producible within a reasonable amount of time, while attempting to keep costs resulting from machine rates low, material deposit rate needs to be significant. AM machines, such as WHAM, are available having deposit rates of up to 1000 kg/hr. and deposit rate is still increasing (Sloan, 2016). Other large scale AM machines, such as Big Area Additive Manufacturing (BAAM) from ORNL and the Large Scale Additive Manufacturing (LSAM) from Thermwood advertise with deposit rates of in between 100 and 250 kg/hr (Sloan, 2018). Figure 5 shows examples of the discussed AM machine from BAAM including their largest asset.

Figure 5 BAAM from ORNL and their largest 3D-printed asset at the moment (Benedict, 2017)

Assuming a 1000 kg/hr deposit rate a 23 tonnes bow section would be produced within a day. However, for a bow section, thinner divisions will be required compared to the 40 to 60 mm nozzle diameters as seen at Thermwood and BAAM machines. Therefore, a 1000 kg/hr. deposit rate is not assumed realistic. Above stated depositions rates are based on single-tool extrusion systems. A machine including multiple deposition tools offers possibilities in increasing deposition rate. Based on above it is concluded AM machines having sufficient deposit rate in order to produce a bow section in a short amount of time are present but additional knowledge on laminate thicknesses and possible machine parameters is required.

3.1.4. Surface finishing

For the bow section of any vessel a smooth surface is required, since this reduces frictional resistance. Machines with high deposit rates make use of relatively thick layers and therefore post-processing is required. In AM there is always a correlation between speed and accuracy (Frazier, 2014). Although referred to metal AM this also accounts for AM – ME. In comparison to the use of AM alone, the combination of additive and post-processive, might cause a shorter total building time with a more accurate end-result than when solely (highly accurate – and thus slow) AM is used. The combination of additive and subtractive machining (also called: Hybrid Manufacturing (HM)) in one single machine is a growing combination of processes (Lorenz, Jones, Wimpenny, & Jackson, 2015). Figure 6 shows the inside of the LSAM machines in which additive and subtractive is fully integrated.

Figure 6 Hybrid AM machines LSAM – Thermwood (Sloan, 2018)

Direct speed of subtractive machining depends on cutting speed, cutting depth and cutting width. Indirectly, speed depends on machine abilities, subtractive material and toolpath generation. Post-processing increases overall building time, machine investments and waste during the building process. Therefore, not having to post-process by subtractive machining would be beneficial. Methods of gaining a smooth surface with the use of solely AM are shown based on Automated Tape Placement (ATP) or Automated Fibre Placement (AFP) technologies. Within ATP and AFP unidirectional impregnated tapes are molten onto a pre-produced mould. Examples of the technology are provided in figure 7

Figure 7 AFP of double curved smooth surfaces Coriolis/Electroimpact

Other methods to create a smooth surface, largely retrieved from the maker's AM industry are sanding, polishing, resolving the AM material by using a solvent, filling the stepwise cavities with filler and 'hot rolling' the layers. Regarding large outside surfaces of an AM bow section above methods are labour intensive and costly and should therefore carefully taken into account.

3.1.6. Costs

This subparagraph discussed initial expected costs for an AM-ME bow section. Previously discussed, increased deposit rate reduces indirect production costs but might increases costs for equipment. Larger machines are more cost efficient due to scale enlargement in proportion to smaller machines. FDM offers the possibility to make use of cheap pellet materials as seen in the injection industry. Initial costs of an AM produced bow section were calculated to be in between 46.000,- EUR and 180.000,- EUR, based on 0.80,- to 1.60,- EUR/kg for materials based on cheap thermoplastic resin and fibres, 60 to 120 hours of production based on high deposit rate and 500,- to 1100,- EUR/hr machine rate. In this paragraph cost items for machine rate are further elaborated.

Calculated machine rate is dependent on initial machine investments, production rate, operational time, energy consumption and more. For a 10 x 10 x 5 meter AM machine rough estimations are calculated to be in between 500,- and 1100,- EUR/hr provided in *Appendix 4.1 Machine rate calculation.* Cost input is based on reference machines and offers from various equipment suppliers and 3D-printing companies. The method of machine rate calculation is based on (Buirma et al., 2017), in which indications for operational hours, depreciation time and labour costs are provided. Cost items are presented with a relatively large range due to unforeseen circumstances and safety margins but based on substantiated input from third parties.

In previous sub-paragraphs it was concluded AM-ME offers sufficiently large and upscaling building dimensions, deposit rates and corresponding machine rates to be able to reach a competitive production strategy compared to steelwork.

3.2. Cross plied AM material deposition

In this paragraph it is discussed at what extend AM-ME strategies will be able to comply with cross-plied or woven material deposition and fibre orientations since all divisions within a composite vessel need to be cross-plied or woven. No solutions for a AM woven material structure are found except examples retrieved from (Quan et al., 2015) but this is not applicable on large scale FDM material deposition.
To show AM offers the possibility to produce cross-plied laminates the paragraph is subdivided in anisotropic material behaviour, multi angle AM, deposited print as new building platform and non-planar AM. Anisotropic material behaviour brings increased material strength in a particular direction. Multi angle AM offers the possibility to deposit material in multiple directions. To deposit a cross-plied laminate, pre-deposited parts act as new building platform. In order to increase the range of fibre orientations, Non-planar AM is discussed.

3.2.1. Anisotropic material behaviour

This sub-paragraph discusses anisotropic and orthotropic material behaviour as the result of layer wise AM deposition (Seul, 2017). In this instance mechanical material properties differ along it's individual axes. The direction in which the layer is oriented is the strongest, since tensile strength of uni-directional glass fibres is very high. This offers the opportunity to direct the fibres towards the direction in which strength is most needed. In case of Continuous Fibre Additive Manufacturing (CFAM) within traditional AM processes, in which continuous fibres are deposited within the bead of resin, the ratio of material properties is even larger since there is no mechanical connection resulting from fibres in between deposited layers.

Resulting from various datasheets of Stratasys materials and reviews, z-height strength is sometimes only 30% reduced compared to the unreinforced material strength parallel to deposition direction. Another example shows 65% of the tensile strength was residual (Bagsik, Schöppner, & Klemp, 2010). In *Appendix 1.20 Layer adhesion strength* multiple examples of AM research are used to estimate resulting material properties. Appropriate pre-heating, after pressure, IR control and polymer adhesives, show potential to increase interlayer strength even further. Discussed in previous chapter, composite laminates are to be either cross-plied or woven, in order to minimize orthotropic effects. Since woven laminates are to author's knowledge not possible to produce using AM, all laminates within the AM bow section need to be cross-plied. The following sub-paragraph discusses the ability of AM to deposit cross-plied laminates.

3.2.2. Multi angle AM

This sub-paragraph discusses multi-axis AM, which is one of the necessities to be able to deposit cross-plied laminates. Recent developments in AM show material deposition in which the material is not deposited from above (0°) but from a wider variety of angles. This is called multi angle or multi plane AM (I. B. Ishak, J. Fisher, & P. Larochelle, 2016). The angle of deposition can also be adjusted during production and thus the orientation adapts to the geometry of the object. By implementing this strategy, the use of supporting structures and a higher degree of shape freedom is generated. Examples are shown in figure 8.

Figure 9 Various examples of multi-plane/angle AM Continuous Composites / (Dai et al., 2018)

To produce a multi-plane AM part a multi-axis AM configuration is required. Most conventional AM machines contain three axes. CNC-cutting machines as well as industrial robots often use 6 axes. An industrial 6-axis robot connected to a 3-axis CNC machine makes up for 9 axes, developed by the AM company 'KRAKEN', figure 10. Multi-axis machines are able to approach a specific location out of all surrounding directions.

Figure 10 9 axis robot on a gantry and 6-axis metal-AM machine. (Kraken / 3D Hybrid Solutions - Multiax)

The company 'V-shaper' introduced their newest asset which is a 5-axis AM machine able to deposit polymer materials using multiple axes. Multi axis technology is already well established within the metal Hybrid-Manufacturing industry (Yamazaki, 2016). In these machines multi axis additive and subtractive manufacturing technology is combined and previously produced parts serve as building platforms for following parts. Figure 11 shows small scale multi-axis AM within the FDM industry.

Figure 11 examples of FDM multi-axis additive manufacturing (V-shaper)

Multi-axis AM offers clear benefits for production of complex parts constructed out of non-isotropic AM materials. It is a powerful tool to solve part of the restrictions within AM due to layer adhesion, material overhang and desired material deposition orientations. To be able to deposit to deposit cross-plied laminates, multi-axis AM is required. In following paragraphs additional required AM strategies are discussed.

3.2.3. Deposited print as new building platform

This paragraph discusses deposited prints as new building platform as necessity to be able to produce all sub-divisions within a bow section cross-plied. In recent years additional interest is gained in 'multi-plane' additive manufacturing in which the orientation of the deposited material beads is variable. Using this technology a hollow cube can be produced without the need for supporting material. Furthermore, it enables avoiding a large part of overhang constraints. Another advantage is the possibility to produce multiple objects on top of each other while for each object a different angle approach is applied. An example is provided in figure 12

Figure 4 Blocks deposited from different angles. (I. Ishak, J. Fisher, & P. Larochelle, 2016)

Besides multi-plane AM offering the possibility to construct parts in multiple directions, it bypasses overhang constraints and thus avoids excessive supporting material. A part can be constructed out of two different parts on top of each other of which the second part can be printed by using a different orientation approach. When hollow objects are produced, the adjacent surfaces in between the two parts can be deposited using a different angle, which results in a multi laminated double wall. An example is shown in figure 13. The adjacent surfaces of the two parts can be deposited cross-plied.

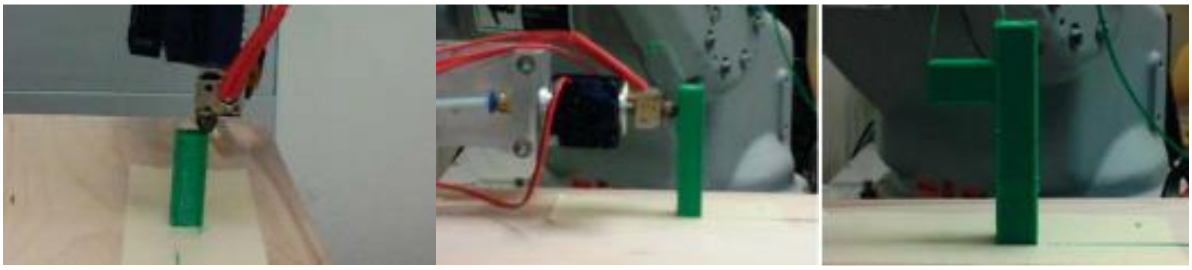


Figure 13 *Object produced in two pieces (I. Ishak et al., 2016)*

Since a bow section consist of a lot different sub-divisions, stiffeners, girders and bulkheads, oriented in a wide variety of directions, using pre-deposited parts as new building platform is a necessity, in order to deposit all divisions cross-plied. However, due to pre-deposited parts and the deposition tool, the orientation freedom is restricted. Following paragraph discussed non-planar AM, in order to increase deposition freedom.

3.2.4. Non planar AM

To reduce the amount of AM restrictions further, this paragraph explains Non-Planar AM, in which the geometry of the tool head is taken into account, since it moves out of the 2D plane of deposition. The movement freedom of the tool head is restricted when already produced objects are used as building platform. A more pointy tool head reduces these restrictions because the tool is able to deposit material in between already deposited parts. Apart from the nozzle geometry being important for angular AM deposition, it also allows to orient the nozzle not perpendicular onto the orientation of deposition but rotated until a maximum of the pointedness of the deposition tool. Illustrations are provided in figure 14

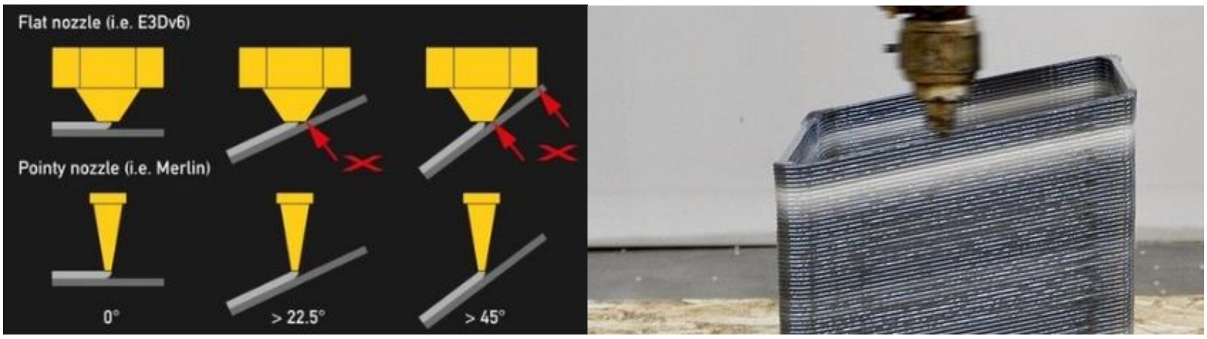


Figure14 *Non-planar AM applied in small-scale AM-machines.(Rodriguez, 2016)*

To visualise the additional possibilities using Multi-axis and Non-Planer AM, taking tool geometry and non-planar material deposition into account the following building block is discussed in figure 15

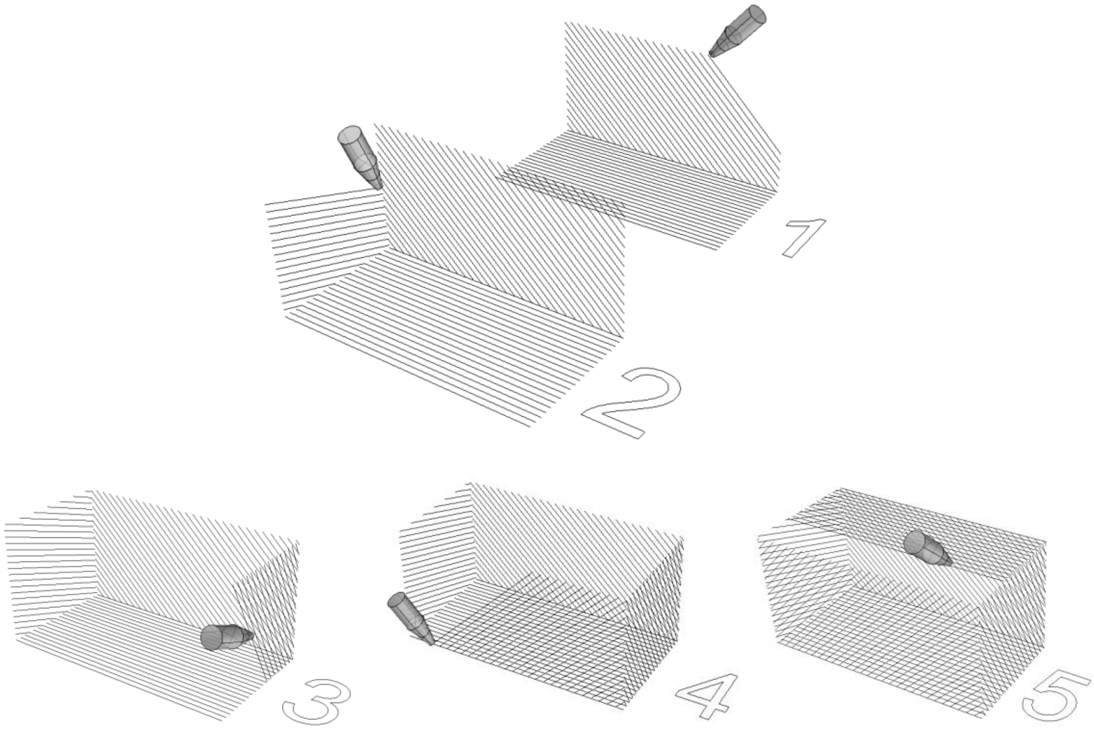


Figure 15 building up a hollow cube using multi-axis/non planar AM

As visualised, the restrictions of orientation have become smaller using Non-planar AM and pointy nozzle tools. Only the surfaces or sides of some building blocks will not be reached by the nozzle from every angle. Using multi-axis and non-planar AM, in combination with a pointy tool the illustration in figure 16 is in theory possible although no existing example has been found.

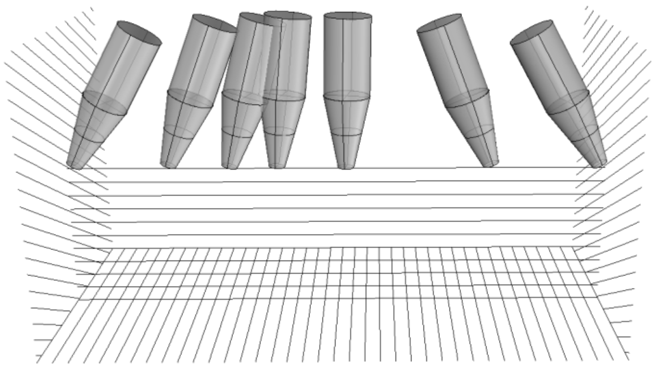


Figure 16 Theoretical possibility of non-planar, multi axis material deposition.

The combination of Multi-axis AM, deposited prints as building platform and Non-Planar AM offer the possibility to produce cross-plied laminates with significantly improved deposition orientations. The following paragraph discusses this using an example.

3.2.5. Cross-plied AM

The combination of Multi-angle AM, Non-planar AM and depositing material on top or against pre-deposited structures offers the possibility to deposit multi-oriented double walls as presented in figure 17. Adjacent walls are cross-plied, in which the first block is used as vertical building platform for the second one. On top of these blocks it is possible to deposit another block having a different orientation than both of the underlying surfaces.

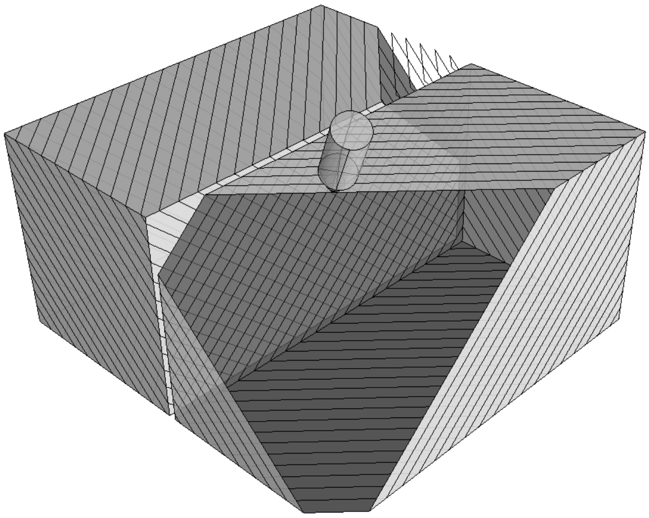


Figure 17 *Multi-angle AM to produce cross-plied divisions.*

Based on above information about thermoplastic composite mechanical properties and cross-plied AM strategies it is concluded minimum required regulations about laminates need to be cross-plied can be met. This is a crucial part of the deposition strategy of the entire bow section since otherwise the bow section will not be strong enough in one direction due to insufficient mechanical bonding resulting from the lack of mechanical connection from fibres in between layers. Based on the nozzle tool, pre-deposited parts, cross-plied requirements and overhang constraints a 270° orientation freedom is expected substantiated in *Appendix 1.20.1 Material Deposition Freedom*

3.3. AM - ME materials

In this paragraph it is demonstrated AM-ME materials including fibre reinforcements are able to comply with mechanical requirements as stated by the rules. First, an introduction is provided in the components available for a thermoplastic composite, consisting of resin, fibres and additives. An initial material selection is provided. Secondly, insight is provided in the calculated mechanical properties of the thermoplastic composite, which needs to comply with stated rules on mechanical properties. Finally, insight is provided in methods to account for requirements on material handling, in order to account for material integrity.

3.3.1. Components thermoplastic composite

This sub-paragraph is divided in polymer, short fibre, continuous fibre and additives which are generally the available components within a thermoplastic composite.

Polymer

Thermoplastics (in addition to thermosets) tend to melt when heat is added which makes them suitable for material extrusion. Based on deposit rate, building dimensions and material costs, and due to improved specific strength in combination with fibres, the AM-ME process is assumed promising. A thermoplastic polymer material is not a common material for an inland waterway vessel. (only thermoset composite and steel). Therefore, it must be made credible that thermoplastic materials can be used in a bow section in terms of strength and durability.

The amount of suitable thermoplastic AM materials has increased significantly over the years (Doubrovski, 2016). This is made possible due to extensive research on how to improve processing properties and material characteristics. In general, all thermoplastic materials can be used in polymer extrusion machines However, some features, such as shrinkage coefficient and crystallinity determine polymer behaviour in the printing process. Thermoplastics can be divided in commodity, engineering and high temperature polymers. For an inland waterway vessel only commodity polymers are optional based related to cost price.

Based on minimum required mechanical properties, material durability, material costs and chemical resistance the selection of available resins is significantly reduced. This is done using CES EDUPACK charts and limits. Based on costs and mechanical properties Polyethylene terephthalate (PET) shows highest interest. Table 5.

Resin	Costs (EUR/kg)	Tensile (MPa)	E-modulus (GPa)	Durability salt water	Durability chemicals	Durability UV
Polypropylene (PP)	1.19-1.33	22.5-33.5	1.37-1.58	Excellent	Excellent	Poor
Polyethylene (PE)	1.56-1.61	22.1-31.0	1.07-1.09	Excellent	Excellent	Fair
Poly.terepth. (PET)	0.88-1.15	70.0-75.0	2.76-3.1	Excellent	Acceptable	Fair
Polyamide (PA)	2.80-2.94	58.5-71.5	1.33-1.65	Excellent	Unacceptable	Poor
Polystyrene (PS)	2.06-2.09	35.9-51.7	2.28-3.28	Excellent	Excellent	Fair

Table 5 Optional resin materials (CES.EduPack, 2018)

Short fibres

This sub-paragraph discusses the possibility to include short fibre reinforcement to improve mechanical material properties. Reinforcing the resin with short (<5 mm) or long (>5 mm) fibres a short fibre thermoplastic composite material is obtained. Fibres not only strengthen the polymer but also provide anti-warp abilities during the deposition process (Love et al., 2014). To prevent warping (lifting and deformations of the AM object) in LSAM, (chopped) carbon and glass fibres are used. Since carbon is too expensive for the MCS the focus is on glass fibres.

Adding fibres increases the specific strength and stiffness of the resin. The longer the fibre become the more effect they have on mechanical properties. In table 6 a general understanding on specific strength and specific stiffness is provided based on averaged input from (CES.EduPack, 2018) applicable the previously listed available polymers.

Material	Density Kg/dm^3		Yield strength (MPa)	Specific strength kNm/kg		Young's modulus (Gpa)	Specific stiffness MNm/kg
Steel	7.85		250	31.8		205	26.1
Unfilled resin	1.2		50	41.6		3	2.5
+Short/long fibre	1.4		100	71.4		8	5.7

Table 6 Specific strength & stiffness comparison (CES.EduPack, 2018)

Concluded from the graph, unfilled resin shows an improved specific strength over steel (higher = better) but far from feasible specific stiffness (higher = better). Resins reinforced with short/long fibres show more interesting results but specific stiffness is still significantly. A bow section is stiffness driven to be able to comply with the regulations on deflection and strength driven not to exceed material stresses. Taking into account anisotropic material properties and the large differences in specific stiffness it will be hard to stay within allowable deflection. Since divisions need to be cross-plied a reduction factor on strength and stiffness is required reducing the strength and stiffness of a cross-plied laminate. Since span width is to be reduced or laminates need to become very thick, expected weight reduction will not be reached. Resulting values are presented in table 7.

Material	Density Kg/dm^3		Yield strength (MPa)	Specific strength kNm/kg		Young's modulus (Gpa)	Specific stiffness MNm/kg
Steel	7.8		250	31.8		205	26.1
Unfilled resin	1.2		50	41.6		3	2.5
Short/long fibre	1.4		75	53.6		5.5	3.9

Table 7 Specific strength & stiffness comparison with cross-plied reduction (CES.EduPack, 2018)

Deduced from the table the use of fibre reinforced resin improves properties in terms of strength, but stiffness requires additional material. Also, taking into account the losses as a result of layer adhesion, excess material and safety factors, solely short fibre reinforcements will not be sufficient to reach the intended weight reduction. The following paragraph discusses the use of continuous fibre/direct roving as reinforcing fibre, in order to improve specific strength and stiffness.

Continuous fibres

This section discussed the use of continuous fibres within AM. Besides short and long fibres a polymer can be reinforced using continuous fibres or direct roving. Within the thermoset composite industry unidirectional, cross-plied or woven fabrics are used. The goal is to orient the fabrics in the optimal direction. Within the AFP industry UD tapes having unidirectional fibres are deposited onto each other. The technology of depositing continuous fibres within AM is relatively new but gains additional interest all over the world. This process is called Continuous Fibre Additive Manufacturing (CFAM). CFAM and AFP are two different processes that have a lot in common.

CFAM is used to produce reinforced structures and geometries while AFP lends itself to deposit multi-directional composite surfaces. It is therefore not surprising that various industries and companies are discovering the advantages of a combination of these processes. CFAM is constrained with overhang, impregnation of the fibres at the nozzle, a step-wise surface and difficulties in deposition of multi-directional orientations. AFP is constrained by not being able to make sharp corners, requires more expensive materials (UD-tapes) and requires a supporting shape (mould) to pull the fibres over. Software strategies differ, but the general concept of depositing fibre-reinforced resin is equal. AFP technology is well established compared to the, relatively new, CFAM technologies (August, Ostrander, Michasiow, & Hauber, 2014). CFAM is the combination of AM including fibre reinforcements. Various options are developed to impregnate and implement the fibres into the deposited resin (Rietema, 2015) but the technology is still in its early stage. Following figure 17 shows some examples of CFAM processes.

Figure 17 Various CFAM developments (Orbital Composites)

An example of a more established CFAM technology (Figure 18) is provided underneath retrieved from CompositesWorld – Orbital Composites, 2017. The company is trying to erase the line between CFAM and AFP.

Figure 18 Latest CFAM technologies, retrieved from Composites World – Orbital composites (Gardinger, 2018).

A small amount of data on maximum fibre content in CFAM is available since the technology is relatively new. Small scale AM machines offer percentages of about 30%. Experiments were performed using up to a maximum of 60% weight content of E-glass continuous fibres (Vaneker, 2017). An important note is that during these experiments, commingled yarns were used to improve the ability to impregnate the fibres at the extrusion nozzle. Commingled yarns, a combination of polymer and reinforcing fibres is more expensive. The use of high pressured nozzles, as seen at Orbital Composites, makes the impregnation of a higher weight percentage of direct roving achievable.

To calculate specific strength and stiffness for thermoplastic composites containing continuous fibres additional composite theory is required, which will be discussed in the following chapter. To provide a first estimation on specific strength and stiffness following table 7 is listed in which averaged input for cross-plied laminates are shown based on reference composites and CES EDUPACK. In this table the reduction factor for cross-plied is already taken into account.

Material	Density Kg/dm^3		Yield strength (MPa)	Specific strength kNm/kg		Young's modulus (Gpa)	Specific stiffness MNm/kg
Steel	7.85		250	31.8		205	26.1
Unfilled resin	1.2		50	41.6		3	2.5
Short/long fibre	1.4		75	53.6		5.5	3.9
Therm. composite	1.6		260	162.5		19	11.8

Table 7 Specific strength & stiffness comparison cross-plied (CES.EduPack, 2018)

Based on the calculated specific strength a 80% weight reduction is achievable. Based on specific stiffness 54% additional weight is required which Is dependent on geometry, span widths and laminate thicknesses of the cross-plied laminates. This means most components within a composite bow section will be stiffness driven since this is the critical design requirement.

Additives

To improve polymer properties 'additives' can be inserted within the compound. Additives are substitutes/chemicals in the shape of powder, resin and/or foam to adjust or improve polymer properties. From a wide selection of available additives, following in particular show a positive impact on the performance of an AM bow section:

<u>Antimicrobials / Bio stabilizers</u>: *these types of additives are presumably used in textile and healthcare industry but it can prevent degradation of the polymer due to microbial attack. At the surface of the underwater ship a wide variety of algae, molluscs and microbes attach to the hull over time. Anti-microbial additives provide a deceleration of apposition.*

<u>External lubricants:</u> *these can be divided into three categories; lubricants, which have a function to minimize frictional forces between moving surfaces, adhesives, improving mechanical binding by*

increasing interfacial forces and surfactants, which create a surface active film via polar and non-polar ends causing a lubricant-like effect (Fulmer, 2000).
Fillers/Extenders: *these are added for various reasons. They include glass, carbon, and talc fillers to improve quality and strength. Also natural fillers such as wood, bamboo and flax are used. Other filler materials such as anti-slip can be added to improve for example surface texture on deck.*
Flame retardants: *these are added in accordance to requirements for flammability and flame retardancy. By adding flame retardants, a polymer can even become self-extinguishing. (CES.EduPack, 2018)*
Heat-stabilisers: *these are added to inhibit or retard the polymer's degradation process caused by for example by oxidation, thermal degradation and ozonolysis.*
Impact modifiers: *these are added to improve the toughness of the polymer resin.*
Light (UV) stabilisers: *these provide a long term protection against UV degradation and breaking of the polymer chain length due to light beams (sunlight).*
Pigments: *these can be added to provide the polymer with a certain colour or gradient.*

The specific amount of additives required for an optimal compound differs from case by case and varies with the recipes prescribed by the compounding companies. On average in between 1% and 5% of each additive is required to maintain or improve resin properties. As additives are more expensive than the polymer, usually in between three and eight EUR/kg, this might have a negative impact on the total material costs price.

3.3.2. Mechanical properties AM-ME materials

This subparagraph discusses the resulting mechanical properties of the composite laminate and whether these will comply with the stated rules. Most selected thermoplastic resins do not comply with minimum stated raw material properties. To increase tensile modulus, resin can be filled with powder, short fibre or long fibre. Another possibility is by adding reinforcing or toughening additives which strengthen the resin in terms of stiffness and tensile strength. The combination of a regular resin with a small percentage of another (high performance) resin offers increased mechanical properties. This is called a resin blend.

Minimum required laminate properties are provided taking into account the laminate type cross-plied. Mechanical laminate properties can be calculated using composite theory or reinforced materials can be compared using (CES.EduPack, 2018). In table 8 first insight is provided in mechanical laminate properties based on (CES.EduPack, 2018). Values are an approximation based on a polyester based thermoplastic composite comparable to PET.

Mechanical property	Cross-plied laminates (MPa)	AM laminates (MPa) (CES)
f_c	40%	40%
Ultimate tensile strength	173	170 - 340
Tensile modulus	13330	14800 - 21200
Ultimate compressive strength	139	230 - 254
Shear modulus	2920	5520 - 6730

Table 8 Minimum required laminate mechanical property comparison (Lloyds.Register, 2017a)

The specific material type and orientation strategy determines final mechanical properties but based on raw material properties of PET resin + glass fibres and based on calculated required mechanical properties of composites, thermoplastic composites show beneficial properties and are allowed based on mechanical cross-plied laminate properties.

3.3.3. Material handling

This sub-paragraph discusses the technological aspects regarding material handling. Discussed in previous chapter there are rules prescribed for thermoset composite material handling. For AM, other regulations apply. Stated by (Bergsma et al., 2016), material integrity, regulations and classification of AM Is one of the main challenges. Optional methods to deal with these challenges are listed below.

Layer adhesion is influenced by a number of factors such as irregular material cooling, void cavities, material shrinkage and layer misalignments. Adding reinforcements does not improve layer adhesion since no mechanical connection between layers is established. In figure 19 pre-heating using infra-red light is shown. As well al infra-red imaging to control surface temperature and figure 20 shows rollers and tampers which provide after-pressure to improve layer adhesion and reduce shrinkage cavities.

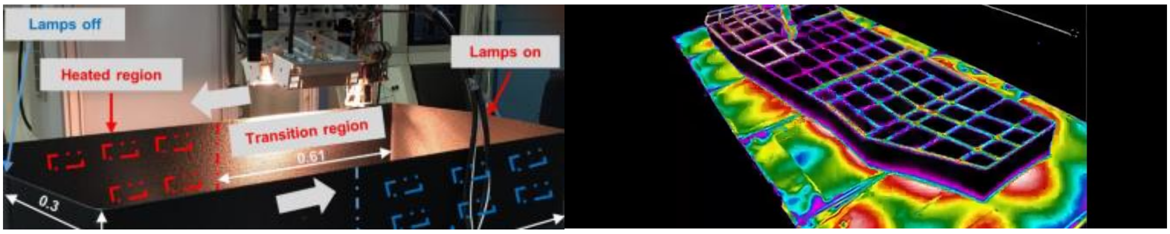


Figure 19 BAAM using infra-red to pre-heat previous layers. Thermwood using IR control. (BAAM / Thermwood)

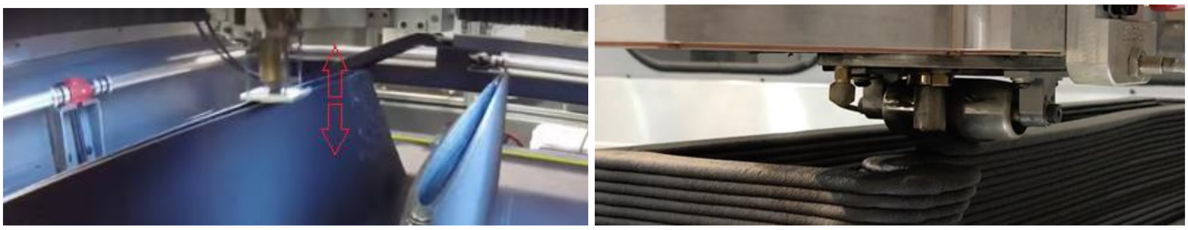


Figure 5 Tamper and roller to apply pressure deposition (BAAM / Thermwood)

Comparable technology is seen within the Automated Fibre Placement (AFP) industry as presented in technical drawings in figure 21

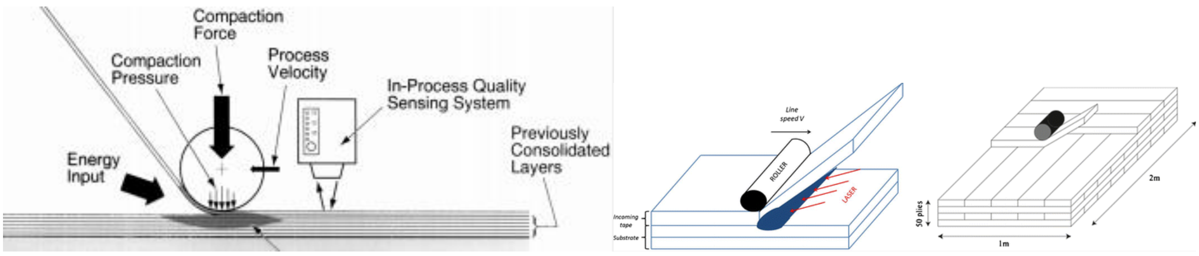


Figure 21 AFP technology and systems to control tape adhesion (Chinesta et al., 2014; Lamontia et al., 2003)

Main difference between AFP and AM is that filaments or tapes are pulled along a surface requiring an initial supporting surface, while AM pushes molten material onto previously deposited material. To be able to secure layer adhesion throughout the entire building process and in order to prohibit layer delamination or object deformation, closed loop systems are applied to intervene when sensors detect object instability. Examples of control systems are thermal control through infra-red light, pre-heating of layers for optimal adhesion temperature and material flow control based on scans and machine speed control (Hu & Kovacevic, 2003).

Within the AM industry in Holland there are few companies able to produce parts which can be classified. RAMLAB recently revealed it's (steel) vessel propeller which was approved by BV. CEAD, a Dutch FDM 3D printer manufacturer is able to produce classified functional parts using standardized machines. To be able to do so, material integrity should be known throughout the entire object. Also, data during deposition is to be collected and stored, in order to trace back possible flaws. Based on findings above it can be concluded material integrity is a challenge but being able to demonstrate all layers are properly fused and no unknown material or fibre distortions are present, a Class-approved process is within reach.

3.4. Fire Resistance AM-ME materials

In this paragraph it is repeated being able to comply with requirements on fire-resistance the use of thermoplastic materials is challenging and not achievable without external fire safety provisions.

3.4.1. Heat-stabilizers/Flame retardants

This sub-paragraph discusses the effect of heat-stabilizers and flame retardants. Composite materials used in AM are called combustible. Fire-divisions need to be able to withstand a fire test. Since within a bow section not all areas are subjected to A-Class (0-30) fire-resistance measure are taken to be able to protect fire-class divisions for open fire and emerged heat in case of a fire. The use of flame retardants allows resin to become more fire resistant. Within CES the range is in between highly flammable and self-extinguishing. However, there are various properties affected by heat of which the most important ones are melting point, glass-transition temperature, heat deflection temperature and maximum service temperature. Since the use of flame retardants will not be able to protect the material sufficient, these can only be used as extra protection, to reduce fire spreading and to save time to be able to escape.

3.4.2. Fire-resistant panels

Since thermoplastic composites as well as thermoset composites are combustible, additional fire protection measures are required. Apart from fire prevention and extinction equipment such as fire detection systems and sprinkler installations, and flame retardants within the resin, fire divisions as a whole need to be protected against direct exposure to fire. This paragraph discusses fire resistant panels serving as fire protection.

Fire panels serve as insulation layer between the division and the heat-source. Panels protect the division so that the hot side of the division does not reach a maximum temperature. As is stated by the rules, the unexposed side of the division is not allowed to reach a temperature above 140 °C and no part of the division can reach a temperature of 180 °C. Therefore it is required to cover all parts of the division including corners, trusses and connections. Fire resistant panels need to be installed after construction via class approved methods. In particular, two fire panel providers show highest interest, FIPRO and PROMAGUARD, of which examples are presented in figure 22 and 23

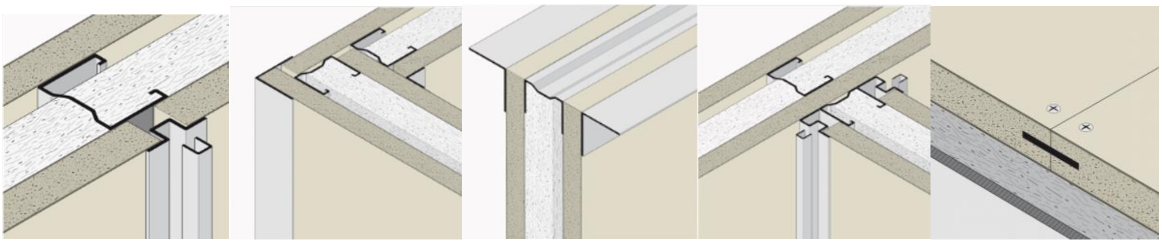


Figure 22 Connection of fire-resistant panels from FIPRO.

The manufacturer PROMAGUARD offers more lightweight Class-A approved non-combustible fire panels specially applicable for Fibre Reinforced Polymers (FRP). Pictures are presented in figure 23

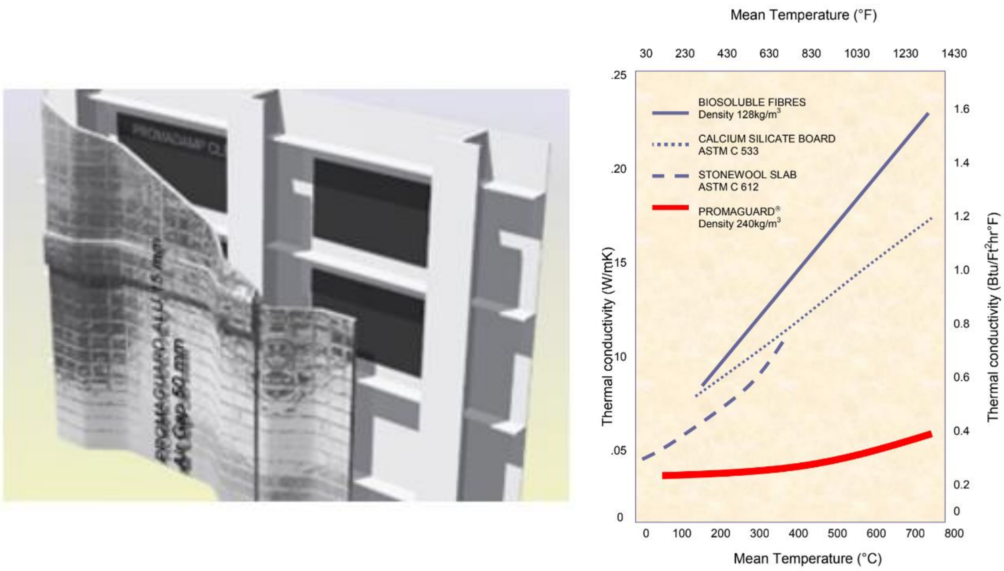


Figure 23 *Various options for A60 class bulkheads as provided by PROMAGUARD*

Advantages of FIPRO panels as retrieved from the catalogues are high temperature resistance (non-combustible), lightweight (2400 kg/m^3), high thickness/insulation ratio, 10 mm thickness for A30 and A60 Fire Class, low required space, nontoxic and improved properties over a 50 mm insulation method. Graphs (figure 24) illustrating the insulation properties of PROMAGUARD panels provides insight in the ability to protect thermoplastic polymers from surrounding temperatures increasing T_g and T_m.

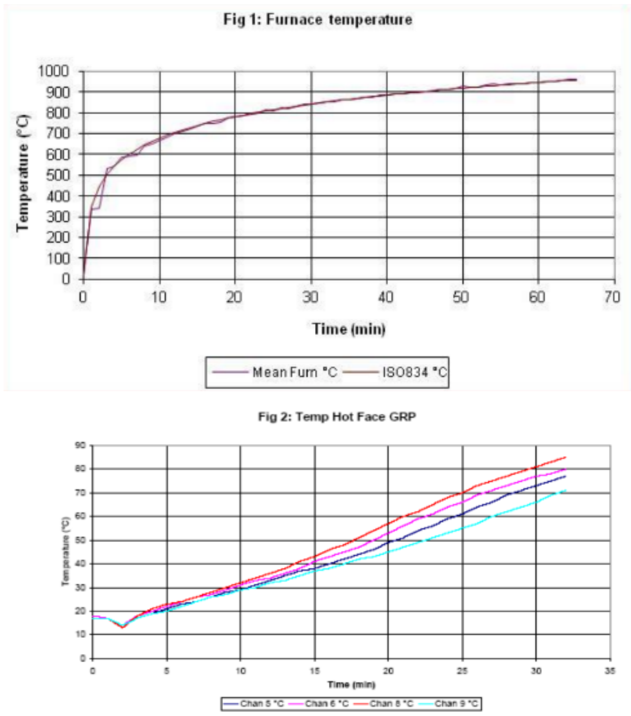


Figure 24 *Furnace temperature created during a fire-test and corresponding temperature of hot side of FRP panel covered with 'Promaguard'.*

The graphs above show an increasing temperature on the hot side of the GRP which after 30 minutes does not reach temperatures above a maximum of 85° which is far below the melting point of the selected polymers. Since fire resistant panels are a necessity, cost price needs to be taken into account. Based on conversations with the manufacturers very specific cost factors are based on the amount of panels ordered, methods of connection and required dimensions but in between 30 EUR/m^2 and 50 EUR/m^2, depending on the type and manufacturer is assumed realistic. Both these values are taken into consideration in the final cost estimation taking into account the amount of m^2 fire class divisions within the bow section being approximately 300 m^2 in the reference bow section. The consequential extra EUR 9.000,- to 15.000,- needs to be compensated in sectional production costs.

Concluding from above it is required to have fire-resistant panels installed taken into account in the final cost calculations. Initial costs do not directly reject the production of an AM-ME bow section but does have a significant impact and need to be compensated to offer a competitive business case.

3.5. Conclusions

In previous chapter is was discussed how AM-ME is able to comply with stated requirements. AM-ME does not reject the production of a bow section in terms of dimensions, deposit rate, surface finishing and expected costs. Keeping cost low enough will be a challenge since AM is still a relatively new production process and steel vessel building is relatively cheap. Material costs of around 1.5,- EUR/kg, a 23 tonnes bow section, a deposit rate of in between 200 and 600 kg/hr and a machine rate of in about 500 EUR/hr results in a competitive bow section, taking into account additional costs items resulting from fire resistant panels. The ME process offers lightweight, high strength, thermoplastic composite materials which are deposited cross-plied. Current technological aspects such as control and closed loop systems are listed to comply with additional rules on material integrity, which are one of the main challenges in case of an object produced for the MCS.

4. Bow section composite material

This chapter discusses sub-question 4; What AM-ME polymer and reinforcing material is best suited for inland waterway vessels? A determining factor is the specific material of which the bow section is constructed from, in terms of direct material costs and achievable weight reduction. From AM production perspective, the material determines building speed, post-processing, building costs and installation possibilities. From performance perspective material's density, strength, flexibility and durability determines, among others, weight reduction, structural layout, division thicknesses and life-time span.

