Maximizing the Use of Composite Materials in Offshore Electrical Substations Applied to Non-Structural Elements

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Maximizing the Use of Composite Materials in Offshore Electrical Substations Applied to Non-Structural Elements

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MASTER THESIS

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Nomenclature

Symbol	Description	Unit
ϵ	Elongation at break	%
ρ	Density	g/cm^3
σ_T	Tensile strength	MPa
σ_y	Yield strength	MPa
E	Young's modulus	GPa
E_{flex}	Flexural modulus	MPa
T_g	Glass transition temperature	°C
δ_b	Deflection due to bending	mm
δ_s	Deflection due to shear	mm
θ	Honeycomb's internal angle	radians
K_c	Impact strength	kJ/m2
t_f	Component failure time	years
t_m	Maintenance time	years
b	Grate width	mm
C	Core depth	mm
I	Moment of inertia	mm^4
L	Grate length	mm
l	Diagonal length of honeycomb's cell	mm
P	Point load	N
q	Inspection quality	[−]
t	Cell thickness	mm

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ABSTRACT

The race to gain offshore wind energy a larger proportion of the energy market increases the need to reduce operational costs. Such costs occur during maintenance where corrosion is a factor.
Having to compete with the oil and gas industry. The offshore wind sector faces the same challenge as any other offshore sector; corrosion. However, The term corrosion is not limited to saltwater and humidity but also UV radiation. The purpose of an offshore structure is to support the function of the equipment on board. Any excess weight of the supporting structure is irrelevant as long as the integrity is ensured.
In addition, decreasing structural weight can lower the costs pertaining to transportation, construction as well as O & M. Undoubtedly, the two main concerns are corrosion and weight. By considering using alternative materials, both challenges are tackled. The use of glass-reinforced polymer is already evident in oil and gas. Hence, to further reduce the cost in the supply chain. Polymers are now considered. Currently, experiments for polymers are being conducted in Cefan department of Navantia. The results are promising with additive manufacturing.
Non-structural elements are not subjected to strict regulations. This increases design flexibility that allows material properties to be fully utilised according to the design. Offshore non-structural components such as handrails, grating, cable trays and HVAC vents can all be made from composites. Yet, the main challenge of glass-reinforced plastic is recycling. thermoplastic presents an alternative solution to the design for manufacturing as well as an advantage in terms of sustainability.

1 INTRODUCTION

An electrical substation is one of many offshore structures that face corrosion. The goal of minimising corrosion is mainly due to maintenance. For primary structures, corrosion gives rise to safety concerns.
In the first section of the paper, composite materials and traditional materials used in offshore structures are given an overview. The advantages and disadvantages of each composite material are discussed in terms of their functions. Emphasis is made on manufacturing which is related to design flexibility. In terms of manufacturability, polymers offer superior properties over composite materials. This allows polymers to be taken into consideration for their applications on offshore substations. After various types of composite materials such as glass-reinforced polymers and aramid composites are reviewed. Their suitability for offshore substations is studied. This is done to determine the potential areas of application. Moreover, the challenges associated with degradation and costs incurred with composite materials are identified.
Furthermore,safety considerations regarding the potential materials are outlined in the material selection section. These aspects influence the material choices from the design to manufacturing and maintenance. A number of material properties established from the study are used as a input to CES Edupack program. With a suitable alternative material selected, design validations can be done with finite element analysis.
At last, composite materials are investigated from an economical perspective via market analysis. The final section includes the outlook of the offshore wind industry as a whole. Factors that accelerate and slow down the growth of the composite and offshore wind industry are explained.

1.1 Background and Motivation

In a wind farm, the voltage from each wind turbine is below the requirement for power transport. It is not possible to directly send power generated from the offshore to the grid. An offshore substation can be seen as a connecting point between a wind farm and an onshore grid. It serves the purpose of transforming the power to a higher voltage for supply.
The size of the offshore substation depends on the distance of the wind farm from the coast. The distance is categorised into 4 zones.