In this chapter the resulting AM-ME material is discussed based on initial material requirements and accompanied with the initial list of available materials. Initial raw material requirements based on costs, mechanical properties, melting point, glass transition temperature, UV-, water- and chemical resistance help determine a feasible resin and fibre material. Raw material selection is done in §4.1.Thermoplastic composite calculations are required to retrieve final material properties, in order to be able to calculate the bow section on strength and stiffness. This way, final weight reduction and cost price can be derived. Using composite theory, final mechanical material properties are calculated in §4.2 . This paragraph also offers insight in toughness and fatigue. Since the use of recycled material content allows for lower material costs, offering decreased production costs and a more interesting business case, this topic is discussed in §4.3. In §4.4. final material costs are provided, discusses final material costs.

4.1. Specific material selection

In this paragraph a composite material selection is done. A final choice on resin, fibre and additives is presented based on raw material requirements and required material properties.

4.1.1. Resin

To reduce the amount of available polymer materials a selection of the most important material properties is provided resulting from cost perspective, functional requirements and fire safety. Since no clear rules apply for thermoplastic composite vessels and corresponding material properties, regulations on thermoset materials and steels are used as reference, listed in table 9

1	AM production	*The material should in first instance be producible using AM-ME technology.*
2	Material costs	*Assuming improved specific strength material cost price of under 3 EUR/kg is selected.*
3	Fire resistance	*The selected material should be able to comply with A30 Class fire notation, including fire safety provision such as fire resistant panels.*
4	Chemical resistance	*Due to chemicals in surrounding water and within the vessel the material is to be chemical resistant. (oil, fuel, lubricants)*
5	Weather resistance	*The material is subjected to UV-radiation, fresh and salt water splashing, acid rain and wind and wave (and river bottom) erosion.*
6	Strength	*The raw materials should comply with the minimum stated mechanical strength properties*
7	Stiffness	*The raw material should comply with the minimum stated mechanical stiffness properties*

Table 9 initial criteria for material selection using selection charts in (CES.EduPack, 2018).

The material selection is divided in three phases. In the first phase, material types, costs and mechanical properties are assigned in (CES.EduPack, 2018) using 'limits' and 'chart'. First order selection criteria are listed below:

1. All non-polymer and thermoset materials are neglected *Ref 1)*
2. All materials more expensive than 3 EUR/kg are neglected (*Ref 2)*
3. Only glass fibres (E-glass) is taken into account (between 30% and 60%) (*§2.4.1.)*
4. All materials with tensile strength lower than 80 Mpa (*§2.4.1.)* and tensile modulus lower than 3.4 GPa (*§2.4.1.)* are neglected
5. All material with shear modulus lower than 1.3 GPa (*§2.4.1.)* are neglected.
6. All materials with E-modulus lower than 3 GPa (*§2.4.1.)* are neglected

The resulting thermoplastic polymers meet initial cost and strength requirements based on minimum required mechanical properties and initial criteria.

In the second selection of material criteria, temperature properties are evaluated. This selection is based on melting point, glass transition temperature, HDT and maximum and minimum service temperature. In this instance, resins having higher temperature resistance is beneficial, although fire resistant panels serve as main protection.

Melting temperature: *is the temperature at which a material turns abruptly from solid to liquid. For polymers, a melting point is only reported for semi-crystalline materials and refers to the melting of the crystalline domains in the polymer. (CES.EduPack, 2018)*
Glass-transition temperature *is also called Tg, and is a property of non-crystalline solids, which do not have a sharp melting point. It characterizes the transition from true solid to viscous liquid in these materials. (CES.EduPack, 2018)*
Heat-deflection temperature (HDT) *is the temperature at which stiff plastics lose stiffness under a certain pressure. (CES.EduPack, 2018)*
Maximum service temperature *is the highest temperature at which material can be used for an extended period without significant problems, such as oxidation, chemical change, excessive creep, loss of strength, or other primary property for which the material is normally used (CES.EduPack, 2018)*

Fire resistant panels offer protection of 80 degree Celsius for 30 minutes. In warm countries inside temperatures of machinery rooms can reach significant value's, although composite shows isolating abilities. Most critical temperatures are glass transition temperature and maximum service temperature since these are reached first. An absolute minimum of 85°C is assumed for all criteria, although melting temperature and HDT needs to be higher in order to maintain the original shape while loadings are applied. Since temperature for thermoplastics is more critical than with thermoset materials, values are gradually increased to see what polymers are excluded from the selection, at what temperature ranges.

The third order material criteria is based on UV, water and chemical resistance, toughness and fatigue properties. In (CES.EduPack, 2018), UV and water is annotated in between unacceptable, limited, acceptable and excellent. Chemical resistance, depending on the type of chemical, is annotated from satisfactory to unsatisfactory. The resin is to be chemical resistant in case of spilled chemicals within the waters, or leakage from the vessel's fuel tanks. Based on thermoset composites and steels, values for elongation and fatigue are selected, presented in table 11.

UV resistance *should be acceptable or excellent in CES EduPack*
Salt water resistance *should be acceptable or excellent in CES EduPack*
Chemical resistance *should be satisfactory in CES EduPack, based on comparable thermosets*
Brittleness (elongation) *should be more or equal than 2%, based on comparable thermoset elongation*
Fatigue strength (MPa at 10^7 cycles) *should be higher than 100 MPa, based on comparable thermosets*

	UV-resistance	Salt water resistance	Chemical resistance	Brittleness (elongation)	Fatigue (MPa)
Resin	≥ acceptable	≥ acceptable	≥ satisfactory	≥ 2%	100

Table 11 Assumed minimum required third order selection criteria

Using 'charts and limits' in (CES.EduPack, 2018) results in a narrow selection of available materials of which Polyethylene terephthalate (PET), reinforced with glass fibres proves to be the most promising. This thermoplastic composite complies with all stated criteria from the first, second and third order criteria. It is very cheap, while very strong. The combination of PET and glass offers a high performance composite. Thermal properties of PET are superior to thermal properties of alternative polymers. Also, PET shows interesting weathering, chemical and fatigue properties. PET is one of the most common thermoplastic polymer resins of the polyester family and is used in a wide variety of applications such as clothing, containers for foods, bottles. In figure 25 the PET molecule structure is provided.

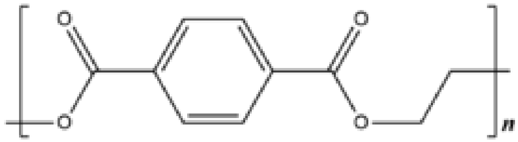


Figure 25 molecule structure of PET (Wikipedia, 2018)

Unfilled PET does not comply with minimum required raw resin mechanical properties which can be compensated by adding a small amount of stronger resin. Al second selection was made based on mechanical and temperature properties. PET + Polycarbonate (PC) blends offer increased mechanical and temperature abilities. Since Polycarbonate is more expensive, the amount added needs to be minimized. By adding five to ten percent PC within the resin, mechanical and temperature abilities are increased while maintaining an average low cost price. Datasheets of PET, PC, and PET/PC blends are provided in *Appendix 1.13 PET/PC datasheets.* This paragraph discussed the choice for a PET + 5-10% PC addition. The following paragraph discusses the type and amount of reinforcing fibres added.

4.1.2. Fibres

Primarily based on cost factors the amount of available fibre types is limited. Within composite shipbuilding most used fibres are E-glass fibres related to cost price (<2 EUR/kg). The fibre type complies with minimum required raw material properties as stated by the rules. In *Appendix 1.14 datasheets E-glass* the datasheet of E-glass is provided.

Within AM, glass fibres are used in various forms. Short fibres (<5 mm), long fibres (> 5 mm) and continuous fibres (∞) are commonly used. The optimal fibre weight content and fibre shape is based on technological AM capabilities, minimum raw material requirements and the difference in strain (ε_f and ε_m) between two combined materials in a composite structure. Adding short glass fibres increases mechanical properties of the resin. This reduces the ratio difference in strain (ε_f and ε_m) in between resin and continuous fibres and therewith causing a material with a higher ultimate tensile strength. To reach the strongest material properties a maximum amount of direct roving percentage should be used while maintaining material properties such as brittleness and layer adhesion. A perfect fibre impregnation is crucial. 40% weight content of continuous fibres is significant for AM-ME processes, but it is the minimum required. Examples have shown possibilities to deposit 40% continuous fibres.

Continuous fibre weight needs to be at least 40%. The goal is to compose a material which, in combination with the geometry, will be strong and stiff enough to be able to reduce the weight of the bow section by about 30% to 50%. The difference in percentage of long and continuous fibres affects the thermoplastic composite properties. In figure 26 a schematic representation of continuous and discontinuous, aligned and random oriented fibre reinforced composite properties is shown as well as the schematic stress-strain curves for brittle fibres and ductile matrix materials (Clayton, 1987).

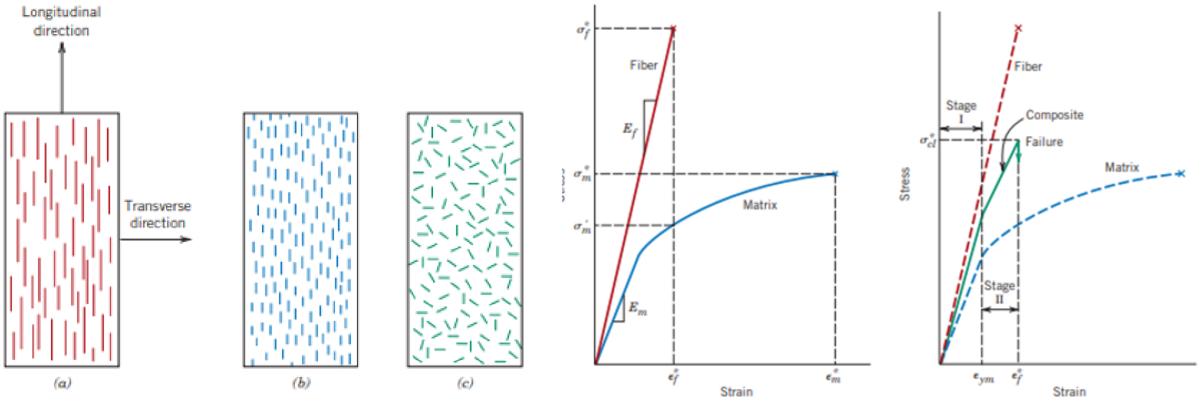


Figure 26 schematic representation of various fibre orientations and a schematic stress-strain curve for brittle and ductile material. (Clayton, 1987).

With the use of raw material properties laminate calculations are performed to find strengths in all directions. For laminate calculations ply assumptions (Mallick, 2007) are taken into account, retrieved from (Lupasteanu, Taranu, & Popoaei, 2013) and listed underneath:

1. Fibres are uniformly distributed throughout the matrix.
2. Matrix is voids free.
3. Fibres and matrix are perfectly bonded.
4. Applied force is either parallel or normal to the fibre direction.
5. The ply is initially in a stress-free state.
6. Fibres and matrix behave as linearly elastic material.

Within AM, the uniformly distribution of the fibres throughout the resin is relatively unknown. No matrix is void free related to step-wise layer effect and shrinkage cavities. Perfect bonding relies on the fibre coating and process of impregnation. Since a bow section is subjected to dynamic loads, applied forces are not parallel of normal to the fibre direction. To comply with these uncertainties significant safety factors need to be taken into consideration. Seen at Orbital Composites and CEAD, full impregnation is achievable using high-pressured nozzles, also allowing for better bonding and void-free laminates. Also, CEAD offers Class-approved parts so it can be assumed part of these uncertainties are solved having weight reduction as penalty related to safety factors.

With respect to composite theory, since a perfect bonding between fibre and matrix is assumed formula (6) counts:

$$\varepsilon_f = \varepsilon_m = \varepsilon_c \tag{6}$$

In which ε_f, ε_m and ε_c are longitudinal strains for fibre, matrix and composite. Since assumption 6 counts, equations (7) is applicable :

$$\varepsilon_f = \frac{\sigma_f}{E_f}, \qquad \varepsilon_m = \frac{\sigma_m}{E_m} \tag{7}$$

To be able to estimate optimal material composition for strength the difference in material's strain ε is compared. Strain of the material is calculated by dividing the tensile strength (σ) by the E-modulus (E) of the respective material. An explaining picture is provided in figure 27:

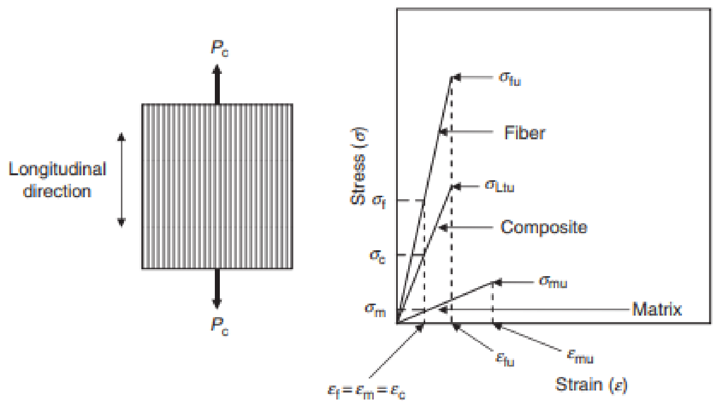


Figure 27 Stress – strain ratio matrix, fibre and composite (Mallick, 2007)

The smallest (ε) value of either resin or fibre is used to calculate maximum tensile strength for a single anisotropic ply (8):

$$(\sigma_1) = \left[\frac{E_{11}}{1 - v_{12}v_{21}}\right](\varepsilon_1) \quad (5)$$

This implies the composite material becomes strongest when ε_f and ε_m are as equal as possible. Since the ε_f of E-glass is significantly higher than the ε_m a different resin and fibre reinforcement ratio can be proposed. Optimizing for equal strain σ and E for E-glass and various PET/PC + glass filled resins show the strain of a 10% short/long glass fibre compound is most equal to the strain calculated for continuous E-glass fibres. Adding 7% long E-glass fibres and 40% direct roving a total of 48 wt% glass is achieved offering optimal strain behaviour while complying with minimum stated requirements.

4.1.3. Additives

For a thermoplastic bow section additives offer advantages for object performance and lifespan. The exact percentage and type of each additive will depend on a case by case basis and is compiled by compounding companies. However, the percentage of required additives are usually in between 1% and 5% of the weight percentage resin, which has significant impact on material price since additives tend to be more expensive compared to virgin polymer.

Previously discussed, composite materials used in AM are called combustible. Fire-divisions need to be able to withstand a fire test. Since within a bow section not all areas are subjected to A-Class (0-60) fire-resistance measure are taken to be able to protect fire-class divisions for open fire and emerged heat in case of a fire. Since PET/PC can be produced containing heat-stabilisers and fire retardants the polymer can be compounded so that it burns slowly, up until becoming partly self-extinguishable (CES.EduPack, 2018). This however affects PET material properties in a negative way (Wang, Chen, Tang, & Du, 2003) and makes the material more expensive. In (Camino & Costa, 1988) the phosphoric flame retardant PSTPP is discussed which provides PET a non-dripping nature if more than 0.4% of the powder is added. To be able to pass a fire test the sample should not ignite (nor melt) and it should maintain its original strength for the duration of the test. Since above the glass transition temperature the polymer will start becoming weaker it is concluded only adding flame retardants will not be sufficient to pass a fire test. As flame retardants improve the dripping nature of the polymer, and delay ignition, it can be effective in cases of smaller fires and spreading fire.

For the bow section a selection of additives is provided based on recommendation from various compounding companies for outside objects under influence of sun and salt water. Also, as extra, anti-microbial agents, pigments and impact modifiers are added listed in table 12. The amount of additives, (as well as the amount of reinforcing fibres), are denoted in weight percentage (wt%), in contrast to volume percentage, and thus based on density.

Additive	Weight percentage (wt%)	Cost (EUR/kg)
UV-stabilizers	4-6	3,- to 4 ,-
Impact modifiers	2-3	3,- to 4,-
Pigments (black)	1-2	2,- to 4,-
Anti-microbials	2-3	3,- to 4,-
Flame retardants	5-8	4,- to 5,-

Table 12 Additives selection, weight percentage and costs

From previous paragraph it was concluded most promising material compound is a 40 wt% PET including 5 wt% PC addition. The resin compound is reinforced using 40 wt% continuous fibre including 7 wt% short fibres to level critical strain. Since no additives are required for the glass reinforcing volume within the resin, and approximately 50 wt% glass is used, less wt% of additives are required for the final thermoplastic composite. A recipe of additives is discussed in order to improve secondary properties such as toughness, UV-resistance and anti-microbials. Table 13 offers the final composite composition.

Additive	Weight percentage (wt%)
Polyethylene Terethalatate (PET)	40
Polycarbonate (PC)	5
Continuous fibres (Direct Roving)	40
Short fibres (SH)	7
Additives	8

Table 13 Final thermoplastic composite composition

Since the composition of the thermoplastic composite is known, the following paragraph uses raw material properties to calculate final laminate properties.

4.2. Properties bow section composite material

In this paragraph mechanical properties of the final thermoplastic composite material are calculated using composite theory, subdivided in mechanical properties, toughness and fatigue.

4.2.1. Mechanical laminate properties

In this paragraph an introduction is provided on composite theory to calculate final mechanical composite properties. The polymer matrix in combination with long fibres (>5mm) and direct roving, produced via CFAM forms an orthotropic composite material. ($E_1 \neq E_2 \neq E_3$). However it is common to approximate the properties transverse to the fibre to be isotropic ($E_2 = E_3$) which is called transversely isotropic (Roylance, 2000). An AM laminate is deposited in layers onto each other and therefore the AM laminate should be assumed orthotropic, while on smaller level, a layer itself shows transversely anisotropic properties. Since cross-plied laminates are connection only due to layer adhesion, as well as individual layers itself, final composite properties are assumed to be transversely anisotropic in which the direction equal to the fibre direction is exponentially stronger than in both other directions.

For initial strength and stiffness calculations of transversely isotropic and orthotropic materials, Elasticity-modulus (E), Poisson's ratio (ν), Ultimate tensile strength (σ) and Shear Modulus (G) are required (Eckold, 1994). An example of one single transversely anisotropic ply is demonstrated in figure 28

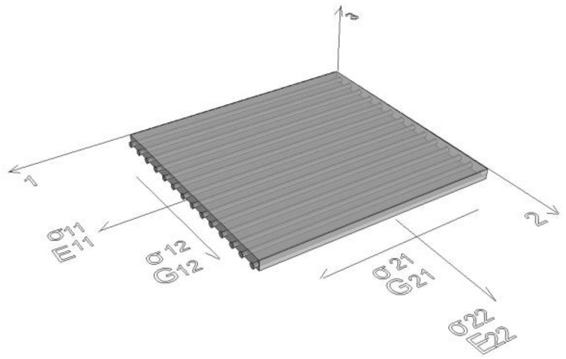


Figure 28 Transversely anisotropic laminate consisting out of one single ply.

For a transversely anisotropic laminate the local compliance matrix and inverse local elasticity matrix are used (Roylance, 2000) as presented in 9 to 12. In the matrices stresses and strains are related.

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ 2\varepsilon_{12} \end{pmatrix} = \begin{bmatrix} \frac{1}{E_1} & \frac{-v_{12}}{E_2} & 0 \\ \frac{-v_{12}}{E_1} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} \tag{9}$$

$$(\sigma_{123}) = [Q](\varepsilon_{123}) \tag{10}$$

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Sym & Q_{22} & 0 \\ Sym & Sym & Q_{66} \end{bmatrix} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ 2\varepsilon_{12} \end{pmatrix} \tag{11}$$

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} = \begin{bmatrix} \frac{E_{11}}{1 - v_{12}v_{21}} & \frac{v_{21}E_{11}}{1 - v_{21}v_{21}} & 0 \\ Sym & \frac{E_{22}}{1 - v_{12}v_{21}} & 0 \\ Sym & Sym & G_{66} \end{bmatrix} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ 2\varepsilon_{12} \end{pmatrix} \tag{6}$$

Figure 29 Inverse elasticity matrix of a transversely anisotropic ply. (Roylance, 2000)

To calculate the laminate strength of the final compound for which input data is retrieved from (CES.EduPack, 2018) density (ρ), Young's modulus in x-direction (E_{11}) and Poisson ratio (v_{12}) is required and the Rule of Mixture is applied (Liu, 1997). For Youngs-modulus in y-direction (E_2), Shear modulus (G_{12}, G_{23}) Halpin-Tsai equations count (Affdl & Kardos, 1976). To calculate the resulting transversely anisotropic laminate properties the following input for individual material components is provided based on input from (CES.EduPack, 2018)., presented in table 14

Data Ply

Fibre volume fraction (continuous)	f	40	F_c
Fibre volume fraction (long)	f_l	10	F_l
Fibre density	ρ_f	2.6 e3	Kg/m^3

Fibre E_f longitudinal	E_f	85	GPa
Fibre E_{ft} transversal	E_{ft}	15	GPa
Fibre Poisson ratio	V_f	0.23	-
Fibre tensile strength	σ_f	2.05 e3	MPa
Fibre compressive strength	X_f	5 e3	MPa
Fibre G shear modulus	G_f	36	GPa
Matrix density	ρ_m	1.31 e3	Kg/m^3
Matrix E_m longitudinal	E_m	4.83	GPa
Matrix E_m transversal	E_{mt}	2.9	GPa
Matrix Poisson ratio	V_m	0.386	-
Matrix tensile strength	σ_m	106	MPa
Matrix compressive strength	X_m	102	MPa
Matrix G shear modulus	G_m	2.13	GPa

Table 14 Input for composite theory calculations (CES.EduPack, 2018).

Above listed value's serve as input for further composite strength calculations. For transversely anisotropic material following formula's (13) to (20) , retrieved from (Roylance, 2000) and lecture notes from Kaminski, 2018, Tu-Delft provide input for strength and stiffness calculations.

$$Density: \rho_c = f \cdot \rho_f + (1-f) \cdot \rho_m \tag{7}$$

$$Longitudinal\ elasticity\ modulus: E_{11} = f \cdot E_f + (1-f) \cdot E_m \tag{8}$$

$$Transversal\ elasticity\ modulus:\ E_{22} = \frac{E_{ft}}{f + (1-f) \cdot \frac{E_{ft}}{E_m}}, \quad E_{33} = E_{22} \tag{15}$$

$$Poisson's\ ratio: v_{12} = f \cdot v_f + (1-f) \cdot v_m \tag{16}$$

$$Transversal\ Poisson's\ ratio: v_{23} = v_{12} \cdot \frac{E_{22}}{E_{11}}, \quad v_{31} = v_{21} \tag{17}$$

$$Composite\ shear\ modulus: G_{12} = \frac{G_f}{f + (1-f) \cdot \frac{G_f}{G_m}}, \tag{18}$$

$$Transverse\ shear\ modulus: G_{23} = \frac{E_{22}}{2(1+v_{23})}, \quad G_{13} = G_{23} \tag{19}$$

$$Average\ tensile\ strenght\ longitudinal: \sigma_{11} = f \cdot \sigma_f + (1-f) \cdot \sigma_m \tag{20}$$

If it is assumed the fibres within the matrix fail before the matrix does, due to lower fibre strain, equation (21) for tensile strength applies. To find the fibre volume at which the composite becomes stronger than solely the matrix equation (21) needs to be solved for f, using σ_m, to find the required fibre content.

$$\sigma_{composite} = (f \cdot E_f + (1-f) \cdot E_m) * \varepsilon_f \tag{9}$$

To calculate the working strength of the composite, which determines the fibre content at which the material becomes damage tolerant equation (22) applies, which need to be solved for f:

$$working\ strenght\ \sigma_{composite}: f \cdot \sigma_f = (f \cdot E_f + (1-f) \cdot E_m) * \varepsilon_f \quad (10)$$

The ultimate tensile strength of the composite is determined by the ratio between fibre and matrix and their corresponding individual tensile strengths. When a small fibre volume fraction f is applied the longitudinal stress leads to fibre failure. The composite will then fail when the ultimate matrix tensile strength is reached. This is calculated by (23):

$$\sigma_1 = \sigma_m(1-f) \quad (11)$$

Layer Adhesion

For an AM laminate the ultimate tensile strength in transverse directions is the result of weaker layer adhesion. Since no mechanical reinforcements are present in between layers the tensile strength has a maximum value of the yield strength of solely the matrix, including layer strength reduction. Based on a 70% layer strength reduction provided in *Appendix 1.20 Layer adhesion estimation* ultimate tensile stress in transverse direction for PET/PC having a yield limit of 60 MPa, tensile stress becomes; 60 * 0.7 = 42 MPa applicable on single laminates.

In *§2.4.3.* maximum allowed stress value's as a fraction of the ultimate shear strength are expressed. For stress and strength analyses not all individual components will be referenced but a stress fraction of 0.25 (minimum) and 0.33 (average) is assumed since most components, as well as global limiting stress criteria, are subjected to these fractions. Ultimate shear strength for composites using a simplified calculation is in between 0.3 and 0.5 of the ultimate unidirectional tensile strength, perpendicular to fibre direction. Using (20) , and a conservative fraction of 0.4, this accounts for a 353.44 MPa maximum stress value for uni-directional laminates. An additional 0.25 stress fraction value corresponds to a 88.36 MPa maximum stress value in unidirectional direction.

To calculate the E-modulus of the final laminate including a strength factor based on the orientation of the fibres a scale factor η is used. In figure 30 various scaling factors are noted corresponding to the fibre directions visualised. The thermoplastic composite used in the AM bow section mainly consists out of Bi-directional (0°-90°) and Bi-axial (45°,-45°) laminates, with a minimum of two plies, and thus scaling factors in between η=0.5 and η=0.25 are used. This depends on the location and the direction of the leading forces. More than two plies in different directions are assumed to be random (in plane) having a scaling factor of η=0.38 :

$$E_{11} = \eta \cdot f \cdot E_f + (1-f) \cdot E_m \quad (12)$$

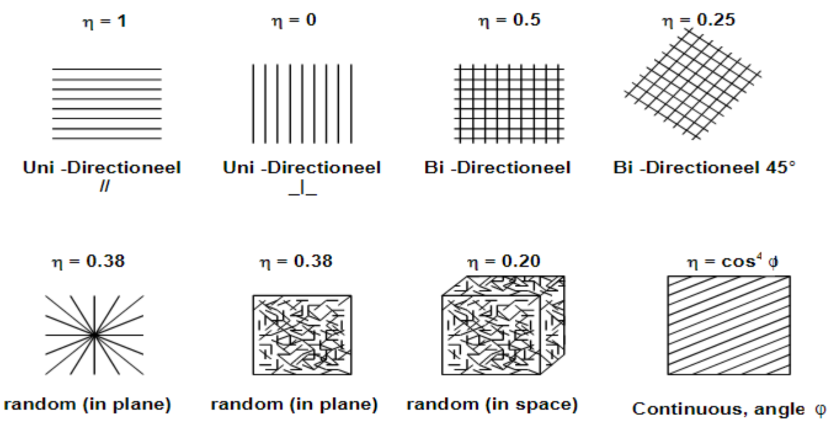


Figure 30 Effect of reinforcement resulting from orientation of the fibres. (lecture notes Kaminski 2018, TU-Delft)

Resulting from the previous stated elasticity matrix for anisotropic laminates an ultimate tensile strength is retrieved using following formula's (30):

$$Q_{11} = \frac{E_{11}}{1 - v_{12}v_{21}}, \qquad Q_{12} = \frac{v_{21}E_{11}}{1 - v_{12}v_{21}}, \quad \varepsilon_f = \frac{\sigma_f}{E_f}, \qquad \varepsilon_m = \frac{\sigma_m}{E_m} \tag{13}$$

For ultimate tensile strength in x and y direction following formulas (31) are applied:

$$(\sigma_1) = \left[\frac{E_{11}}{1 - v_{12}v_{21}}\right](\varepsilon_1), \qquad (\sigma_2) = \left[\frac{v_{21}E_{11}}{1 - v_{12}v_{21}}\right](\varepsilon_2), \tag{14}$$

Another failure criteria for composite analysis is compressive strength. There are three compressive failure modes seen in composite structures; micro buckling, kinking and rupture (Rosen, 1965) retrieved from (Naik & Kumar, 1999). Compressive strength for a unidirectional composite ply is calculated using:

$$X_{11} = 2f\sqrt{\frac{f \cdot X_f \cdot X_m}{3(1-f)}} \tag{15}$$

Above equations provide sufficient information to be able to apply material properties for strength and stiffness analyses including input for various failure modes such as laminate tearing and compressive failure. It was discussed tensile strength perpendicular to an AM layer is reduced to 70% of the tensile strength of the virgin resin. It was calculated the residual tensile strength in y and z direction is 42 MPa and allowable shear stress in x-direction is 88.36 MPa. Table 15 provides resulting AM laminate properties based on above composite theory and calculations. In *Appendix 1.15 Composite calculations* an overview of composite calculations is provided.

Safety factors

Related to previously stated assumptions on composite theory (Mallick, 2007) in combination with unknown AM material properties, sufficient Safety Factors (SF) need to be taken into account, depending on the type of property and whether it is calculated resulting other material properties. Following safety factors are assumed, based on :

-Layer adhesion reduction:	30%	(§4.2.1.)
-Uniform fibre distribution:	~ %	
-Perfect bonding resin fibre:	~ %	
-Void free matrix	~ %	
-Stepwise AM layer effect:	10%	(§1.3.1.)
-Orientation freeform fibre (±260°):	25%	(§3.2.5.)

Resulting material properties including mechanical safety factors calculated to be as follows:

Material properties:	Ind.	Value:	SF	Values (SF):	Unit:
Density composite	ρ	1838	10%	2012.8	Kg/m^3
Youngs modulus x	E_{11}	36.89	-30%	25.82	GPa
Youngs modulus y	E_{22}	4.28	-30%	2.99	GPa
Youngs modulus z	E_{13}	4.28	-30%	2.99	GPa
Strain matrix longitudinal	ε_m	0.0219	0%	0.0219	E/σ
Strain matrix transverse	ε_m	0.0366	0%	0.0366	E/σ
Strain fibre longitudinal	ε_f	0.0241	0%	0.0241	E/σ
Strain fibre transverse	ε_f	0.1367	0%	0.1367	E/σ
Poisson's ratio x	v_{12}	0.323	0%	0.323	-

Poisson's ratio y	v_{23}	0.0375	0%	0.0375	-
Poisson's ratio z	v_{31}	0.0375	0%	0.0375	-
Shear modulus xy	G_{12}	3.4	-30%	2.38	GPa
Shear modulus yx	G_{23}	2.06	-30%	1.442	GPa
Shear modulus xz	G_{31}	2.06	-30%	1.442	GPa
Compressive strength x	X_{11}	269.32	-30%	188.52	MPa
Compressive strength y	X_{22}	102	-30%	71.4	MPa
Compressive strength z	X_{33}	102	-30%	71.4	MPa
Tensile strength x single ply	σ_{11}	883.6	-30%	618.52	MPa
Tensile strength y single ply	σ_{22}	60	-30%	42	MPa
Tensile strength z single ply	σ_{33}	60	-30%	42	MPa
Tensile strength x Bi-axial	σ	268.6	-30%	188.02	MPa
Tensile strength y Bi-directional	σ	473.6	-30%	331.52	MPa
Interlaminar shear	V_{int}	13.8	-30%	9.66	MPa
Maximum shear stress	V_x	88.36	0%	88.36	MPa

Table 15 *Final calculated composite properties*

The calculated laminate properties serve as input value's for material properties to calculate the bow section on strength and stiffness.

4.2.2. Toughness/Brittleness

In this sub-paragraph insight is provided in the toughness/brittleness of the final composite. The material is to be flexible enough to withstand vibrations and wave forces without showing macro or micro cracks but it should stay within boundaries of allowable deflection. According to CES, a virgin polymer is assumed brittle when its elongation is below 2%. Virgin PET as well as PC show elongations of in between 50% an 90%. Glass reinforcement drastically reduce elongation in between 35% and 5%. The use of continuous glass fibres, referencing to critical strain, becomes critical since the composite will fail when the glass fibres break. The elongation of E-glass direct roving is in between 2.6% and 2.8% at yield. The amount of strain is therefore to be determined at maximum deflection. Maximum deflection on global and local scale was determined to be 36 mm at a nine meter span width meaning the composite is elongated at about 0.4% at max which is far below the critical elongation at yield.

To improve the elongation of the resin in case this is the most critical components in terms of strain, a small amount of rubber-like resin can be added such as, among others, styrene-ethylene/butylene-styrene (SEBS). Elongation was improved by a factor ten. (Keskkula, 2000) These material serve as impact modifiers as previously discussed toughening the resin and improving micro and macro toughness abilities.

4.2.3. Fatigue

One of the challenges stated by (Bergsma et al., 2016) is that AM fatigue properties are still unknown. Since depreciation time for a vessel is about thirty years fatigue properties of the composite material need to be outlined. Because it is currently impossible to do this for the final AM composite an overview is provided for the raw material properties. Considering fatigue, the PET polymer itself shows interesting properties (Lechat, Bunsell, Davies, & Piant, 2006). PET is, among other materials, used as fibres in mooring ropes and tensioners. In figure 31 graphs are shown providing insight in the lifetime data for PET fibres. As can be deduced the number of cycles increases significant when the 70% to 80% of the maximum breaking load is reduced. Based on previous calculations for allowable stresses maximum % of breaking load for a bow section is below 50%. For an AM bow section the amount of cycles should be estimated in a lifetime and the height of the load. Although an inland waterway vessel sails for a longer period of time, the maximum load on relatively smooth waters will not reach high value's most of its operational time.

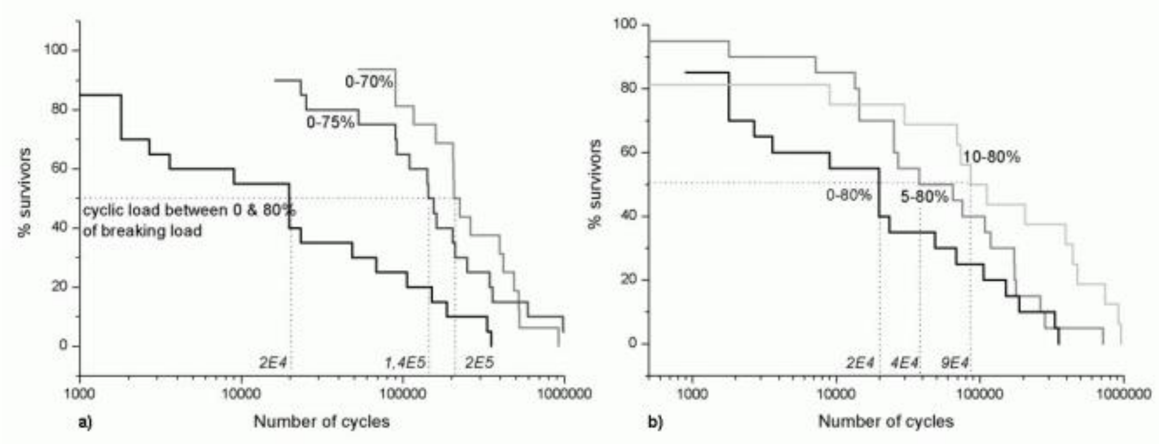


Figure 31 Lifetime data for PET fibres (Lechat et al., 2006).

To estimate whether this load-case has a significant effect on the material properties it is compared to steel and composite using fatigue ratio. A comparison is provided in figure 32. It is concluded PET and PET/PC blends show beneficial fatigue and tensile strength properties compared to thermoset composites as already used within the MCS.

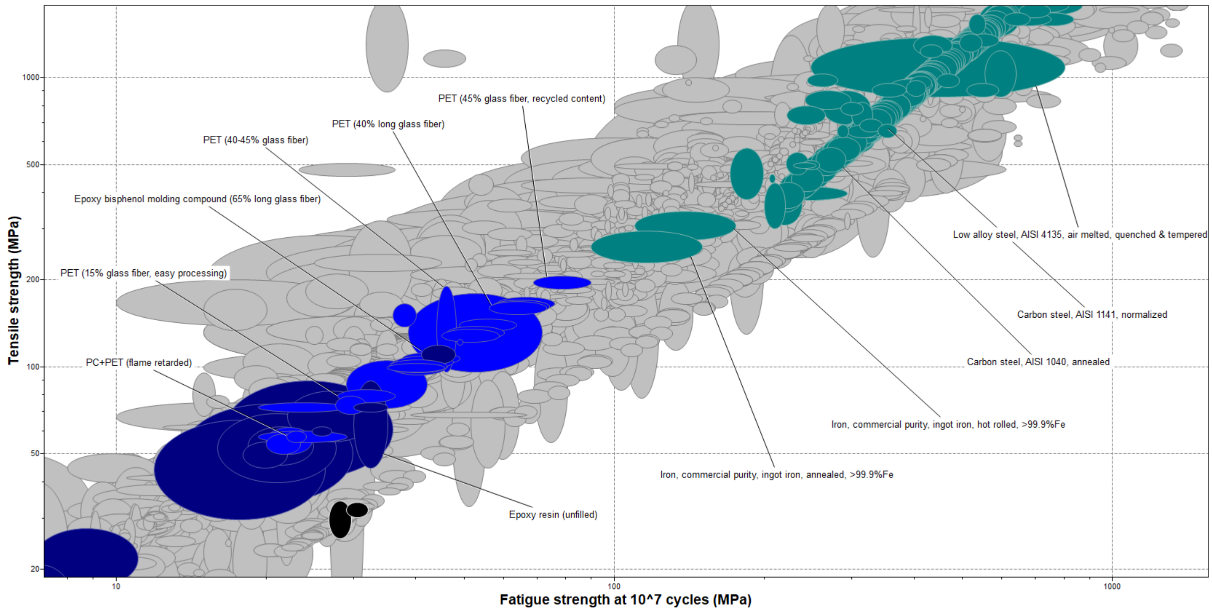


Figure 32 fatigue strength versus tensile strength of a wide range of PET (+PC) polymers (light-blue), metal alloys (green) and thermoset epoxies (blue) (CES.EduPack, 2018)

Equally important are the fatigue properties of (impregnated) direct roving. Since E-glass fibres are already widely used in composite structures the material has been a proven technology with respect to fatigue, although the impregnations of the fibre by the polymer is of great importance. The materials itself do not show disturbing fatigue properties but it will be the question what fatigue properties arise resulting from the AM process, in particular layer adhesion in between layers and interlaminar shear and tensile strength. Fatigue properties resulting from the specific material and production process maintains unknown but it is concluded the raw materials, PET and E-glass fibres show positive fatigue properties.

Creep is hard to determine and will need extensive testing. Although the use of continuous fibres within a thermoplastic material reduces the freedom for creep (Silverman, 1987), it should still be accounted for. Various studies are performed on creep for thermoplastic materials but not specifically for PET/PC using AM-production methods. An obvious method to reduce the effects of creep is by using additional trusses and supporting elements or additional fibre orientations.

4.3. Recycled content

In this paragraph the use of recycled content within the material is discussed. Apart from thermoplastic materials being suitable for re-use, and a significant percentage of the compound can be already recycled, this makes up for a good business case. A more obvious reason is related to costs, since, depending on the quality and amount, recycled content is relatively cheap. In underneath paragraph the current status of recycled content, it's usage and the expected consequences are explained.

Currently in the US, approximately 14% to 20% of the PET post-industrial and post-consumer waste is being recycled according to IHS Markit analysis. Post-Industrial waste is produced in large quantities. Worldwide, increasingly, institutions are working on methods to remove thrown away plastics from the oceans. The polymers PP, PE and PET constitute the largest share. Recycled content is not as easy available as virgin materials and there are insecurities with respect of material purity and unambiguity but the industry is becoming more improved in guaranteeing the quality and properties of larger batches of recycled content. Since weathering and second usage of PET polymers causes degradation of the chains within the material, physical and mechanical properties are lost. This process can be straightened by blending PC in it which also altering the T_g (glass transition temperature) of the blend. According to (Fraïsse, Verney, Commereuc, & Obadal, 2005) blending PC with recycled PET it is possible to create new and pure material out of 100% PET/PC waste material using specific twin-screw compounding techniques.

PET is the most favourable packaging material for beverages and therefore it is widely available all over the world. Recycling of the material has been hard since there was insufficient knowledge about how to maintain the material's properties for second usage. Currently, super-clean recycling processes are available for PET able to decontaminate post-consumer contaminants to concentration levels of virgin PET materials (Welle, 2011). Another new method of recycling PET + glass fibre material in order to return the mechanical properties and purity of the material is done via radiation treatment. A reactive additive is used to bond together the matrix and fibres improving tensile, bending and impact resistance significant. A new type over recovery plant is discussed able to produce new PET material with equal high purity monomers equivalent to new virgin PET material (Genta, Yano, Kondo, Matsubara, & Oomoto, 2003). Still, based on information from various compounding companies a 20% virgin material influx is advised in every recycling process in order to guarantee original material properties

In 2017 the company 'Ionica' reveals methods to be able to fully regenerate *'Virgin quality'* PET from post-consumer waste. Waste PET is separated to its main components to produce new PET material from. The combination of the technological improvement for PET regeneration, advantageous virgin and regenerated material prices and the growing interest for a circular economy supports a choice for recycled/regenerated PET influx. In conclusion it can be stated PET material lends itself for recycling, even when particles such as glass fibres are in it. The described techniques offer interesting methods to be able to use recycled PET material for an AM bow section without mechanical property reduction as a consequence. As can be concluded from figure 33 cost price for regenerated PET ranges in between 0.66 EUR/kg and 1.42 EUR/kg. Various wholesale markets offer recycled PET from up to 0.50,- EUR/kg, bearing in mind the expected quality.

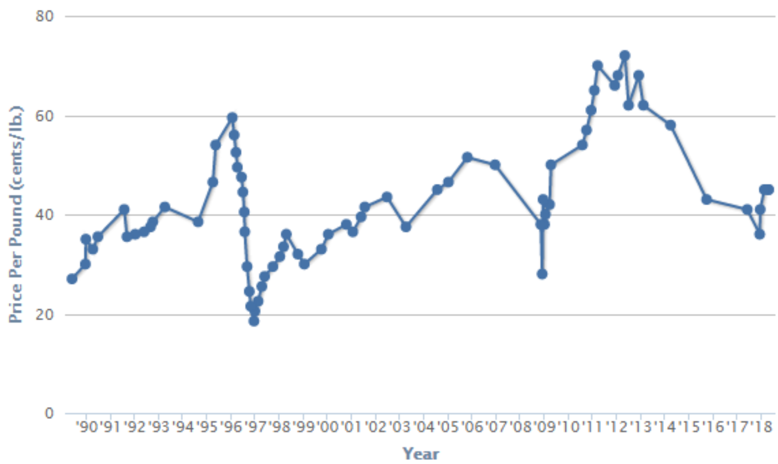


Figure 33 Regenerated PET prices (retrieved from Plasticnews)

Besides a sustainable approach of material usage, the cost factor is a substantiated argument to use recycled PET content. Since the polymer allows to be fully recovered it does not necessarily affect mechanical properties. As the polymer is available all over the world, recycled content should be collected and regenerated as close as possible to minimize transportation costs. The use of 80 wt% of recycled content for the resin factor lowers material costs approximately 10% allowing the object to maintain its quality based on regenerated resin.

4.4. Material costs

In this paragraph a summary is provided on the final material costs for an optimistic and pessimistic scenario. To be able answer sub-question 7: What will be the final weight reduction and cost price of the AM bow section and can it become Class approved?, composite material prices and prices of fire resistant panels are evaluated.

Based on recycling prices for PET a potential cost price of in between 0.60 EUR/kg and 1.20 EUR/kg for larger quantities is estimated based on several wholesale markets, (Alibaba, Plasticker), several compounding companies and CES EduPack. Virgin PET is offered from 0.90,- EUR/kg on various wholesale markets although prices are widely divergent. Polycarbonate (PC) as well as recycled content is offered for in between 1.30,- EUR/kg and higher (Alibaba, Plasticker). Various offers from compounding companies (Polyvectris) state a cost price of in between 0.90,- and 1.70,- EUR/kg for larger quantities of PET/PC blends, including short fibres. Minimum cost price for direct roving as well as short and long fibres offered on various wholesale markets is on average in between 0.70,- EUR/kg and 1.10,- EUR/kg for larger quantities. Cost prices for additives are diverse but do not seem to go for less than two to five EUR/kg for large quantities. Depending on the amount of required percentage per additive (usually in between one % and five %) the cost price for additives can reach a significant share of the total. No expenses for compounding are required since mixing multiple materials can be done at the production site. Resulting costs are presented in table 16.

Material item	EUR/kg		Weight %	Costs	Costs	Weight %	Costs	Costs
	Opti.	Pessi.	Virgin	Optimistic	Pessimistic	Recycled	Optimistic	Pessimistic
PET virgin	€ 0.90	€ 1.30	40%	€ 0.36	€ 0.52	8%	€ 0.07	€ 0.10
PET recycled content	€ 0.60	€ 1.20	0%	€ -	€ -	32%	€ 0.19	€ 0.38
PC virgin	€ 1.30	€ 1.70	5%	€ 0.07	€ 0.09	1%	€ 0.01	€ 0.02
PC recycled content	€ 0.90	€ 1.40	0%	€ -	€ -	4%	€ 0.04	€ 0.06
Direct roving E-glass	€ 1.00	€ 1.60	40%	€ 0.40	€ 0.64	40%	€ 0.40	€ 0.64
Long fibre E-glass	€ 1.10	€ 1.70	7%	€ 0.08	€ 0.12	7%	€ 0.08	€ 0.12
UV stabilizers	€ 3.00	€ 5.00	2%	€ 0.06	€ 0.10	2%	€ 0.06	€ 0.10
Flame retardants	€ 2.00	€ 4.00	2%	€ 0.04	€ 0.08	2%	€ 0.04	€ 0.08
Impact modifiers	€ 2.00	€ 4.00	2%	€ 0.04	€ 0.08	2%	€ 0.04	€ 0.08
Antimicrobials	€ 2.00	€ 3.00	1%	€ 0.02	€ 0.03	1%	€ 0.02	€ 0.03
Pigments	€ 2.00	€ 4.00	1%	€ 0.02	€ 0.04	1%	€ 0.02	€ 0.04
Total:			100%	€ 1.08	€ 1.69	100%	€ 0.97	€ 1.65

Table 16 Composite material costs for all individual components

A detailed cost price for fire resistant panels is hard to find since suppliers base their cost price on a case by case basis. Based on various conversations with heat resistant panel suppliers cost prices in between 30,- EUR/m^2 and 50,- EUR/m^2 are assumed feasible. All fire divisions make up for about 300 m^2 based on the inner space of the reference geometry accounting for in between EUR 9000,- and EUR 15000,- additional expenses on fire resistant panels. Taking into account a 23 tonnes bow section, fire resistant panels would add up in between 0.39,- and 0.65,- EUR/kg. Final material costs are in between 1.36,- EUR/kg and 2.34 EUR/kg, depending on various factors such as quantity, quality and certification. However, machinery rooms of steel vessels are also covered with insulation materials, so the final additional expenses will be less. These insulation materials are far less expensive than the Fipro or Promagurad panels to protect composite materials. Cost factors resulting from taxes, transport and installation are discussed in the final chapter of this thesis.

4.5. Conclusions

In this chapter a choice is made on the thermoplastic composite material. Based on raw material's mechanical, temperature and durability aspects a resin type, fibre type and additive recipe is selected. Using composite theory the mechanical properties of PET/PC including continuous and short fibre reinforcements are calculated serving as direct input for further strength and stiffness calculations. Final composite properties also comply with stated regulations on composite laminates. A recipe of additives is provided in order to improve composite characteristics in weathering conditions and performance. Additional conclusions are derived on material toughness and fatigue to show the basic components of the composite show no disturbing properties but additional knowledge is required resulting from the AM process. Regarding material costs and an interesting (environmentally friendly) business case the use of recycled material content is evaluated. The final compound is calculated for costs, resulting in between 0.97,- EUR/kg material for an optimistic scenario and 1.69,- EUR/kg for a pessimistic scenario. Compared to steel, solely depending on material price, the optimistic scenario is competitive, given the fact the material allows to be more expensive since less material weight is required.

5. Structural arrangement, Weight reduction and Production constraints

In this chapter sub-question 5 is treated in which the structural layout of the bow section is calculated on strength and stiffness. First, a more detailed bow section and subdivision layout is generated. Design pressures and material properties are assigned to the reference geometry and calculated for stresses and deflections which are to be within the scope on local and global level as stated by the rules.

Since components are to be installed after production is performed, this affects the location or shape of the structural arrangement. In §5.1 the type and location of relevant components and the effect on the layout is discussed. Since AM offers complexity for free, providing much more geometrical freedom, the option for optimised topology and integrating components is discussed. Manual calculation offer first insight in expected span widths and laminate thicknesses. In §5.2. these outcomes are scaled towards the geometry of the complete reference bow section and compared to a traditional steel version to gain insight in the expected weight reduction. In §5.3. software Hyperworks is used to optimise fibre direction and laminate thickness of the complete bow section in order to reduce weight even further. In §5.4. discusses the method of depositing the optimised laminate geometry using AM-ME strategies and corresponding deposition constraints. Conclusions from this chapter are presented in §5.5.

5.1. Composite bow section geometry

In this paragraph the internal layout of the composite bow section is generated to perform strength and stiffness analyses. First, critical equipment and components are discussed influencing the geometry in terms of access space, since these are to be installed after the bow section is completed. Secondly, a choice for deduction of the internal structure is provided, since AM offers complexity for free and therefore, the design space can have a very diverse layout. Based on the geometry of the internal structure, manual calculations show insight in initial span widths, laminate thicknesses and the amount of stiffeners required. Outer space and inner structure offer a proposal on the final thermoplastic bow section for further optimization.

5.1.1. Equipment and components

In this paragraph the location of the components is discussed and at what extend these influence the internal structures of the bow section. Since the aim is to produce the bow section in one piece to minimize operational and assembly costs, all components are to be installed after production has taken place. Therefore, sufficient access spaces and reinforcing structures need to be present.

A selection of relevant rules is provided in §2.3.4. applicable on the most influencing components discussed. Solely rules affecting the general layout of the bow section are listed. Detailed regulations which do not have significant effect on the overall structure are either indirectly listed in §6.1, in which assembly is discussed, or are not taken into account within this master thesis. Various components apply forces on the bow section which need to be distributed throughout the hull. All compartments need to provide access and all components are to be installed are production has taken place. The location of the listed components is maintained as equal as possible to the reference bow section. To gain insight in the location and effect on the internal structure each component is shortly addresses underneath:

-Ballast tank: *The ballast compartment is produced using AM and will be part of the hull since water does not significantly affect the composite material. Access is required towards all compartments within the ballast section in the front of the bow section. Pumps and valves will need to be installed.*
-Fuel tanks: *Although PET/PC shows good chemical resistance pre-produced tanks provide a safer and more redundant solution. Usually these tanks are produced out of steel or Polyethylene (HD)PE. Instalments of tanks requires access space and tanks itself also need to be accessible for inspection.*
-Power supply: *Diesel engines, diesel electric propulsion or full-electric propulsion requires instalment of components after hull production and requires sufficient supporting elements.*
-Bow thruster: *The bow thruster is assembled as unit and inserted from outside and inside via sufficient access spaces. Various types of bow thrusters are available.*

-Housing: *The outside of the housing structure can be inserted as pre-produced part after hull production or it can be part of the thermoplastic bow section. Since housing is to be fire-class approved, sufficient fire protection from inside and outside is required.*
-Access spaces: *All division and spaces require access via manholes or shutters. Fire or water resistant doors are to be installed after production.*
-Anchor winch, windlass: *Heavy deck components are installed from above and outside and require sufficient structural supporting elements within the bow section.*
-Other components: *Other components consist of bollards, a car crane, pipelines, electricity and shutters. Attention is required since these can extend assembly time significant related to composite installation procedures.*

In figure 34 main components are presented as well as their location and orientation. An exploded view offers insight in method of instalment and the effect of the bow section's structure.

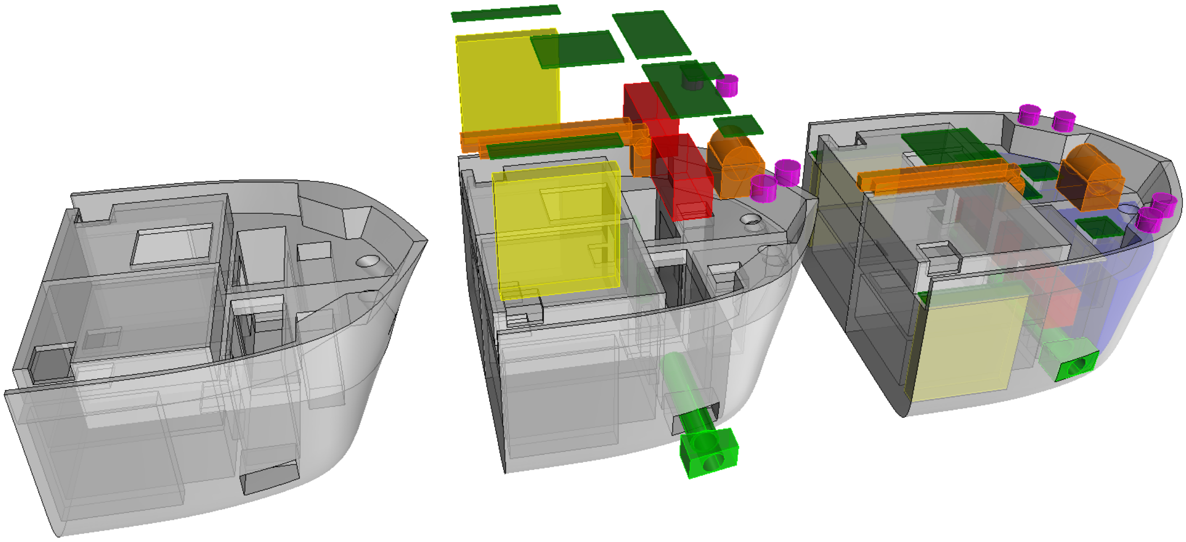


Figure 34 Location of components and required access spaces.

As presented in previous paragraph the layout of a composite AM bow section required adjustments due to the fact components need to be assembled afterwards and additional fuel tanks need to be installed. Also, various forces are to be distributed into the hull at the location of installed components. The resulting space is considered as a design space in which the internal structure is fitted. Following paragraph discusses various methods to generate the layout of the internal structure.

5.1.2. Internal structure selection

In this paragraph the internal structure of the bow section is discussed. Various methods are available to design the internal structure. since with AM, complexity comes for free. Three methods in particular are shortly discussed underneath.

-Perform Topology Optimization to generate internal design layout
-Improved layout possibilities taking into account complexity for free resulting from AM
-Internal layout of existing reference bow section

Topology optimization
Topology Optimization is a design method introduced in the eighties. Due to the increased shape freedom AM offers, the combination of topology optimization and AM is considered to be a powerful tool (Gaynor, 2015). The method is based on the definition of a design domain including applied loads

and boundary conditions. It can be formulated as a maximum strength problem using a minimum amount of material. Throughout the years topology algorithms have improved significant and a wide variety of optimization methods is developed such as Solid Isotropic Material Method (SIMP), Evolutionary Structural Optimization Method (ESO) and Bidirectional Structural Optimization Method (BESO), retrieved from (Jiang, 2017). However, a tool which takes into account anisotropic/orthotropic material behaviour is less known. A method is described in (Jiang, 2017), called the Solid Orthotropic Material Penalization (SOMP), or the Continuous Fibre Angle Optimization (CFAO) when fibre filled 2D composite surfaces are optimised for orientation.

In (Jiang & Smith, 2017) a variety of topology optimization algorithms is discussed which optimise geometry and fibre orientation in a 2D plane. The SIMP/SOMP method in combination with CFAO is able to take into account an AM object including layer wise production. Optimised material distribution and orientation can be retrieved per layer. In (Jiang & Smith, 2017) an example is provided (figure 35) in which three cases of deposition directions are examined.

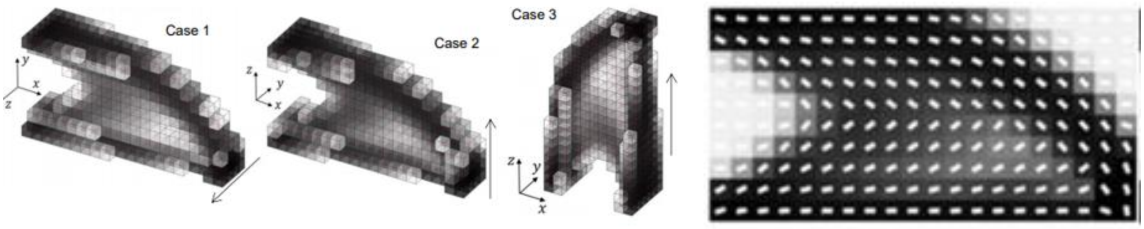


Figure 35 optimised direction including (fibre) orientation distribution (Jiang & Smith, 2017)

In (Hoglund & Smith, 2015) the SIMP method is modified for orthotropic material elements. An example is provided in which a beam, subjected to a load and two constraints on each end is optimised using SOMP and a distinction is made between horizontal and vertical AM strategy (figure 36) . In this work only 2D optimization is considered, and thus restricted to in-plane AM strategies.

Figure 36 Horizontal and vertical AM strategy including orthotropic material behaviour in a 2D plane (Hoglund & Smith, 2015)

In (Jiang, 2017), an additional overview of topology optimization methods is discussed highlighting their constraints and possibilities. The CFAO method is discussed as well as the Free Material Optimization (FMO). In this method the stiffness tensor components of the material is relaxed so material properties are varied point by point. Since these optimization results do not correspond to the AM-FDM layer-wise production abilities it is in general not possible to execute using AM techniques.

Another approach is the Discrete Material Optimization (DMO) in which the design candidates, such as fibre directions and material thicknesses are defined in advance. The approach is found to be not applicable on FDM processes due to the constantly adjusted fibre orientations. In conclusion, the combination of SIMP with CFAO is currently assumed most effective for designing FDM parts in orthotropic material, although the methods optimizes only two dimensional compliances.

Another difficulty in the combination of topology optimization and AM is the constraint for overhang. Various approaches are discussed in which overhang is taken into account in the optimization algorithm. Self-supporting algorithms for three dimensional AM-structures were implemented by (Langelaar, 2016) as well as (Gaynor, 2015). Isotropic materials were considered in these papers. In (Krishna, Mahesh, & Sateesh, 2017) an example is provided to show differences in topology optimization for which a solid beam is assumed with and without an outer non-design space shell. (figure 37) This method is required when optimising a bow section having an impenetrable outer shell.

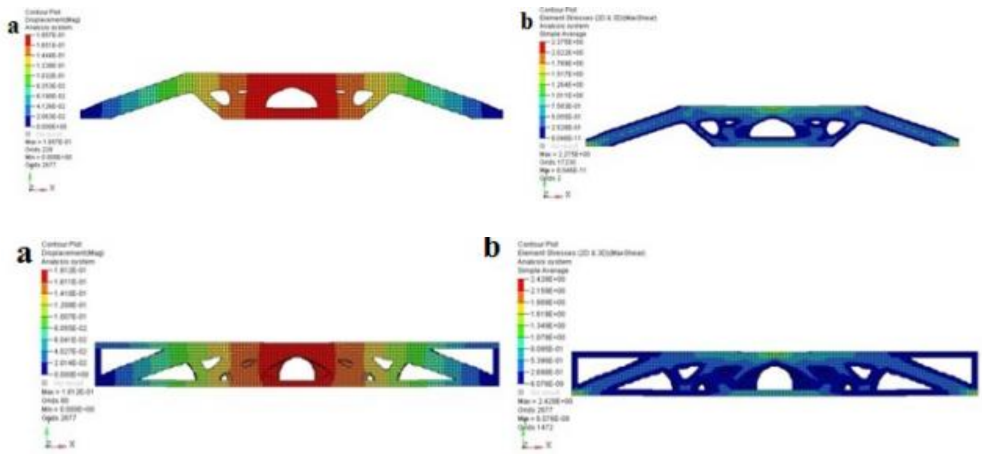


Figure 37 difference in optimization in and excluding a non-design space (Krishna et al., 2017)

Software combining three dimensional topology optimization using SIMP / SOMP methods and CFAO are limited (Jiang, 2017). For an optimal optimization tool applicable on FDM additional factors should be taken into consideration such as orthotropic material behaviour, overhang constraints, heat conduction and layer adhesion. A tool combining AM developments such as Multi-axis and Non planar AM is not commercially available. (Jiang & Smith, 2017) state *''To author's knowledge, the literature has yet to address topology and material orientation optimization for the application of FDM printed parts in 3D''.*

Based on above it is concluded optimizing for weight-stiffness compliance is not yet possible for what can be achieved with the latest AM developments, such as multi-axis deposition, orthotropic material properties and non-planar AM. Additionally, in (Pino, 2018) it is concluded topology optimization for large scale objects is currently unrealistic due to extensive computing power required. Therefore, within this master thesis, topology optimization is not used as method to generate the internal structure of the design space of the bow section.

Complexity for free

Based on (Buirma et al., 2017) AM offers various opportunities for optimizing geometries within a ship hull. Although this research is applicable on steel AM, optimization strategies discussed might also be applicable on composite structures. Examples are found in differences in plate thicknesses, merging of joints and curvatures in stiffeners. Material is deposited at the location where it is most efficient, instead of using straight extrusion profiles and steel plates. In (Buirma et al., 2017), various optimised stiffener configurations are listed, presented in figure 38 offering about 6% weight reduction.

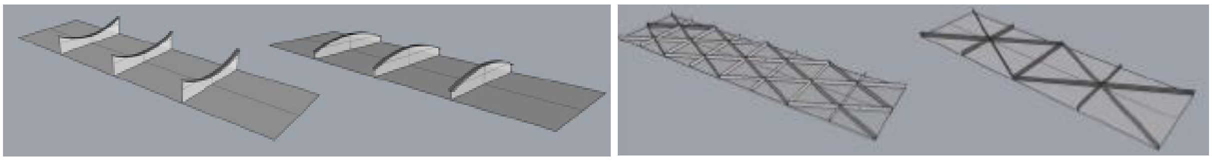


Figure 38 Options for plate stiffener configurations (Buirma et al., 2017)

Besides optimised stiffener configurations, complexity for free offers a wide variety of possible lightening hole configurations, closed compartments and more without adding extra costs or causing excessive material usage. Knees can be integrated offering an integrated solution for outer shell, decks and stiffeners. Other possible option are curved corners or additional material deposition surrounding sharp edges in order to diffuse stresses more optimal towards surrounding structures. This minimizes local stress points. Since the research in (Buirma et al., 2017) focusses on steel AM and no sufficient comparable data is available for composite structures it is concluded the analysis of more complicated structures, using complexity for free is hard to validate. In addition, a comparison with existing structures offers more usable data. Optimization possibilities resulting from shape freedom can be derived from the research in (Buirma et al., 2017), and serve as extra. Based on various calculated stiffener configurations a 5% weight reduction was expected.

Reference bow section

A reliable and informative approach to calculate the internal structure on strength and stiffness is to take the internal structure of an existing reference bow section into account. An initial layout of the internal structure is retrieved from (Lloyds.Register, 2008), and combined in the reference steel bow section. Based on the mechanical properties of the composite material, the geometry is to be adjusted. Since specific stiffness is lower, this can be done by either adding thicknesses or reducing span widths. The reference geometry is a surface geometry (girders, bulkhead, decks) and since orthotropic composite laminates are produced, the fibre direction can be optimised in order to reduce mass ever further.

Available optimization approaches for composites in Hyperworks is Free-Form Optimization (topology), which generates optimal designs considering most efficient material layout based on constraints, load cases and manufacturing process parameters. Considering AM, the following parameters; freeform in 3D planes, orthotropic material behaviour, interlamellar layer adhesion, overhang, continuous loops, heat convection and bridging are not implemented. Another method is called Topography Optimization which optimizes bead patterns for thin walled structures based on allowable bead dimensions. Free-size optimization is performed to find the optimal wall thicknesses for structures and also identifies the optimal ply shape, thickness and orientation in composite structures. This optimization strategy is used for the internal structure and outer hull of the composite bow section.

Based on above it is chosen to take the internal structure of a reference bow section into account for further analyses. The layout is based on prescribed rules from (Lloyds.Register, 2008). The anisotropic laminates are optimised using Free-Size optimization software Hyperworks. First, initial manual calculations are used to determine the ratio between span width, laminate thickness and amount of stiffeners required.

5.1.3. Span widths and laminate thicknesses based on manual calculations

This paragraph provides insight in strength and stiffness of an AM bow section using thermoplastic composite material and cross plied laminates. For a rough estimation of required plate thickness, optimal fibre orientation and corresponding stresses/deflections, an initial strength analysis is performed onto various critical elements. Deduced from the rules critical elements are chosen to be an outer plate, deck, main girder and bulkhead. Simplified thermoplastic geometries are calculated on stress and deflection. The mechanical abilities of an element produced in thermoplastic composite can be influenced by the following factors:

-Material quality	(fibre and resin selection)
-Fibre quantity	(fibre percentage)
-Fibre orientation	(number of plies and corresponding orientations)
-Laminate thickness	(nozzle diameter, local thickness)
-Geometry	(ribs, trusses, span width, closed volumes, supporting beams)
-Manufacturing quality	(cooling, heat-transfer, layer adhesion)

For this analysis, material quality, fibre quantity and manufacturing quality is kept unchanged since these are already chosen. Residual methods of varying in strength and stiffness is due to fibre orientation, laminate thickness and an adjusted geometry. For each chosen critical element a tool with underlying formula's is used to find the optimum and to make a rough comparison over traditional steel manufacturing. Although steel vessels are subjected to other design pressures, allowable deflections and material stresses, the identical calculations are performed taking into account steel properties. Final calculated weight reduction of the bow section is not based on these outcomes but serve as additional comparison as when the composite bow section would have been manufactured in steel.

Steel comparison (specific strength)

To provide an initial comparison between steel and thermoplastic multi oriented composite material a simple fixed and loaded beam is discussed as presented in figure 39.

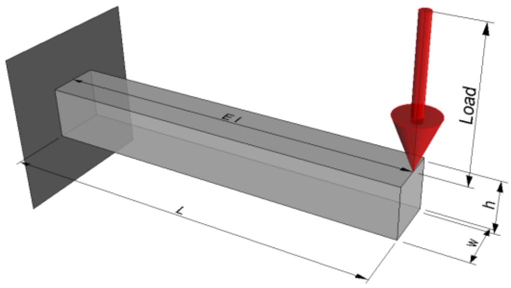


Figure 39 Simply supported beam under loading

Deflection is calculated using formula (33) (Boresi, Schmidt, & Sidebottom, 1985). Resulting stress is calculated using formula (34). Steel material properties are assigned as well as composite material properties using uni-directional fibre orientation, so without scaling factor for E-modulus and stresses applied.

$$\delta = \frac{FL^3}{3EI} \tag{16}$$

$$\sigma = \frac{My}{I} \tag{17}$$

One way to reach equal stiffness is related to geometry thickness: First, thickness in adjusted until maximum allowable stress is reached resulting in a 63% weight reduction. Secondly, thickness is adjusted to reach equal deflection of both the steel version and composite version. In this comparison, 53% possible weight reduction is calculated. Another option is related to span width. With compensated thickness and a 50% span reduction, 74% weight reduction is expected. Reducing span means additional stiffeners are required. Taking into account an extra 15% weight related to extra stiffening members per division, weight reductions of about 66% reduction is calculated. In addition, since laminates require cross-plied laminates, a scaling factor of in between 0.25 and 0.5 for E-modulus is required. Minimum required manufacturing constraints such as nozzle diameter and cross plied prohibit a laminate from becoming too thin so final weight reduction will be lower. In *Appendix 2.1. Steel comparison/specific strength* calculations for steel comparison are presented. The model is also used to validate the accuracy of software 'Hyperworks' which shows an average difference of 2.77% in the outcome of calculations due to mesh accuracy and the implementation of Poisson's ratio.

For further analysis on specific bow section components these are the sequential steps to reach highest weight reduction:
-Determine optimal fibre orientation
-Aim for minimum allowable laminate thickness (ratio adding stiffeners / increasing thickness)
-Aim for minimum required number of plies
-Keep within bounds for maximum deflection and stress by either increasing thickness of reducing span

Following analyses are applicable on divisions of the reference bow section. In order to estimate final possible weight reduction following input parameters need to be known:
-Material stiffness and strength including safety factors (E-modulus, maximum stress)
-Ply thickness (corresponding to nozzle diameter)
-Number of plies for scaling factor(unidirectional, cross-plied, multi oriented)
-Maximum allowable deflection (based on span width, stated by the rules)
-Geometry limits (depending on the type of division, usually thickness and span width)

To be able to calculate possible weight reduction manufacturing constraints need to be known. The thickness of the deposited bead resulting from nozzle diameter needs to be calculated. This is approximated using the steel reference bow section's area an calculating the allowable averaged thicknesses, listed in table 16.

Weight reference composite bow section	23000	kg
Total area reference bow section	525.69	m^2
Average number of laminates	2.5	
Extra weight for additional stiffeners	20	%
Total area cross-plied laminates	1577.5	M^2
Density composite material	1.828	Kg/m^3
Resulting allowed nozzle thickness	7.98	mm

table 16 *Nozzle thickness estimation*

Although it is possible to reduce nozzle diameter this will affect building time. Since building time is a direct and significant cost item a thicker nozzle diameter and accompanies layer height is beneficial.

Outer plate

The outer plate of the bow section is subjected to hydrostatic pressure and hydrodynamic pressure in the selected load case illustrated in figure 40 For fibre orientation with a minimum of two plies. Bi-directional fibre orientation is proposed, corresponding to a 0.5 scaling factor. To increase the strength of the outer plate the number of plies and thickness per ply can be increased or the span of supporting beams/stiffeners can be decreased. All three options result in additional weight.

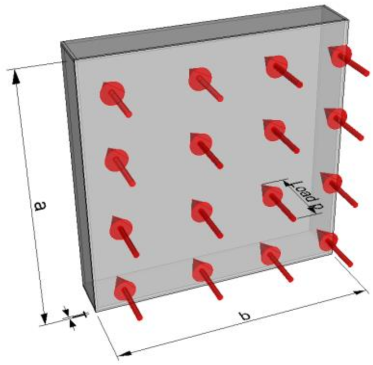


Figure 40 Outer plate element under pressure

According to flat plate theory in 'Advanced mechanics of materials' (Boresi et al., 1985) a flat, material independent plate, having length, width and applied pressure can be calculated using formula's (35) to (38) which include laminate's stress limit and the ratio between the length of the fixed edges w/l. For a square plate b/a = 1. Based on figure 42 the values correspond to the moment coefficients. The pressure applied on the plate (maximum pressure) based on design pressures from Rules is 64 N/mm^2 which is assumed uniformly distributed.

$$M = Cpb^2 \tag{18}$$

$$\sigma = \frac{6M}{t^2} \tag{19}$$

$$t = \sqrt{\frac{6M}{\sigma}} \tag{20}$$

$$\delta_{max} = C(1-\nu^2)\left(\frac{pb^4}{Eh^3}\right) \tag{21}$$

Figure 41 Ratio of bending moment M per unit width of rectangular plates with fixed edges. (Boresi et al., 1985)

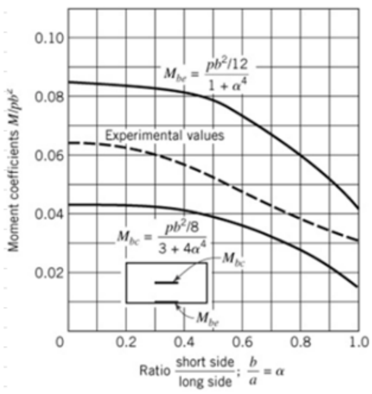


Figure 42 Accompanied graph to determine Moment coefficients based on ratio. (Boresi et al., 1985)

There is a correlation between span width and laminate thickness stated by the rules. First, span width of 1000 x 1000 mm laminate is assumed corresponding to a minimum required 21.7 mm thickness and maximum allowable 10 mm deflection. A 21.7 mm thick laminate complies with both requirements and offers 25% weight reduction compared to an identical plate in steel.

Reducing span offers increased weight reduction so in the second analysis span is reduced to 1000 x 500 mm. With a minimum required laminate thickness of 11 mm and maximum allowable deflection of 5 mm, weight is reduced by 57%. A minimum thickness of 11 mm is too thin for a cross-plied AM material deposition and corresponding nozzle diameter (production time). Also, reducing span requires additional weight for stiffening members. A span of 750 mm results in 16 mm laminate thickness offering cross-plied deposition and 36% weight reduction compared to steel. In *Appendix 2.2. Outer plate weight reduction* calculations are shown including reference Hyperworks analyses.

Deck

Weather and interior decks are subjected to much smaller pressures than outer plates, and can therefore be either thinner or supported with less stiffeners/supports. A minimum required laminate thickness and minimum number of two plies (cross plied) remains present. Deck elements are considered using equal theory as outer plates, figure 43.

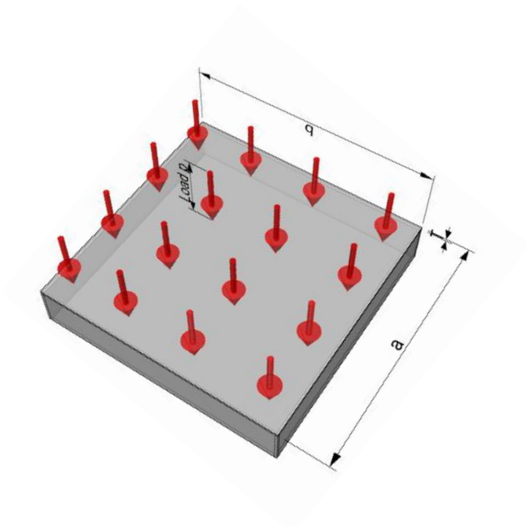


Figure 43 Deck plate element under pressure

Although decks can become thinner, a minimum laminate thickness related to manufacturing is still present. Therefore deck elements do not significantly contribute to weight reduction, depending on the final laminate thickness. A span width of 1000 x 1000 mm deck thicknesses and a 16 mm laminate thickness offers 25% weight reduction. Span needs to be increased to improve options for weight reduction. Most optimal span ratio according to the theory is already taken into account. By increasing span width it is assumed identical weight reduction as was calculated for an outer plate element is possible. In *Appendix 2.3. Deck plate weight reduction* calculations on deck plates are provided.

Main girder

A main girder is subjected to the strictest requirements regarding deflection and stress. A bottom girder close to the cargo bulkhead is chosen for initial comparison, calculated for stress and deflection. Prescribed design bending moments for a bow section are based on vertical wave bending moment and still water bending moment and equal 20075 kNm. The bending moment is divided by the number of girders in bottom and deck structure to calculate bending moment applied per girder. Fibre orientation for a girder is logically done in length direction but rules prescribe a minimum of two ply orientations. A reduction factor $\eta = 0.80$ for E-modulus is assumed since most plies will be in length direction. Figure 44 present a simplified girder section:

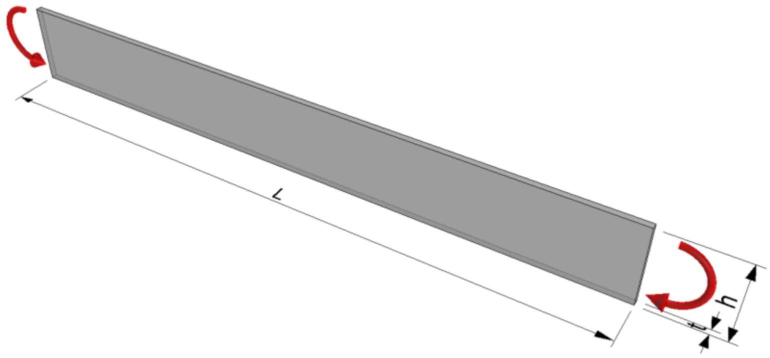


Figure 44 *Simplified girder geometry*

Since the height of the girder is restricted by the maximum height of the double bottom, thickness of the girder is the resulting variable. The girder is assumed as a straight beam with dimensions 3000 mm x 300 mm. Beam theory (Boresi et al., 1985) and formula's 39 and 40 are used to calculate stresses and deflection.

$$\delta = \frac{ML^2}{8EI} \tag{22}$$

$$\sigma = \frac{My}{I} \tag{40}$$

Since the girder is stiffness driven and E-modulus of thermoplastic composite is significantly lower, deflection will increase. Related to the maximum allowable stresses within the composite potential weight reduction of girders is 32% compared to a steel version, but deflection is the critical factor. To reach equal maximum allowed deflection, 138% additional material is required compared to steel. Residual possibilities to reduce weight are increasing number of girders, reducing span width (adding transverses), increasing girder height (max. double bottom height) or by changing girder geometry (move fibres outside). Presented in *Appendix 2.4 Main girder analysis* a girder thickness of 34 mm offers 66% weight reduction but deflection is increased by a factor seven. A reduced span of 33% offers a 33% weight reduction compared to steel having a girder thickness of 56 mm. This factor will be reduced since extra transverses and thus extra material is required.

Bulkhead
A bulkhead is subjected to a significant higher design pressure compared to other elements since the cargo hold can be filled with bulk material. For calculations on deflection and stresses the bulkhead is modelled as a plate supported by reinforcing trusses. Both trusses and plates are individually optimised for minimum weight. A simplified bulkhead configuration is presented in figure 45

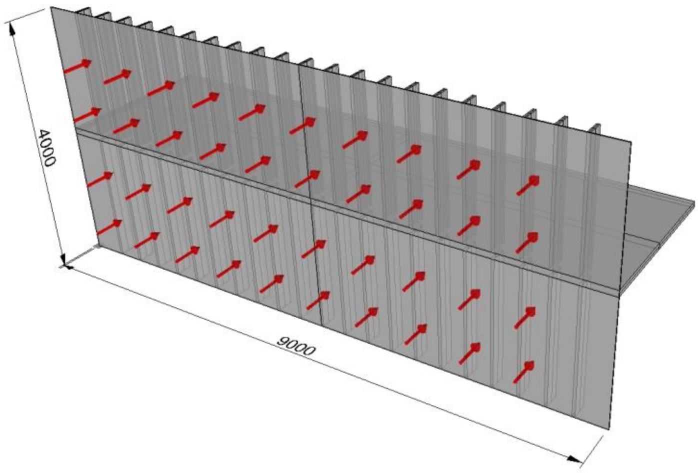


Figure 45 Simplified bulkhead geometry

Bulkhead stiffeners are assumed to be clamped beams under pressure loading. It is assumed these are clamped in the bottom, middle deck and upper deck. Deflection is calculated using formula for clamped beams under distributed load (Hibbeler, Statics, 2015). For plate calculations in the bulkhead equal theory is used as was done with outer plate calculations to find optimal span width and laminate thickness but pressures are significantly higher (41).

$$\delta = \frac{PL^4}{384EI} \tag{41}$$

A calculator tool is provided in *Appendix 2.5 Bulkhead analyses* . Obvious variables are beam height, laminate thickness and the amount of stiffening members while maintaining maximum allowable stresses and deflection. Based on the manual calculations 43% weight reduction is calculated for girder stiffeners based on material stress. Based on deflection, 108% extra material is required. Reducing span width is hard since this would require extra decks or longitudinals, depending on the orientation of stiffeners. Increasing stiffener height results in less usable space within the bow section. Reducing span offers 38% weight reduction for equal deflection compared to steel having a thickness of 21 mm. For Girder plates, based on material stress, 67% weight reduction compared to steel is calculated possible.

Above calculates weight reduction show insight in the difference between an identical steel version. Final weight reduction for the AM bow section is based on the difference in weight calculated from steel thicknesses and total area retrieved from the rules. All calculations show it is possible to stay within maximum allowable deflection and material stresses. Calculated laminate thicknesses are used to determine final AM bow section weight.

Components

Since various components exert forces onto the composite hull structure, proper stiffening of the hull is required. This applies for load-cases, moving objects, vibrational components and resulting pressures. The following options for stiffening the composite are discussed:

-Fibre orientation: *at locations in which extra stiffening is required the fibre, orientations should be redirected towards the calculated optimal orientations.*
-Laminate thickness: *locally increasing laminate strength by increasing thickness of the material/laminate or adding additional plies.*
-Use of ribs and trusses: *instead of increasing laminate thickness additional ribs and trusses can be added.*

-Casted cavities: *a cavity or void surrounding a high-strength location van be filled using thermoplastic/thermoset (glass filled) resin.*
-External/additional strengthening: *using steel or other materials as framing (including sufficient connections) a stronger construction is produced. The composite hull is to be reinforced at the locations of attachments of the metal frame.*
-Different AM material: *by locally changing the main compound and using different (stronger) material or material with a higher amount of fibres local strengthening can be established.*

Moving parts cannot touch the composite material since the PET/PC compound is more prone to abrasion and difficult to repair. Moving parts will have to be guided over metal or another polymer which is highly abrasion resistant. Vibrations within the composite caused by the propeller/bow-thruster/engine need to be known and properly accounted for. It is concluded, provided the calculated weight reductions based on material stresses, sufficient extra stiffening members can be added to support loads and moments exerted by components.

5.2. Weight estimate AM bow section

To calculate the weight of the AM bow section first, the reference geometry is adjusted based on reduced span widths calculated in previous paragraph. Additional girder stiffeners and shell stiffeners are inserted. For this weight calculation, lightening holes are removed related to a stiffness driven design and improved manufacturing abilities related to surface deposition.

All calculated components remained within their maximum allowable deflections and stresses. Compared to an identical steel version, in between 25% and 67% weight reduction for different components is calculated. Since the steel bow section is subjected to other requirements, these reductions are not used for final calculation on weight reduction for the complete AM bow section. Adding laminates and stiffeners related to reduced span width and increasing thickness and volumes, does affect building time and resulting weight of the bow section. Since production speed is usually restricted by material cooling (and secondary machine abilities) adding extra reinforcements does not necessarily increase building time and thus building costs as a result of extra machine building time. When machine speed is the limiting factor, building costs will be increased by additional machine time.

In previous paragraph initial deflection, stresses and weight is manually calculated for various simplified components. In this paragraph these outcomes are scaled towards the complete reference bow section. This is done by assuming all components within the reference bow section as either bottom plate, outer plate, deck plate, bulkhead, longitudinal, transverse, girder, stiffening or additional member with thicknesses assigned based on previous calculations. In figure 46 and table 17 the adjusted reference bow section is presented divided in components by colour. Based on results for laminate thicknesses in previous paragraph it is concluded a weight reduction of approximately 43% compared to the 40 tonnes steel reference bow section is achievable.

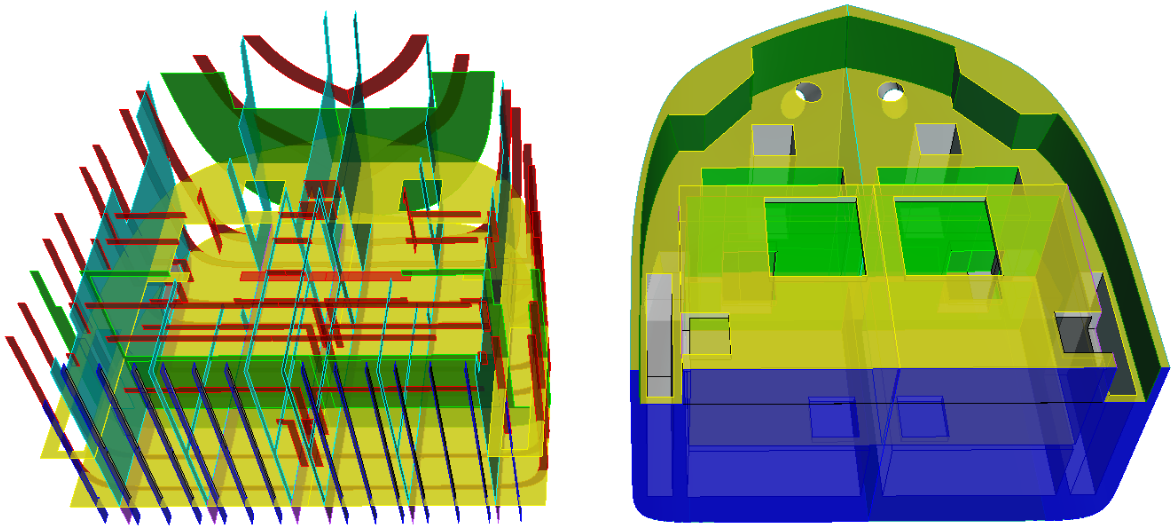


Figure 46 Composite reference layout for weight calculation

	A (m2)	t (m)	Vol	Weight	
				1.828	
All	664.95				
Bottom plates	35.4	0.016	0.57	1.04	
Bulkhead stiffeners	11.6	0.021	0.24	0.45	
Bulkhead plates	31.3	0.016	0.50	0.92	
Girders	29.3	0.056	1.64	3.00	
Outer plates	101.6	0.016	1.63	2.97	
Decks	105.9	0.016	1.69	3.10	
Stiffeners	28.2	0.008	0.23	0.41	
Longitudinals	112.7	0.016	1.80	3.30	
Transverses	62.6	0.016	1.00	1.83	
Housing	59.20	0.016	0.95	1.73	
Additional	87.15	0.008	0.70	1.27	
Total:	664.95			20.01	tonnes

Table 17 Composite reference layout for weight calculation

Concluded from above paragraph a complete bow section would weight approximately 20 tonnes, which is 50% weight reduction compared to the 40 tonnes steel version. including part of the safety factors for mechanical material properties. This excludes possible lightening holes to reduce weight even further and includes an integrated housing but excludes strengthening divisions and foundations for machinery. Safety factors for excessive material deposition add an extra 10%. Safety factors resulting from void cavities, bonding and fibre distribution remain difficult to obtain. Related to dynamic loading, safety factors from laminate deposition perspective (void cavities, full impregnation and perfect bonding) an additional 10% is added for this estimation. Above stated results in an approximated 24 tonnes bow section. In contrast to the reference steel bow section of in between 35 and 40 tonnes, a weight reduction of in between 30% and 40% seems achievable. The effect of laminate optimization and freedom of material deposition is discussed in the following paragraph.

5.3. Laminate optimization

In this paragraph the initial reference geometry including manually assigned fibre orientations is optimised for fibre direction and laminate thickness to see whether additional weight reduction is achievable. For optimization simulations, software Hyperworks is used, in which ply calculations are performed. The paragraph is subdivided in a reference laminate geometry, applied constraints and loads, applied material properties, and an optimization for fibre direction and laminate thickness.

5.3.1. Optimization objective

In this sub-paragraph the laminate geometry for optimization is discussed. For simplification of the geometry (*max 100.000 nodes for student version*) the number of divisions within the geometry is reduced. Based on initial manual calculations an initial fibre direction, number of ply's and ply thickness is assigned. To optimise divisions of the bow section the following is possible:

-Increase/decrease the number of plies within a laminate (number of plies)
-Increase the number of reinforcing trusses, stiffeners (adjust geometry)
-Increase the thickness of a single ply (laminate thickness)
-Optimise fibre orientations of the ply's within the laminate (fibre orientation)

For this optimization the reference geometry is fixed, as well as the number of plies (minimum, cross plied). Therefore, only ply thickness and fibre orientation is optimised. Discussed in §3.2.5. the combination of multi axis and non-planar AM offers an averaged 270° deposition freedom, depending on the location and specific deposited surface. Since it is at this stage impossible to see whether deposition is possible at every location all fibre orientation freedoms are unrestrained. This is compensated by a 25% safety factor after optimization is performed. To check software Hyperworks on ply calculations, *Appendix 2.6 Hyperworks ply comparison* offers a comparison between manual ply calculations and an example of ply orientation optimization.

5.3.2. Mesh, Constraints, Loads, Material

This sub-paragraph discusses how the geometry is prepared for optimization. The geometry is meshed using 70 mm mesh sizes and 2D-automesh in Hyperworks. Rear surfaces (connection midship) are constrained as a uniformly distributed connection and mid-section surfaces (symmetry) are constrained in y-direction. Calculated loads (Pressures, Moments, Forces) and weight loads of components are assigned on applicable nodes. In *Appendix 2.7 Weight component*, forces resulting from weight components are calculated. Figure 47 and 48 shows the meshed, constrained and loaded bow section in Hyperworks, including a subdivision layout having individually assigned laminate constraints.