- Between 0 to 10 km
- Between 10 to 50 km
- Between 50 to 100 km
- above 100km

From the distance between 0 to 10 km, the distance is relatively close therefore, a station is not needed. The next region is between 10 to 50 km. In this region, a small substation is required. However, a shunt reactor for reactive power compensation is not needed. In between 50 and 100km, an offshore substation with shunt reactors is set. The size and capacity of a station in this region and beyond become more complex. Lastly, if a wind farm has a distance beyond 100km from the coastline, a high voltage direct current supply is applied.

In brief, the economical difference between AC (alternating current) and DC(direct current) is due to the distance of power transport. Direct current has a higher initial cost than alternating current. However, the cost of transport per distance of direct current is less expensive. A break-even distance is found to be approximately above 90 km. Hence, a wind farm that is located beyond 90km from a shore should consider using a High voltage direct current supply. A graph [33] in the appendix illustrates the cost and distance difference between AC and DC.

Furthermore, another difference is the foundation types. The types depend on water depth, environmental loads, seabed conditions and size of the structure to be supported. The most common type of foundation currently is jacket foundation. designing process of a substation has to take into account permanent loads, operational loads, and accidents such as ship collisions.

The offshore substation has many auxiliary equipment to support its main function. Systems such as HVAC (heating ventilation and air conditioning) and FIFI (fire fighting) are required by most class societies. Drains and diesel generator sets are also essential for a substation to operate in an offshore environment. Besides, a substation can have an extra supporting structure like a helipad. These systems influence the ways a substation can be assembled. whether it be modular, self-installed or divided topside.

The auxiliary functions on a substation are reduced to the minimum as much as possible to reduce unnecessary weights. The objective of this study is to investigate weight-saving and maintenance reduction possibilities in terms of material used for non-structural elements.

2 COMPOSITE MATERIALS

The researched data from the oil and gas industry can be used to assess the nature of corrosion on offshore structures. Recently, more studies have been directly related to the offshore wind industry. For an offshore structure, 3 different locations can be considered, fully submerged, splash and tidal zone and atmospheric. These locations present different conditions for corrosion. According to [2], the corrosion rates at these 3 locations are present in terms of distance corroded per year.

Table 1: Offshore corrosion rate of steel [3]

Zone	Corrosion rate [mm/year]
Submerged	0.08
Tidal/splash	0.10-0.25
Atmospheric	0.05-0.10

The corrosion mechanisms of fiber-reinforced polymer are different to steel. This means that the data above does not apply to composite components. Hence, It is essential to investigate the corrosion mechanisms of fiber reinforced polymers in offshore environments. In the following section, various types of resins and fibers are explored. Finally, the degradation mechanisms of each type of composite as well as protection methods are examined.

2.1 Fiber reinforced polymers

2.1.1 *Types of resins*

A composite material is made by combining 2 materials with different mechanical properties to improve its overall mechanical properties. The combination of different types of resins and fiber creates specific properties of composites. The resins are polymers which can be distinguished mainly by chemical composition and the level of cross-linking.
Most resins used for composites are highly cross-linked polymers due to their inability to be re-shaped under heat. With this property, thermo-setting polymers are suitable binding materials for composites. Furthermore, the chemical composition of the polymers gives the composite its unique mechanical properties.
Creating a composite material using high-performance thermoplastics as resins is technically viable. However, due to its nature of high viscosity, thermoplastics are less suitable to be used as a binding material [9]. an exception for the use of thermoplastics can be seen in the aerospace industry [7]. These thermoplastics are polypropylene, polyamide, polyethene and polybutylene [10]

The list below discusses the mechanical properties of the main types of resins that are suitable for the manufacturing of composites.