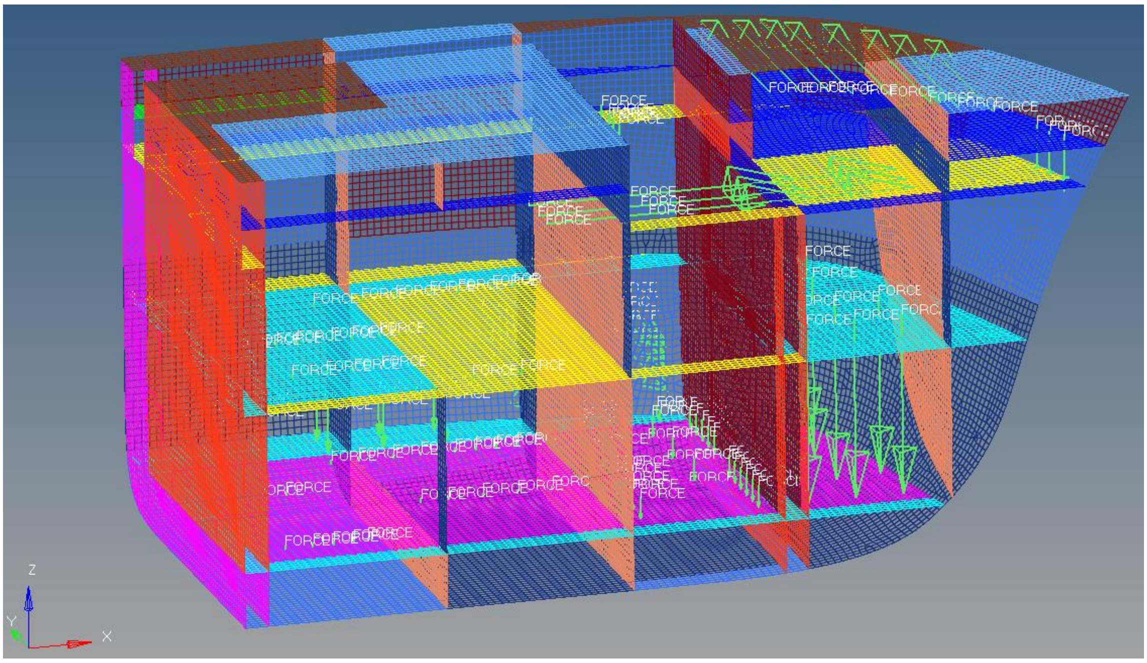


Figure 47 *Laminate mesh including weight components (green)*

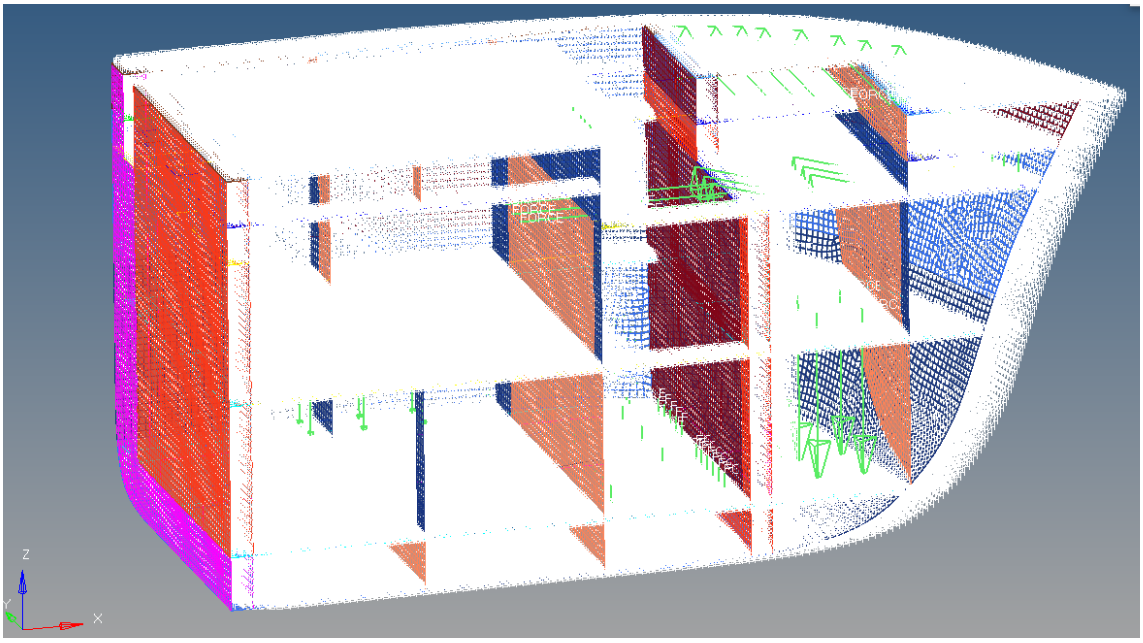
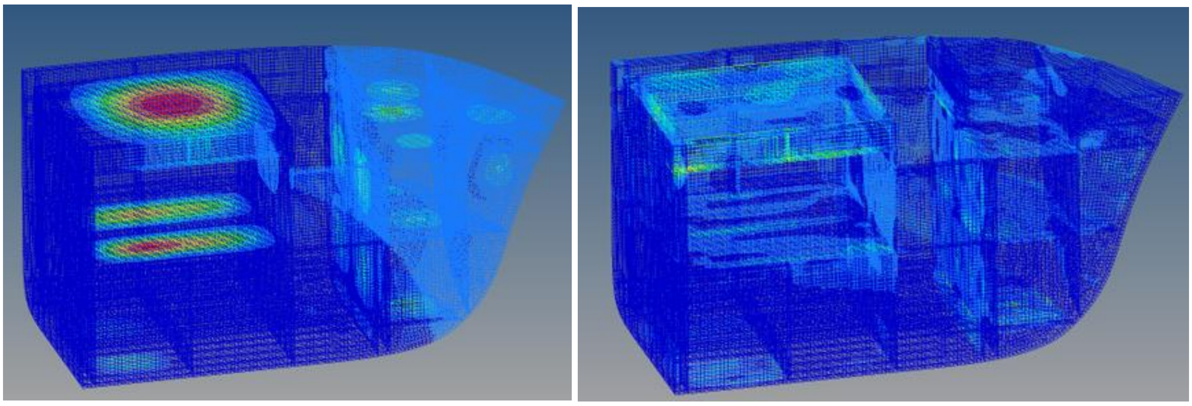


Figure 48 *Laminate mesh including constraints, pressures (white arrows) and weight components (green)*

In Hyperworks, anisotropic material properties without safety factors for laminates are assigned per ply. Safety factors for material properties are currently excluded since this paragraph estimates the potential additional weight reduction related to laminate optimization based on a simplified geometry.

5.3.3. Reference weight

Since no stiffeners are inserted in the reference geometry for optimization larger surfaces show increased laminate thickness. Results from the manual calculations, an approximated laminate thickness is assigned per component. Identical initial laminate orientations are applied as was done for components in the manual calculations. Based on these input values a 23.5 tonnes bow section is estimated, as presented in figure 49.

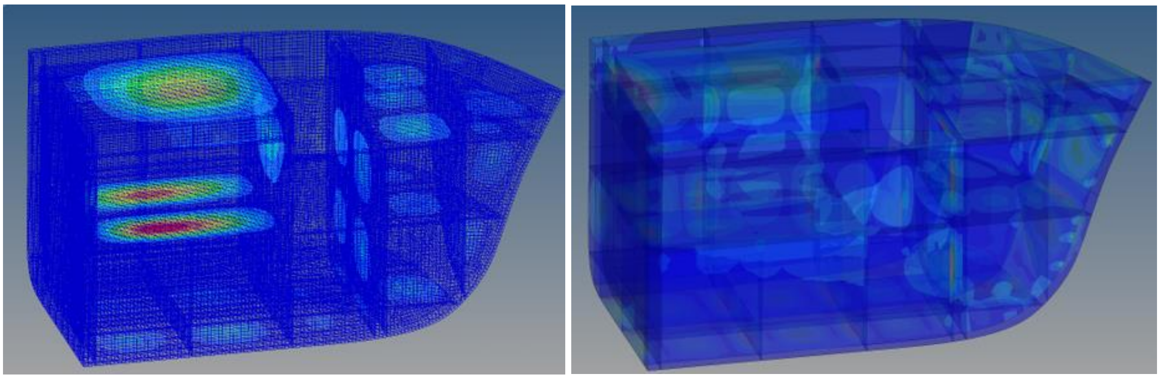


Deflection (mm)	Stress (MPa)	Resulting weight (tonnes)
22	63	23.5

Figure 49 result for deflection and stress after assigned calculated properties

5.3.4. Laminate optimization

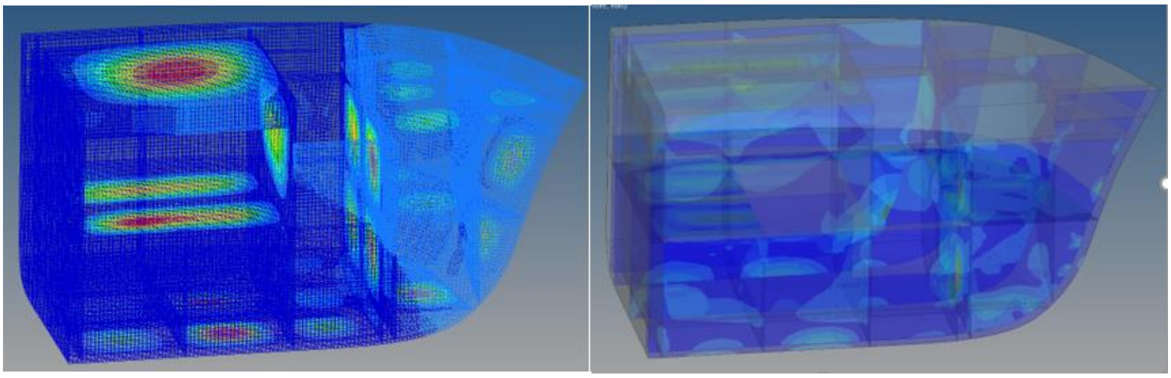
The goal is to optimize for minimum weight while complying with minimum requirements. The objective function stated to minimize weight and the optimization variables are fibre direction and ply thickness. For the optimization analysis, constraints on maximum deflection (36 mm) and maximum material stress (60 MPa) are assigned related to additional safety factors for stresses. The optimization consists out of two optimization steps, first for thickness, secondly for orientation. It is assumed all ply directions have a 360 degree freedom. Minimum ply thickness of 8 mm and a maximum ply thickness of 60 mm are assigned based on increased weight and AM possibilities resulting in a 11 tonnes bow section and 56 tonnes bow section respectively. The objective function is to minimize mass (ply thickness). Optimization for ply thickness results in the following, presented in figure 50:



Deflection (mm)	Stress (MPa)	Resulting weight (tonnes)
35	63	22.2

Figure 50 Results for deflection, stress and weight after thickness optimization

The second step of the optimization includes fibre orientation as presented in figure 51. A bow section weighing 20.7 tonnes is generated.



Deflection (mm)	Stress (MPa)	Resulting weight (tonnes)
34	67	20.7

Figure 51 Result for deflection and stress after thickness + orientation optimization

From above simulations it is concluded when fibre orientations and laminate thicknesses are optimised, based on the geometry, applied loads and pressures and assigned initial laminate properties, up to 12% additional weight reduction is possible, compared to manually assigned ply properties. Taking into account the deposition restrictions resulting from multi axis AM, being 25%, final ply optimization results in an additional 9% weight reduction, depending on the initially chosen laminate thicknesses and orientations. It should be noted the amount of extra weight reduction achievable in this instance is based on initially assigned laminate thicknesses and orientations. These are based on statically loaded, simplified components including scaling factors for mechanical properties based on the number of plies. A different initial estimation results in a different outcome after optimization.

5.4. Bow section production strategy

In this paragraph is it presented how AM is used to deposit the material in the optimised configuration, subdivided in machine configuration, AM strategy and post-processing/finishing. In previous optimizations a 360° freedom of laminate orientations was used for optimization. Multi-axis AM deposition does not allow 360° deposition freedom due to nozzle tool geometry, overhang, pre-deposited parts and the requirement of cross-plies laminates. To show at what level the complete bow section can be produced using AM this paragraph treats deposition freedom for production assuming the previously expected 270° orientation freedom. First, insight is provided in the machine configuration. Secondly, material deposition sequence is discussed followed by an option for post-processing the outer surface.

5.4.1. Machine configuration

To reduce cost and building time and to show the possibilities of material deposition freedom, an AM machine configuration is shortly discussed. Maximum deposit rate is an interaction of nozzle output, amount of nozzles, cooling rate and machine speed. Output per nozzle can go up to 1000 kg/hr but this is not achievable with a 8 mm nozzle diameter based on maximum machine speed. A larger number of nozzles increases machine costs and complicatedness but reduces building time significant. Due to the wide variety of stiffeners, surfaces and divisions it is assumed layer length can be extended to find an optimal in terms of material cooling. Finally, an approximated maximum machine speed based on robotic maximum speed is the limit for machine speed. In *Appendix 3.2 Calculator machine variables* a calculator using approximated values is provided to find the optimum of these variables.

Based on above discussed variables an optimum was found using eight extruding systems having nozzle diameters of eight mm diameter. Increasing the amount of extruding nozzle's reduces building time by an equal factor while machine investments do not rise equally and thus machine rate increases less fast. An additional number of extruding nozzles is beneficial in terms of cost price. Figure 53 shows the configuration of the machine able to produce the bow section in one piece.

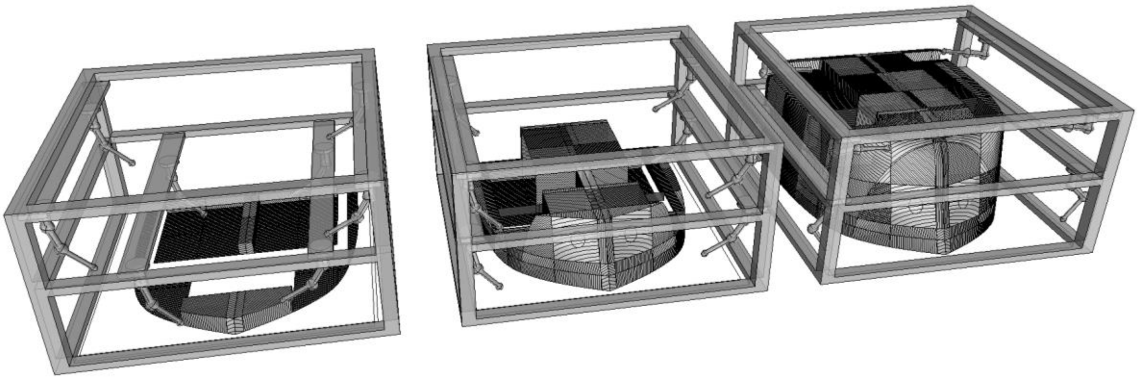


Figure 53 Option for machine configuration

The 10 x 10 x 5 m AM machine offers two layers of deposition tools, divided in its symmetry plane. The choice for robots compared to a gantry system is due to the fact robots can move independent from each other while mounted on the same track. This way, tracks can move slowly from the centre of the machine outwards while robots are designed to move fast. To be able to reach the five meter height of the object, two layer of deposition tools are required.

5.4.2. Material deposition strategy

AM offers a wide variety of possible deposition strategies and based on available software, designers input and vessel usage the geometry will differ on a case by case basis. Figure 54 presents the base theory of cross-plied material deposition. Based on the tool geometry and the sequence of build-up the freedom of deposition can be increased.

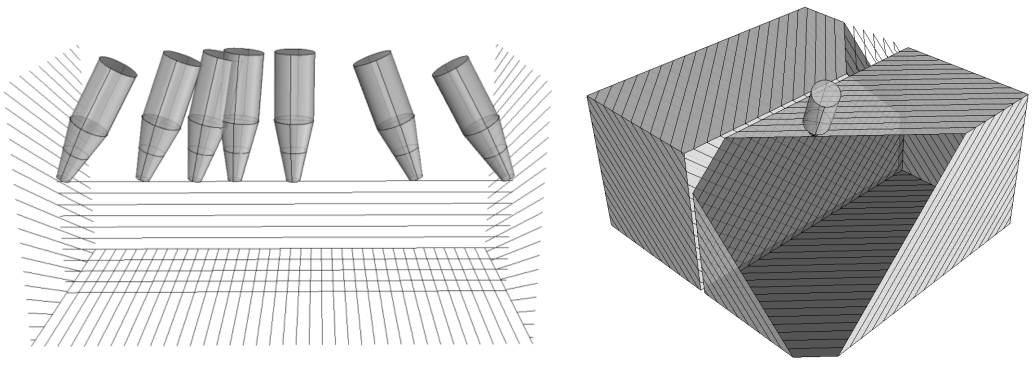


Figure 54 Previous example showing non-planar AM and a cross-plied laminates

By starting in one corner of the building platform and working a way up to the diagonal opposite corner of the building area the freedom of open surfaces and building directions is maximised. This is illustrated in figure 55 in which a simplified bow section is build up in different elements in which each element is deposited using a different orientation of approach. After sections and decks are deposited, an outer shell offering 100% orientation freedom is deposited.

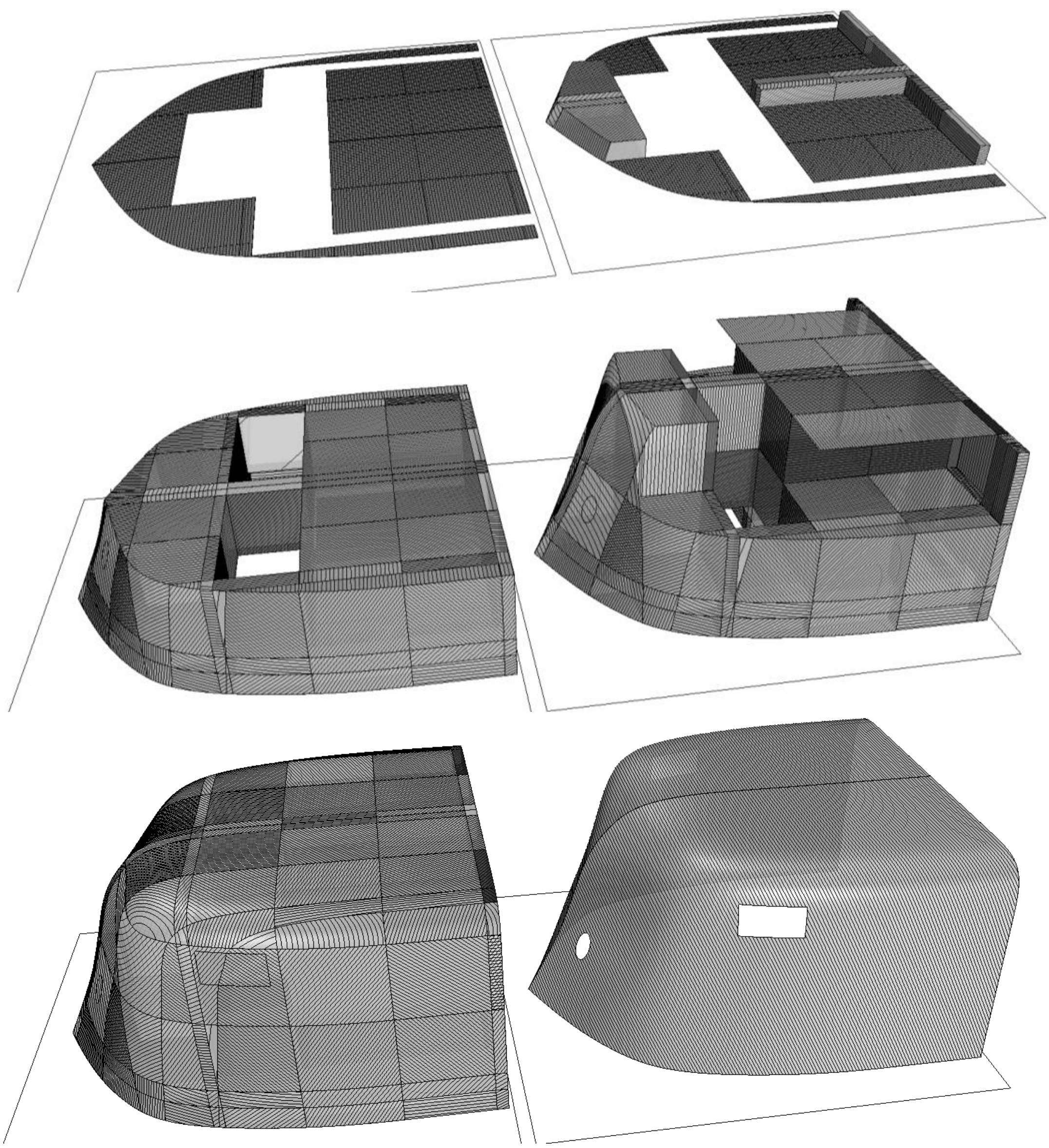


Figure 55 Visualised build-up strategy of a general bow section

Above example is presented without details, access spaces and stiffeners. Figure 56 presents a part of a double bottom having access openings and lightening holes in between every building block. A more complete sequence of build strategy for the complete bow section is provided in <u>*Appendix 3.3. Deposition strategy sequence.*</u>

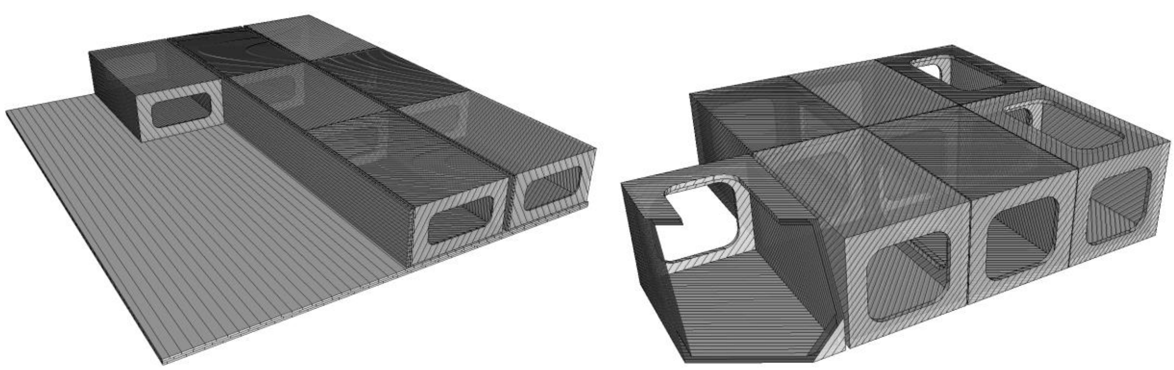


Figure 56 Double bottom with in between girders and access holes

The strategy of building blocks being deposited in diagonal direction from one corner of the machine to the opposite diagonal corner offers the widest possible deposition freedom and allows cross-plied laminates in the entire section.

5.4.3. Installation of systems

After sectional production is done, systems can be installed from above since access spaces are provided. The difficulty is to offer connected access spaces throughout the entire bow section, since it is impossible to add structural members after production is done. Large insertion holes in upper deck and in between decks offer space for installation. Openings in structural members usually require extra stiffening members in surrounding area's to comply with removed material, especially in upper deck, presented in figure 57.

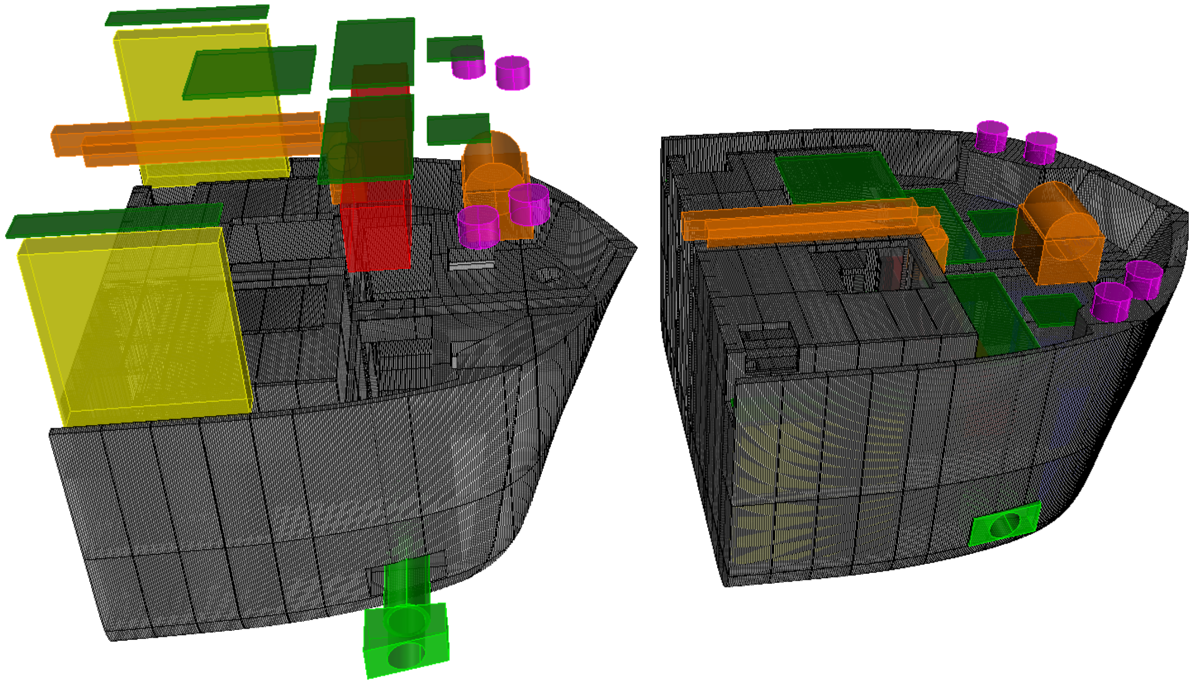


Figure 57 Bow section including installation of components

5.4.4. Post-processing

The outer shell needs to be smooth to reduce frictional resistance. Also, a step-wise outer surface will not be accepted due to the fact microbes and algae's will have an attractive surface to settle on. Post-processing via CNC routing will increase building time and breaks down continuous fibres in the outer shell. Other methods of post-processing as previously discussed, based on manual post-processing tend to be too labour intensive or costly.

For post-processing two options seem to provide a realistic opportunity. One possibility is to deposit a final layer of unreinforced PET/PC polymer to smoothen out the underlaying layers. A roller-bead as presented in *§3.1.5.* to improve layer adhesion can be helpful to depress and smoothen out the layer. Deposition of a final unreinforced layer, serving as protection and reducing the effect of osmosis also offers the possibility to manually sand the outer shell. Equal technology is used in AFP technology in which UD-tapes are pulled tightly over a pre-produced surfaces. The option to pull wide strips of PET UD tape over the outer shell is also available, but more expensive in terms of material and extra required machinery. The second possibility comprises manual labour and manual extrusion making use of rotational extrusion disks or rollers. The disk or rollers spread the molten polymer, exiting from the centre of the tool. Such a device could also be mounted on an AM machine, although, since the finish is not to be extremely accurate, and assembly time takes longer than the bow section's build-up, adding this finishing layer manually might prove to be more cost efficient during outfitting.

The final outer layer is to be provided with additional additives such as an increased amount of impact resistance, anti-microbials and UV stabilizers. Adding these only in the outer layers saves costs and unnecessary chemicals throughout the overall structure of the bow section. It is concluded post-processing remains an issue and further research is required in order to estimate the best solution.

5.5. Extrapolation to entire vessel

In this paragraph the extrapolation to the entire vessel is shortly addressed. The master thesis focussed on the bow section of the inland waterway vessel related to its dimensions and technical obstacles. The stern offers identical challenges. The midship, consisting of in between 5 to 8 midship sections should also be produced competitively.

Main difference between midship sections and a bow section are the exerted bending forces and moments. Also, midship sections will be cheaper related to a higher block coefficient (Kerlen) and the fact that multiple identical sections are produced, compared to a one-off. The extrapolation towards a complete vessel is divided in the following critical aspects: deflection and costs. Discussed in previous chapter, the thermoplastic material offers high strength but reduced stiffness. Deflection is the critical factor. Based on (Lloyds.Register, 2017a), the midship section allows an absolute maximum deflection of 250 mm, based on a 50 m midship and L/200 main girder requirement. In the CompocaNord report, in which a comparable inland waterway vessel is calculated, a maximum length deflection of 100 mm is taken into account.

Methods to reduce deflection are increased laminate thickness, increased girder height, or by replacing material (fibres) more to the outer regions. Since thermoplastic composite is less stiff compared to steel, and midship sections are more prone to deflection, potential weight reduction is reduced unless a penalty for amount of cargo (increased girder height) is approved.

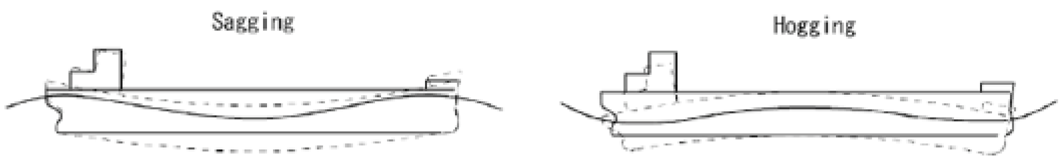


Figure Hogging and sagging (Buirma et al., 2017)

The other main difference is related to cost price. As was previously stated, the bow section will be produced for a higher cost price per kg steel (in between 2.5 and 3.0 EUR/kg) compared to a midship section since a bow section requires more steel in more complicated configurations (double curved, manual assembly), and thus requires more extensive labour.

5.6. Conclusions

In previous paragraph it is concluded the components required within the bow thruster demand adjustments in the subdivisions mainly regarding access spaces. Since tanks, power supply and bow thruster are large components to be assembled after production is done, access space through the main deck is required. For comparison on weight, the internal subdivision layout of a reference steel vessel is used, adjusted to fit external components in. First estimations using manual calculations on various simplified structural components show thicknesses and span widths, extrapolated to a complete bow section offering weight reductions of about 46% are expected.

To stay within the bounds of deflection as stated by the rules, additional divisions and stiffeners are required. Using optimization software Hyperworks, optimal fibre directions and laminate thicknesses are generated in order to decrease weight even further. A simplified reference geometry having increased safety factors for material properties is used to minimize the number of nodes. This geometry is calculated on initial weight, weight after laminate thickness optimization and weight after fibre orientation optimization resulting in about 9% additional weight reduction, depending on the initial chosen laminate properties. Weight reduction is -10% decreased resulting from excessive material and -10% related to unknown safety factors related to mechanical material properties. Based on a 46% initial weight reduction, -10% excessive material, -10% safety factors, +9% laminate optimization, a 36% weight reduction is expected resulting in about . Based on the cumulated weight reduction it is assumed the bow section weighs approximately 24 tonnes. Extrapolated to the entire vessel, subjected to higher hogging and sagging moments, less weight reduction is achievable.

6. Installation of Components

To answer sub-question 6, how are the required components installed, the installation of equipment should be examined. The connection of components to the hull needs to be rigid enough and long-lasting, but installation and maintenance is required with a certain ease and acceptancy. In this chapter relevant machinery and equipment is elaborated on instalment and maintenance providing insight in the potential, costs and time for installation of components within the bow section after AM bow section construction is completed. In §6.1 , installation and assembly is discussed which is important since methods of installation are very different from traditional outfitting. In §6.2 most influencing individual components are highlighted. Production costs of solely the bow section geometry shows positive results but installation of components brings consequences on costs and time evaluated in §6.3. In §6.4., this chapter is concluded.

6.1. Installation/assembly

In this paragraph installation and assembly of components is discussed. For easy assembly of standard components, the connecting surface has to be smooth, without a layer-wise surface finish. In addition, components are to be connected using credible solution in terms of time and costs. Adjacent surfaces need to be watertight. Most promising methods are discussed below:

-CNC cutting: *CNC cutting the entire surface of the bow section will be time-consuming and costly but options in which only certain details are being post-processed are considered. Area's that are fitted within the bow section, however, will not be reached by the CNC machine after material deposition. Interrupting the AM process for trimming is not an option due to material cooling and flying chips during machining.*
-Manual post-processing: *Manual cutting tools for thermoplastic post-processing are available but surfaces inside a composite bow section which will require post-processing are relatively large and the melting properties of thermoplastic material makes post-processing difficult. Thereby, excluding workforce from sectional construction but having to deploy extra manhours for surface-finishing is devious. For limited use or finishing manual post-processing could be an option.*
-Elastomer AM: *Using printable elastomers, flexible material can be deposited. Dual-extrusion enables this possibility although, large scale dual-extrusion is still in an early phase of development.*

-Gaskets/elastomer sheets: *To avoid CNC-cutting and manual post-processing, elastomer gaskets can be used to fit in between components. Gaskets smoothen the layer-wise surface, provide water tightness, provide a certain flexibility (if required), and can be easily replaced.*
-Heat treatment: *Using hot rollers, heat-guns and other heat treatment equipment the thermoplastic material can be re-melted and shaped into the required surface. Unless it is done automatically, it is not a reliable strategy since unknown and uncontrollable tensions are inserted into the material. For finishing of smaller areas, this method could provide a solution.*
-Inserts: *During the printing process it is possible to add an insert on which new material is added. (Klahn, Leutenecker, & Meboldt, 2014) Insert can also be inserted after production. Pre-drilled holes will be required for the use of inserts. Accurate positioned holes can be drilled using a mould. Examples of inserts are threaded rods, screws, nuts and expandable screws.*
-Bolted connections: *For bolted connections accurate pre-drilling is required to remove material and avoid layer cleavage. Since all surfaces are multi-oriented cleaving is less of an issue. Adequate stress diffusion is required in the form of rings, gaskets and stress dividers.*
-Laser assisted hybrid welding: *In case steel components need to be fitted in a laser welding machine can provide an opportunity to connect the attaching surface (Roesner et al., 2011). Laser assisted Metal Plastic is a process in which metal and polymer sheets are welded together.*
-Manual plastic extrusion: *This is done via plastic extrusion guns which pre-heat's the surface and then applies a bead of molten polymer along the edges of connecting components. The guns are used in the polymer-welding industry to for example produce (HD)PE fuel tanks and provide a reliable polymer adhesion.*
-Thermoplastic resin infill: *Apart from manual plastic extrusion a certain amount of (glass-filled) polymer resin can be heated and casted ,greased or pumped into a cavity or void. Equipment to properly heat and apply the resin is required.*
-Epoxy resin infill: *Holes can be filled with (glass-filled) epoxy or polyester resin specially engineered for a proper connection with PET/PC compounds. Adding short glass fibres makes up for a strong and rigid resin which can be used to close holes, fill cavities, and connect components or inserts. ISO-NPG (isoftaal-npg) resins provide sufficient bonding on PET/PC using proper preventative measures such as adhesive resin and sanding. (Poly-service)*
-Glue: *The use of glue is a potential and promising use of connecting elements which is used more often within the MCS (Roland, Manzon, Kujala, Brede, & Weitzenböck, 2004).*

To keep water from entering the bow section adjacent surfaces need to be impermeable for water. In (Lloyds.Register, 2017a), methods are prescribed to properly close composite hulls using laminates and filler. For thermoplastic materials, other methods provide solutions, discussed underneath.

-Manual plastic extrusion: *deposit a layer of molten polymer around the edges. (does not apply for a steel-to-resin connection)*
-Gaskets/elastomer sheets: *expanding or dilating gaskets in between components.*
-Thermoset/thermoplastic resin infill: *casting or spraying resin into the cavities/voids.*
-Lubricants: *apply appropriate waterproof lubricants in between all components.*

Above stated methods are the most realistic methods of connecting components based on conversations with various 3D-printing companies. The best method will be different case by case, based on the type of component, the cost factor and whether the fitting is through-hull, moving, inside the bow section or load-bearing. Per component one should find the fastest and cheapest method of connection in order to reduce cost, risks and assembly time.

Repair of broken components should be taken into consideration to prevent the need for docking or excessive repair time and repair provisions. Components need to able to be disassembled, repaired and re-installed without damaging the hull. This in contrast to steel, which can be repaired using welding of plates. The use of gaskets, bolted connections, lubricants and removeable fillers shows highest interest, since these can be disconnected without damaging or interfering the hull structure, and without the need for equivalent materials to close the gaps after repair is done. On the other side, inseparable components are less prone to leakage and vibrations.

Concluded from this paragraph there are various options for installation and assembly present but the most logical methods depend on case by case basis. In *Appendix 4.1 assembly selection* a selection for each method based on time, costs, required equipment and more is presented. An importance rate + value is assigned to each factor. The use of bolted connections, inserts, resin infill, gaskets and glue show highest interest.

6.2. Components in detail

In this paragraph most influencing components are discussed on installation and instalment of critical components based on weight, function and dimensions. This paragraph provides some options for instalment, however, more in depth knowledge and experience is required to be able to demonstrate feasible solutions.

Bow Thruster

Although various propulsion systems are present for a Class III inland waterway vessel three variations, the 'stuurooster', 'kanalen' and 'tunnel' bow thruster are most common. Main components of the bow thruster are a tunnel/shaft, hull foundation, power supply, transmission gear, inlet and outlet and the propeller. Figure (57) shows various types of bow thruster units.

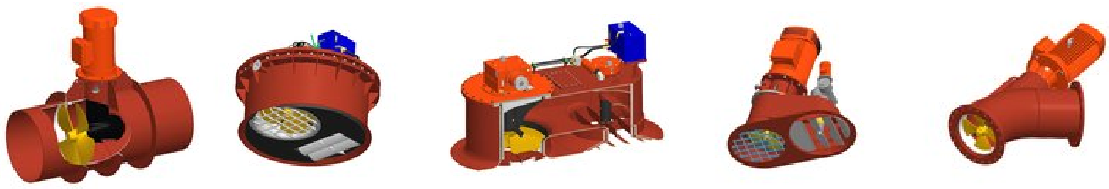


Figure 57 different types of unit-bow thrusters

Bow thrusters, regardless of the type, are usually sold as pre-assembled units. In most cases these are welded or bolted into a recess in the hull and underlying structures. To connect the bow thruster to the composite structure first, holes for bolts are pre-drilled using a frame. The bow section is inserted in a smoothened recess from outside with in between gaskets and lubricants. Bolts are inserted from outside. A frame on the inside including rivets and stress dividers is placed in the back. Lock tight bolts are tightened with in between gaskets and lubricants. In figures 58 and 59 below, two examples of an AM fitting of the bow thruster is presented:

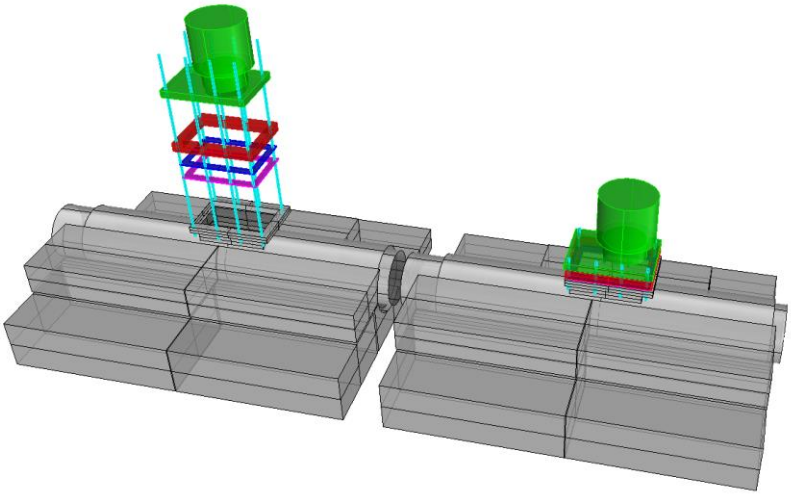


Figure 58 Option to assemble bow thruster unit in bow thruster tube

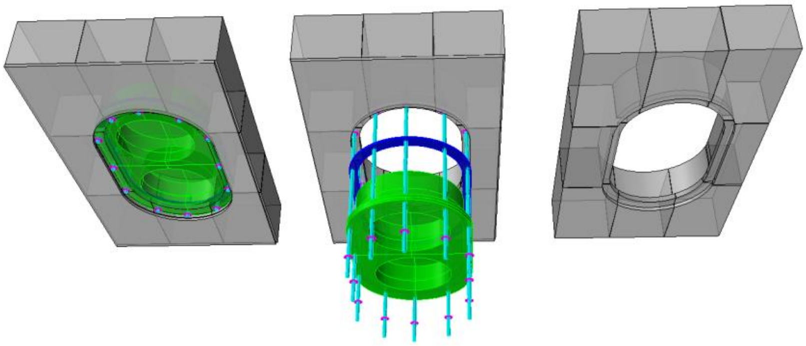


Figure 59 examples of the connection of the thruster unit in ship hull

Since the bow section is through hull additional interest is to be provided on water tightness and forces exerted by the bow section. Vibrations and resulting forces require extra stiffening members and supporting structures surrounding the bow thruster unit.

Power Supply

Power supply for powering the bow thruster within inland waterway vessels is achieved by diesel propulsion, diesel electric propulsion or fully electric propulsion. Besides the main diesel engine, an emergency generator is present. Main diesel engines charging battery packs within the bow section is also an option. Recent cases show completely electric inland shipping vessels.

A diesel engine for powering systems and propulsion within the bow section is placed in the machinery room combined with its auxiliary equipment often behind the watertight bulkhead. For the Class III inland waterway vessel a 210 kW diesel engine or diesel generator is assumed. The engine(s)/generator(s) require a proper machinery room, insulated, fire proof, equipped with ventilation shafts ,water protection and sufficient access and storage spaces. A rigid base is required to deal with vibrations and impacts forces. For assembly, engine foundations holes are equipped with engine mounts. The engine frame is inserted over the engine foundations for alignment. Surrounding spaces are filled with reinforced thermoset/plastic resin. The engine is inserted through the holes in main and in between deck and fixed to its frame. In figure 60 a proposal for engine foundation construction and assembly is provided.

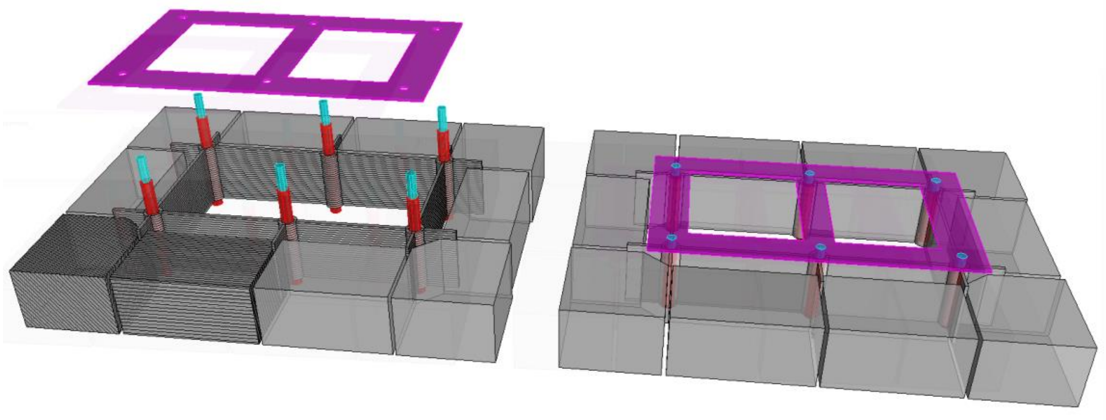


Figure 60 *Proposal for an AM engine foundation*

Since power supply is heavy and brings vibrations, additional interest onto surrounding structures is required. The amount of stiffeners and ribs around the engine foundation can be increased according to the need. The holes in which foundation poles (red) are placed are filled using reinforced resin. The inside of the poles allows for threaded rods or inserts (blue), on which the engine steel frame can be connected. The engine itself is connected onto the rigid steel-frame (purple).

Energy Storage

Although PET/PC blends provide acceptable resistance against chemicals and acids, the materials are not ideal for holding fuel. (HD)PE is a widely used material for tanks if no steel welded tanks within the bow sections hull and floor are used. In theory (HD)PE is a thermoplastic material which also lends for AM deposition and thus tanks can be produced within the bow section using a dual nozzle/deposition tool at the specific location. High-safety measures, double tank walls and the use of a different materials debounce the claim for also 3D-printing the (HD)PE tanks. Besides, simply shaped (cubic) tanks produced out of (HD)PE plating are difficult to produce cost effectively using AM.

Whether energy storage is done by external tanks for diesel fuels or by using battery packs, both require strong surrounding hull structures and supportive floors. In every case, tanks will need to provide access space to enter the tanks for inspection and remove them for repair or replacement. First, supportive elements are connected within the recess space and pre-produced tanks are lowered. Additional connectors and pipes are installed. Using wedged and dividers, the tanks are aligned and fixed into place. Inserts are mounted surrounding the tanks, provided with lubricated gaskets. Pre-produced shutters are installed and bolts are tightened. In figure 61 an option are presented in which an (HD)PE /steel tank is fitted in.

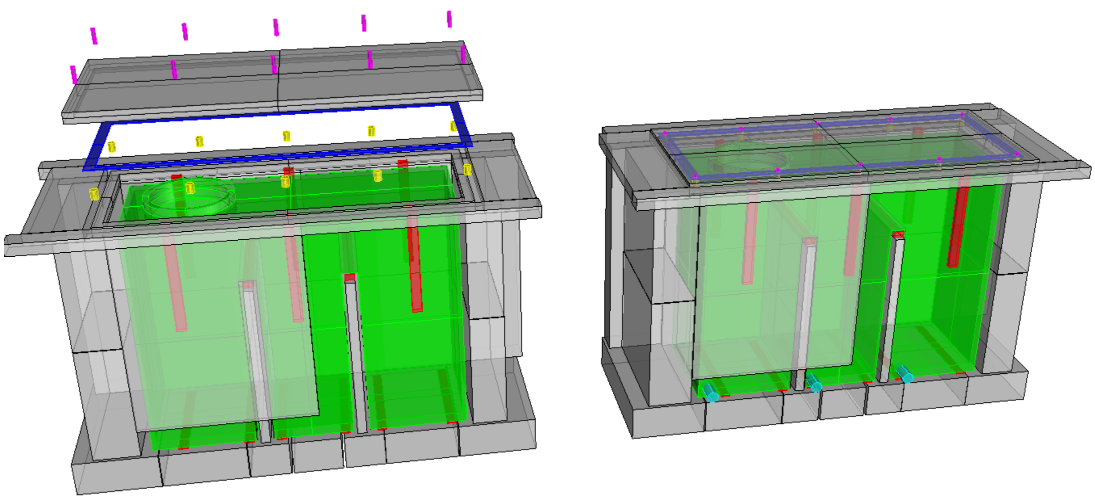


Figure 61 *Proposed option for embedding a tank*

Since AM deposition is not accurate enough for a direct fit, extra space is provided and filled from underneath and aside using supporting hard flexible materials and wedges. The opening in the hull is to be closed using shutters, to provide access to the tanks. Using gaskets and inserts the shutters are impermeably closed but allow removing without damaging the composite material. Shutters will not be produced using AM but will be constructed out of steel or HDPE plating.