- **Unsaturated polyester resin** is generally low-cost. They are widely used in mass-produced parts. Unsaturated polyester possesses a good balance between mechanical and electrical properties. However, it is important to note that saturated polyester is thermoplastics. The resin is commonly manufactured with glass fiber in an open-mold compression molding where up to 50 % of styrene is added to reduce its viscosity
- **Vinyl ester resin** is known for its fast curing property. it has the advantage of the manufacturability of polyester and the performance of epoxy. Vinylester is similar to polyester but it has a longer molecular chain. This characteristic gives Vinyl ester a higher impact strength than polyester. Vinyl ester is resistant to water erosion as it has less ester group than polyester. This makes Vinyl ester suitable for marine applications but it comes with a higher cost than polyester.
- **Epoxy resin** has a different manufacturing method compared to polyester as it is cured with a hardener and not a catalyst. This makes it challenging to manufacture structural components with epoxy composite. However, epoxy contributes strength, durability and chemical resistance to a composite. Epoxy is used for its strength . Their application as FRP tendons and cables is also common. Such application is currently being studied for offshore mooring lines. Its superior property comes with a high cost and difficult manufacturing process.
- **Phenolic resin** is based on a combination of aromatic alcohol and an aldehyde, such as phenol, combined with formaldehyde. Phenolic refers to the presence of a benzene ring. These phenol groups give a fire-resistant property to the resin which is highly desirable for offshore safety applications However, the mechanical properties of phenolic resins are lower than epoxy resins because the chemical reaction during curing results in voids in the composite. [9]

It has been summarised by [8] that glass fibers are the most common use for their performance and cost. Phenolic resins combined with glass fiber give fire resistance properties at low costs. From the degradation studies, it can be concluded that epoxy composite has the best properties in terms of corrosion resistance.

2.2 Degradation of composites

All resins are subjected to UV radiation. They require additives and surface protection. Both UV A and B break down cellular and chemical composition. In addition, degradation is not only caused by UV radiation but also by humidity. The resistivity of fiber reinforced polymers to humidity depends greatly on their resins and fiber orientation. Generally,

polyester is the most commonly used resin. However, it is not as durable and more susceptible to water and UV light degradation. Vinyl has a longer lifespan than polyester but it has a higher cost for raw materials.
Continuous fibers have been shown to carry more moisture into the laminate plane via capillary action. This makes the composite with continuous less suitable for application in a humid environment. [34]
For epoxy and glass composites, water absorption is saturated after 30 days. The level of mechanical properties reduces after 30 days but the degradation is stabilised when the saturation level is reached. As a result, the flexural and tensile properties also stabilise. Epoxy and glass composite has no change in fatigue life after a test at 85 per cent of its ultimate tensile strength in the presence of UV and water.
For polyester composite, only tensile strength stabilises but not flexural strength. Flexural slope increases after the saturation level is reached. It takes polyester composite 65 days to reach the saturation level. Lastly, for the composite of vinyl ester and glass fiber, both tensile and flexural strength do not stabilise at all after the saturation level. Vinylester is also subjected to biodegradation. Its bond can be broken by hydrogen-producing bacteria. For matrix-dominated composite, transversal strength is affected by cyclic exposure to UV and water. Yet, this is not the case for longitudinal fiber composite. [35]

2.2.1 *Degradation mechanisms*

As well as moisture, UV degradation is another mechanism that changes the physical properties of fiber reinforced polymer. [6] finds that in terms of moisture, distilled water without the presence of NaCl has a more detrimental impact on the structure integrity because the presence of salt crystals in non-distilled water prevents further diffusion.
The major effects of UV light are listed below. [4]

Figure 1: Fiber blooming of glass reinforced polymer [75]

In figure [34] a snow-covered glass reinforced polymer panel is shown. The snow melts in the grid line due to the heat-conducting aluminum frame. Fiber blooming can be seen at this location.

1. Fiber blooming occurs When the fibers are exposed to the surface due to an eroded polymer matrix. This leads to fibre splinters which could be a handling issue for personnel
2. Chalking is a result of photo-oxidation of polymer matrix that happens on the surface. This results in brittleness which causes other potential issues.[5]
3. De-coloration can happen as a result of exposure to UV radiation. It will affect the aesthetics of the surface.

2.2.2 *Degradation protection and maintenance*

There are various ways that UV degradation can be prevented. Standard resins are naturally transparent so adding a pigment, additives or UV inhibitors can prevent degradation due to UV radiation. Moreover, adding a polyester ’veil’ to the outer layer during the pultrusion process can also prevent the fiber bloom to protrude outside. Since, UV is a surface phenomenon, using a more resin-rich surface can essentially give a surface coating to the material. The corrosion rate at different locations is assessed to create maintenance strategies which minimise the costs of operation and maintenance.
However, in cases where fiber blooming is not acceptable, polyurethane paint can be used. Lastly, the overall costs of maintenance are not only the costs of the parts to be replaced. The quality of inspection also matters. A proposal from [2] is given that the quality of inspection be ranked from 0 to 1 where 0 is when the component has already exceeded 90 % of its lifespan and 1 is when the lifespan has only passed 50 %.

$$\frac{t_m}{t_f} => 0.5 + (1 + q) \cdot 0.4 \tag{1}$$

The inspections are done only when the equation [1] is satisfied. This shows the function of a component plays a role in determining q and optimisation can be done to reduce unnecessary inspection for less critical components. Therefore, to reduce unnecessary expenses, investigating other possibilities to eliminate corrosion for secondary structures is the main focus of many researchers.

3 NON STRUCTURAL COMPONENTS

The term non-structural elements refers to the components on offshore structures that do not serve a structural function. They make up most of the auxiliary systems and provide comfort and safety to the station as a whole.
According to DNV offshore for offshore unit [70], there are 3 main structural categories. 1) Special 2) Primary and 3) Secondary. The explanation of each category can be seen in the table [12] in the appendix.
There are several components below that are made of composite materials. This proves that the application of composite materials is a viable solution to corrosion and weight savings.

3.1 Hand rails

The hand rail's function is for safety. It ensures safe access to and from offshore structures under slippery conditions. Handrails prevent personnel from the risk of falling as well. Traditionally, handrails are made of marine-grade steels steel. 316L steel is commonly used in marine conditions. It is corrosive resistant although it weighs more than composites. For non-structural components, steel is an overkill.
Glass-reinforced polymer handrails are made by a manufacturing process called pultrusion. It is a continuous manufacturing process where the cross-section of the produced parts is constant.
The pultrusion process is achieved by pulling fibreglass that is contained as a bundle through a resin bath. The fibreglass is saturated and it would be reinforced when cured. During the pultrusion process, a surface protection layer can be Incorporated. Such layer protects the top surface of handrails from UV degradation and fibre blooming.
The saturated fibreglass is then pulled through a die. A heated die which can have various shapes, depending on the desired cross-section of the final products. Pulling in pultrusion is a continuous process. It allows the curing of glass-reinforced fibre, resulting in a hardened, permanent shape. In the final stage of the manufacturing process, a saw can be used to cut the pultruded part to a specified length.
Mold blockage can occur during the manufacturing process due to blockading of fiberglass. A factor that leads to mold blockage is the die temperature. Low temperature at the entrance of the mold may cause a blockage on the inside of the mold. Moreover, a regular check of the inner mold surface will ensure that parts will not break out. In case the inner mold surface is too rough, failures may occur.
In addition to mold blockade, Another complication of pultrusion process is part bending. Even temperature inside the mold has to be ensured so the curing rate is equally distributed. Apart from the temperature of the mold. The symmetry of fiberglass roving can affect

product quality. Uneven distribution of glass fiber can result in bending and torsion of parts because shrinkage can occur when cooled. For the asymmetric cross-section part, an additional cooling device is required to ensure the quality standard. Lastly, the colour of the final product can be affected if heating is not done evenly. Uneven heating causes colour transfer due to shrinkage. The correct ratio between the filler and the resin has to be checked to prevent separation [23].