Manholes/Access

According to the rules all spaces and areas need to be accessible for inspection and control. This implies manholes, lightening holes and other openings are to be embedded in the composite hull. Lightening holes only provide an opening to make the vessel lighter and do not need further post-processing. Manholes and access points often need to be able to provide watertight closure, doors or shutters. Sufficient strengthening or the edges of the openings are required to assemble window frames or hinges. Using pre-drilled holes, inserts, proper lubrication, gaskets and a standard frame the window for a watertight door is established. First, holes are pre-drilled using a frame. In between the frame and composite lubricated gaskets are placed. The watertight door is placed into its frame. A frame and lubricated gasket is placed at the backside, tightened with lubricated bolts. Figure 62 proposes an examples such an opening.

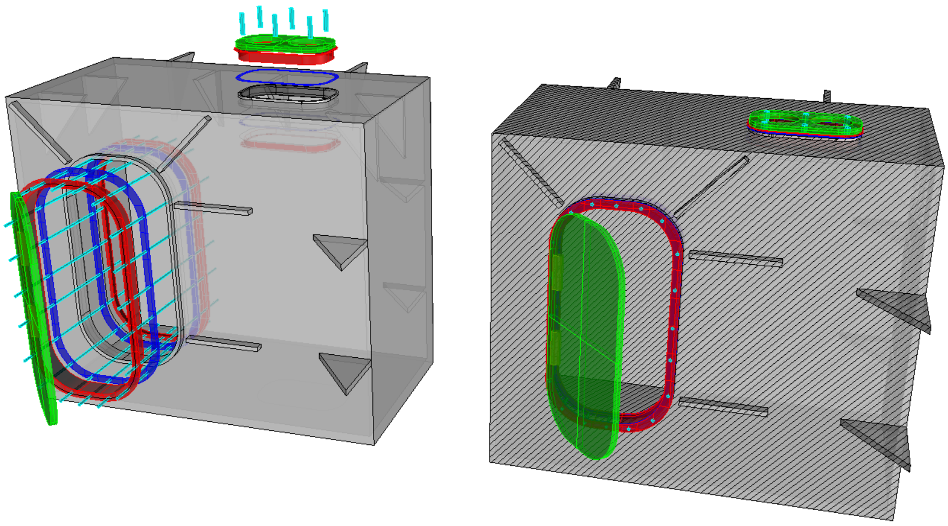


Figure 62 *Examples of a watertight door, a fitting and a series of lightening holes inside the double bottom.*

Using equal dimensions of most openings, doors and shutters, the same pre-fabricated steel frames and moulds for drilling inserts can be used in all cases. This reduces assembly time and manufacturing costs. Manholes and lightening holes in the structure do not need additional post-processing or assembly.

Housing

Housing within a bow section is the living space for assistance crew. Two distinctly different methods for housing are discussed, one which is produced using AM and inseparably connected with the bow section, and one which is produced separately (steel) and assembled afterwards. By already manufacturing housing within the bow section the structure could help in stiffening the vessel. Although strength and stiffness calculations are performed taking into consideration a merged housing, pre-produced housing should also be discussed. First, housing foundations are installed using bolted connection or reinforced thermoset resin. Vibration dampeners are installed and the housing is lowered through the bow section opening. It is tightened using pre-produced steel connectors. Finally, additional components, pipes and connectors are installed, presented in figure 63.

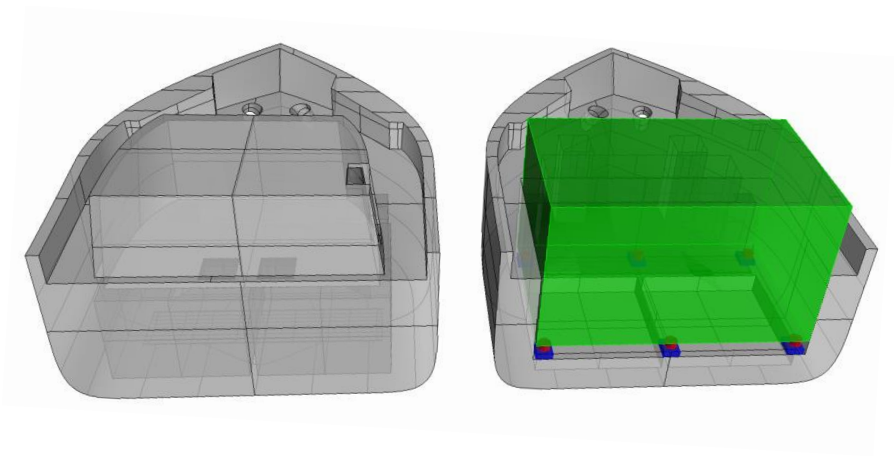


Figure 63 Bow section with and without integrated housing

Important aspects with respect to housing are fittings and pipes which need to penetrate through divisions while maintaining fire safety, water tightness and access space. Housing is to be protected from vibrations and sound. Another point of attention is the protection from outside fire. Although housing is covered by fire resistant panels from the inside, a fire from outside makes the outer surface to melt. This underlines the choice for external (steel) housing.

Anchoring system

The anchoring system of a Class III inland waterway vessel consists of anchors and accompanied chain, anchors holes, anchor winch and chain locker which is usually embedded behind the collision bulkhead. The anchor chain will damage the soft composite structure when it is released so anchor holes need to be executed in steel. The foundation of the anchor needs to be able to withstand high pulling forces when the ship is anchoring and should also transfer pulling forces into structural elements inside the hull. Based on a solution retrieved from the CompocaNord report the anchor winch is bolted through deck to connect it's foundation onto structural deck stiffening material. On top of the deck the forces are distributed using additional plates and underneath the stiffening material stress dividers are assembled. Figure 64 shows the anchor winch construction developed for the CompocaNord. A similar solution is proposed for the AM Bow section since above is already calculated and approved. First, holes are pre drilled using a frame. Lubricated gaskets are placed in between frame and composite after which the anchoring system is placed. Bolts/steel rods are inserted including stress dividers/rivets and bolts are tightened.

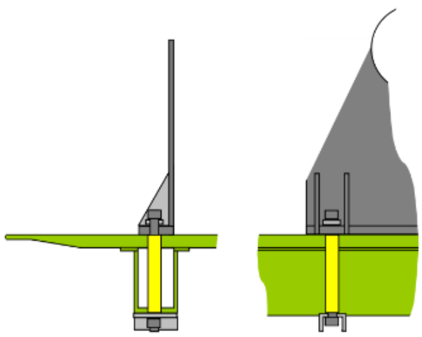


Figure 64 Anchor winch connection retrieved from CompocaNord report

Bollards

Based on the type and height of boulders present the breaking strength of mooring lines determines the structural requirements of the surrounding AM material. Figure 65 shows the anchor winch construction developed for the CompocaNord.

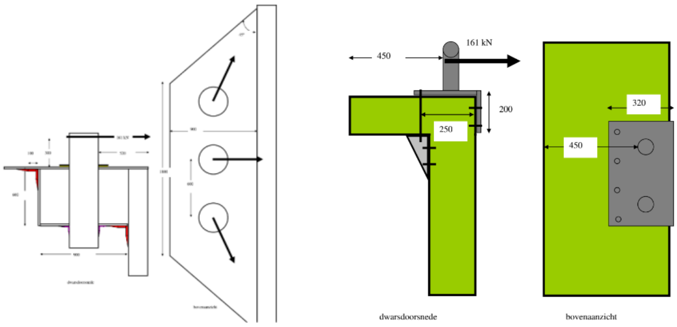


Figure 65 Boulder solution retrieved from CompocaNord report.

Equal solutions are usable in an AM Bow section. Through hull fittings need to be coated and properly lubricated at all sides to prevent water from entering the construction.

Car crane

The car crane on the foreside deck delivers a momentum onto the structural elements. For the CompocaNord this was solved by using a wider base plate and extra bolted connections through the foredeck and through underneath structural elements. In an alternative option draft boxes are used to connect the beam with the foundation of the car crane, as provided in figures 66

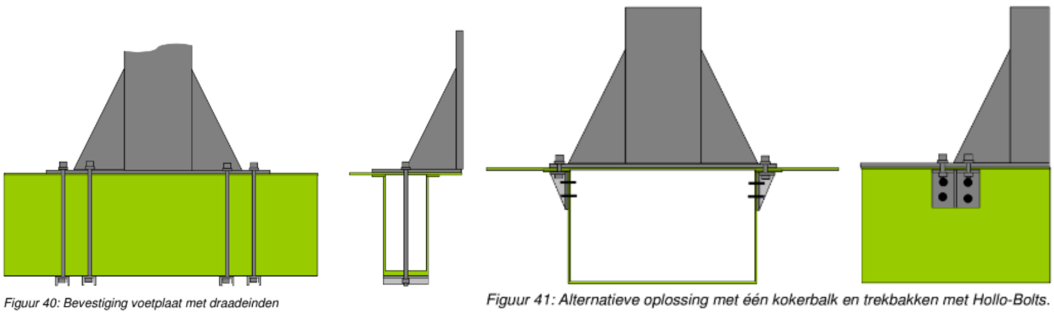


Figure 66 Car crane solutions retrieved from CompocaNord report.

Sufficient supporting members are required surrounding the car crane. With the use of through-deck fittings, sufficient stress dividers, gaskets and lubricants are required. The surface on which the wide baseplate is located is either to be smoothed out using post-processing, either thick gaskets are added in between.

Pipes

Throughout the entire bow section pipes for fuel, water and ballast are present. Pipes need to penetrate through walls, decks and openings and thus need proper sealing and support. Supporting members, cylindrical recess spaces and openings are to be implemented so that a minimum of assembly time and processing time is needed. In figure 67 a proposal on pipe assembly is provided.

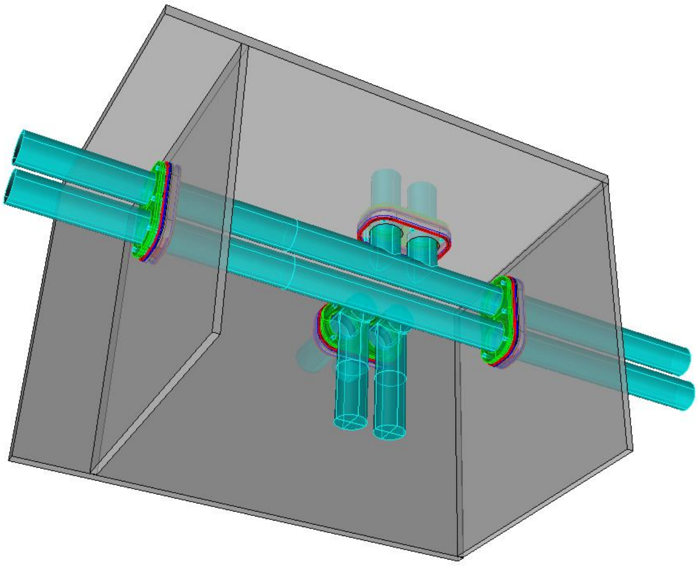


Figure 67 proposed method to assemble pipes/lines

Through hull fittings need proper insulation and assembly. Most fittings have to be able to resist high pressures and fire resistance. Adding components which are not through-hull, but only function to hold components, can be easily welded onto class divisions using manual extrusion guns. Sufficient contact surface allows for the use of glue. Higher demanding objects need to be connected using pre-drilled holes, inserts and bolted connections.

Concluded from this paragraph for most components bolted connections using gaskets and frames seems the most promising in terms of assembly, leakage and durability. Also, bolted components are relatively easy to disassemble, in order to perform repair or maintenance work. Smaller components which are less load demanding can be connected using manual plastic extrusion and glue. The use of reinforced plastic components instead of steel components offers additional connection freedom.

6.3. Installation time and costs

This paragraph provides insight in required installation time and costs, since these need to be taken into account to be able to calculate final building time and costs of a bow section and complete vessel. In contrast to welding steel parts onto steel structures, assembly of components onto a composite structure sometimes requires extra actions. It is important to find practical and efficient methods to install all components. As previously discussed, Design For Manufacturing (DFM) and Design For Assembly (DFA) are important and in combination with AM a powerful tool since AM offers complexity for free. Concluded from previous paragraph the following methods of assembly seem to provide solutions for larger components:

-Equally dimensioned pre-produced (AM) openings, edges and holes.
-Standardized gaskets in between all components.
-Standardized frames for pre-drilling, stress dissemination and assembly.
-Specialized tools for manual extrusion and post-processing.

Holes and openings should be produced as equal as possible (a minimum amount of variations) so that gaskets and frames can be equal in dimensions in order to standardize components. Frames for pre-drilling are the same frames which are assembled at that specific location to minimize actions. Based on a very rough comparison on steel welding an estimation is done on additional assembly time, costs and required equipment. This is done by splitting assembly in tasks, given an estimated percentage based on manufacturing, preparation, instalment, alignment, assembly and finishing. Assigned percentages on time and costs are provided in *Appendix 3.4 Assembly time/costs*. It is concluded assembly time of bolted components compared to welded components usually takes in between 17% longer and costs (including extra time) rise with an approximated 20%. This is a rough estimation based on conversation with 3D-printing companies and additional research is required in order to come to more substantial conclusions. Since fire-resistant panels also need to be installed, additional installation cost arise. Based on conversations with fire resistant panel suppliers an approximated 8000,- was expected.

Since it is assumed outfitting takes longer and will be more expensive, the ratio between the total costs and manufacturing time of the bow section, compared to solely outfitting costs and time is provided. Outfitting takes in between 10% and 15% of the total hull construction. For a bow section, having additional components, this ratio is higher so 20% is assumed. Based on 80% manhours and 20% direct costs, additional time and direct cots result in 3.5% more expensive total building costs of the bow section. Since hull/sectional construction is 40% of the total building costs, extra expenses related to outfitting will be 14%.

6.4. Conclusions

In previous chapter various options for assembly of components are discussed but exact determination of time and effort is hard to estimate and largely based on assumptions. First, DFA needs to be incorporated in the engineering process as much as possible. This requires more extensive engineering and development time, but offers shorter or cheaper installation time. Examples of DFA are recess/excess spaces for alignment of components, pre-deposited holes for inserts, supports for pipelines, signs and supports ventilation shafts and pipes. Secondly, a wide variety of manual assembly tools is available. Each individual component demands it's optimal assembly methods and accompanied tools. Bolted connections and gaskets seems a method often required. Smaller parts can be assembled using manual polymer extrusion. Standardization of additional equipment's, such as dimensions of frames and doors, and openings for pipelines can help in reducing installation time. Example calculations show an increase in installation time and costs. Additional assembly time is expected to be 17% and additional costs are expected to be 20% which is 1.42% of the complete vessel manufacturing costs.

7. Weight reduction, Costs, Classification.

This chapter answers the final sub-question 7, which also helps answering the main question. In §1.0 it was concluded highest impact in the MCS would be cost efficiency and delivery time of the entire vessel. In order to keep ahead of shipyard competitiveness, object performance cannot be decreased unless a significant advantage in cost price is noticeable. In §1.1 it was stated main challenge of the combination of AM within the MSC is to gain class approval. In this chapter, AM competitiveness over traditional manufacturing is addressed in terms of cost, weight reduction and the possibility to become class-approved. §7.1 discusses theoretical weight reduction, and the effects on building costs and operational costs. Within AM, weight reduction directly influences machine time, material usage and production costs. In §7.2., bow section cost price is discussed based on direct manufacturing costs and additional expenses resulting from installation of components. In §7.3. insight is provided in the ability to become class-approved.

7.1. Weight reduction

In this paragraph the final weight of the bow section is discussed following from adjusted geometry, composite material and the optimization analyses. Final weight is estimated using manual reference calculations substantiated with software checks. Additional weight is reduced using composite optimization to find optimal laminate thicknesses and fibre directions. Due to less uniform fibre distribution, less predictable layer adhesion and various other losses occurring during the AM process, sufficient safety factors are to be taken into account.

Based on specific strength of the final composite material a theoretical weight reduction of 80% can be achieved. Additional material or structural adjustments are required to comply with specific stiffness. Throughout the research following uncertainties have raised, which are compensated by safety factors as discussed throughout the corresponding paragraphs:

Layer adhesion reduction:	30%
Uniform fibre distribution:	10%
Perfect bonding	,,
Void cavities	,,
Stepwise layer effect	10%
Orientation freedom fibre deposition	25%

Layer adhesion, is compensated within material properties. The stepwise layer effect is causing approximately 10% extra material and deposition freedom is compensated after the optimization analysis. Other factors are hard to determine and are set at 10%.

Based on manual calculations applicable on various structural components and extrapolated to an entire bow section a calculated weight reduction of 36% seems achievable. Variables such as span width, fibre orientations, geometry (length, width, height) and laminate thickness are varied to find an optimal combination to reduce weight but comply with rules stated on stresses and deflection. A comparable bow section geometry is optimised for fibre direction and laminate thickness using software Hyperworks. First, results from manual calculations are applied in the comparable geometry in Hyperworks. Secondly, the bow section is first optimised for thickness followed by an optimization for fibre orientation offering an extra 9% weight reduction, depending on the initially chosen thicknesses and orientations. Averaged weight reduction compared to a steel variant based on manual calculations resulted in a 45% to 55% weight reduction but since steel vessels are subjected to other requirements, it remains unknown whether this expectation counts.

Based on above it is assumed a final weight reduction of 36% is achievable offering a bow section weighing 24 tonnes instead of the 35 to 40 tonnes for a traditional steel bow section. Extrapolated towards the entire inland waterway vessel, not taking into consideration different load cases and structural layout, a theoretical weight reduction of 36% for the entire vessel seems achievable. Since midship sections are subjected to higher bending loads, less weight reduction is achievable for an entire vessel.

A 50% hull weight reduction offers a 7% to 10% extra cargo capacity or the vessel allows to sail at higher speeds, or consumes less fuel. According to (Buirma et al., 2017), resulting profit margins are significantly improved. Additional weight reduction could be achieved using topology optimization or by fully using the benefits resulting from AM being complexity for free, but additional research and developments are needed.

7.2. Production cost

In this paragraph a complete overview is provided on production costs for individual sections, installation and finishing, including necessary additional equipment's and installation time. Related to combustible AM material, fire resistant panels are to be installed, extra assembly time resulting from components is assumed and possibly more expensive assembly equipment's are required. First, solely AM production cost are discussed and calculated using multiple methods. Based on previous research AM production costs is calculated to be (18):

	Material (€/ton)	Mass (tonnes)	Machinehour costs (€)	Machinehours (hr.)	Total:
Optimistic	0.97,-	22	600,-	70	63.340,-
Pessimistic	1.69,-	25	1000,-	100	100.042,-

Table 18 More detailed production costs

An optimistic and pessimistic scenario is provided but the range is much smaller. Raw material cost is calculated to be in between 0.97 EUR/kg and 1.69 EUR/kg depending on the amount of recycled content, quality, required additives and type of supplier. The mass of the object is calculated to be in between 22 and 25 tonnes, deposited within an approximated 3 to 5 days, using a total machine rate of in between 600 and 1000 EUR/hr.

Two methods of calculating machine rate and production costs are provided in *Appendix 4.1. Machine Rate Calculation* and *Appendix 4.2. Production costs* in which investment costs, maintenance hours, the number of shifts and more are taken into account. In *Appendix 4.2 Deposit rate estimation*, a theoretical estimated deposit rate is provided taking into account number of nozzles, layer height, machine speed and surface area.

Since fire resistant panels are a necessity, cost factors resulting from purchase and installation need to be taken into account. It was calculated in between 9000,- EUR and 15.000,- EUR was issued on fire resistant panels. Installation is expected to be an additional 8.000,- EUR based on conversations with suppliers. Since traditional steel vessels are equipped with insulation materials as well, though less expensive, and less extended, final additional expenses on panels is less than calculated.

On top of sectional production costs and fire resistant panels, outfitting, assembly and additional required materials are added. Based on the approximation tool in which outfitting is split, entire extra outfitting equals 3.5% of the bow sectional costs resulting in about 14.000,- EUR. Since installation and outfitting is not well specified related to lack of proven data, this estimation requires further research. Compared to the building costs of a traditional bow section in between 15% and -22% cost reduction is calculated possible negligible except for most optimistic scenario's in which low material prices, machine rates, deposit rates and bow section weight is assumed. All of these factors need to be present since a small variation in cost factors has a considerable effect on total costs. Machine rate is calculated based on a performance rate so it is important the machine is able to produce other (funded) parts during the rest of its operational availability.

7.3. Classification

Discussed in §1.1. producing a Class-approved vessel is one of the main challenges related to new production processes and materials. In chapter 2 most important regulations are listed summarized in table 19:

Requirements		§	Item	Goal
Functional	1	§2.1.	Purpose requirements	Satisfied
	2	§2.1.	Class-notation composite vessels	TBD
Market driven	3	§2.2.	Weight	Satisfied
	4	§2.2.	Building time < traditional	TBD
	5	§2.2.	Durability	TBD
	6	§2.2.	Production costs	TBD
Structural	7	§2.3.1.	Material structure	Satisfied
	8	§2.3.2.	Design pressures	Prescribed
	9	§2.3.3.	Maximum allowable global and local deflection	Satisfied
	10	§2.3.4.	Regulations on components	TBD
Material	11	§2.4.1.	Minimum required raw material properties	Satisfied
	12	§2.4.2.	Mechanical laminate properties	Satisfied
	13	§2.4.3.	Maximum allowable material stresses	Satisfied
	14	§2.4.4.	Class-approved material handling	TBD
Fire resistance	15	§2.5.1.	Non-combustible or equivalent material	Satisfied
	16	§2.5.2.	Class A-30 fire resistance	Prescribed

Table 19 More detailed production costs

1: The AM Bow section will be able to perform identical operational actions and deployments
2: Whether the AM bow section will be Class-approved is dependent on a wide variety of factors resulting from various Class requirements.
3: A significant weight reduction of 36% is calculated offering a 24 tonnes bow section. This is important for an interesting business case and to reduce building and material costs.
4: Building time of solely the bow section is reduced but assembly time takes longer. This can be compensated but additional research is required on the assembly part.
5: Selected AM materials show positive mechanical, temperature and durability properties.
6: Final cost price is hard to calculate and therefore a positive and negative scenario is provided. Specified material price, machine rate and building time and bow section weight largely determine the final production costs. Relatively small variations can have significant effect on final costs.
7: Multi-axis AM offers the possibility to deposit cross-plied laminates, as prescribed by the rules.
8: Since weight is reduced, design pressure on the AM bow section can be collected
9: Since weight is reduced, maximum allowable deflection on local and global level is reached
10: Various untreated rules applicable on secondary components are applicable.
11: Polymers and fibres comply with minimum stated raw material properties.
12: The combination of resin and fibre, offering thermoplastic composites complies with minimum stated mechanical laminate properties.
13: Since weight reduction is achieved, the bow section maintains within the maximum on material stresses.

14: Material handling for thermoset materials is prescribed before, during and after production. Since thermoplastic material require heat to be deposited, other handling requirements count before, during and after deposition. Although various closed loop control systems are readily available offering Class-approved material deposition, additional research is required.

15: Fire-panels are installed to protect the bow section from internal fire. What happens during fire from outside remains a question. Also, heat-deflection resistance is only to be controlled performing extensive fire tests.

16: Using fire resistant panels, divisions can become A-30 fire Class-approved.

It is concluded most important regulations do not directly prohibit the use of thermoplastic materials and AM as production method but additional research is required to come to determining conclusions.

7.4. Conclusions

In previous chapter, weight reduction, costs price and Class-approval are discussed. It is concluded that due to the fact it is possible to use multiple tools having very high deposit rates, the complete bow section can be produced within a few days instead of a few weeks. Short sectional production time is not necessarily beneficial but does decrease machine time and thus machine costs. However, machines having higher deposit rates are more expensive, but this is not linearly coupled. Using thermoplastic composite materials with optimised fibre directions less material is required, reducing the bow section's weight to 24 tonnes, compared to the 38 tonnes for a steel bow section. Due to this, machine time is reduced having a significant effect on cost price, which is estimated to be 100.000,- EUR, compared to the estimated 115.000,- EUR for positive scenario's for a steel bow section. To gain Class-approval, additional research is required mostly specified on fire resistance and process control within manufacturing.

8. Conclusions and future recommendations

In this chapter all relevant conclusions are clustered providing an answer the main question and sub-questions as well as recommendations for future research.

In the introduction it is discussed why AM matches the MCS as manufacturing process and why AM-ME is assumed most beneficial. A reference bow section is used as case study. The main question: Can an AM-ME thermoplastic composite Class III inland waterway vessel's bow section be produced competitively compared to steel and what is the expected possible weight reduction is stated.

Sub-question 2 discusses most critical requirements on composite inland waterway vessels based on (Lloyds.Register, 2017a). In sub-question 3, possibilities resulting from AM-ME manufacturing to be able to comply with the requirements are explained. In sub-question 4, a thermoplastic composite materials are selected and calculated on mechanical properties using composite theory offering input value's for further calculations on weight reduction. Sub-question 5 discusses potential weight reduction for inland waterway vessels using AM and thermoplastic composite material. In sub-question 6, installation methods, time and costs of critical components is presented. All sub-questions offer input for final estimations on weight reduction, cost price and class approval, discussed in sub-question 7, which helps answering the main question.

It is concluded significant weight reduction is achievable using AM-ME and accompanied thermoplastic composite material. Depending on the specific material properties, bow section geometry and manufacturing constraints, weight reductions of about 36% are expected. When safety factors resulting from unfamiliar material properties and excessive material a minimized, additional weight reduction can be gained.

With respect to cost price, directly related to weight reduction, solely optimistic scenario's offer cost reduction. Additional weight reduction, cheaper machinery and competitiveness within the AM-ME industry will reduce cost price in the future.

Related to classification, critical requirements show abilities to gain Class-approval but additional insight is required on fire resistance, materials and classification/standardization of AM-ME manufacturing processes. No direct rejection is noticed in one of the three addressed opportunities and challenges for a competitive bow section for inland waterway vessels. Taking into account the potential for weight reduction, when class-approval is gained and cost items are further reduced, an AM inland waterway vessel offers a competitive alternative for traditional steel manufacturing offering significant weight reductions.

Appendix

Appendix 1.1 Theoretical weight reduction

40 tonnes bow section	40		tonnes
Theoretical weight reduction specific strength	70%	12	tonnes
layer adhesion	30%	3.6	
Escessive material	15%	1.8	
Uniformly divided fibres	25%	3	
Material integrity	20%	2.4	
Total:		22.8	tonnes
Weight reduction %		43%	

Appendix 1.2. Functional requirements bow section

Within the scope of above possibilities most bow sections will have the following in common as ***primary*** *function requirements, their absence causing the vessel to sink immediately;*

-keeps seawater from entering the bow section through the submersed part
-keeps seawater from entering the bow section through the part above water
-keeps air from entering the bow section unless it is for ventilation
-strong enough not to break while the vessel is laying idle or sailing
-stiff enough not to bend more than prescribed while the vessel is laying idle or sailing
-protect the cargo bulkhead and watertight bulkhead from damaging
-protect components inside bow section
-protect bow section components from fire for a prescribed duration and fire fierceness
- help vessel not to sink by added buoyancy

Besides primary function requirements there are ***secondary*** *function requirements within the bow section which are meaningful to have, their absence causing the vessel have to stop sailing and moor as soon as possible;*

-makes water gets redirected along both bow sides
-provide sufficient sight forward from out of wheelhouse
-withstand continuous long term forces from outside
-withstand occasional short term forces from outside
-help the vessel with guiding and steering
-be able independently from rest of vessel perform all necessary tasks
-use emergency generator when all other components in bow section have failed
-provide sufficient electrical power
- contain/house all elements that were designed to be part of the bow section
-tall enough to prevent water from reaching deck while laying idle or sailing
-Bow section should provide housing for bow thruster and funnel, engines, generators, anchoring equipment, bollards, tanks, ballast, connectors, pipes, electrical equipment's.

Appendix 1.3. Calculated weight bow section

Rijn-Hernekanaalschip (Europaschip)

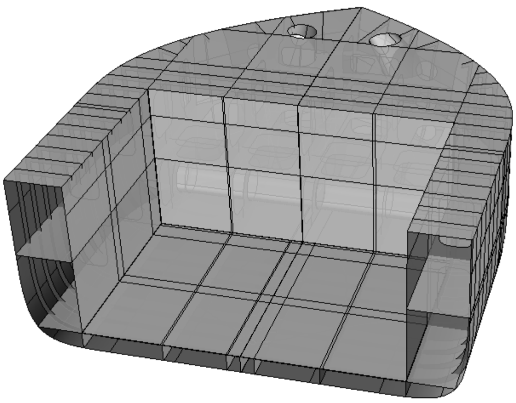
Lengte 85 meter - breedte 9,50 meter - diepgang 2,50 meter - laadvermogen 1.350 ton

Class III inland waterway vessel		Dimensions			
Length vessel		85000	mm	85	m
Beam vessel		9500	mm	9.5	m
Draught vessel laden		2500	mm	2.5	m
Draught vessel empty		1500	mm	1.5	m
Height above waterline		4000	mm	4	m
Cargo capacity				1350	tonnes
Block coefficient vessel		0.95		0.95	
Displacement vessel laden		1.918E+12	mm3	1917.8125	m3
Displacement vessel empty		1.151E+12	mm3	1150.6875	m3
Lightweight vessel				567.8125	tonnes
0.15 x LxBxD (check)		0.15		1211.25	tonnes
Deadweight vessel				1350	tonnes
Length bow section		9500	mm	9.5	m
Beam bow section		9500	mm	9.5	m
Draught bow section laden		2500	mm	2.5	m
Draught bow section empty		1500	mm	1.5	m
Height above waterline		4000	mm	4	m
Block coefficient 1/4 (laden/empty)		0.9		0.9	
Block coefficient 2/5 (laden/empty)		0.7		0.7	
Block coefficient 3/6 (laden/empty)		0.6		0.6	
Percentage block coefficient		0.7333333		0.73333333	
Displacement bow laden		1.655E+11	mm3	165.458333	m3
Displacement bow empty		9.928E+10	mm3	99.275	m3
Lightweight bow section					
Steelweight 0.15 x LxBxD (check)		0.15		33.84375	
Factor extra steel		20%		40.6125	

Appendix 1.4. Minimum required weight bow section from Regulations

Vessel Data:								
INDEX		DATA			OUTPUT		DATA	
L	Length vesesel	85	m					
B	Breadth vessel	9	m					
T	Draft vessel	4	m					
D	Depth	2.5	m					
				2.3.3.				
					S	Frame spacing	622.0495225	mm
					S	Frame spacing	469.1858429	mm
					S	Frame spacing average	545.6176827	mm
s	Spacing secondary stiffeners	0.5	m					
				4.3.3.				
H	framing depth	3.5	m		h_1	Load head		m
					h_2	Load head		m
					h_3	Load head	0.45	m
					h_4	Load head	3.14	m
					h_5	Load head	1	m
				6.4.3.				
d	depth double bottom	0.5	m					
				1.5.3.				
					t	Thickness deck plating > 0.075L	5.6	mm
					t	Thickness deck plating 0.25L - 0.075L	5.6	mm
					t	Thickness deck plating platform deck	4	mm
					t	Thickness crown or bottom of a tank	0	mm
					t	Thickness oil tanks	5	mm
					t	Thickness ballast water tanks	5.5	mm
					t	thickness upper flange of under deck plating	38.40047304	mm
Af	Girder face area	1474.59633	cm^2					
				2.5.3.				
					t	Keel bar thickness	41.45	mm
					H	Keel bar height	134.5	mm
					A	Bar stern	51	mm
					t	Thickness plate stern	11.8	mm
					t	Bottom and side shell plating	7.2054181	mm
le	Span stiffener	2	m					
				3.5.3.		Single bottom		
					df	Web depth at centreline floors	360	mm
					Z	Modulus floors	607.5	cm^3
					t	Web thickness floors	5.6	mm
					t	Web and face plate thickness centerline girder	5.6	mm
					w	face plate width centerline girder	70	mm
					Z	Modulus centerline girder	939144.4363	cm^3
					t	Web thickness centerline girder	5.6	mm
					Z	Modulus bottom transverses centerline girder	773413.0652	cm^3
					t	Web thickness bottom transverses centerline girder	5.6	mm

Etc.



Unit	Thickness mm	Area mm2	Area	Volume
Bottom	7.2	56700000	0.057	0.408
Side shell	7.2	115200000	0.115	0.829
Deck	5.6	63090900	0.063	0.353
Girders	8	44714202	0.045	0.358
Stiffeners	7	21804305	0.022	0.153
Longitudinals	8	34456587	0.034	0.276
Transverses	7	58859984	0.059	0.412
Inner bottom	6	79976220	0.080	0.480
Additional divisions	7	118700549	0.119	0.831
Total:				4.100
Density				7.8
Weight				31.9782

Appendix 1.5. Calculated building time

Data Vessel:	Cc	Shipyard condition coefficient Carreyette	227
AM BOW	Ck	shipyard condition coefficient Kerlen	1
	Ws	Net steel weight in tonnes	40
	L	Length	9
	B	Beam	9
	D	Depth	4
	Cb	block coefficient ship	0.75
Kerlen:	f	constant	0.953156333
	k	manhours per ton of steel	52.55410897
	MHs	Manhours for steelwork	2102.164359

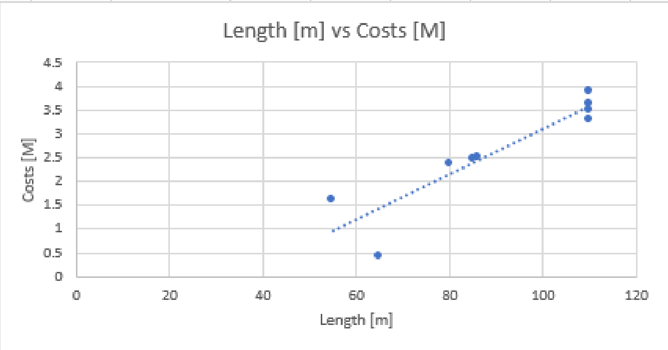
$$f = 0.866 \cdot {C_b}^{-1/3}$$

$$k = C_k \cdot f \cdot (45.36 \cdot \left(\frac{LBD}{1000}\right)^{-0.115} + 3.5)$$

Workday estimation															
Number of working weeks a year	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Number of working days a week	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Number of shifts a day	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Number of working hours a shift	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Amount of people working simultaneously	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Efficiency factor	0.5	1	0.99	0.9801	0.9703	0.9606	0.95099	0.94148	0.93207	0.92274	0.91352	0.90438	0.89534	0.88638	0.87752
Nymber of manhours per ton of steel	52.5541														
Number of manhours for bow section	2102.16	2102.16	2102.16	2102.16	2102.16	2102.16	2102.164	2102.16	2102.16	2102.16	2102.16	2102.16	2102.16	2102.16	2102.16
Number of hours including efficiency	4204.33	2102.16	2123.4	2144.85	2166.51	2188.4	2210.501	2232.83	2255.38	2278.16	2301.18	2324.42	2347.9	2371.62	2395.57
Number of working hours	4204.33	1051.08	707.799	536.212	433.302	364.733	315.7858	279.104	250.598	227.816	209.198	193.702	180.608	169.401	159.705
Number of working shifts	525.541	131.385	88.4749	67.0265	54.1628	45.5916	39.47323	34.888	31.3248	28.4771	26.1497	24.2127	22.576	21.1751	19.9631
Number of working days	525.541	131.385	88.4749	67.0265	54.1628	45.5916	39.47323	34.888	31.3248	28.4771	26.1497	24.2127	22.576	21.1751	19.9631
Number of workweeks	105.108	26.2771	17.695	13.4053	10.8326	9.11832	7.894646	6.97759	6.26495	5.69541	5.22995	4.84254	4.51519	4.23503	3.99262
Number of years	2.62771	0.65693	0.44237	0.33513	0.27081	0.22796	0.197366	0.17444	0.15662	0.14239	0.13075	0.12106	0.11288	0.10588	0.09982
Amount of sections simulsatenously	3														
Relative Number of workweeks	35.0361	8.75902	5.89833	4.46843	3.61085	3.03944	2.631549	2.32586	2.08832	1.89847	1.74332	1.61418	1.50506	1.41168	1.33087

Appendix 1.5.1. Calculated building costs

Complete vessel	Length	Euro's [M]
De Vries	110	3.9
VBD	80	2.36
VBD	110	3.63
VBD	85	2.48
VBD	65	0.42
Schuttevaer	110	3.3
EICB	86	2.5
EICB	55	1.6
EICB	110	3.5



Bow section				
Weight	40.6125	tonnes		
Price	€ 3.00	EUR/kg		€ 121,837.50
Total:				€ 121,837.50
Weight	40.6125	tonnes		
Manhours per ton of ste	52.55410897	hr		
Manhours for steelweigh	2102.164359	hr		
Hourly rate manhours	€ 35.00	EUR		€ 73,575.75
Costs per ton of steel	€ 950.00			€ 38,581.88
Total:				€ 112,157.63

Appendix 1.6. categorization and design pressures

Underneath tables provide input required for additional calculations on pressures, deflection and general layout.

Item	Pt, Ch, Sc	Outcome
Number of total bulkheads	3.2.4.	5
Position collision bulkhead	3.2.4.	0.05 L_L and 0.08 L_L
Cofferdams (in between)	3.2.5.	Fuel oil, lub oil, tech.water
Equipment Number (EN)	3.5.5.	86
Craft type factor k_r	3.5.5.	0.9
Nr of Anchors + weight	3.5.5.	1; 117 kg

Table: shows relevant numbers and constants needed for further calculations and categorization

Item	Pt, Ch, Sc	Outcome
Service Group	1.2.3.	G1
Significant wave height (m)	5.2.3.	0.6
Maximum wave height (m)	5.2.3.	1.0
Hull form pressure factor disp. mode	5.2.3.	1.95
Froude Number	5.2.4.	0.14
Tailor Quotient	5.2.4.	1.301

Table: shows design pressures and …

Item	Pt, Ch, Sc	Outcome
Design pressure structural component	5.3.2.	
Hull notation factor H_f	5.3.2.	1.0
Service area notation factor G_f	5.3.2.	0.6
Service type notation factor S_f	5.3.2.	1.0
Craft type notation factor C_f	5.3.2.	1.0
Stiffening type factor δ_f primary	5.3.2.	0.5
Stiffening type factor δ_f secondary	5.3.2.	0.8

Table: categorization according to shape and function

Underneath formulas determine maximum applicable design pressures and moments.

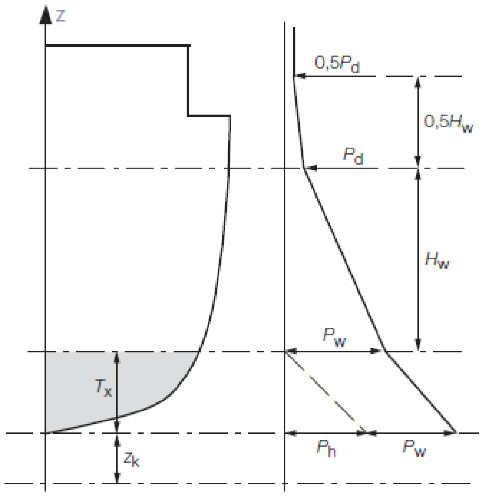


Figure: shows the units

Froude number:

$$F_n = \frac{0.515 \cdot V_m}{\sqrt{g \cdot L_{WL}}}$$
$$V_m = 8\ knots$$
$$L_{WL} = 80$$
$$F_n = \frac{0.515 \cdot 8}{\sqrt{9.81 \cdot 80}} = 0.14$$

Taylor Quotient:

$$\Gamma = Tailor\ Quotient = \frac{V}{\sqrt{L_{WL}}} = \frac{12}{\sqrt{85}} = 1.301$$

(2) Hydrostatic pressure shell plating:

$$P_h = 10\big(T_x - (z - z_k)\big)\ kN/m^2$$
$$T_x = 0.5\,, 2.5$$
$$z = 0, 2.5$$
$$z_k = 0$$
$$P_h = 0, .., 25\ \ kN/m^2$$

(3) Hydrodynamic wave pressure: (the greater of)

$$P_m\ kN/m^2$$
$$P_p\ kN/m^2$$

$$P_m = 10\ f_z\ H_{rm}\ kN/m^2$$
$$f_z = vertical\ distribution\ factor$$
$$f_z = k_z + (1 - k_z)\left(\frac{z - z_k}{T_x}\right)$$
$$k_z = e^{-u} = e^{-0.03} = 0.956$$
$$u = \left(\frac{2\pi - T_x}{L_{wL}}\right) = \left(\frac{2\pi - 2.5}{85}\right) = 0.0445$$
$$L_{wl} = 85$$
$$x_{wl} = 80$$
$$z = 0$$
$$z_k = 0$$
$$f_z = k_z + (1 - k_z)\left(\frac{z - z_k}{T_x}\right) = 1$$

$$H_{rm} = C_{w,min}\left(1 + \frac{k_r}{(C_B + 0.2)}\left(\frac{x_{wl}}{L_{WL}} - x_m\right)^2\right)$$
$$C_w = 0.0771 L_{WL}(C_b + 0.2)^{0.3} e^{(-0.0044 L_{WL})}$$
$$C_B = 0.85$$
$$x_{wl} = 80$$
$$C_w = 0.0771 * 80(0.85 + 0.2)^{0.3} e^{(-0.0044*80)} = 4.401$$
$$x_{wl} = 80$$
$$C_{w,min} = \frac{C_w}{k_m} = \frac{4.401}{1.46} = 3.014$$
$$k_m = 1 + \frac{k_r(0.5 - z_k)^2}{(C_b + 0.2)} = 1 + \frac{1.95(0.5 - 0)^2}{(0.85 + 0.2)} = 1.464$$
$$k_r = 1.95\ (hull\ form\ wave\ pressure\ factor)$$
$$x_m = 0.45 - 0.6\,F_n = 0.366$$

$$H_{rm} = 3.014\left(1 + (\frac{1.95}{(0.85 + 0.2)})(\frac{80}{85} - 0.366)^2\right) = 1.614$$

$$x_{wl} = 80$$
$$C_w = 0.0771 \cdot L_{WL}(C_b + 0.2)^{0.3} e^{(-0.0044 \cdot L_{WL})}$$
$$C_w = 0.0771 \cdot 85(0.85 + 0.2)^{0.3} e^{(-0.0044 \cdot 85)} = 4.575$$
$$L_{WL} = 85$$

$$P_m = 10\ \cdot 1 \cdot\ H_{rm}\ kN/m^2$$
$$P_m = 10\ \cdot 1 \cdot 1.465 = 14.65\ kN/m^2$$

$$P_p = 10\ H_{pm}\ kN/m^2$$

$$H_{pm}\ = 1.1\left(\frac{2x_{wl}}{L_{WL}} - 1\right)\sqrt{L_{WL}} = 1.1\left(\frac{2 \cdot 80}{85} - 1\right)\sqrt{85} = 7.88$$

But not less than

$$f_L\sqrt{L_{WL}}$$
$$f_L = 0.3\ for\ L_{WL} > 80$$
$$f_L = 0.3\sqrt{85} = 2.765$$

$$P_p = 10 \cdot 7.88 = 78.8\ kN/m^2$$

$$P_S = P_H + P_W$$
$$P_S = 25 + 14.65 = 39.65\ kN/m^2$$

(4) Pressure on weather and interior decks:

$$P_{wh} = f_L(6 + 0.01 \cdot L_{WL})(1 + 0.05\Gamma) + E\ kN/m^2$$
$$E = \frac{0.7 + 0.08 L_{WL}}{D - T} = \frac{0.7 + 0.08 \cdot 85}{4 - 2.5} = 5\ kN/m^2$$
$$f_L = 0.3\ for\ L_{WL} > 80$$
$$L_{WL} = 85$$
$$D = 4$$
$$T = 2.5$$
$$\Gamma = Tailor\ Quotient = \frac{V}{\sqrt{L_{WL}}} = \frac{12}{\sqrt{85}} = 1.301$$
$$P_{wh} = 0.3(6 + 0.01 \cdot 85)(1 + 0.05 \cdot 1.301) + 5 = 7.18\ kN/m^2$$

(5) Impact pressure displacement mode:

$$P_{dh} = \Phi_{dh}\left(19 - 2720\left(\frac{T_x}{L_{WL}}\right)^2\right)\sqrt{L_{WL} \cdot V}\ kN/m^2$$
$$\Phi_{dh} = 0.18$$
$$T_x = 2.5$$
$$P_{dh} = 0.18\left(19 - 2720\left(\frac{2.5}{85}\right)^2\right)\sqrt{85 \cdot 8} = 78.13\ kN/m^2$$

(8) Design pressure deckhouse and bulwark:

$$P_{dhp} = C_1 P_d\ kN/m^2$$
$$C_1 = 1.25$$
$$P_d = P_{wh}$$
$$P_{wh} = 7.18$$
$$P_{dhp} = 1.25\ \cdot 7.18 = 8.975\ kN/m^2$$

(9) Design pressure watertight and deep bulkheads:

$$P_{bh} = 11.2 \cdot\ h_b\ kN/m^2$$
$$h_b = 7.2 \cdot h_b\ kN/m^2$$
$$h_b = load\ head\ in\ metres$$
$$P_{bh} = 11.2 \cdot 7.2 \cdot 2 = 161.28\ kN/m^2$$

(10) Design load supported by a pillar:

$$P_{PI} = S_{gt} b_{gt} P_c + P_a\ kN$$

$$P_c = basic\ deck\ girder\ pressure$$
$$P_a = load, in\ kN, from\ pillars\ or\ pillars\ above$$
$$S_{gt} = spacing, or\ mean\ spacing, of\ girders\ or\ transverses$$
$$b_{gt} = distance\ between\ centres\ of\ two\ adjacent\ spans\ of\ girders$$

$$P_{PI} = 2 \cdot 2 \cdot 7{,}47 + 0 = 29.88\ kN$$

(11) Cargo deck design pressure:

$$P_{cd} = W_{CDP}(1 + 0.5a_x) kN/m^2$$
$$W_{CDP} = 7.47$$
$$a_x = 1$$
$$P_{cd} = 7.47(1 + 0.5 \cdot 1) = 11.21\ kN/m^2$$

(13) Vertical wave bending moments:

$$M_W = F_f D_f M_o\ kNm$$
$$F_f = -1.1\ for\ sagging$$
$$F_f = \frac{1.9C_b}{C_b + 0.7} for\ hogging = 1.04$$
$$C_b = 0.85$$
$$L_R = Rule\ length = 83$$

aft end		0.4*83 = 33	0.65*83 = 54		Forward end
0		1.0	1.0		0

$$D_f = 0.2415\ (interpolation)$$
$$M_o = 0.1 L_f G_f {L_R}^2 B(C_b + 0.7) kNm$$
$$L_f = 10.75 - (3 - 0.01L_R)^2 = 7.14$$
$$L_R = rule\ length = 83$$

$$G_f = 0.5\ for\ G1$$
$$C_b = 0.85$$
$$M_o = 0.1 \cdot 7.14 \cdot 0.5 \cdot 110^2 \cdot 9.5(0.85 + 0.7) = 63607.58\ kNm$$
$$M_W = -1.1 \cdot 0.2415 \cdot 63607.58 = -16897\ kNm$$

(14) Wave shear forces:

$$Q_W = \frac{3K_f M_O}{L_R} kN$$
$$K_f(positive\ shear\ force) = 0$$
$$K_f(negative\ shear\ force) = 0$$
$$Q_W = \frac{3 \cdot 0 \cdot 63607.58}{110} = 0\ kN$$

(17) Still water bending moment:

Own calculation				Lloyds			
Lengte	9	m		B	9		
Breedte	9	m		T	2.5		
Diepte	2.5	m		cB	0.9		
Block	0.66			r=Lc/L			
				Lc	12		
				L	80		
Volume	133.65	m3					
				r	0.15		
Gewicht water	136.99125	ton					
				K1	0.01039	0.00927	
Gewicht boeg	30	ton		K2	0.07512	0.04775	
Gewicht components	40	ton		Mho	-302.469984	-250.993	
Totaal	70						
				K3	0.00668	0.01974	
Opdrukkend gewicht	66.99125	ton		K4	0.0808	0.09	
g	9.81						
				Mso	444.8	2266.56	
F=m*g	657.18416	kN		Mso	5679.36	5679.36	
				MSo	6124.16	7945.92	kNm
Arm	4.5	m					
				MSt	4409.3952	5721.062	
Moment	2957328.7	Nm					
	2957.3287	kNm		Moment	2449.664	3178.368	kNm

(15) Dynamic bending moments and associated shear forces:

$$M_{DW} = F_f D_f |M_D| = 0\ kNm$$

(1) Design pressure structural components:

$$Design\ Pressure = \delta_f H_f G_f S_f * load\ criterion$$
$$\delta_f = primary, secondary, 0.5, 0.8$$
$$H_f = 1.05$$
$$G_f = 0.6$$
$$S_f = 1.0$$
$$load\ criterion = load\ pressure\ on\ relevant\ component$$

Appendix 1.7. Span deflection ratio's

Item		f_δ
Shell envelope	Sandwich construction	100
Bottom structure	Secondary stiffening	150
	Primary girders and web frames	200
Side structure	Secondary stiffening	150
	Primary girders and web frames	200
Main/strength deck structures	Sandwich construction	100
	Secondary stiffening	200
	Primary girders and web frames	**250**
	Hatch covers	100
Superstructure/deckhouse laminates	Generally	50
	Coach roof	100
	House top	50
	Lower decks	100
Superstructure deckhouse stiffeners	Generally secondary	100
	Generally primary	150
	Coach roof secondary	150
	Coach roof primary	200
	House top secondary	100
	House top primary	100
	Lower decks secondary	150
Deep tank structures	Laminates sandwich construction	100
	Laminates secondary members	100
	Stiffeners primary members	200
Watertight bulkhead structures	Laminates sandwich construction	50
	Laminates secondary members	50
	Stiffeners primary members	150

Table Maximum allowed deflection ratio based on span of various components.