Figure 2: Offshore composite handrails [76]

A common type of resin used in the making of the composite by pultrusion is polyester resin. Some variants of this polyester are called Isophthalic polyester. It has a benzene ring in the chemical composition which gives the material a fire retardant property. Fiberglass makes up the matrix of the composite.
The assembly method of handrails can be done in different ways depending on the scenarios. The selection of the installation method entirely depends on the load case of the handrail as well as where the location of the handrail.
The load and the deflection requirement of handrails on offshore substations are not specified in DNV offshore rules. This is because handrail is classified as secondary elements. The handrails are installed on the edge of all the stairs and each deck of the offshore substation.
Many installations of handrails use the base foot to fix the vertical rail to the floor. However, the installation of handrails on the substations is located on the grating. Therefore, the use of the base foot is not applicable. An alternative method is to use a kickplate, seen in

figure [3].
Regardless of the grating material, the frame where the grates are secured is always marine-grade steel. This allows a kick plate to be easily installed with a screw to the frame.
The fixation to the floor is the only main difference, 90 degrees elbow joint and 3/4 ways tee are used to assemble the rails to form the final assembly.
Finally, the span of the rail should be selected as the greatest width possible that can carry the required load. This will save weight by reducing the assembling components needed.

Figure 3: handrail installation method with a kick-plate [41]

3.2 Cable trays

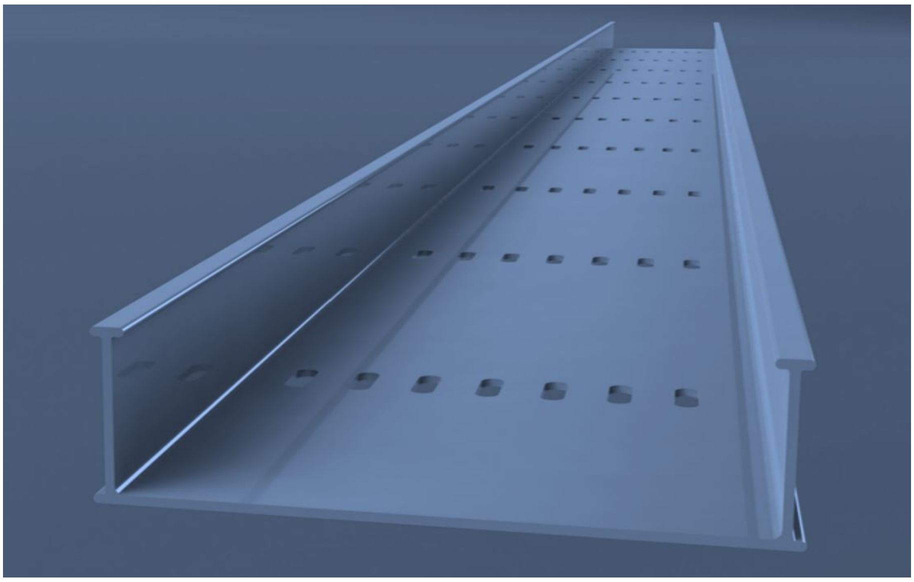

Figure 4: Glass reinforced Polymer Cable tray [77]

Cable trays on offshore substations have essential functions for power transportation from the wind farm to the grid on land. Its function revolves around the efficiency and safety of the substation. The more organised the cables, the faster maintenance tasks can be done. This consequently reduces delays and operational costs.

In the current stage of the offshore industry, there are uses of glass-reinforced polymer. This is evident in the oil and gas industry. Their goal is similar to the offshore wind industry which is to reduce weight and corrosion. Like handrails, GRP cable trays are made by pultrusion, figure [4] shows an example of a solid bottom cable tray that is made of GRP.

Important aspects that have to be considered for cable trays are firstly the mechanical properties of the material. The next aspect is relating to fire safety. This is because in most cases, live cables produce heat from conduction. Therefore, the material selected to make the cable tray has to have fire-retardant properties. Furthermore, the design of the cable tray has to take into account electromagnetic interference between the cables.

Causes of the fire on an offshore substation is a short circuit. Therefore, cable trays play a crucial role in preventing the fire from spreading. The behaviour of fire on cable trays is studied in [11]. The study is conducted from an experiment by having different cable arrangements on a wall with the same cable tray settings. The result of this study shows that with densely packed cable trays, fire can spread faster in the initial stage. However, when the cable trays are set further apart, the vertical spreading of fire from the bottom to the top trays is even faster in the final stage.