Appendix 1.8. relevant components regulations

Securing of machinery	5.2. Collision load	(Lloyds.Register, 2017b) *(Pt 9, Ch 1, S5)*

Bedplates and machinery is to be securely fastened to the vessel to restrain dynamic forces from vertical and horizontal acceleration. In (Lloyds.Register, 2017a) (Pt 9, Ch 1, S5) the collision load is prescribed critical for securing machinery and unless accurately provided rule 5.2.1. applies in which p_{coll} is calculated out of various parameters such as factors for materials, vessel speed, etc.

$$g(collision) = 1.2\frac{p_{coll}}{\Delta g} \tag{23}$$

For a composite Class III inland waterway vessel collision acceleration is calculated to be 1.117 m/s^2. Machinery fittings should withstand the decelerating mass of the engine.

Bow thrusters	3.2. Design	(Lloyds.Register, 2017b) *(Pt 5, Ch 17, S2)*

According to Waterway Guidelines (Brolsma & Roelse, 2011) *a Class III inland waterway vessel has an installed bow thruster propeller power of in between 160 and 210 kW. The arrangement of the bow thruster is to be such that the vessel can be satisfactory propelled while maintaining a speed of not less than 6.5 km/h, and is to be provided with two independent means of steering. The bow thruster unit is to be adequately supported and stiffened.*

Manholes composite vessel	6.16 Manholes	(Lloyds.Register, 2017a) *(Pt 8, Ch 3, S7)*

In the inner bottom, floors and side girders adequate access is to be provded by manholes, with specified dimensions ans locations, avoiding openings in and around stiffening members, and tanks to avoid structural integrity.

Access	7.16 Access	(Lloyds.Register, 2017a) *(Pt 8, Ch3, S7)*

These rules prescribed all compartments within the craft are to be accessible. Compartments include tanks, double bottom, cofferdams. The rule has a large impact on the structural layout of the AM bow section since division will need to be interrupted. No access is to be provided in bulkheads.

Anchoring equipment		*(Lloyds.Register, 2017a) (Pt 3, Ch 5, S5)*

Based on the craft's Equipment number (EN) = 760, Service Group (G3) and Craft type factor (k) = 1.0 in 5.2 Materials a single anchor of 1575 kg is prescribed. In (Lloyds.Register, 2017b) (Pt 3, Ch 12, S5, 5.6) *it is written the total required mass can be divided over one or two anchors. In* (Lloyds.Register, 2017a) (Pt 3, Ch5, S6, 5.6.1) *based on the weight of the anchor a chain cable length of 220 meters is prescribed including a mild steel chain cable diameter of 44 mm. This makes up for approximately 2200 kg of additional chain weight.*

Windlass		*(Lloyds.Register, 2017a) (Pt 3, Ch 5, S8)*

The windlass is to be able to exert a continuous duty pull of 72.6 kN. For an anchor breakout pull a required 49.0 kN is advised and for brake holding load 345.6 kN is required. Thus, a maximum force of 346 kN is exerted onto the windlass. Dimensions of the windlass and the angle of the cable determine the resulting forces onto the deck.

Mooring lines	7.4 Towlines	(Lloyds.Register, 2017a) *(Pt 3, Ch 12, S5)*

Based on the equipment number of 760 minimum towline length should be 180 meters with corresponding minimum breaking strength of 486.5 kN should be available. Four mooring lines are prescribed with each a length of 170 metres and minimum breaking strength of 137.3 kN. This is important for the construction of the bow section at the location of the bollards.

Bollards	7.5 Bollards	(Lloyds.Register, 2017a) *(Pt 3, Ch 5, S7)*

*A sufficient amount of mooring lines should be secured on bollard on all sides of the craft able to hold not less than 1.5 times the breaking strength of the mooring lines, which results in a force 1.5 * 137.3 = 205.95 kN per mooring line.*

Fittings and attachments		(Lloyds.Register, 2017a) *(Pt 8, Ch 2, S5)*

For composite vessels there are various methods discussed to connect fittings and attachments onto the laminate. Inserts and bolts (4.3) are the most dominant solutions, each subjected to regulations on *location and means of connection. Attachments need to be avoided nearby brackets, corners, openings and other areas of high stress. Laminate surrounding the fittings is to be properly stiffened to transfer stresses. In case inserts are used to connect fittings onto they need to be able to resist crushing and need to properly transfer stresses into the surrounding material. When bolts are used to connect fittings into or through the laminate, or to be connected into inserts, various pitch requirements are discussed. Fittings (5.6) which penetrate the hull are to be sealed with resin or other compound. Proper care should be taken to transfer stresses to prevent cracking or bending of the hull which can cause leakage. The exposed edges (5.10) or through-hull fittings need to be sealed watertight with laminates or equivalent reinforcements.*

Appendix 1.9. minimum required thermoset mechanical properties

	Specific gravity	Tensile modulus N/mm^2	Shear modulus N/mm^2	Poisson's ratio
Polyester	1.20	3400 = 3.4 GPa	1300 = 1.3 GPa	0.36
Vinylester	1.44	3500 = 3.4 GPa	-	-
Epoxy	1.38	3500 = 3.4 GPa	-	0.39

Table Minimum required thermoset resin properties

Regarding costs, for a composite bow section, E-glass direct roving will be used. Minimum required fibre properties are shown in table 2:

	Specific gravity	Tensile modulus N/mm^2	Shear modulus N/mm^2	Poisson's ratio
E glass	2.56	69000 = 69 GPa	28000 = 28 GPa	0.22

Table Minimum required fibre properties E glass.

Appendix 1.10. minimum required laminate properties

Mechanical property (MPa)	N/mm^2	30%	40%	50%	60%
f_c	Fibre content				
Ultimate tensile strength	$200 f_c + 25$	85	105	125	145
Tensile modulus	$(15 f_c + 2) x 10^3$	6500	8000	9500	11000
Ultimate compressive strength	$150 f_c + 72$	117	132	147	162
Compressive modulus	$(40 f_c – 6) x 10^3$	6000	10000	14000	18000
Ultimate shear strength	$80 f_c + 38$	62	70	78	86
Shear modulus	$(1.7 f_c + 2.24) x 10^3$	2750	2920	3090	3260
Ultimate flexural strength	$502 f_c^2 + 106.8$	151.9	187.1	232.3	287.5
Flexural modulus	$(33.4 f_c^2 + 2.24) x 10^3$	5246	7584	10590	14264

Table 2 Minimum mechanical properties for strand mat (CSM) laminates.

Mechanical properties for woven roving (WR) and cross-plied (CP) glass reinforced polyester resin laminates at 0/90° orientations are shown in table 4:

Mechanical property	N/mm^2	30%	40%	50%	60%
f_c	Fibre content				
Ultimate tensile strength	$400 f_c - 10$	110	150	190	230

Tensile modulus	$(30\ f_c - 0.5) \times 10^3$	8500	11500	14500	17500
Ultimate compressive strength	$150\ f_c + 72$	117	132	147	162
Compressive modulus	$(40\ f_c - 6) \times 10^3$	6000	10000	14000	18000
Ultimate shear strength	$80\ f_c + 38$	62	70	78	86
Shear modulus	$(1.7\ f_c + 2.24) \times 10^3$	2750	2920	3090	3260
Ultimate flexural strength	$80\ f_c^2 + 106.8$	130.8	138.8	146.8	154.80
Flexural modulus	$(33.4\ f_c^2 + 2.2) \times 10^3$	5206	7544	10550	14224

Table 3 Mechanical properties for woven roving (WR) and cross-plied (CP) glass reinforced polyester resin laminates at 0/90° orientation.

Mechanical properties for uni-directional glass reinforced polyester resin laminates at 0/90° degrees orientations are shown in table 5:

Mechanical property	N/mm^2	30%	40%	50%	60%
f_c	Fibre content				
Longitudinal elastic modulus	$(50.5\ f_c - 6.87) \times 10^3$	8280	13330	18380	23430
Transverse elastic modulus	$(19.6\ f_c^2 - 15.7\ f_c + 6.6) \times 10^3$	3654	3456	3650	4236
In-plane shear modulus	$(7.3\ f_c^2 - 5.9\ f_c + 2.4) \times 10^3$	1287	1208	1275	1488
Longitudinal tensile strength	$656\ f_c - 89.3$	107.5	173.1	238.7	304.3
Longitudinal compressive strength	$530\ f_c - 72.1$	86.9	139.9	192.9	245.9
Transverse tensile strength	$68.4\ f_c^2 - 55\ f_c + 23$	12.7	11.9	12.6	14.6
Transverse compressive strength	$196\ f_c^2 - 157\ f_c + 65.6$	36.1	34.1	36.1	41.9
In-plane shear strength	$73.4\ f_c^2 - 59.2\ f_c + 24.5$	13.3	12.6	13.3	15.4

Table 4 Mechanical properties for uni-directional glass reinforced polyester resin laminates at 0° orientation.

Appendix 1.11. limiting stress criteria

Item		Tensile	Compr.	Shear
Shell envelope	Bottom shell laminate	0.25	0.25	-
	Side shell laminate	0.30	0.30	-
	Keel	0.25	0.25	-
Bottom structure	Secondary stiffening	0.30	0.30	0.30
	Primary girders /web frame	0.33	0.33	0.33
	Engine girders	0.33	0.33	0.33
Side structure	Secondary stiffening	0.30	0.30	0.30
	Primary girders /web frame	0.33	0.33	0.33
Main deck	Laminate	0.30	0.30	-
	Secondary stiffening	0.30	0.30	0.30
	Primary girders and web frame	0.33	0.33	0.33
Superstructure	Laminate	0.30	0.30	-
	Stiffening	0.33	0.33	0.33
Bulkheads collision	Laminate	0.26	0.26	-
	Secondary	0.32	0.32	0.32
	Primary	0.32	0.32	0.32
Bulkheads watertight	Laminate	0.33	0.33	-

	Secondary	0.40	0.40	0.40
	Primary	0.40	0.40	0.40

Table 5 Maximum allowed tensile, compression and shear expressed as a fraction of the ultimate shear strength of the laminate.

	Operational mode	Tensile	Compr.	Shear
Global craft	$\Gamma \geq 3.0 \; or \; \Delta \leq 0.04(L_R B)^2$	0.33	0.33	0.33
	$\Gamma \geq 3.0 \; and \; \Delta \leq 0.04(L_R B)^2$	0.25	0.25	0.25

Table 6 Maximum allowed tensile, compression and shear expressed as a fraction of the ultimate shear strength of the laminate.

Appendix 1.12. A-Class divisions

Spaces	Control Centres	Stairwells	Muster Areas	Lounges	Machinery spaces A	Galleys	Store rooms
Control Centers	-	Ao	Ao/Bo(1)	Bo	A3o	Ao	Ao
Stairwells		-	Ao	Bo	A3o	Ao	Ao
Muster Areas			-	Ao/Bo(2)	A3o	Ao	Ao
Lounges					A3o	Ao	Ao
Mach. spaces A					A3o/Ao(4)	A15	Ao
Galleys						-	Ao/Bo(5)
Store rooms							-

Table … Annotation for various Class divisions.

(1) Divisions between control centres and internal muster areas shall correspond to type Ao, but external muster areas only to type Bo.
(2) Divisions between lounges and internal muster areas shall correspond to type Ao, but external muster areas only to type Bo.
(3) Divisions between cabins, divisions between cabins and corridors and vertical divisions separating lounges according to CH 1, Sec 6m {3.5.1} shall comply with Bo.
(4) Divisions between machinery spaces of Category A shall comply with type A3o; in other cases they shall comply with type Ao.
(5) Bo is sufficient for divisions between galleys, on the one hand, and cold-storage rooms and food store rooms, on the other.

Fire test
The thermoplastic Class divisions will need to undergo a Fire-Test as stated in (Lloyds.Register, 2017a) (*Pt 17, Ch 1, 2.2 Fire test 2.2.1*.). Not only will the bow section be subjected to direct rules for heat-resistance, it should also maintain its strength and stiffness during the test to be performed at 1 of the recognised test laboratories according to IMO (IMO, 2011).
In (MSC, 1996) Fire Test protocols and requirements are prescribed. The Fire Test Procedure Code (FTP) was developed by IMO in the frame of the International Convention for the Safety of Life at Sea (SOLAS). Fire tests of the International Standards Organization (ISO) are used. In table 7 a selection of applicable tests for an inland waterway bow section is shown:

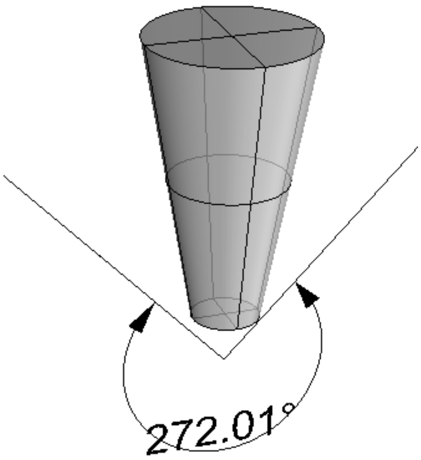
FTP Code	Type of test	Referred test method	Similar test method
Part 1	Non-combustibility test	ISO 1182	-
Part 2	Smoke and Toxicity Test	ISO 5659-2	-
Part 3	Fire Resistance Test for Fire Resistant Divisions	IMO A.754(18)	ISO 834-1
Part 4	Fire Resistant Test for Fire Resistant Divisions	-	-

Part 5	Surface Flammability Test	IMO A.653(16) IMO A.687(17)	ISO 5658-2
Part 6	Test for Primary Deck Coverings	IMO A.653(16)	ISO 5658-2

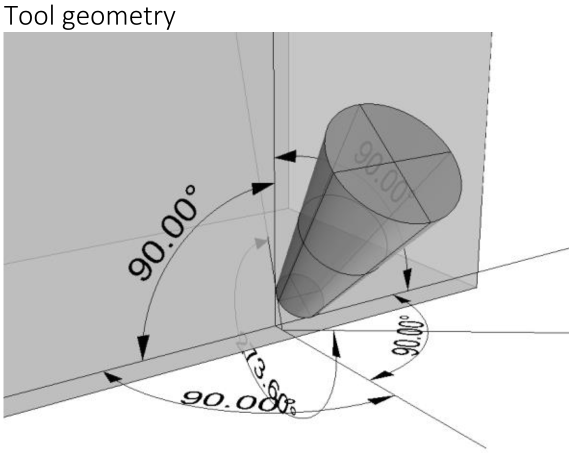
Table 7 applicable test procedures for an AM bow section

A fire test is executed by exposing a pre-produced test sample (2m x2m) to an in temperature increasing fire source for the time it should be able to resist this temperature. Simultaneously bending and compression pressure is applied and deformation is measured.

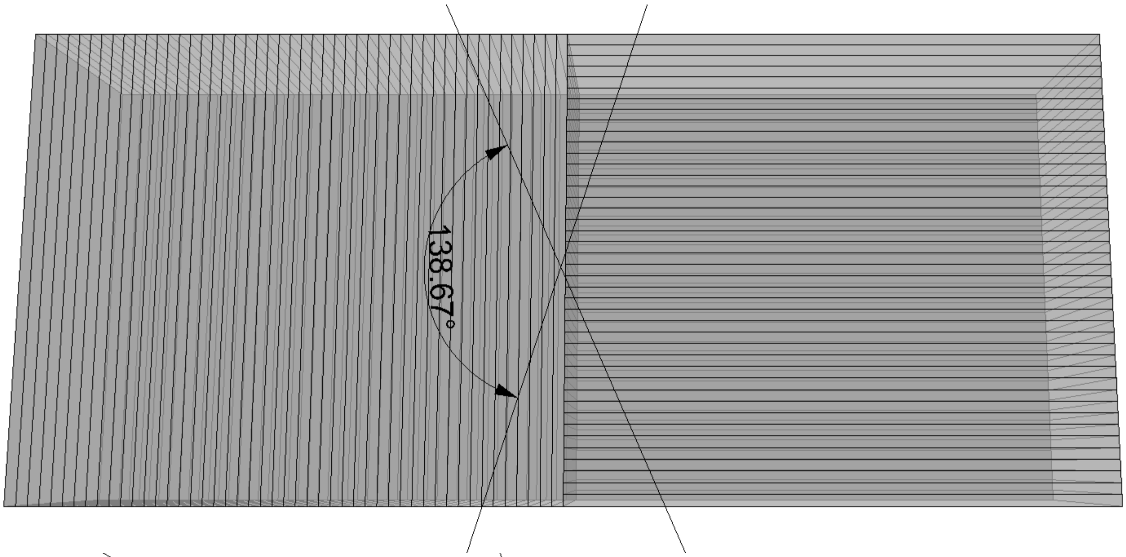
Appendix 1.20.1 Orientation freedom

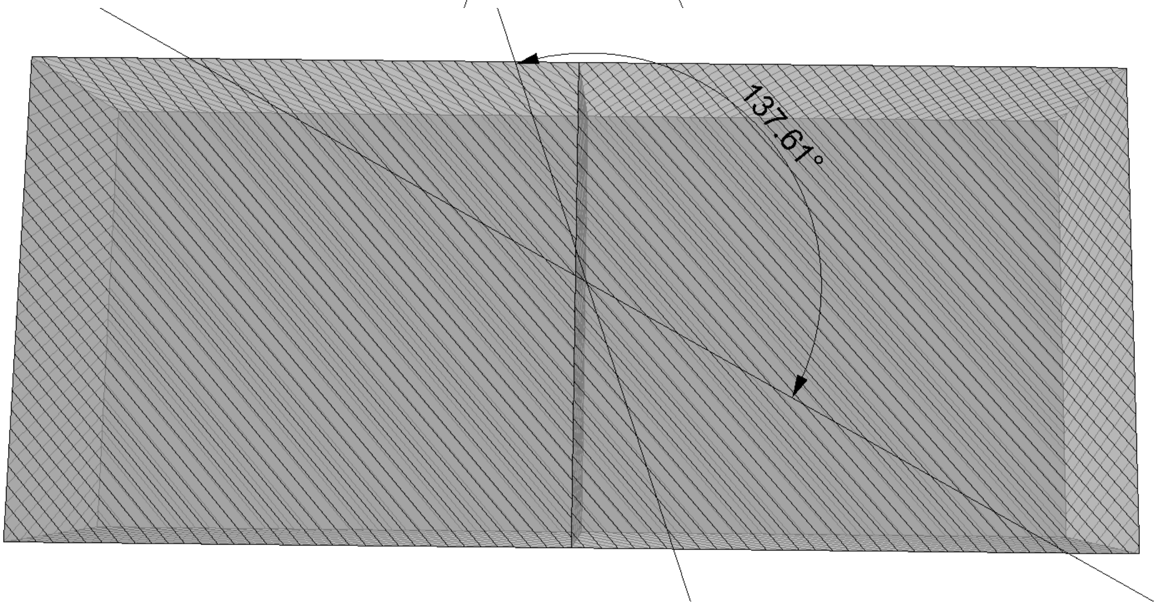


Tool geometry



Pre-produced parts





Cross-ply requirements

Since the larger part of the bow section offers 360 degree freedom (topsides, outer shell, starting points, using multi-axis deposition, a 25% freedom reduction is assumed)

Appendix 1.20. Layer Adhesion estimation

Luvocom 3F PAHT CF 9742 BK															
Tensile strength (MPa)	170	145					85.29411765	%							
Elongation (%)	1	2.8													
E-modulus (Gpa)	15	14					93.33333333	%							
Luvocom 3F PAHT (onversterkt)															
Tensile strength (MPa)	83.77	77.62					92.65846962	%							
Elongation (%)															
Uitrekken bij Fmax (%)	3.5	3.53													
Breuk bij rek (%)	5.04	5.37													
E-modulus (Gpa)	3.47	3.2					92.21902017	%							
							Moulded difference						X Y Z difference		
ULTEM (onversterkt)	x		y		z		x		y		z		xy	yz	zx
Tensile strength (MPa)	84	63.25		45.87		40.75	75.29761905	%	54.607	%	48.512	%	72.52173913	88.838	64.427
Elongation (%)															
Uitrekken bij Fmax (%)	72	6.35		5		2.29									
Breuk bij rek (%)		5.65		4.99		2.29									
E-modulus (Gpa)		2.03		1.46		2.09							71.92118227	143.15	102.96
ULTEM 1010 Resin	x		y		z										
Tensile strength (MPa)		64				42									65.625
Elongation (%)															
Uitrekken bij Fmax (%)															
Breuk bij rek (%)		3.3				2									
E-modulus (Gpa)		2.8				2.2									78.571
ABS-ESD7	x		y		z										
Tensile strength (MPa)		35.8				19.8									55.307
Elongation (%)															
Uitrekken bij Fmax (%)															
Breuk bij rek (%)		3				1									
E-modulus (Gpa)		2.4				2.6									108.33
ESD PEKK															
Tensile strength (MPa)		88.9				59									66.367
Elongation (%)															
Uitrekken bij Fmax (%)															
Breuk bij rek (%)		4.7				2.3									
E-modulus (Gpa)		3.1				2.9									93.548
ULTEM 9085															
Tensile strength (MPa)		68.6				42									61.224
Elongation (%)															
Uitrekken bij Fmax (%)															
Breuk bij rek (%)		5.8				2.2									
E-modulus (Gpa)		2.15				2.26									105.12

Appendix 1.13. PET/PC Datasheets

Datasheet PET

Polyethylene Terephthalate (unfilled, semi-crystalline)

Tradenames ⓘ

Arnite, Astapet, Bapolene, Certene, Cleartuf, Eastar, Kopet, Laser+, Lighter, Lofex, Marpol, Mylar, Octal, Papet, Polyclear, Preformance, Ramapet, Relpet, Selar, Skyrol, Surespec, Texpet, Traytuf, Tripet, Umapet, Valox, World, Xcel

Typical uses ⓘ

Electrical fittings and connectors; audio/visual tapes; industrial strapping; capacitor film; fibers.

Composition overview

Compositional summary ⓘ

(CO-(C6H4)-CO-O-(CH2)2-O)n

Material family	ⓘ	Plastic (thermoplastic, semi-crystalline)
Base material	ⓘ	PET (Polyethylene terephthalate)
Polymer code	ⓘ	PET

Composition detail (polymers and natural materials)

Polymer	ⓘ	100	%

Price

Price	ⓘ	* 1.64	-	1.67	EUR/kg
Price per unit volume	ⓘ	* 2.25e3	-	2.35e3	EUR/m^3

Physical properties

Density	ⓘ	1.37e3	-	1.4e3	kg/m^3

Mechanical properties

Young's modulus	ⓘ	2.76	-	3.1	GPa
Yield strength (elastic limit)	ⓘ	* 65	-	70	MPa
Tensile strength	ⓘ	70	-	75	MPa
Elongation	ⓘ	65	-	75	% strain
Compressive modulus	ⓘ	* 2.76	-	4.14	GPa
Compressive strength	ⓘ	* 75.8	-	103	MPa
Flexural modulus	ⓘ	2.99	-	3.09	GPa
Flexural strength (modulus of rupture)	ⓘ	* 70	-	75	MPa
Shear modulus	ⓘ	* 0.994	-	1.49	GPa
Bulk modulus	ⓘ	* 4.94	-	5.19	GPa
Poisson's ratio	ⓘ	* 0.381	-	0.396	
Shape factor	ⓘ	4.9			
Hardness - Vickers	ⓘ	* 17	-	20	HV
Hardness - Rockwell M	ⓘ	82	-	87	
Hardness - Rockwell R	ⓘ	120	-	125	
Fatigue strength at 10^7 cycles	ⓘ	* 19.3	-	29	MPa
Mechanical loss coefficient (tan delta)	ⓘ	* 0.00966	-	0.0145	

Impact & fracture properties

Fracture toughness	ⓘ	* 4.75	-	5.25	MPa.m^0.5
Impact strength, notched 23 °C	ⓘ	2.86	-	3.15	kJ/m^2
Impact strength, unnotched 23 °C	ⓘ	590	-	600	kJ/m^2

Thermal properties

Melting point	ⓘ	255	-	265	°C
Glass temperature	ⓘ	68	-	80	°C
Heat deflection temperature 0.45MPa	ⓘ	105	-	115	°C
Heat deflection temperature 1.8MPa	ⓘ	70	-	80	°C
Maximum service temperature	ⓘ	115	-	120	°C
Minimum service temperature	ⓘ	* -58	-	-38	°C
Thermal conductivity	ⓘ	0.138	-	0.151	W/m.°C
Specific heat capacity	ⓘ	1.1e3	-	1.2e3	J/kg.°C
Thermal expansion coefficient	ⓘ	75	-	80	µstrain/°C

Datasheet PC

Polycarbonate (copolymer, High-heat)

Tradenames ⓘ

4Lex, Accucomp, Alcom, Altech, Anjacom, Anjalon, Apec, Ashlene, Avp, Bach, Calibre, Calibre Megarad, Carbotex, Cheng, Colorrx, Coolpoly, Diaalloy, Dialon, Durolon, Ekalon, Electrafil, Emerge, Encom, Enviroplas, Epimax, Epitec, Epival, Eppc, Estacarb, Geo-Tech, Hopelex, Hylex, Infino, Iupilon, Kophos, Kotex, Kumhosunny, Lexan, LNP Colorcomp, LNP Lubricomp, LNP Thermocomp, Lubricomp, Lucent, Lupoy, Makrolon, Makropol, Marcoblend, Naxel, Naxell, Nemcon, Next, Nexus, Nirion, Nova, Novalux, Novarex, Omnicarb, Panlite, Perlex, Petrotene, Plaslube, Polylon, Pryme, Ramtough, Scantec, Selon, Shuman, Sicoklar, Sindustris, Spartech, Tairilite, Tarflon, Tarolon, Tekanate, Terez, Thermocomp, Trirex, Tristar, Tuffak, Tynec, Wonderlite, Xantar, Xylex

Typical uses ⓘ

Safety shields and goggles; lenses; glazing panels; business machine housing; instrument casings; lighting fittings; safety helmets; electrical switchgear; laminated sheet for bullet-proof glazing; twin-walled sheets for glazing; kitchenware and tableware; microwave cookware, medical (sterilizable) components.

Composition overview

Compositional summary ⓘ

Linear polycarbonate copolymer from bis-phenol A (OC6H4C(CH3)2C6H4OC=O)n and bis-phenol TMC (OC6H4C(C5H7(CH3)3)2C6H4OC=O)n

Material family	ⓘ	Plastic (thermoplastic, amorphous)
Base material	ⓘ	PC (Polycarbonate)
Polymer code	ⓘ	PC

Composition detail (polymers and natural materials)

Polymer	ⓘ	100			%

Price

Price	ⓘ	* 3.04	-	3.26	EUR/kg
Price per unit volume	ⓘ	* 3.47e3	-	3.85e3	EUR/m^3

Physical properties

Density	ⓘ	1.14e3	-	1.18e3	kg/m^3

Mechanical properties

Young's modulus	ⓘ	2.21	-	2.4	GPa
Yield strength (elastic limit)	ⓘ	64.1	-	76	MPa
Tensile strength	ⓘ	57.2	-	69	MPa
Elongation	ⓘ	70	-	90	% strain
Compressive modulus	ⓘ	* 2.21	-	2.34	GPa
Compressive strength	ⓘ	* 76.9	-	86.9	MPa
Flexural modulus	ⓘ	2.2	-	2.4	GPa
Flexural strength (modulus of rupture)	ⓘ	82.7	-	96.5	MPa
Shear modulus	ⓘ	* 0.789	-	0.836	GPa
Bulk modulus	ⓘ	* 3.71	-	3.89	GPa
Poisson's ratio	ⓘ	* 0.392	-	0.408	
Shape factor	ⓘ	4.3			
Hardness - Vickers	ⓘ	* 19	-	22	HV
Hardness - Rockwell M	ⓘ	75	-	91	
Hardness - Rockwell R	ⓘ	* 111	-	123	
Fatigue strength at 10^7 cycles	ⓘ	* 22.1	-	28.8	MPa
Mechanical loss coefficient (tan delta)	ⓘ	* 0.0171	-	0.0181	

Impact & fracture properties

Fracture toughness	ⓘ	* 3.83	-	4.6	MPa.m^0.5
Impact strength, notched 23 °C	ⓘ	6.55	-	16	kJ/m^2
Impact strength, notched -30 °C	ⓘ	6.55	-	13	kJ/m^2
Impact strength, unnotched 23 °C	ⓘ	590	-	600	kJ/m^2
Impact strength, unnotched -30 °C	ⓘ	590	-	600	kJ/m^2

Thermal properties

Glass temperature	ⓘ	160	-	205	°C
Heat deflection temperature 0.45MPa	ⓘ	152	-	195	°C
Heat deflection temperature 1.8MPa	ⓘ	140	-	179	°C
Vicat softening point	ⓘ	158	-	203	°C
Maximum service temperature	ⓘ	* 128	-	144	°C
Minimum service temperature	ⓘ	-47	-	-37	°C
Thermal conductivity	ⓘ	0.197	-	0.201	W/m.°C
Specific heat capacity	ⓘ	1.2e3	-	1.3e3	J/kg.°C
Thermal expansion coefficient	ⓘ	70	-	137	µstrain/°C

Appendix 1.14. E-glass Datasheets

Datasheet E-glass

Glass, E grade fiber					

Typical uses ⓘ

Reinforcement, as single fibers or yarn or woven mat, in PMCs, MMCs, and CMSs

Composition overview

Compositional summary ⓘ

54%SiO2-15%Al2O3-12%CaO

Form	ⓘ	Fiber
Material family	ⓘ	Glass
Base material	ⓘ	Oxide

Composition detail (metals, ceramics and glasses)

Al2O3 (alumina)	ⓘ	12	%
CaO (calcia)	ⓘ	34	%
SiO2 (silica)	ⓘ	54	%

Price

Price	ⓘ	* 1.46	-	2.92	EUR/kg
Price per unit volume	ⓘ	* 3.72e3	-	7.59e3	EUR/m^3

Physical properties

Density	ⓘ	2.55e3	-	2.6e3	kg/m^3
Porosity (closed)	ⓘ	0			%
Porosity (open)	ⓘ	0			%

Mechanical properties

Young's modulus	ⓘ	72	-	85	GPa
Yield strength (elastic limit)	ⓘ	* 1.8e3	-	1.85e3	MPa
Tensile strength	ⓘ	1.95e3	-	2.05e3	MPa
Elongation	ⓘ	2.6	-	2.8	% strain
Compressive strength	ⓘ	* 4e3	-	5e3	MPa
Flexural modulus	ⓘ	* 72	-	85	GPa
Flexural strength (modulus of rupture)	ⓘ	3.3e3	-	3.45e3	MPa
Shear modulus	ⓘ	* 30	-	36	GPa
Bulk modulus	ⓘ	* 43	-	50	GPa
Poisson's ratio	ⓘ	0.21	-	0.23	
Shape factor	ⓘ	1			
Hardness - Vickers	ⓘ	300	-	600	HV
Fatigue strength at 10^7 cycles	ⓘ	* 1.6e3	-	1.7e3	MPa
Mechanical loss coefficient (tan delta)	ⓘ	* 1e-5	-	1e-4	

Impact & fracture properties

Fracture toughness	ⓘ	* 0.5	-	1	MPa.m^0.5

Thermal properties

Glass temperature	ⓘ	* 550	-	580	°C
Maximum service temperature	ⓘ	350	-	360	°C
Minimum service temperature	ⓘ	-273			°C
Thermal conductivity	ⓘ	1.2	-	1.35	W/m.°C
Specific heat capacity	ⓘ	800	-	805	J/kg.°C
Thermal expansion coefficient	ⓘ	4.9	-	5.1	µstrain/°C

Appendix 1.15. Overview composite calculations

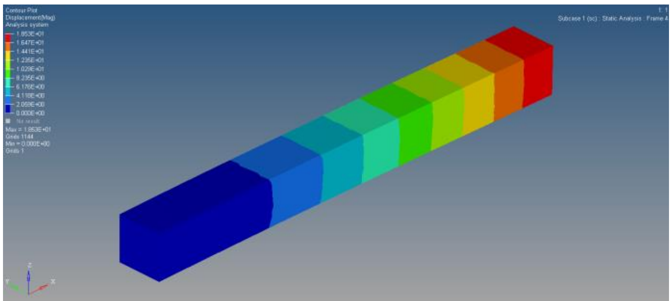
PET/PC			
40% continuous fibre			
Fibre volume fraction (continuou	V	0.4	Fc
Fibre volume fraction (long)	V	0.1	Fl
Density fibre (roving)	ρ	2600	kg/m3
Density long fibre	ρ	2600	kg/m3
Density PET/PC resin + 10% glass	ρ	1330	kg/m3
Ply thickness	t	8	mm
Fibre angle	°	0, 45, 90	deg
Fibre Ef longitudinal	Ef	85	GPa
Fibre Eft transversal	Eft	15	GPa
Fibre Poisson ratio	Vf	0.23	
Fibre tensile strength	σf	2.05E+03	MPa
Fibre compressive strenght	Xf	5000	MPa
Fibre G shear modulus	Gf	36	GPa
Matrix Em longitudinal	Em	4.83	GPa
Matrix Em transversal	Em	2.9	GPa
Matrix Poisson ratio	Vm	0.386	
Matrix tensile strength	σm	106	MPa
Matrix compressive strenght	Xm	102	MPa
Matrix G shear modulus	Gm	2.13	GPa
strength factor BI-axial		0.25	
Strenght factor BI-directional		0.5	

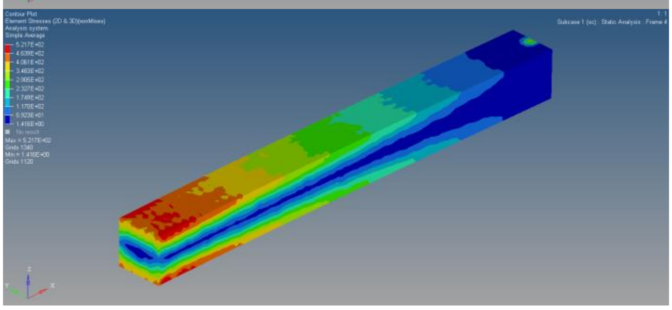
Density	rho	1838	kg/m3
E-modulus 11	E11	36.8980	GPa
E-modulus 22	E22	4.2815	GPa
E-modulus 33	E33	4.2815	GPa
Shear	G12	3.4153	Gpa
Shear	G13	3.5679	Gpa
Shear	G23	3.5679	Gpa
Poisson 12	v12	0.3236	
Poisson 13	v13	0.0375	
Poisson 23	v23	0.0375	
Compressive strength 11	C11	269.3201	MPa
Compressive strength 22	C22	3.5500	MPa
Compressive strenght 33	C33	3.5500	MPa
strain matrix longitudinal	εml	0.0219	
strain matrix transverse	εmt	0.0366	
strain fibre longitidinal	εfl	0.0241	
strain fibre transverse	εft	0.1367	
Tensile strength 11	σ1	883.6	MPa
Tensile strenght 22	σ2		MPa
Tensile strenght 33	σ3		MPa
Working Tensile (fibre fail)	σ1	883.6	MPa
Tensile strenght 11 (E-formule)	σ1	900.84	MPa
Tensile strenght 22 (E-formule)	σ2	104.53	MPa
Tensile strenght 33 (E-formule)	σ3	104.53	MPa
Tensile strenght fibre	σf	820.00	MPa
E-modulus Bi-axiaal	E11	9.2245	Gpa
E-modulus Bi-direc.	E11	18.449	GPa
Tensile strength BI-ax	σ1	220.90	MPa
Tensile strength BI-direc.	σ1	441.8	MPa
Tensile strength BI-ax (E-formule)	σ1	268.6	MPa
Tensile strength BI-direc. (E-formule)	σ1	473.6	MPa
Compressive strengh	X11	1960.2	MPa
Compressive strengh	X22	3.55	GPa
Compressive strengh	X33	3.55	GPa

Appendix 2.1. Steel comparison / specific strength

Beam				
Length	1	m	1	m
Width	0.1	m	0.1	m
Heigth	0.1	m	0.227	m
grav. Acc	9.81	m/s2	9.81	m/s2
Mass load	10000	kg	1000	kg
F=mg	98100	N	9810	N
M=FL	98100	Nm	9810	Nm
Material	Steel		Composite	
Density	7.8		1.838	
E-modulus	210	Gpa	36	Gpa
Scaling factor	1		0.5	
E-modulus	210	Gpa	18	Gpa
Moment of Inertia	8.33333E-06	m4	9.74757E-05	
E*I	1750		1754.56245	
Deflection	18.68571429	mm	1.863712517	mm
FL^3/3EI				
Stress	588600000	Pa	11422694.02	Pa
M*y/I	588600	kPa	11422.69402	kPa
	588.6	Mpa	11.42269402	Mpa
Weight/Volume				
Volume beam	0.01	m3	0.0227	m3
Volume increase			55.94713656	%
Mass beam	78	kg	41.7226	kg
Mass decrease			46.50948718	%

Hyperworks comparison





1: Hyperworks deflection (1)

2: Hyperworks stress (1)

Comparison Steel/Composite

Beam				
Length	1	m	1	m
Width	0.1	m	0.1	m
Height	0.053	m	0.082	m
grav. Acc	9.81	m/s2	9.81	m/s2
Mass load	1000	kg	1000	kg
F=mg	9810	N	9810	N
M=FL	9810	Nm	9810	Nm
Material	Steel		Composite	
Density	7.8		1.838	
E-modulus	210	Gpa	26	Gpa
Scaling factor	1		1	
E-modulus	210	Gpa	26	Gpa
Moment of Inertia	1.24064E-06	m4	4.59473E-06	
E*I	260.53475		119.4630667	
Deflection	12.55110883	mm	27.37247663	mm
FL^3/3EI				
Stress	209540761.8	Pa	87537180.25	Pa
M*y/I	209540.7618	kPa	87537.18025	kPa
	209.5407618	Mpa	87.53718025	Mpa
Weight/Volume				
Volume beam	0.0053	m3	0.0082	m3
Volume increase			35.36585366	%
Mass beam	41.34	kg	15.0716	kg
Mass decrease			63.54233188	%
Maximum yield	200	Mpa	88	Mpa

Beam				
Length	1	m	1	m
Width	0.1	m	0.1	m
Height	0.053	m	0.106	m
grav. Acc	9.81	m/s2	9.81	m/s2
Mass load	1000	kg	1000	kg
F=mg	9810	N	9810	N
M=FL	9810	Nm	9810	Nm
Material	Steel		Composite	
Density	7.8		1.838	
E-modulus	210	Gpa	26	Gpa
Scaling factor	1		1	
E-modulus	210	Gpa	26	Gpa
Moment of Inertia	1.24064E-06	m4	9.92513E-06	
E*I	260.53475		258.0534667	
Deflection	12.55110883	mm	12.67179256	mm
FL^3/3EI				
Stress	209540761.8	Pa	52385190.46	Pa
M*y/I	209540.7618	kPa	52385.19046	kPa
	209.5407618	Mpa	52.38519046	Mpa
Weight/Volume				
Volume beam	0.0053	m3	0.0106	m3
Volume increase			50	%
Mass beam	41.34	kg	19.4828	kg
Mass decrease			52.87179487	%
Maximum yield	210	Mpa	88	Mpa

Comparisons on stresses and deflection.