To further improve the fire safety of cable trays, a coating is used. The result from fire retardant coating shows a positive result as the time to failure of the burning cable tray can be delayed up to 15 times, compared to the control group. [12]. Generally, the thicker the coating, the better fire resistance performance it has. Thus, there is a compromise between weight and total safety. All in all, the fire retardant property of the material used to make cable trays is a standard requirement for non-structural offshore elements [71].

In terms of weight optimisation, there is a direct correlation between electromagnetic interference and the geometry of the cable tray. Such electromagnetic interference is called cross talk which is reduced by using a metal cable tray. However, from [13], it is clear that by introducing holes in a cable tray of any suitable material, both weights and cross talk can be reduced.

Ladder cable trays

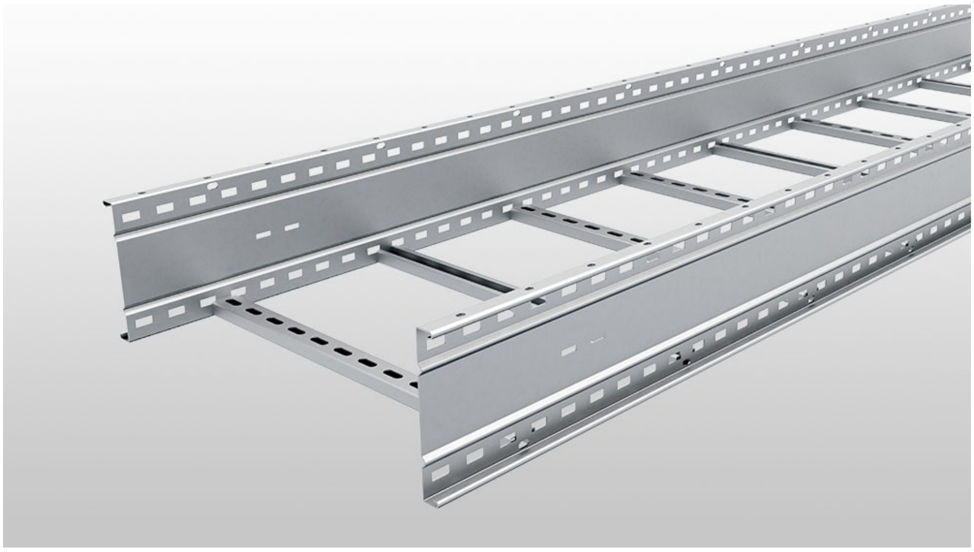

Figure 5: Ladder cable tray [79]

This type of cable tray allows engineers to access the cable easily. Cables are attached and secured on the horizontal support of the tray which makes them highly accessible.
Ladder cable trays do not have a cover. This does not make it suitable for open environment conditions. However, it allows maximum ventilation for the power cables that generate heat from conduction. [78]

Solid bottom cable trays

Figure 6: Solid bottom cable tray [78]

This type of cable support does not allow ventilation like the ladder type. Power cables are not supported by this type due to their incapability to provide ventilation. A solid bottom tray is generally used for delicate cables such as data and communication wiring which do not generate conducting heat.
Solid cable tray is the most suitable for the wiring that requires total enclosure. Therefore, the majority of solid trays are designed with covers. The function of this type of cable tray is also used to prevent signal interference of the cables.

Wire mesh cable trays

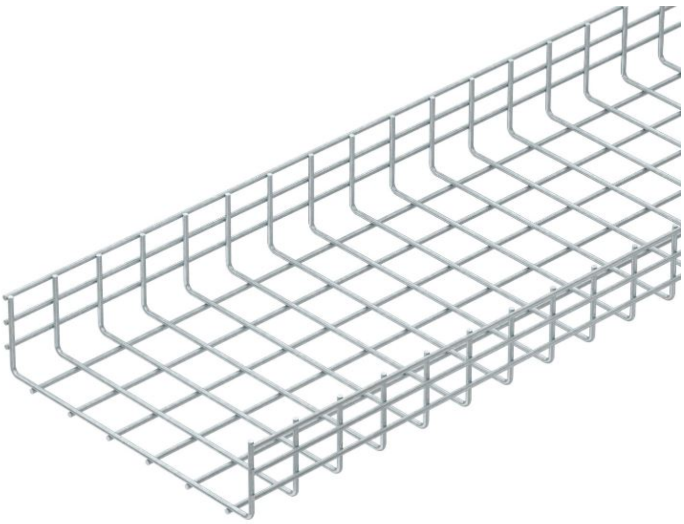

Figure 7: Mesh cable tray [78]

Similar to solid case trays, wire mesh is not used for high-power cables. However, using mesh needs fewer materials, allowing weight saving. The Mesh tray is adjustable and has good ventilation. Moreover, the fact that it has no total enclosure can prevent cable damage from rodents nesting. Another variation that provides similar functions to wire mesh is the channel cable tray. It is a solid bottom tray with channels on the side for ventilation.

3.3 Pipes

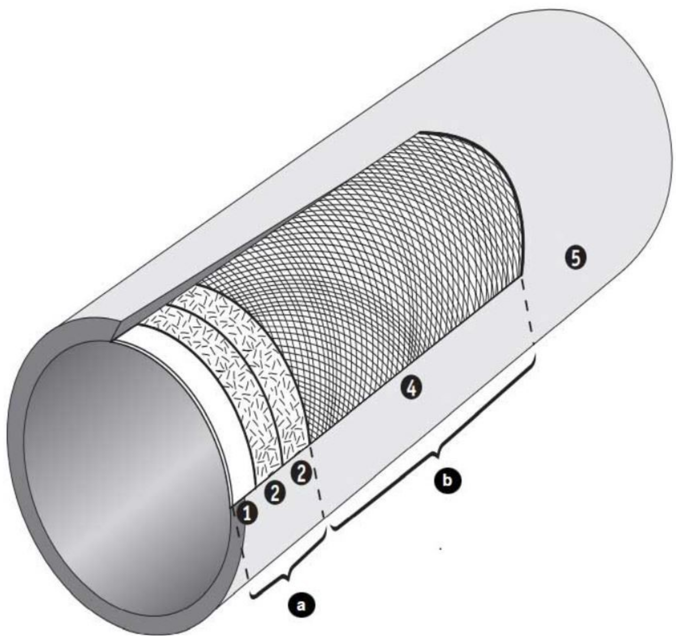

Figure 8: Composite pipes [80]

- 1) C-Glass surface veil
- 2)Chopped Strand Mat
- 3) Woven Roving
- 4) Filament Wound Strand
- 5) Outer surface layer with U.V. filler
- a) Corrosion Barrier (Abrasion Barrier)
- b) Structural Wall (pressure rated thickness)

Cylindrical composite shapes with small diameters can be made with pultrusion for instance, handrails. However, when the diameter is too large, continuous filament winding is used.

Filament winding process
Fiber is sent from the roving to the winding machine through the resin bath. The winding process takes place on a predetermined cylindrical shape called a mandrel. Layers of material are created as the roving carriage moves along the longitudinal direction of the cylinder.
During this process, an important parameter has to be noted. This is the winding angle which is the angle between the mandrel axis to the roving carriage. By changing this angle, the strength of the pipes can be adjusted as the direction of fiber orientation is changed relative to the length of the mandrel.
The winding process continues to create layers until the required thickness is reached. The composite is cured on the mandrel by a designated heat source that ensures even heat distribution. As mentioned, the mechanical properties of the parts will depend on the winding angle. The pipe density has a direct correlation to the tension of roving during the winding process. The inner layer of the pipe can be made with a special type of resin to protect the pipe from the corrosive fluid. Glass-reinforced polymer pipes that are made with a winding process usually have a good strength-to-weight ratio.

Figure 9: Filament winding [81]

Centrifugal casting Another method of producing composite pipes is centrifugal casting. This casting method is another way of manufacturing glass-reinforced polymer pipes. The composition in between the pipe thickness can be controlled.
For instance, the inner layer can have a higher resin percentage compared to the outside to give the pipe corrosive resistance properties. Meanwhile, the outermost layer of the pipe is more reinforced with fibers for structural integrity. This method gives each layer its

specific function. Even though centrifugal casting is a relatively slower process compared to filament winding, This process is viable for heavy-duty pipes [42].