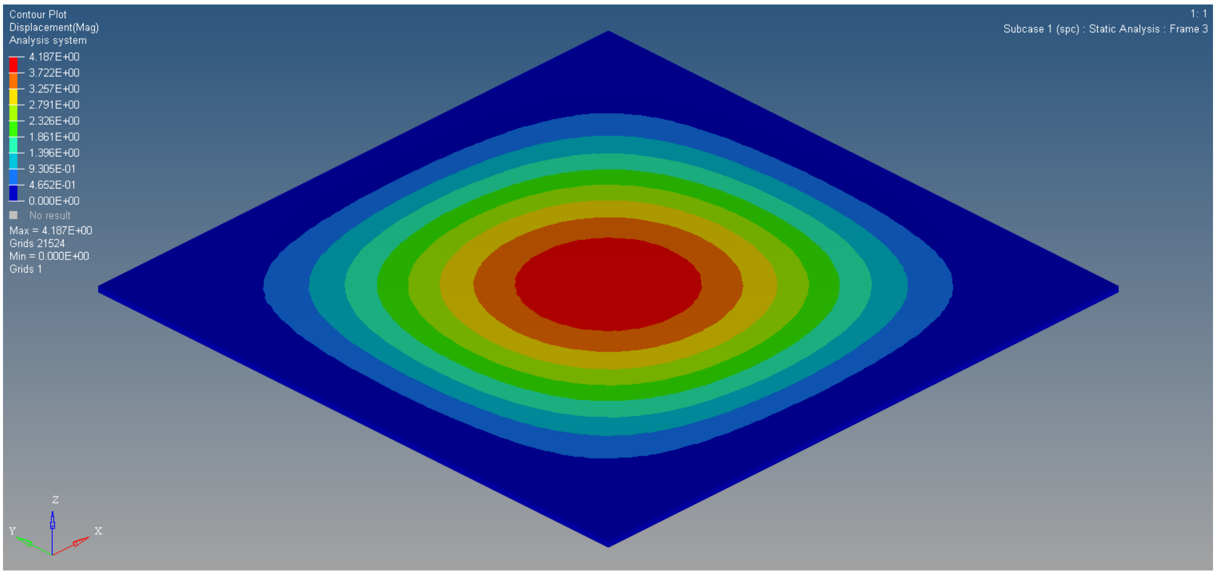
Beam				
Length	1	m	0.5	m
Width	0.1	m	0.1	m
Height	0.0486	m	0.0488	m
grav. Acc	9.81	m/s2	9.81	m/s2
Mass load	1000	kg	1000	kg
F=mg	9810	N	9810	N
M=FL	9810	Nm	4905	Nm
Material	Steel		Composite	
Density	7.8		1.838	
E-modulus	210	Gpa	26	Gpa
Scaling factor	1		1	
E-modulus	210	Gpa	26	Gpa
Moment of Inertia	9.56594E-07	m4	9.68452E-07	
E*I	200.884698		25.17975893	
Deflection	16.27799445	mm	16.23327694	mm
FL^3/3EI				
Stress	249199817.1	Pa	123580690.7	Pa
M*y/I	249199.8171	kPa	123580.6907	kPa
	249.1998171	Mpa	123.5806907	Mpa
Weight/Volume				
Volume beam	0.00486	m3	0.00488	m3
Volume increase			0.409836066	%
Mass beam	37.908	kg	8.96944	kg
Mass decrease			76.33892582	%
Maximum yield	250	Mpa	88	Mpa
Extra weight per stiffener	15%		2.690832	kg
Final weight reduction			69.24060357	%

Comparison on span width reduction

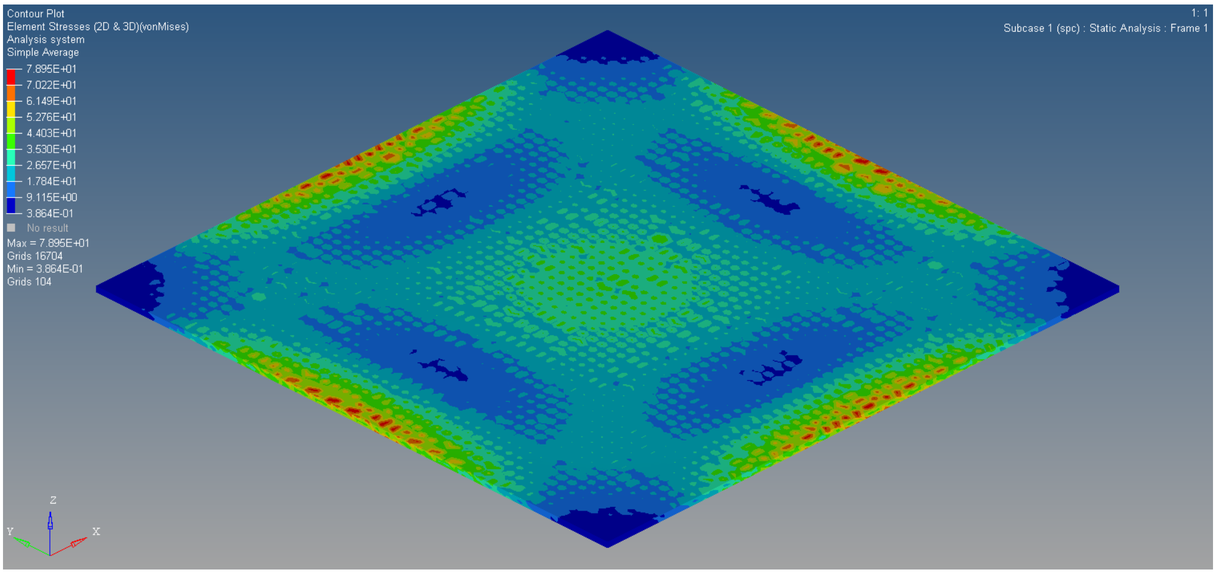
Appendix 2.2. Outer Plate weight reduction

	1000 mm		900 mm	800 mm	700 mm	600 mm	500 mm	400 mm	300 mm	200 mm	100 mm		steel	
Outer plate													Ref.	
Static pressure:	24000	Pa	24000	24000	####	24000	24000	24000	24000	24000	24000		24000	
Dynamic pressure:	40000	Pa	40000	40000	####	40000	40000	40000	40000	40000	40000		40000	
Total pressure:	64000	Pa	64000	64000	64000	64000	64000	64000	64000	64000	64000		64000	Pa
Maximum stress laminate:	60	Mpa	60	60	60	60	60	60	60	60	60		110	
Plate width mm: (short)	1000	mm	900	800	700	600	500	400	300	200	100		1000	
Plate width m:	1	m	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1		1	
Plate length mm: (long)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000		1000	
Plate length m:	1	m	1	1	1	1	1	1	1	1	1		1	
Plate thickness mm:		mm												
Plate thickness m:		m												
short side/long side b/a	1	w/l	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1		1	
C1 (table) (at b/a) (M/pw^2)	0.03		0.035	0.038	0.04	0.048	0.052	0.057	0.06	0.062	0.063		0.03	
M=C*p*(w^2)	1920	Nm/m	1814.4	1556.5	1348	1105.9	832	583.68	345.6	158.72	40.32		1920	
σ=M*(c/I) = 6M/(t^2)	-		-	-	-	-	-	-	-	-	-		-	
Thickness														
t=(6M/σ)^0.5	13.856406	mm	13.47	12.476	11.61	10.516	9.1214	7.6399	5.8788	3.984	2.00798		10.234	
Displacement														
C2 (table) (at l/w)	0.0175		0.022	0.028	0.03	0.037	0.039	0.041	0.042	0.042	0.042		0.032	
(at middle plate)														
C	0.00875		0.0133	0.0199	0.026	0.0328	0.0367	0.04	0.0417	0.0419	0.042		0.016	
v (Poisson)	0.323		0.323	0.323	0.32	0.323	0.323	0.323	0.323	0.323	0.323		0.29	
E (e-modulus) original	36	GPa	36	36	36	36	36	36	36	36	36		210	
Scaling factor	0.38		0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38		1	
E (e-modulus) laminate	13.68	GPa	13.68	13.68	13.68	13.68	13.68	13.68	13.68	13.68	13.68		210	
Displacement:	13.781567	mm	14.943	17.557	16.58	15.295	12.667	9.6167	6.9601	4.446	2.17354		4.1671	mm
Weight/Volume														
Volume	0.0138564	m3	0.0121	0.01	0.008	0.0063	0.0046	0.0031	0.0018	0.0008	0.0002		0.0102	
Material density	1.838		1.838	1.838	1.84	1.838	1.838	1.838	1.838	1.838	1.838		7.8	
Mass plate	25.468075	kg	22.282	18.345	14.94	11.597	8.3826	5.6169	3.2416	1.4645	0.36907		79.822	
Mass plate 1000 x 1000	25.468075		24.758	22.931	21.34	19.329	16.765	14.042	10.805	7.3225	3.69067			
Mass plate 1m x 1m + stiffeners														
Weight savings	68%		69%	71%	73%	76%	79%	82%	86%	91%	95%			
Allowable deflection/span ratio	10		9	8	7	6	5	4	3	2	1			
100														
Minimum required thickness	17.68664		15.918	14.149	12.38	10.612	8.8433	7.0747	5.306	3.5373	1.76866			
omega 1.1	19.455304		17.51	15.564	13.62	11.673	9.7277	7.7821	5.8366	3.8911	1.94553			

Comparison Hyperworks



Hyperworks displacement comparison



Hyperworks stress comparison

Outer plate comparison

	1000 mm		1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm		steel
Outer plate													Ref.
Static pressure:	24000	Pa	24000	24000	24000	24000	24000	24000	24000	24000	24000		24000
Dynamic pressure:	40000	Pa	40000	40000	40000	40000	40000	40000	40000	40000	40000		40000
Total pressure:	64000	Pa	64000	64000	64000	64000	64000	64000	64000	64000	64000		64000
Maximum stress laminate:	88	Mpa	88	88	88	88	88	88	88	88	88		250
Plate width mm: (short)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000		1000
Plate width m:	1	m	1	1	1	1	1	1	1	1	1		1
Plate length mm: (long)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000		1000
Plate length m:	1	m	1	1	1	1	1	1	1	1	1		1
short side/long side b/a	1	w/l	1	1	1	1	1	1	1	1	1		1
C1 (table) (at b/a) (M/pw^2)	0.03		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03		0.03
M=C*p*(w^2)	1920	Nm/m	1920	1920	1920	1920	1920	1920	1920	1920	1920		1920
Thickness													
t=(6M/σ)^0.5	11.441551	mm	11.44155	11.44155	11.44155	11.44155	11.44155	11.44155	11.44155	11.44155	11.4416		6.7882
Thickness	10		8	10	12	14	16	18	21.7	22	24		
Displacement													
C2 (table) (at l/w)	0.0175		0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175		0.018
(at middle plate)													
C	0.00875		0.00875	0.00875	0.00875	0.00875	0.00875	0.00875	0.00875	0.00875	0.00875		0.0088
v (Poisson)	0.323		0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323		0.29
E (e-modulus) original	26	GPa	26	26	26	26	26	26	26	26	26		210
Scaling factor	0.5		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		1
E (e-modulus) laminate	13	GPa	13	13	13	13	13	13	13	13	13		210
Displacement:	38.582751	mm	75.35694	38.58275	22.32798	14.06077	9.419617	6.615698	3.775844	3.623474	2.791		7.8081
Weight/Volume													
Volume	0.01	m3	0.008	0.01	0.012	0.014	0.016	0.018	0.0217	0.022	0.024		0.0068
Material density	1.838		1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838		7.8
Mass plate	18.38	kg	14.704	18.38	22.056	25.732	29.408	33.084	39.8846	40.436	44.112		52.948
Weight savings	65%		72%	65%	58%	51%	44%	38%	25%	24%	17%		
Allowable deflection (span/ratio)	10	mm											
100													
Minimum required thickness	19.713106												
Omega = 1.1	21.684417	mm											

Comparison on thickness

	1000 mm		1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	steel
Outer plate												Ref.
Static pressure:	24000	Pa	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000
Dynamic pressure:	40000	Pa	40000	40000	40000	40000	40000	40000	40000	40000	40000	40000
Total pressure:	64000	Pa	64000	64000	64000	64000	64000	64000	64000	64000	64000	64000
Maximum stress laminate:	88	Mpa	88	88	88	88	88	88	88	88	88	250
Plate width mm: (short)	500	mm	1000	1000	1000	1000	1000	500	1000	1000	1000	1000
Plate width m:	0.5	m	1	1	1	1	1	0.5	1	1	1	1
Plate length mm: (long)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Plate length m:	1	m	1	1	1	1	1	1	1	1	1	1
short side/long side b/a	0.5	w/l	1	1	1	1	1	0.5	1	1	1	1
C1 (table) (at b/a) (M/pw^2)	0.03		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
M=C*p*(w^2)	480	Nm/m	1920	1920	1920	1920	1920	480	1920	1920	1920	1920
Thickness												
t=(6M/σ)^0.5	5.7207755	mm	11.44155	11.44155	11.44155	11.44155	11.44155	5.720776	11.44155	11.44155	11.4416	6.7882
Thickness	10		8	10	12	14	16	10.8	21.7	22	24	
Displacement												
C2 (table) (at l/w)	0.0175		0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.018
(at middle plate)												
C	0.0164706		0.00875	0.00875	0.00875	0.00875	0.00875	0.016471	0.00875	0.00875	0.00875	0.0088
v (Poisson)	0.323		0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.29
E (e-modulus) original	26	GPa	26	26	26	26	26	26	26	26	26	210
Scaling factor	0.5		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1
E (e-modulus) laminate	13	GPa	13	13	13	13	13	13	13	13	13	210
Displacement:	4.5391471	mm	75.35694	38.58275	22.32798	14.06077	9.419617	3.603321	3.775844	3.623474	2.791	7.8081
Weight/Volume												
Volume	0.005	m3	0.008	0.01	0.012	0.014	0.016	0.0108	0.0217	0.022	0.024	0.0068
Material density	1.838		1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	7.8
Mass plate	9.19	kg	14.704	18.38	22.056	25.732	29.408	19.8504	39.8846	40.436	44.112	52.948
Weight savings	83%		72%	65%	58%	51%	44%	63%	25%	24%	17%	
Allow able deflection (span/ratio)	5	mm										
100												
Minimum required thickness	9.8565532											
Omega = 1.1	10.842208	mm										
Additional stiffeners	15%											
Additional weight								2.97756	kg			
Weight saving								56.8862	%			

Comparison on span reduction 500 mm

	1000 mm		1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	steel
Outer plate												Ref.
Static pressure:	24000	Pa	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000
Dynamic pressure:	40000	Pa	40000	40000	40000	40000	40000	40000	40000	40000	40000	40000
Total pressure:	64000	Pa	64000	64000	64000	64000	64000	64000	64000	64000	64000	64000
Maximum stress laminate:	88	Mpa	88	88	88	88	88	88	88	88	88	250
Plate width mm: (short)	750	mm	1000	1000	1000	1000	750	500	1000	1000	1000	1000
Plate width m:	0.75	m	1	1	1	1	0.75	0.5	1	1	1	1
Plate length mm: (long)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Plate length m:	1	m	1	1	1	1	1	1	1	1	1	1
short side/long side b/a	0.75	w/l	1	1	1	1	0.75	0.5	1	1	1	1
C1 (table) (at b/a) (M/pw^2)	0.03		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
M=C*p*(w^2)	1080	Nm/m	1920	1920	1920	1920	1080	480	1920	1920	1920	1920
Thickness												
t=(6M/σ)^0.5	8.5811633	mm	11.44155	11.44155	11.44155	11.44155	8.581163	5.720776	11.44155	11.44155	11.4416	6.7882
Thickness	10		8	10	12	14	16	10.8	21.7	22	24	
Displacement												
C2 (table) (at l/w)	0.0175		0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.018
(at middle plate)												
C	0.0132938		0.00875	0.00875	0.00875	0.00875	0.013294	0.016471	0.00875	0.00875	0.00875	0.0088
v (Poisson)	0.323		0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.29
E (e-modulus) original	26	GPa	26	26	26	26	26	26	26	26	26	210
Scaling factor	0.5		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1
E (e-modulus) laminate	13	GPa	13	13	13	13	13	13	13	13	13	210
Displacement:	18.547198	mm	75.35694	38.58275	22.32798	14.06077	4.528124	3.603321	3.775844	3.623474	2.791	7.8081
Weight/Volume												
Volume	0.0075	m3	0.008	0.01	0.012	0.014	0.016	0.0108	0.0217	0.022	0.024	0.0068
Material density	1.838		1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	7.8
Mass plate	13.785	kg	14.704	18.38	22.056	25.732	29.408	19.8504	39.8846	40.436	44.112	52.948
Weight savings	74%		72%	65%	58%	51%	44%	63%	25%	24%	17%	
Allow able deflection (span/ratio)	7.5	mm										
100						7						
Minimum required thickness	14.78483											
Omega = 1.1	16.263313	mm										
Additional stiffeners	15%											
Additional weight							4.4112	2.97756	kg			
Weight saving							36.12771	56.8862	%			

Comparison on span reduction 750 mm

Appendix 2.3. Deck Plate weight reduction

Deck element

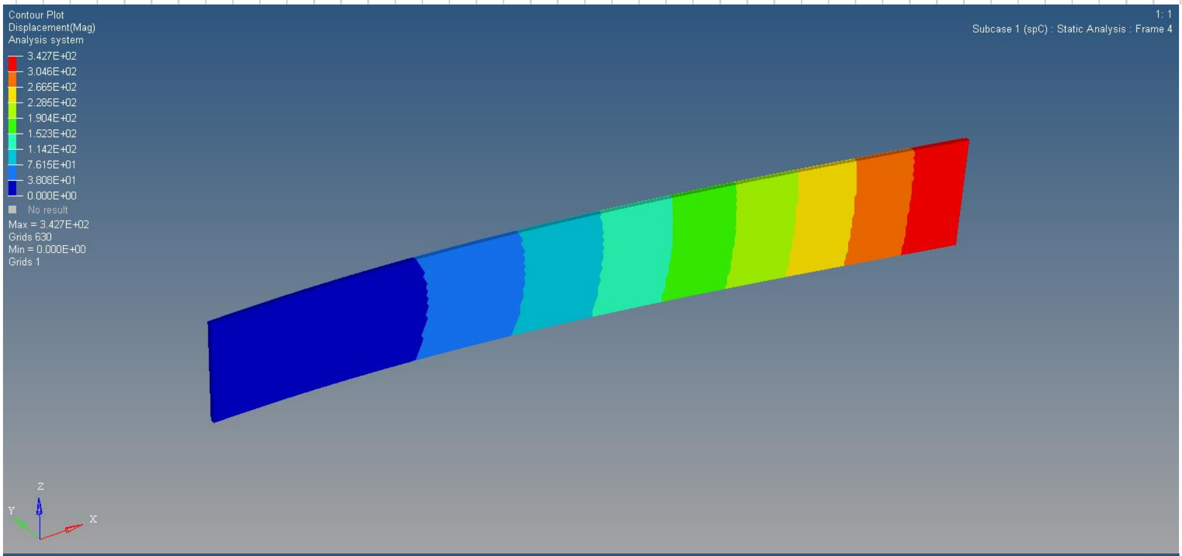
	1000 mm		1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	steel
Outer plate												Ref.
Static pressure:	7180	Pa	7180	7180	7180	7180	7180	7180	7180	7180	7180	7180
Dynamic pressure:	0	Pa	0	0	0	0	0	0	0	0	0	0
Total pressure:	7180	Pa	7180	7180	7180	7180	7180	7180	7180	7180	7180	7180
Maximum stress laminate:	88	Mpa	188	188	188	188	188	188	188	188	188	250
Plate width mm: (short)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Plate width m:	1	m	1	1	1	1	1	1	1	1	1	1
Plate length mm: (long)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Plate length m:	1	m	1	1	1	1	1	1	1	1	1	1
short side/long side b/a	1	w/l	1	1	1	1	1	1	1	1	1	1
C1 (table) (at b/a) (M/pw^2)	0.03		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
M=C*p*(w^2)	215.4	Nm/m	215.4	215.4	215.4	215.4	215.4	215.4	215.4	215.4	215.4	215.4
σ=M*(c/I) = 6M/(t^2)	-		-	-	-	-	-	-	-	-	-	-
Thickness												
t=(6M/σ)^0.5	3.83228	mm	2.62192	2.62192	2.62192	2.62192	2.62192	2.62192	2.62192	2.62192	2.62192	2.27368
Thickness	5		6	7	8	9	10	11	12	16	20	5
Displacement												
C2 (table) (at l/w)	0.0175		0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175
(at middle plate)												
C	0.00875		0.00875	0.00875	0.00875	0.00875	0.00875	0.00875	0.00875	0.00875	0.00875	0.00875
v (Poisson)	0.323		0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.29
E (e-modulus) original	36	GPa	36	36	36	36	36	36	36	36	36	210
Scaling factor	0.38		0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	1
E (e-modulus) laminate	13.68	GPa	13.68	13.68	13.68	13.68	13.68	13.68	13.68	13.68	13.68	210
Displacement:	32.9067	mm	19.0433	11.9923	8.03387	5.64245	4.11334	3.09042	2.38041	1.00423	0.51417	2.19205
Weight/Volume												
Volume	0.005	m3	0.006	0.007	0.008	0.009	0.01	0.011	0.012	0.016	0.02	0.005
Material density	1.838		1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	7.8
Mass plate	9.19	kg	11.028	12.866	14.704	16.542	18.38	20.218	22.056	29.408	36.76	39
Weight savings	76%		72%	67%	62%	58%	53%	48%	43%	25%	6%	
Allowable deflection (span/ratio)	10	mm										
100												
Minimum required thickness	8.53022											
Omega = 1.1	9.38324	mm										

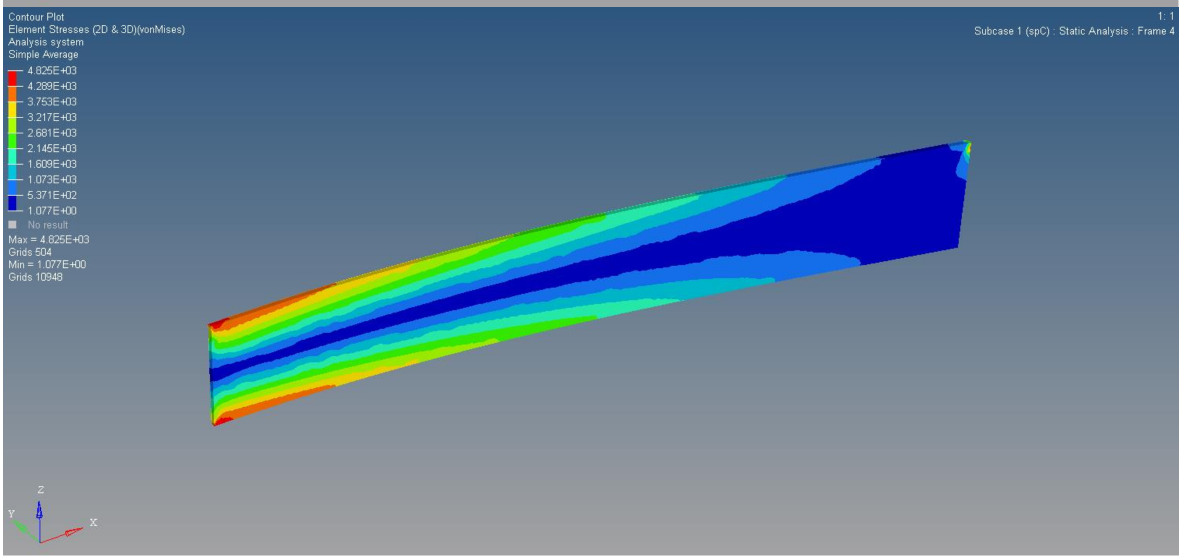
Required laminate thickness

Appendix 2.4. Main Girder analysis

Hyperworks comparison

210	
187.2	kg
0.024	m3
4705.08	Mpa
4705078	kPa
4.7E+09	Pa
378.087	mm
0.37809	m
2509.38	kN*m
20075	kN*m
3178	kN*m
16897	kN*m
0.0224	
0.00011	m^4
210	GPa
1	
210	Gpa
9.81	
7.8	kg.dm3
0.02	m
0.4	m
3	m
0	m
8	
Steel	





Hyperworks comparison

Main girder

Main Girder											Steel	
Number of girders	8			8	8	8	8	8	8		8	
Girder height (highest and lowest)	2	m		2	2	2	2	2	2		2	m
Length girder	3	m		3	3	3	3	3	3		3	m
Heigth girder	0.3	m		0.3	0.3	0.3	0.3	0.3	0.3		0.3	m
Thickness girder	0.056	m		0.03	0.04	0.05	0.06	0.07	0.08		0.0196	m
rho material	1.838	kg.dm3		1.838	1.838	1.838	1.838	1.838	1.838		7.8	kg.dm3
Gravitational acc.	9.81			9.81	9.81	9.81	9.81	9.81	9.81		9.81	
E modulus original	26	Gpa		26	26	26	26	26	26		210	Gpa
Scale factor	0.8			0.8	0.8	0.8	0.8	0.8	0.8		1	
E-modulus laminate	20.8	GPa		20.8	20.8	20.8	20.8	20.8	20.8		210	GPa
Moment of inertia girder	0.057624	m^4		0.03087	0.04116	0.05145	0.06174	0.07203	0.08232		0.0201684	m^4
EI				0.6421	0.856128	1.07016	1.28419	1.49822	1.71226		4.235364	
Bending moment	16897	kN*m		16897	16897	16897	16897	16897	16897		16897	kN*m
Still water bending	3178	kN*m		3178	3178	3178	3178	3178	3178		3178	kN*m
Total bending moment	20075	kN*m		20075	20075	20075	20075	20075	20075		20075	kN*m
Bending moment per girder	2509.375	kN*m		2509.38	2509.375	2509.38	2509.38	2509.38	2509.38		2509.375	kN*m
Deflection												
Maximum deflection	0.007066	m		0.01319	0.009892	0.00791	0.00659	0.00565	0.00495		0.00199963	m
ML^2/(8EI)	7.065983	mm		13.1898	9.892377	7.9139	6.59492	5.65279	4.94619		1.99962521	mm
Stress												
Maximum stress	87094787	Pa		1.6E+08	1.22E+08	9.8E+07	8.1E+07	7E+07	6.1E+07		248842248	Pa
sigma = My/I	87094.79	kPa		162577	121932.7	97546.2	81288.5	69675.8	60966.4		248842.248	kPa
	87.09479	Mpa		162.577	121.9327	97.5462	81.2885	69.6758	60.9664		248.842248	Mpa
Weight/Volume												
Volume	0.0504	m3		0.027	0.036	0.045	0.054	0.063	0.072		0.01764	m3
Weight	92.6352	kg		49.626	66.168	82.71	99.252	115.794	132.336		137.592	kg
Weight saving over steel per girder	32.67399	%		63.9325	51.90999	39.8875	27.865	15.8425	3.81999	%		
Weight saving for all girders	741.0816	kg		397.008	529.344	661.68	794.016	926.352	1058.69		1100.736	kg
Weight saving for all girders	32.7%			63.9%	51.9%	39.9%	27.9%	15.8%	3.8%			
Allowable deflection (span/ratio)	12	mm										
250												
Maximum allowable stress	88	Mpa									250	Mpa
0.33												

Girder stress based

Main Girder										Steel	
Number of girders	8		8	8	8	8	8	8		8	
Girder height (highest and lowest)	2	m	2	2	2	2	2	2		2	m
Length girder	3	m	3	3	3	3	3	3		3	m
Heigth girder	0.3	m	0.3	0.3	0.3	0.3	0.3	0.3		0.3	m
Thickness girder	0.198	m	0.03	0.04	0.05	0.06	0.07	0.08		0.0196	m
rho material	1.838	kg.dm3	1.838	1.838	1.838	1.838	1.838	1.838		7.8	kg.dm3
Gravitational acc.	9.81		9.81	9.81	9.81	9.81	9.81	9.81		9.81	
E modulus original	26	Gpa	26	26	26	26	26	26		210	Gpa
Scale factor	0.8		0.8	0.8	0.8	0.8	0.8	0.8		1	
E-modulus laminate	20.8	GPa	20.8	20.8	20.8	20.8	20.8	20.8		210	GPa
Moment of inertia girder	0.203742	m^4	0.03087	0.04116	0.05145	0.06174	0.07203	0.08232		0.0201684	m^4
EI			0.6421	0.856128	1.07016	1.28419	1.49822	1.71226		4.235364	
Bending moment	16897	kN*m	16897	16897	16897	16897	16897	16897		16897	kN*m
Still water bending	3178	kN*m	3178	3178	3178	3178	3178	3178		3178	kN*m
Total bending moment	20075	kN*m	20075	20075	20075	20075	20075	20075		20075	kN*m
Bending moment per girder	2509.375	kN*m	2509.38	2509.375	2509.38	2509.38	2509.38	2509.38		2509.375	kN*m
Deflection											
Maximum deflection	0.001998	m	0.01319	0.009892	0.00791	0.00659	0.00565	0.00495		0.00199963	m
ML^2/(8EI)	1.99846	mm	13.1898	9.892377	7.9139	6.59492	5.65279	4.94619		1.99962521	mm
Stress											
Maximum stress	24632869	Pa	1.6E+08	1.22E+08	9.8E+07	8.1E+07	7E+07	6.1E+07		248842248	Pa
sigma = My/I	24632.87	kPa	162577	121932.7	97546.2	81288.5	69675.8	60966.4		248842.248	kPa
	24.63287	Mpa	162.577	121.9327	97.5462	81.2885	69.6758	60.9664		248.842248	Mpa
Weight/Volume											
Volume	0.1782	m3	0.027	0.036	0.045	0.054	0.063	0.072		0.01764	m3
Weight	327.5316	kg	49.626	66.168	82.71	99.252	115.794	132.336		137.592	kg
Weight saving over steel per girder	-138.046	%	63.9325	51.90999	39.8875	27.865	15.8425	3.81999	%		
Weight saving for all girders	2620.253	kg	397.008	529.344	661.68	794.016	926.352	1058.69		1100.736	kg
Weight saving for all girders	-138.0%		63.9%	51.9%	39.9%	27.9%	15.8%	3.8%			
Allowable deflection (span/ratio)	12	mm									
250											
Maximum allowable stress	88	Mpa								250	Mpa
0.33											

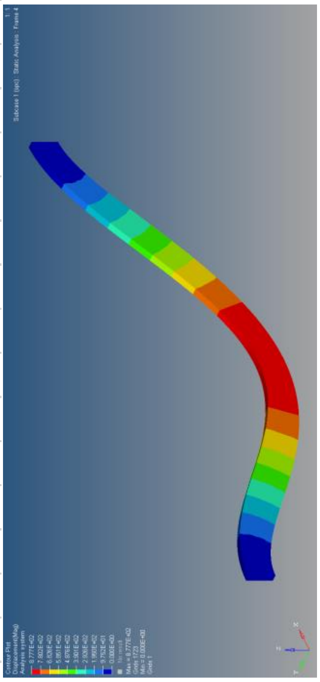
Girder deflection based

Main Girder										Steel	
Number of girders	8			8	8	8	8	8	8		8	
Girder height (highest and lowest)	2	m		2	2	2	2	2	2		2	m
Length girder	2	m		3	3	3	3	3	3		3	m
Heigth girder	0.3	m		0.3	0.3	0.3	0.3	0.3	0.3		0.3	m
Thickness girder	0.07	m		0.03	0.04	0.05	0.06	0.07	0.08		0.024	m
rho material	1.838	kg.dm3		1.838	1.838	1.838	1.838	1.838	1.838		7.8	kg.dm3
Gravitational acc.	9.81			9.81	9.81	9.81	9.81	9.81	9.81		9.81	
E modulus original	26	Gpa		26	26	26	26	26	26		210	Gpa
Scale factor	0.8			0.8	0.8	0.8	0.8	0.8	0.8		1	
E-modulus laminate	20.8	GPa		20.8	20.8	20.8	20.8	20.8	20.8		210	GPa
Moment of inertia girder	0.07203	m^4		0.03087	0.04116	0.05145	0.06174	0.07203	0.08232		0.024696	m^4
EI				0.6421	0.856128	1.07016	1.28419	1.49822	1.71226		5.18616	
Bending moment	16897	kN*m		16897	16897	16897	16897	16897	16897		16897	kN*m
Still water bending	3178	kN*m		3178	3178	3178	3178	3178	3178		3178	kN*m
Total bending moment	20075	kN*m		20075	20075	20075	20075	20075	20075		20075	kN*m
Bending moment per girder	2509.375	kN*m		2509.38	2509.375	2509.38	2509.38	2509.38	2509.38		2509.375	kN*m
Deflection												
Maximum deflection	0.001675	m		0.01319	0.009892	0.00791	0.00659	0.00565	0.00495		0.00163303	m
ML^2/(8EI)	1.6749	mm		13.1898	9.892377	7.9139	6.59492	5.65279	4.94619		1.63302725	mm
Stress												
Maximum stress	69675830	Pa		1.6E+08	1.22E+08	9.8E+07	8.1E+07	7E+07	6.1E+07		203221169	Pa
sigma = My/I	69675.83	kPa		162577	121932.7	97546.2	81288.5	69675.8	60966.4		203221.169	kPa
	69.67583	Mpa		162.577	121.9327	97.5462	81.2885	69.6758	60.9664		203.221169	Mpa
Weight/Volume												
Volume	0.042	m3		0.027	0.036	0.045	0.054	0.063	0.072		0.0216	m3
Weight	77.196	kg		49.626	66.168	82.71	99.252	115.794	132.336		168.48	kg
Weight saving over steel per girder	54.18091	%		70.5449	60.7265	50.9081	41.0897	31.2714	21.453	%		
Weight saving for all girders	617.568	kg		397.008	529.344	661.68	794.016	926.352	1058.69		1347.84	kg
Weight saving for all girders	54.2%			70.5%	60.7%	50.9%	41.1%	31.3%	21.5%			
Allowable deflection (span/ratio)	8	mm										
250												
Maximum allowable stress	200	Mpa									210	

Comparison girder with adjusted span width

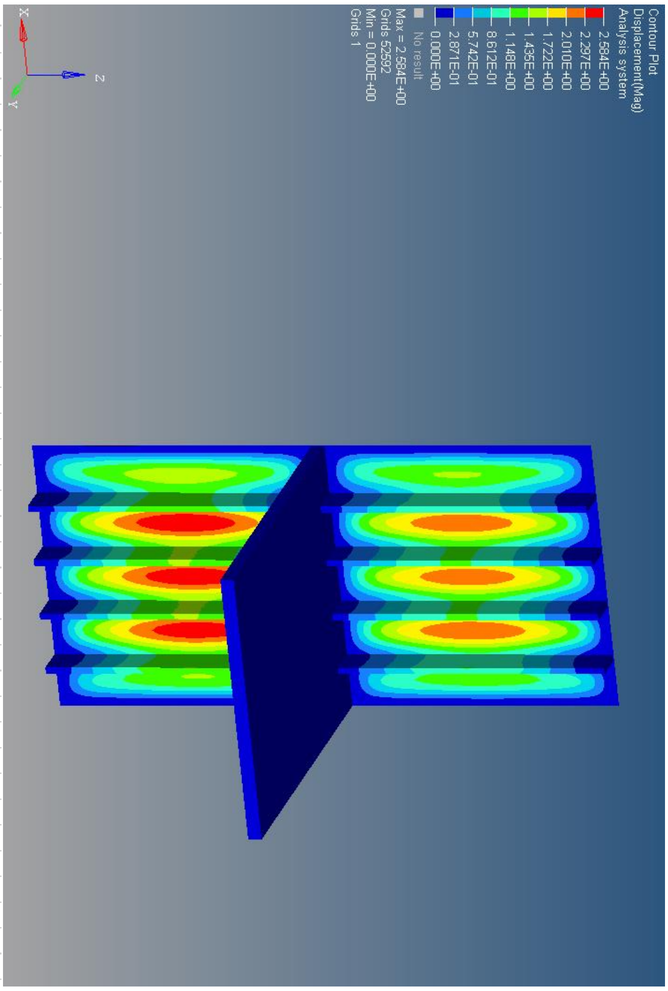
Appendix 2.5. Bulkhead analysis

Stiffener Bulkhead		
Pa	180000	
Mpa	0.18	
kN/m2	180	
Length	4000	
Width	50	
Height	200	
I	33333333.33	
E	210000	
Deflection	857.1428571	mm



Bulkhead stiffener analyses

Bulkhead	Steel	
Design pressure bulkhead	180000	Pa
	0.18	Mpa
Length	2000	mm
Width	12	mm
Height	250	mm
Width plate	400	mm
Moment of inertia	15625000	
E-modulus material	210000	Mpa
Scaling factor	1	
E-modulus relative	210000	MPa
Deflection		
Deflection	0.914285714	mm
Max bending moment		
wl^2/12	24000000	Nm
Stress		
Maximum stress s=My/I	192	Mpa
Weight/Volume		
Volume	0.006	m2
Density	7.8	kg/dm3
Weight	46.8	kg
Allowable deflection span/ra	13.33333333	mm
150		
Maximum allowable stress	210	Mpa
0.4		



Bulkhead stiffener + plate analyses

Bulkhead

Bulkhead	Steel		Bulkhead	Composite		
Design pressure bulkhead	180000	Pa	Design pressure bulkhead	180000	Pa
	0.18	Mpa		0.18	Mpa
Length	2000	mm	Length	2000	mm
Width	6.5	mm	Width	18.3	mm
Height	300	mm	Height	300	mm
Width plate	400	mm	Width plate	400	mm
Moment of inertia	14625000		Moment of inertia	41175000	
E-modulus material	210000	Mpa	E-modulus material	26000	Mpa
Scaling factor	1		Scaling factor	0.8	
E-modulus relative	210000	MPa	E-modulus relative	20800	MPa
Deflection			Deflection		
Deflection	0.976800977	mm	Deflection	3.502872355	mm
Max bending moment			Stress		
wl^2/12	24000000	Nm	wl^2/12	24000000	Nm
Stress			Stress		
Maximum stress s=My/I	246.1538462	Mpa	Maximum stress s=My/I	87.43169399	Mpa
Weight/Volume			Weight/Volume		
Volume	0.0039	m2	Volume	0.01098	m2
Density	7.8	kg/dm3	Density	1.6	kg/dm3
Weight	30.42	kg	Weight	17.568	kg
			Weigth saving	42.24852071	%
Allowable deflection span/ratio	13.33333333	mm	Allowable deflection span/ratio	13.33333333	mm
150			150		
Maximum allowable stress	250	Mpa	Maximum allowable stress	88	Mpa

Stress based

Bulkhead	Steel		Bulkhead	Composite	
Design pressure bulkhead	180000	Pa	Design pressure bulkhead	180000	Pa
	0.18	Mpa		0.18	Mpa
Length	2000	mm	Length	1500	mm
Width	6.5	mm	Width	21	mm
Height	300	mm	Height	300	mm
Width plate	400	mm	Width plate	400	mm
Moment of inertia	14625000		Moment of inertia	47250000	
E-modulus material	210000	Mpa	E-modulus material	26000	Mpa
Scaling factor	1		Scaling factor	0.8	
E-modulus relative	210000	MPa	E-modulus relative	20800	MPa
Deflection			Deflection		
Deflection	0.976800977	mm	Deflection	0.965831044	mm
Max bending moment			Stress		
wl^2/12	24000000	Nm	wl^2/12	13500000	Nm
Stress			Stress		
Maximum stress s=My/I	246.1538462	Mpa	Maximum stress s=My/I	42.85714286	Mpa
Weight/Volume			Weight/Volume		
Volume	0.0039	m2	Volume	0.0126	m2
Density	7.8	kg/dm3	Density	1.6	kg/dm3
Weight	30.42	kg	Weight	20.16	kg
			Weigth saving	33.72781065	%
Allowable deflection span/ratio	13.33333333	mm	Allowable deflection span/ratio	10	mm
150			150		
Maximum allowable stress	250	Mpa	Maximum allowable stress	88	Mpa

Decreased span

Plate bulkhead

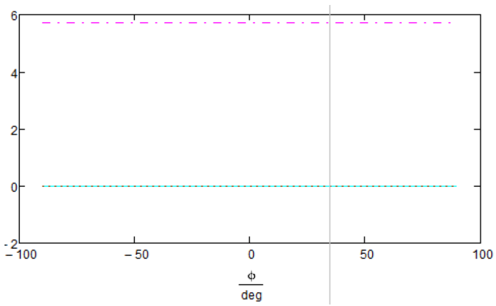
	1000 mm		1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm	1000 mm		steel
Outer plate													Ref.
Static pressure:	180000	Pa	180000	180000	180000	180000	180000	180000	180000	180000	180000		2E+05
Dynamic pressure:	0	Pa	0	0	0	0	0	0	0	0	0		0
Total pressure:	180000	Pa	180000	180000	180000	180000	180000	180000	180000	180000	180000		180000
Maximum stress laminate:	88	Mpa	88	88	88	88	88	88	88	88	88		250
Plate width mm: (short)	400	mm	400	400	1000	1000	1000	1000	500	1000	1000		1000
Plate width m:	0.4	m	0.4	0.4	1	1	1	1	0.5	1	1		1
Plate length mm: (long)	1000	mm	1000	1000	1000	1000	1000	1000	1000	1000	1000		1000
Plate length m:	1	m	1	1	1	1	1	1	1	1	1		1
Plate thickness mm:		mm											
Plate thickness m:		m											
short side/long side b/a	0.4	w/l	0.4	0.4	1	1	1	1	0.5	1	1		1
C1 (table) (at b/a) (M/pw^2)	0.03		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03		0.03
M=C*p*(w^2)	864	Nm/m	864	864	5400	5400	5400	5400	1350	5400	5400		5400
σ=M*(c/I) = 6M/(t^2)	-		-	-	-	-	-	-	-	-	-		-
Thickness													
t=(6M/σ)^0.5	7.6752258	mm	7.675226	7.675226	19.18806	19.18806	19.18806	19.18806	9.594032	19.18806	19.1881		11.384
Thickness	15		12	16	22	24	26	28	30	32	34		
Displacement													
C2 (table) (at l/w)	0.0175		0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175		0.018
(at middle plate)													
C	0.0170632		0.017063	0.017063	0.00875	0.00875	0.00875	0.00875	0.016471	0.00875	0.00875		0.0088
v (Poisson)	0.323		0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323		0.29
E (e-modulus) original	26	GPa	26	26	26	26	26	26	26	26	26		210
Scaling factor	0.8		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8		1
E (e-modulus) laminate	20.8	GPa	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8		210
Displacement:	1.0031916	mm	1.959359	0.826604	6.369388	4.90605	3.858742	3.089524	0.295517	2.06974	1.72556		4.6559
Weight/Volume													
Volume	0.006	m3	0.012	0.016	0.022	0.024	0.026	0.028	0.03	0.032	0.034		0.0114
Material density	1.838		1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838	1.838		7.8
Mass plate	11.028	kg	22.056	29.408	40.436	44.112	47.788	51.464	55.14	58.816	62.492		88.797
Weight savings	88%		75%	67%	54%	50%	46%	42%	38%	34%	30%		
Allow able deflection (span/ratio)	4	mm											
100													
Minimum required thickness	11.130446												
Omega = 1.1	12.243491	mm											

Based on stress

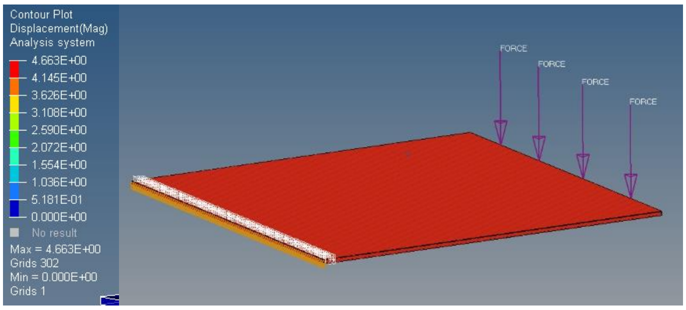
Appendix 2.6. Hyperworks Ply comparison

Data Ply			
Plate length	*L*	*1000*	*mm*
Plate width	*L*	*1000*	*mm*
Fibre volume fraction (continuous)	*V*	*0*	F_c
Fibre volume fraction (long)	*V*	*0*	F_l
Ply thickness	*t*	*10*	*mm*
Matrix E_m longitudinal	E_m	*210*	*GPa*
Load	*F*	*1000*	*kN*

For the thin plate Mathcad (Course: Non-metallic Materials for Marine Structures 2018, TU Delft) is used:

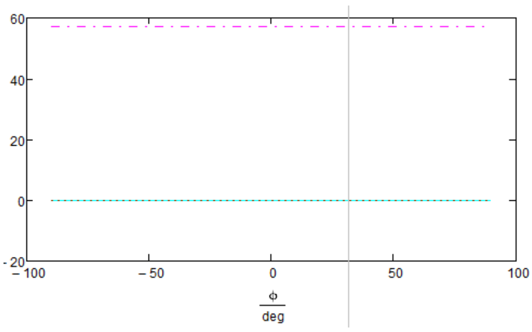


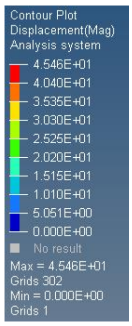
As can be seen the deflection is 5.7 mm in MathCad.



In Hyperworks the deflection is 4.66 mm.

Thin plate 2





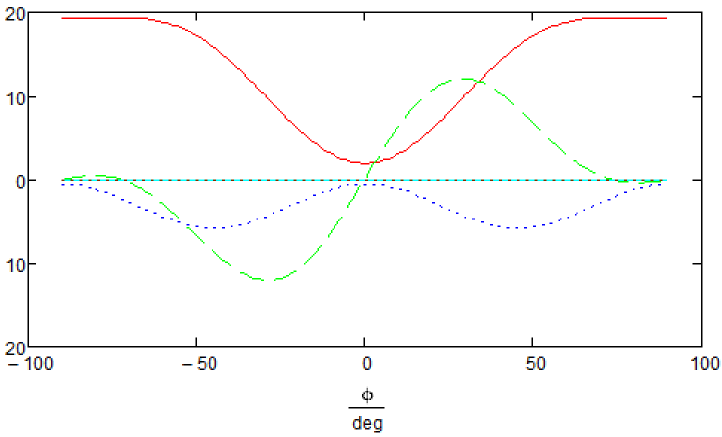
For a second thin plate with a force 100 times larger the deflection in MathCad showed 56 mm and the deflection in Hyperworks 45.4 mm. The difference is due to irregular loading in Hyperworks,

Anisotropic thin plate
For the next reference a comparison is made for an ***anisotropic*** *thin plate composite plate bending deformation using MathCad and Hyperstruct:*

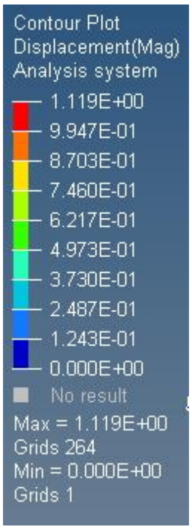
Input data per ply in column#:
1 - fibre volume fraction
2 - ply thickness [mm]
3 - ply UD angle [deg], fibres run under 0deg
4 - fibre E longitudinal [GPa]
5 - fibre E transversal [GPa]
6 - fibre Poisson ratio
7 - fibre tensile strength [MPa]
8 - matrix E longitudinal [GPa]
9 - matrix Poisson ratio
10 - matrix tensile strenght [MPa]

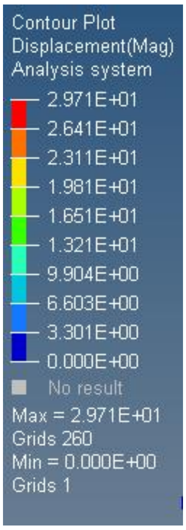
$$\begin{pmatrix} 0.6 & 10 & 0 & 85 & 15 & 0.23 & 2050 & 2.63 & 0.364 & 61.7 \end{pmatrix}$$

Data Ply			
Plate length	*L*	*1000*	*mm*
Plate width	*L*	*1000*	*mm*
Fibre volume fraction (continuous)	*V*	*30*	F_c
Fibre volume fraction (long)	*V*	*30*	F_l
Ply thickness	*t*	*10*	*mm*
Fibre angle	°	*0, 45, 90*	*deg*
Fibre E_f *longitudinal*	E_f	*85*	*GPa*
Fibre E_{ft} *transversal*	E_{ft}	*15*	*GPa*
Fibre Poisson ratio	V_f	*0.23*	
Fibre tensile strength		*2.05e3*	*MPa*
Matrix E_m *longitudinal*	E_m	*2.26*	*GPa*
Matrix Poisson ratio	V_m	*0.364*	
Matrix tensile strength		*61.7*	*MPa*
Fibre G shear modulus	G_f	*36*	*GPa*
Matrix G shear modulus	G_m	*0.81*	*GPa*
Load	*F*	*100*	*kN*



As can be seen from MathCad the deflection of the composite is approximately 19 mm when the fibres are oriented at 90 and -90 degrees and 2 mm when the fibres are oriented 0 degrees. In Hyperstruct these values are found to be 1.19 mm and 29.7 mm. the difference is due to the fact the MathCad code also takes into account the fibre E-transversal and matrix E-transversal and thus is more accurate:





Underneath comparison served as check for laminate orientation optimization

DATA

Student	Length	Width	Thickness	Number of plies	Fiber volumetric fraction	Fiber material	Matrix material
	L	b	t	n	f	-	-
	m	m	mm	-	-	-	-
Grapperhaus, Joep	1	1	10	5	0.6	3	1

MATERIAL DATA

Material	Longitudinal elasticity modulus	Transverse Elasticity modulus	Poisson ratio	Tensile strength
	E	E_t	ν	σ_y
	GPa	GPa	-	MPa
Fiber 1 - Aramid	100	10	0.36	3000
Fiber 2 - Carbon	265	10	0.25	5000
Fiber 3 - Glass	70	15	0.20	2100
Matrix 1	3	n.a.	0.30	30
Matrix 2	6	n.a.	0.30	60
Reference	200	n.a.	0.30	355

$$\textit{Density}: \rho_c = f \cdot \rho_f + (1-f) \cdot \rho_m$$

$$\textit{Longitudinal elasticity modulus}: E_{11} = f \cdot E_f + (1-f) \cdot E_m$$

$$\textit{Transversal elasticity modulus}: E_{22} = \frac{E_{ft}}{f + (1-f) \cdot \frac{E_{ft}}{E_m}}, \quad E_{33} = E_{22}$$

$$\textit{Poisson's ratio}: v_{12} = f \cdot v_f + (1-f) \cdot v_m$$

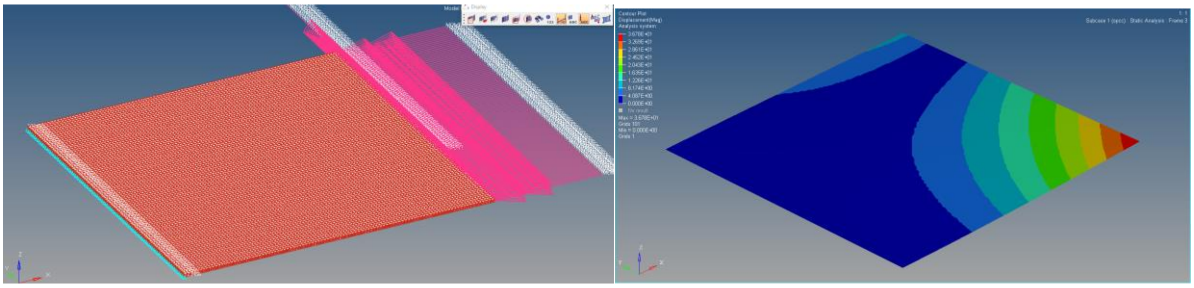
$$\textit{Transversal Poisson's ratio}: v_{21} = v_{12} \cdot \frac{E_{22}}{E_{11}}, \quad v_{31} = v_{21}$$

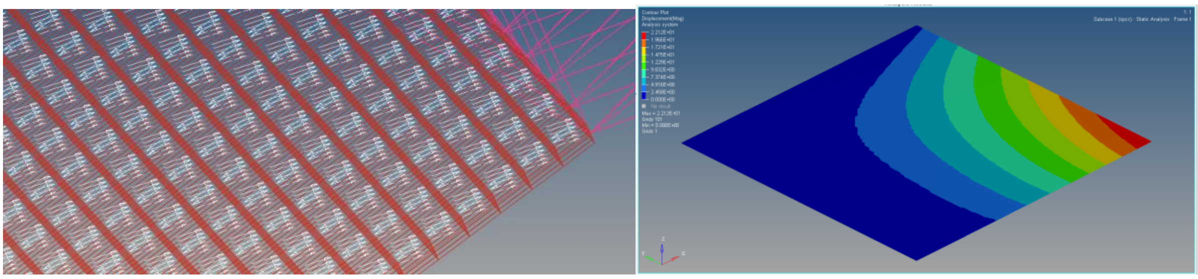
$$\textit{Composite shear modulus}: G_{12} = \frac{G_f}{f + (1-f) \cdot \frac{G_f}{G_m}},$$

$$\textit{Transverse shear modulus}: G_{23} = \frac{E_{22}}{2(1 + v_{23})}, \quad G_{23} = G_{13}$$

fibre	0.6	
rho	1.3	
rho	2.4	
Ef	70	Gpa
Em	3	GPa
Eftf	15	GPa
Eftm	3	GPa
vf	0.2	
vm	0.3	
sig	2100	Mpa
sig	30	MPa
Gf	36	GPa
Gm	1.4	GPa
rho	1.96	
E11	43.2	Gpa
E22	5.769231	GPa
v12	0.24	
v21	0.032051	
G12	3.307087	GPa
G23	2.326303	GPa
G13	2.326303	GPa

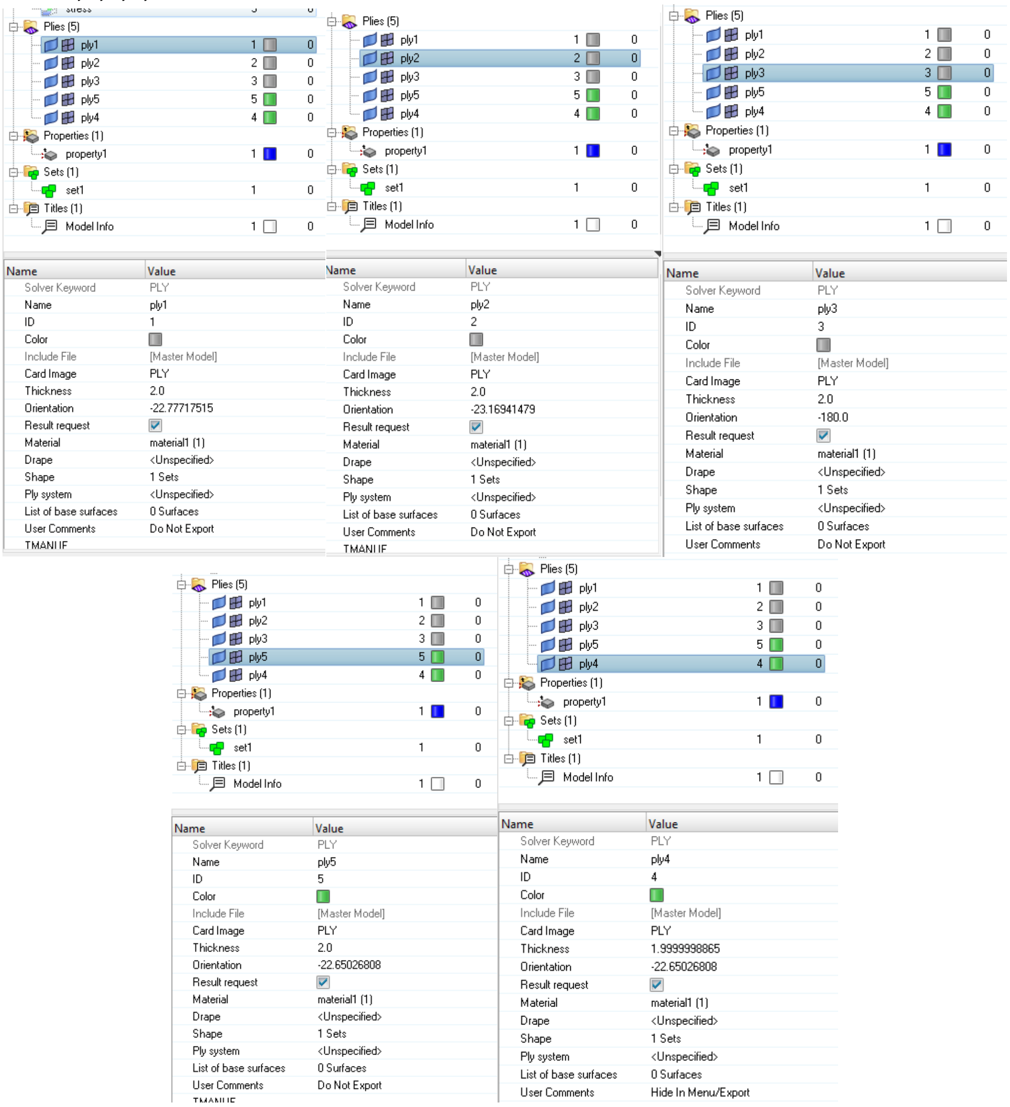
Name	Value
Solver Keyword	MAT8
Name	material1
ID	1
Color	
Include File	[Master Model]
Defined	☑
Card Image	MAT8
User Comments	Hide In Menu/Export
E1	43200.0
E2	5769.0
NU12	0.24
G12	3300.0
G1Z	2326.0
G2Z	2326.0
RHO	1.96





Displacement before: 182 mm
Displacement after: 22 mm

Ply directions 1,2,3,4,5:



Appendix 2.7. Weight components

Underneath table shows applicable loads resulting from components and equipment used as input for topology optimization.

Item	Ref.	Pt, Ch, Sc	Outcome	
Ballast tank	F_B	-	392.4	kN
Fresh water tank	F_W	-	98.1	kN
Filled fuel tank	F_F	-	98.1	kN
Main engine impact load	F_M	9.1.5.	6.5	kN
Main engine weight load	F_{MW}	-	29.4	kN
Additional machinery weight loads	F_{AM}	-	147.2	kN
Bow thruster load	F_B	5.17.2	320	kN
Bow thruster weight load	F_{BW}	-	9.8	kN
Emergency generator weight load	F_{EM}	-	14.7	kN
Windlass load	F_{WL}	3.5.5	346	kN
Anchoring weight load	F_{AW}	-	37	kN
Mooring load (2 lines)	F_{MO}	3.12.5	412	kN
Car crane load	F_C	-	9.8	kN
Housing loads (interior)	F_H	-	39.24	kN
Storage loads	F_S	-	98.1	kN

Item	Nodes	kN per node	Unit	Notes
Ballast tank	10 nodes	39.2	kN	Half weight
Fresh water tank	-	-	-	Other side
Fuel tank	10 nodes	9.8	kN	Full tank
Main engine impact load	6 nodes	1.1	kN	Impact
Main engine weight load	6 nodes	4.9	kN	Weight
Additional machinery weight loads	15 nodes	4.9	kN	Half additional
Bow thruster load	8 nodes	40	kN	Thrust
Bow thruster weight load	4 nodes	2.45	kN	Weight
Emergency generator weight load	-	-	-	Other side
Windlass load	6 nodes	57.6	kN	Pull-out
Anchoring weight load	3 nodes	12.3	kN	Anchor + chain
Mooring load	8 nodes	51.5	kN	2 lines
Car crane load	4 nodes	2.54	kN	Weight + car
Housing loads interior	20 nodes	0.98	kN	Half Interior
Storage loads	20 nodes	4.9	kN	Half storage

$$F_B = m \cdot g$$
$$F_B = 40000 \cdot 9.81 = 392400\ N$$
$$F_W = m \cdot g$$
$$F_W = 10000 \cdot 9.81 = 98100\ N$$
$$F_F = m \cdot g$$
$$F_F = 10000 \cdot 9.81 = 9810000\ N$$
$$F_M = m \cdot g(collision)$$
$$F_M = 3000 \cdot 2.17 = 6510\ N$$
$$F_{MW} = m \cdot g$$
$$F_{MW} = 3000 \cdot 9.81 = 29430\ N$$
$$F_{AM} = m \cdot g$$
$$F_{AM} = 15000\ \cdot 9.81 = 147150\ N$$

$$F_B = T$$
$$F_B = (210\ kW\ bow\ thruster\ ) = 32000\ N$$
$$F_{BW} = m \cdot g$$
$$F_{BW} = \ 1000 \cdot 9.81 = 9810\ N$$
$$F_{EM} = m \cdot g$$
$$F_{EM} = \ 1500 \cdot 9.81 = 14715\ N$$
$$F_{WL} = 346000\ N$$
$$F_{AW} = m \cdot g$$
$$F_{AW} = \ 2200\ (chain) + 1575\ (anchor) \cdot 9.81 = 37000\ N$$
$$F_{MO} = 206000\ N\ (per\ mooring\ line)$$
$$F_{FC} = m \cdot g$$
$$F_C = \ 1500 \cdot 9.81 = 9810\ N$$
$$F_{FH} = m \cdot g$$
$$F_H = \ 4000 \cdot 9.81 = 39240\ N$$
$$F_{FS} = m \cdot g$$
$$F_S = \ 10000 \cdot 9.81 = 98100\ N$$

Appendix 3.2. Calculator machine variables

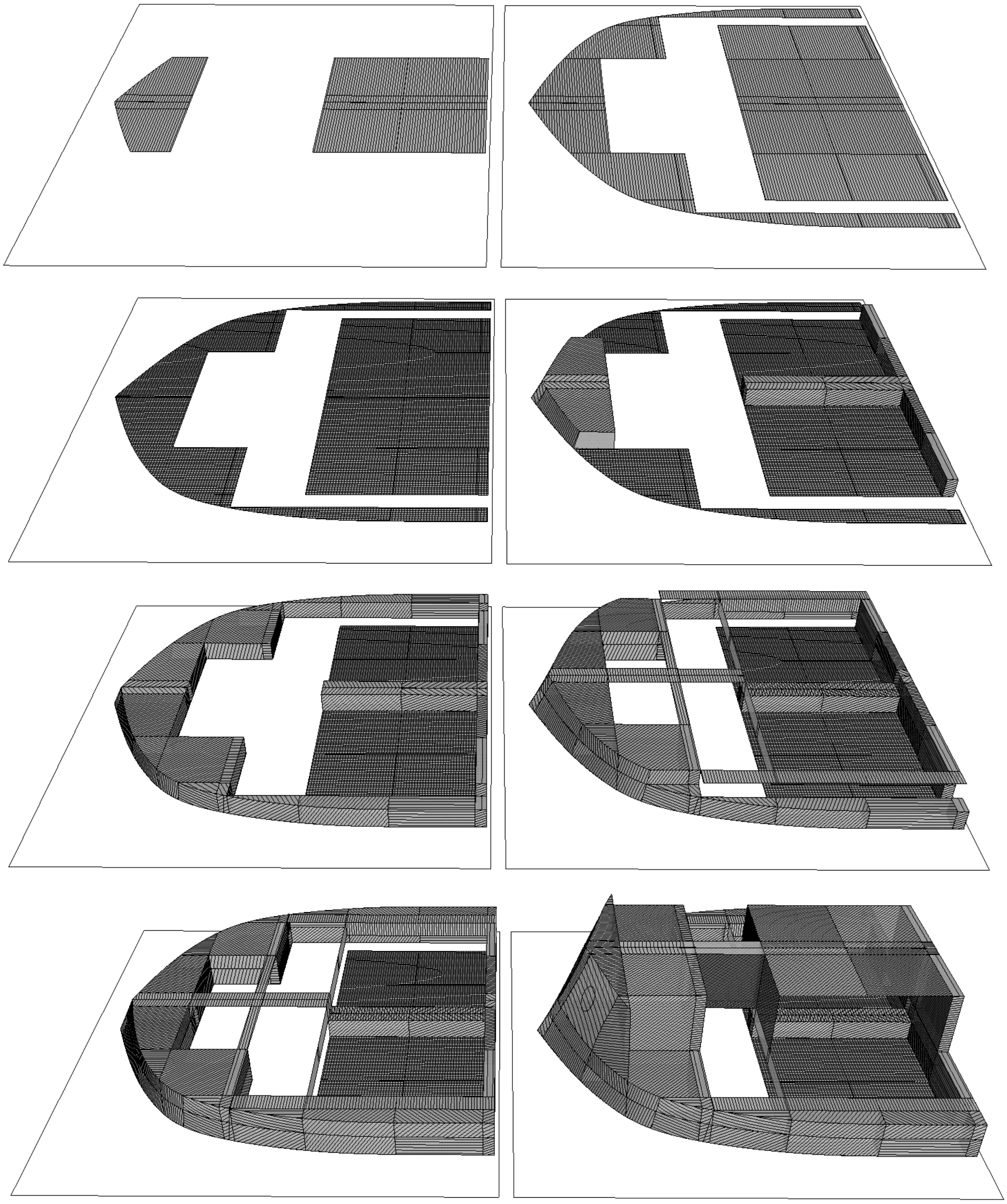
nozzle diameter	8	
number of nozzles	8	
Area bow section	664.95	m2
	664950000	mm2
Number of plies	3	
Total AM surface	1994.85	m2
Total AM surface	1994850000	mm2
Volume bow section	15958800000	mm3
Volume bow section	15.9588	m3
Density material	1828	kg/m3
Weight bow section	29.1726864	tonnes
speed per nozzle	15000	mm/min
kg per nozzle	31.58784	kg/hr
Layer height	2.4	mm
Total layer length	831187500	mm
Total layer length	831187.5	m
Build time on area:	6926.5625	min
	115.4427083	hours
	4.810112847	days
Build time on deposit rate:	115.4427083	hr
Build time on deposit rate:	4.810112847	days

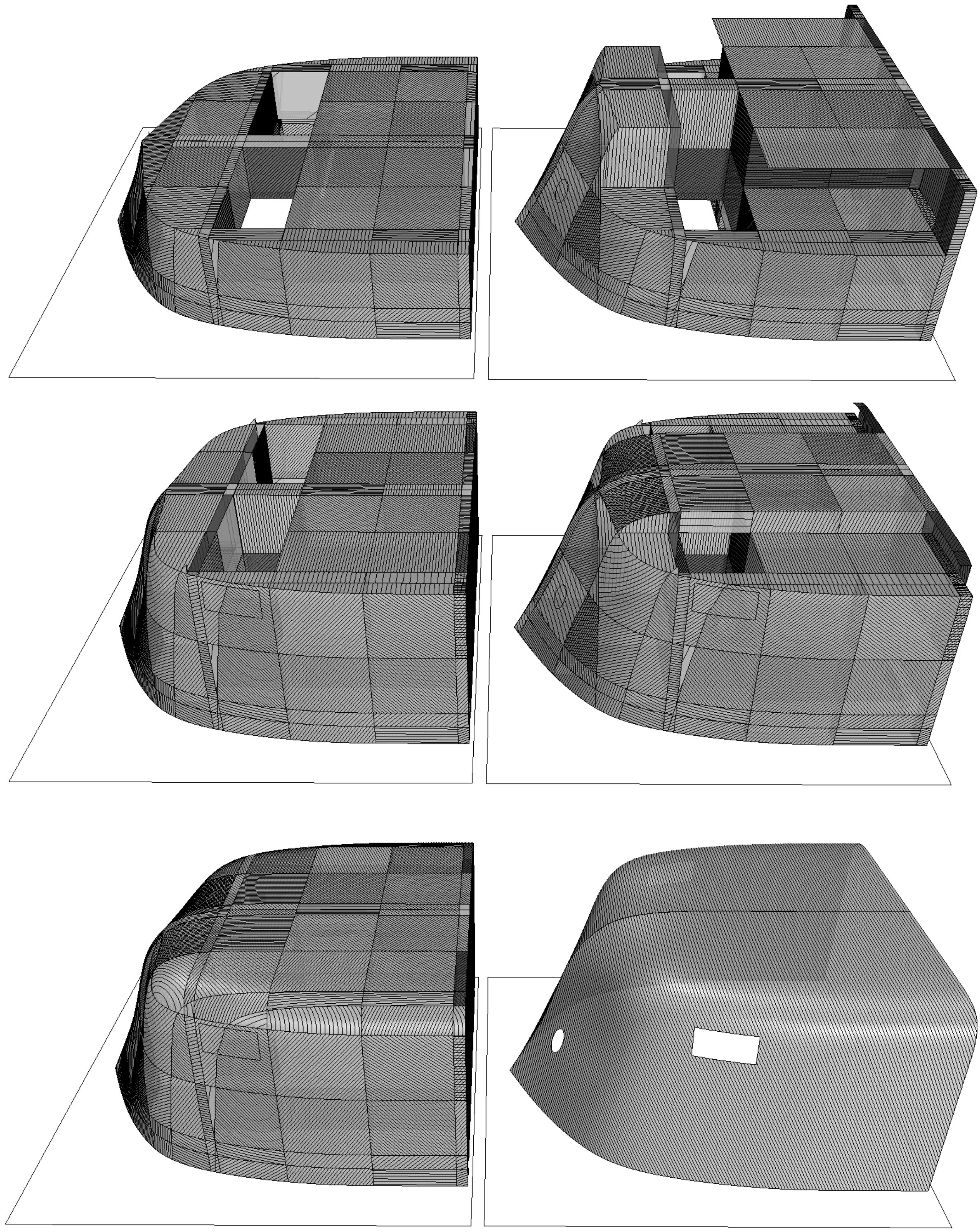
Index	diameter	layer heig	Surface bead	Speed	Volume	Volume	Volume (kg/hr)
	mm	0.3	mm2	mm/min	mm3/min	dm3/min	1.828
	6	1.8	10.8	20000	216000	0.216	23.69
	7	2.1	15	17143	252000	0.252	27.64
	8	2.4	19.2	15000	288000	0.288	31.59
	10	3	30	12000	360000	0.36	39.48
	12	3.6	43.2	10000	432000	0.432	47.38
	14	4.2	58.8	8571	504000	0.504	55.28
	16	4.8	76.8	7500	576000	0.576	63.18
	18	5.4	97.2	6667	648000	0.648	71.07
	20	6	120	6000	720000	0.72	78.97
	22	6.6	145.2	5455	792000	0.792	86.87
	24	7.2	172.8	5000	864000	0.864	94.76
	26	7.8	202.8	4615	936000	0.936	102.66
	28	8.4	235.2	4286	1008000	1.008	110.56
	30	9	270	4000	1080000	1.08	118.45

Machine variables

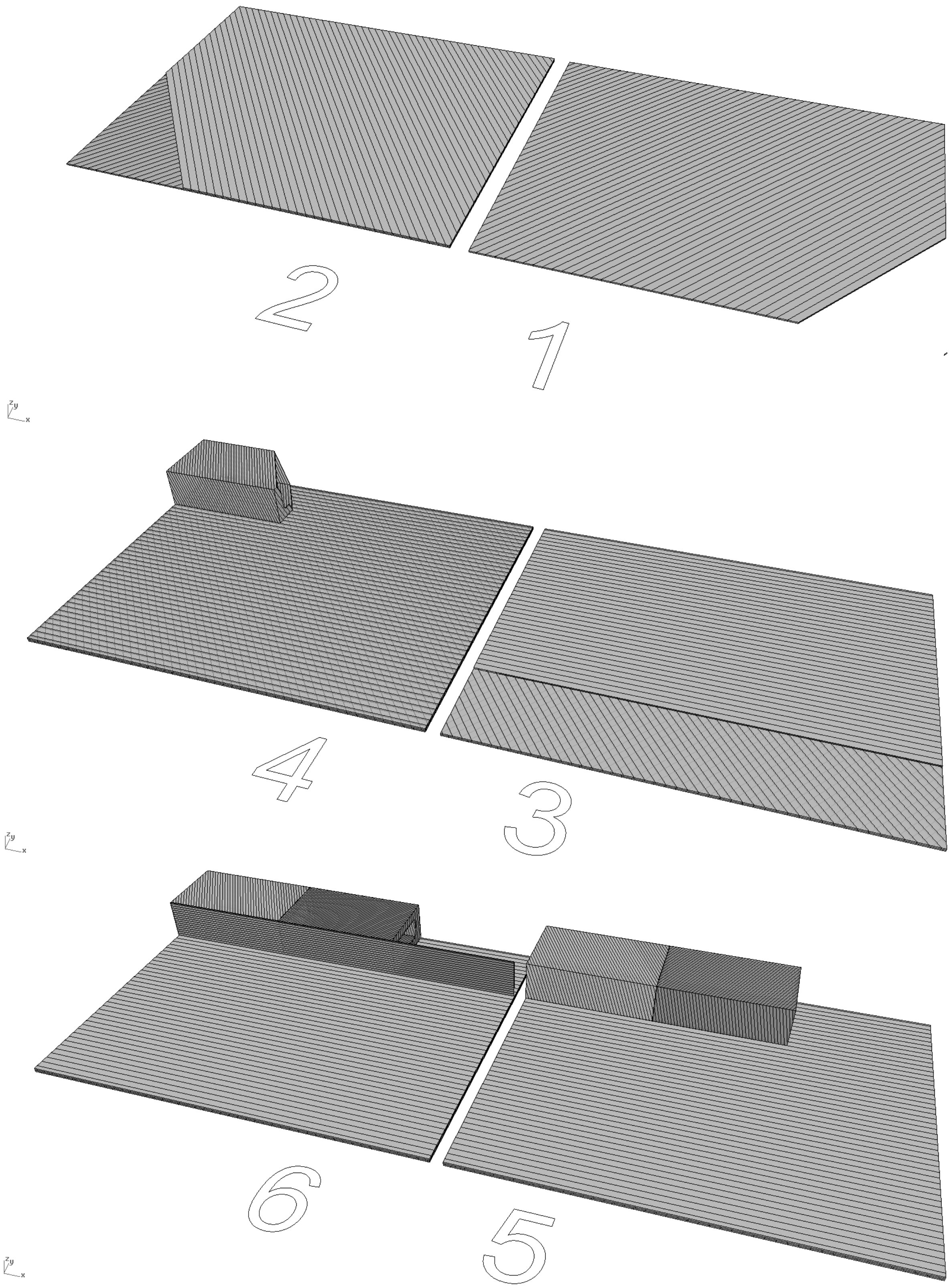
Appendix 3.3. Deposition strategy sequence

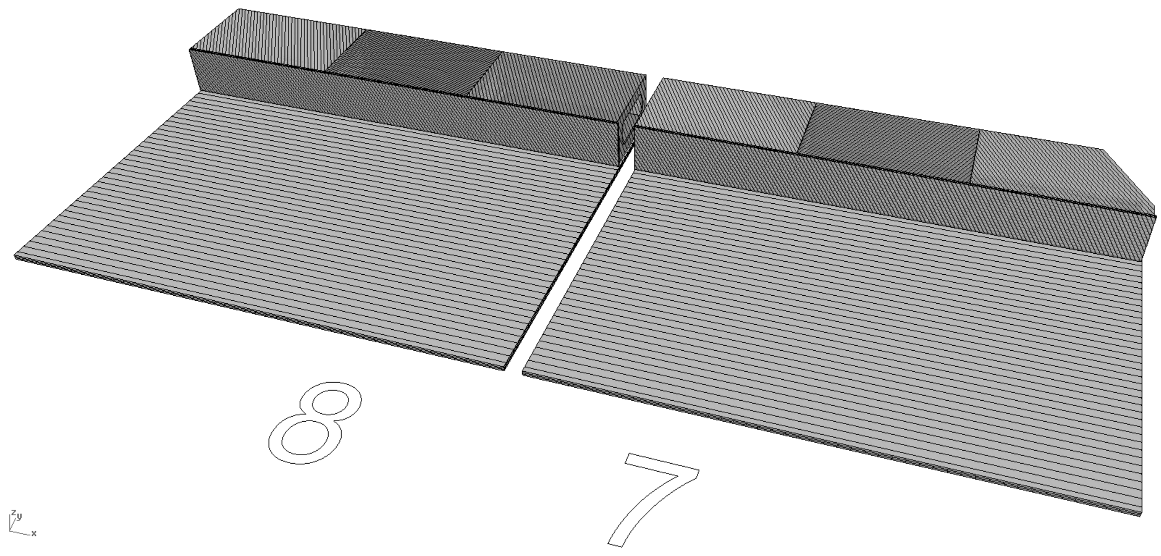
Example complete bow section

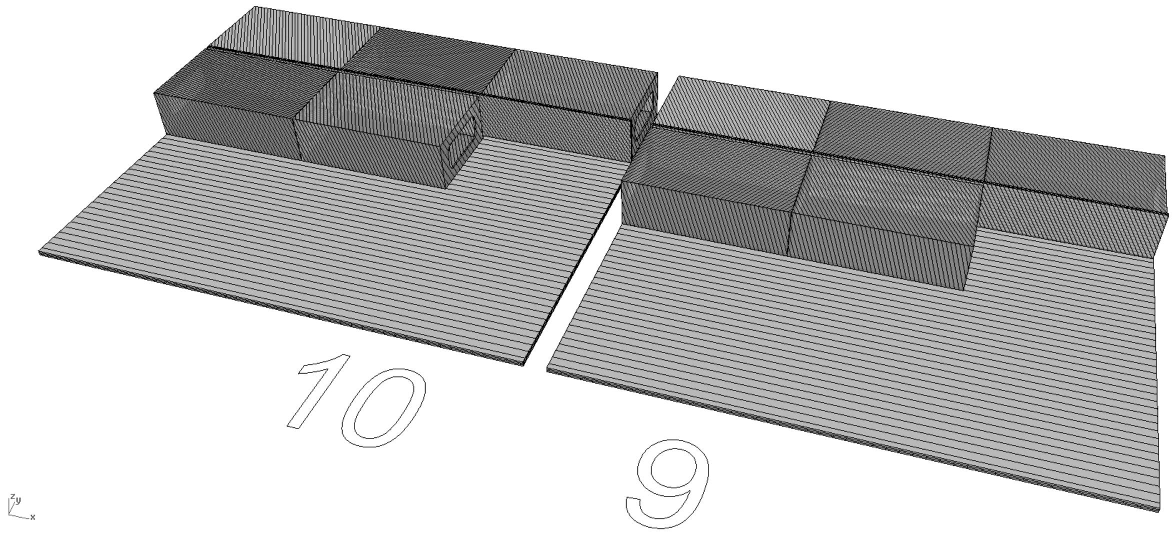


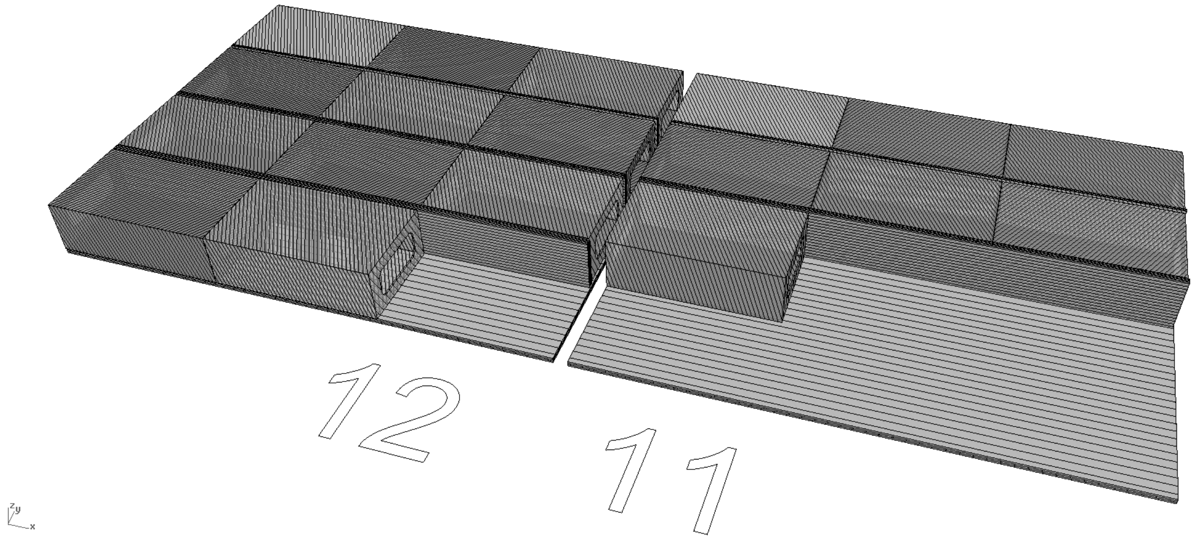


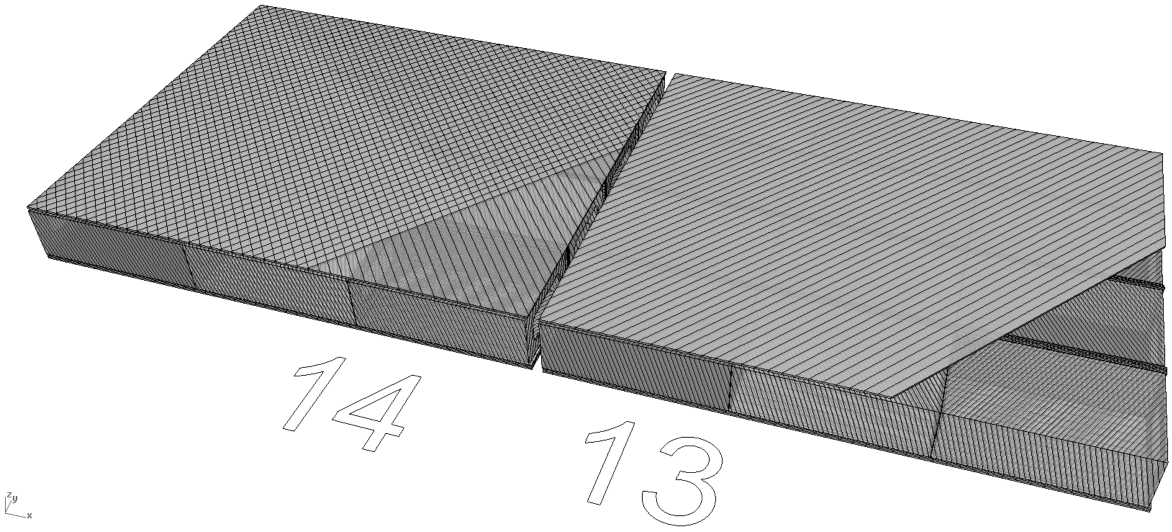
Example double bottom


2
1
4
3
6
5


8
7


10
9


12
11

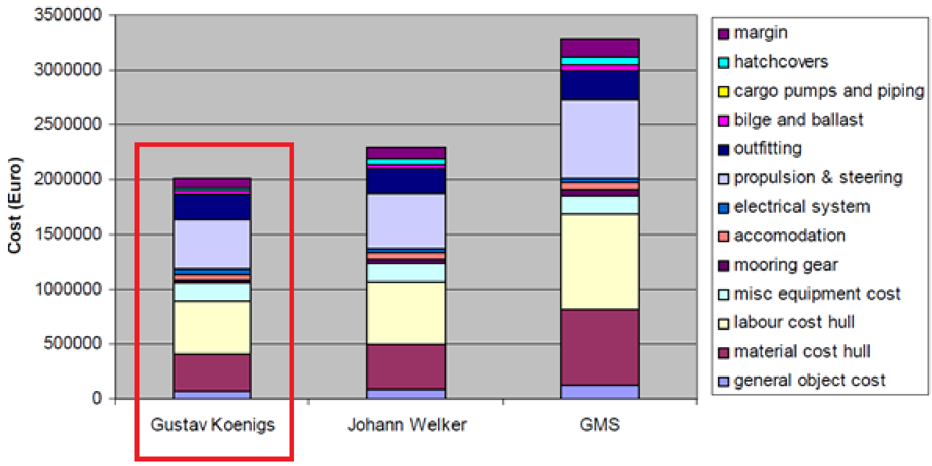

14
13

Appendix 3.3. Assembly selection

1=optimistic																					
5=pessimistic																					
	Costs		Complic.		Time		Exper.		labour		Mach.		Weak		Ugly		Frag.		Repair		Total:
1-5 importancy rate >>>	5		4		3		2		3		2		4		2		5		4		
CNC-cutting	5	25	5	20	3	9	5	10	1	3	5	10	3	12	1	2	3	15	3	12	140
Manual post-processing	4	20	3	12	5	15	4	8	5	15	2	4	3	12	4	8	3	15	3	12	145
Elastomer AM	4	20	4	16	3	9	3	6	1	3	3	6	3	12	3	6	2	10	3	12	117
Gaskets/elastomer sheets	2	10	2	8	3	9	3	6	3	9	2	4	3	12	2	4	3	15	2	8	102
Heat-treatment	3	15	4	16	4	12	4	8	4	12	2	4	3	12	4	8	3	15	2	8	135
Inserts	2	10	2	8	3	9	3	6	4	12	2	4	2	8	3	6	3	15	2	8	104
Bolted connections	2	10	2	8	3	9	3	6	4	12	2	4	2	8	3	6	3	15	2	8	104
Laser assisted Hybrid welding	4	20	5	20	3	9	4	8	2	6	4	8	2	8	2	4	3	15	4	16	131
Manual plastic extrusion	2	10	3	12	2	6	4	8	3	9	3	6	3	12	3	6	3	15	2	8	112
Thermoplastic resin infill	2	10	3	12	2	6	3	6	3	9	2	4	2	8	3	6	3	15	4	16	103
Epoxy resin infill	2	10	3	12	2	6	3	6	3	9	1	2	2	8	3	6	3	15	4	16	100
Glue	3	15	2	8	2	6	3	6	2	6	1	2	2	8	2	4	3	15	4	16	94

Selection of methods of installation

Appendix 3.4. Assembly time/costs



Assembly time	Extra time	Share	Total	Sum	Extra
			100		
Manufacturing of outfitting components	20%	10%	10.00	2.00	
Preparation of components	10%	5%	5.00	0.50	
Preparation of machinery	5%	5%	5.00	0.25	
Installment of machinery	0%	10%	10.00	-	
Handling of components and machinery	5%	5%	5.00	0.25	
Alingment of components	-5%	5%	5.00	-0.25	
Fixtures keeping components in place	0%	5%	5.00	-	
Assembly of components	40%	40%	40.00	16.00	
Removing machinery and fixtures	0%	5%	5.00	-	
Finishing components	-15%	10%	10.00	-1.50	
Total:		100%	100.00	17.25	17.25%
Direct costs	Costs	Share	Total	Sum	Extra
			100		
Additional costs of outfitting components	30%	40%	40.00	12.00	
Additional costs of machinery	20%	20%	20.00	4.00	
Costs of fixtures	10%	10%	10.00	1.00	
Costs of assembly resources	10%	20%	20.00	2.00	
Costs of finishing equipments	5%	10%	10.00	0.50	
		100%	100.00	19.50	20%
Outfitting percentage					
Outfitting percentage of total building	20%				
Outfitting time percentage	80%	93.8%			
Outfitting direct costs percentage	20%	23.9%			
Total:		117.7%			
Extra percentage on total building time:			100		
Outfitting percentage of total building			20%	20	
Bow section percentage of total vessel			10%		
Ratio			24%	23.54	
Extra costs resulting from extra outfitting					3.5%
Bow section hull costs		10%	€ 100,000.00		
Hull costs		100%	€ 1,000,000.00	40%	1.42%
					€ 14,160.00

Extra Assembly time and costs

Appendix 4.1. Machine rate calculation/Production costs

		Optimistic	Average	Pessimistic	365	days
Cost items	Gantry:	€ 500,000.00	€ 550,000.00	€ 600,000.00	24	hours
	Platform	€ 200,000.00	€ 300,000.00	€ 400,000.00		
	Robots:	€ 400,000.00	€ 500,000.00	€ 600,000.00	8760	hours/yr
	Software:	€ 150,000.00	€ 200,000.00	€ 250,000.00	FTE	€ 56,000.00
	Additional machinery	€ 500,000.00	€ 550,000.00	€ 600,000.00		
	Proces control	€ 350,000.00	€ 450,000.00	€ 500,000.00		
	Configuration:	€ 400,000.00	€ 500,000.00	€ 600,000.00		
	Total:	€ 2,500,000.00	€ 3,050,000.00	€ 3,550,000.00		
	Consumables (20% yr)	€ 500,000.00	€ 610,000.00	€ 710,000.00		
Utilisation	Operational time:	70%	65%	60%		
	Performance:	70%	65%	60%		
	Quality:	70%	65%	60%		
Hours	Effective hours /yr	3,004.68	2,405.72	1,892.16		
	Depreciation time (yr):	5	4	3		
	Effective hours (hr)	15,023.40	9,622.86	5,676.48		
Labour	Labour costs (8 people)	€ 2,240,000.00	€ 1,792,000.00	€ 1,344,000.00		
	Overhead (3)	€ 840,000.00	€ 672,000.00	€ 504,000.00		
Machine rate (EUR/hr):		€ 404.70	€ 636.40	€ 1,076.02		

Machine rate estimation

Appendix 4.2. Deposit rate estimation

nozzle diameter	10	
number of nozzles	8	
Area bow section	680.6	m2
	680600000	mm2
Number of plies	2	
Total AM surface	1361.2	m2
Total AM surface	1361200000	mm2
Volume bow section	13612000000	mm3
Volume bow section	13.612	m3
Density material	1828	kg/m3
Weight bow section	24.882736	tonnes
speed per nozzle	12000	mm/min
kg per nozzle	31.58784	kg/hr
Layer height	2.4	mm
Total layer length	567166666.7	mm
Total layer length	567166.6667	m
Build time on area:	5907.986111	min
	98.46643519	hours
	4.102768133	days
Build time on deposit rate:	98.46643519	hr
Build time on deposit rate:	4.102768133	days

Index	diameter	layer height	Surface bead	Speed	Volume	Volume	Volume (kg/hr)
	mm	0.3	mm2	mm/min	mm3/min	dm3/min	1.828
	6	1.8	10.8	20000	216000	0.216	23.69088
	7	2.1	15	17143	252000	0.252	27.63936
	8	2.4	19.2	15000	288000	0.288	31.58784
	10	3	30	12000	360000	0.36	39.4848
	12	3.6	43.2	10000	432000	0.432	47.38176
	14	4.2	58.8	8571	504000	0.504	55.27872
	16	4.8	76.8	7500	576000	0.576	63.17568
	18	5.4	97.2	6667	648000	0.648	71.07264
	20	6	120	6000	720000	0.72	78.9696
	22	6.6	145.2	5455	792000	0.792	86.86656
	24	7.2	172.8	5000	864000	0.864	94.76352
	26	7.8	202.8	4615	936000	0.936	102.66048
	28	8.4	235.2	4286	1008000	1.008	110.55744
	30	9	270	4000	1080000	1.08	118.4544

Deposit rate estimation

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