The centrifugal casting process begins with determining the amount of material required to be deposited inside the rotating mold. The resin used is a special type of resin which does not polymerise during the casting process. The size of the fiber is predetermined such that it is according to the design requirement of the pipes. Fibers are distributed in layers in such a way that would counteract the resistance of the pipes in both transversal and axial directions. The process is done such that the pipe thickness is formed from its outer wall inwards.

According to [43], the mold begins with a slow rotation speed to ensure an even distribution of the raw materials. Once the materials are distributed evenly, the rotation speed is gradually increased to initiate the curing process of each layer. As a result of high mold rotation speed, the deposited materials are compacted into the mold. This removes any possible cavities and air bubbles along the pipe thickness. Consequently, the pipe has an improved compressive strength.

This process is repeated until the desired pipe thickness is created, layer by layer. The fibers used in the centrifugal casting process are not limited to glass fiber. Sand and silica are sometimes used in the barrier and structural layer. Thermosetting polymer is used as the resin. This can be either unsaturated polyester or vinyl ester resins.

The ratio between fibers and resin can be adjusted according to the design requirement. Hence there is compensation between stiffness and flexibility. Both pressure and non-pressure pipes can be formed by centrifugal casting.

The barrier layer is created after the innermost layer. This layer serves as a protection against foreign particles from entering or damaging the lining of the pipes. Next, the structural layer gives the pipe its pressure rating according to the design specification. The last layer is the outer layer protects the pipes from their operating environment, whether it be the salinity of the seawater or the UV radiation. When the final layer is formed, the mold is cooled with water and the pipe is ejected. The pipe-trimming process is accurately controlled by a computer program.

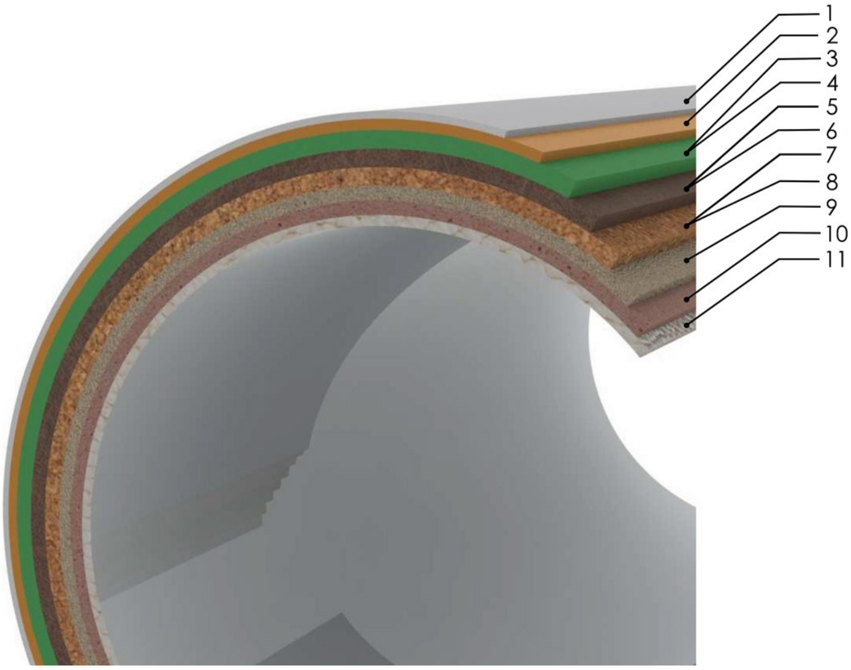

Figure 10: Layers of centrifugal casted pipe [43]

From the figure [10], layers 2 to 9 are structural layers, Their thickness can be increased or decreased according to the required pressure rating. Layer 11 is the lining layer which it is made up of only resin for chemical resistance.

3.4 Grating

For glass-reinforced composite grating, the two main methods are pultrusion and molding. Additionally, there are various types of finishing surfaces [23]. Each manufacturing method gives different functions and properties.

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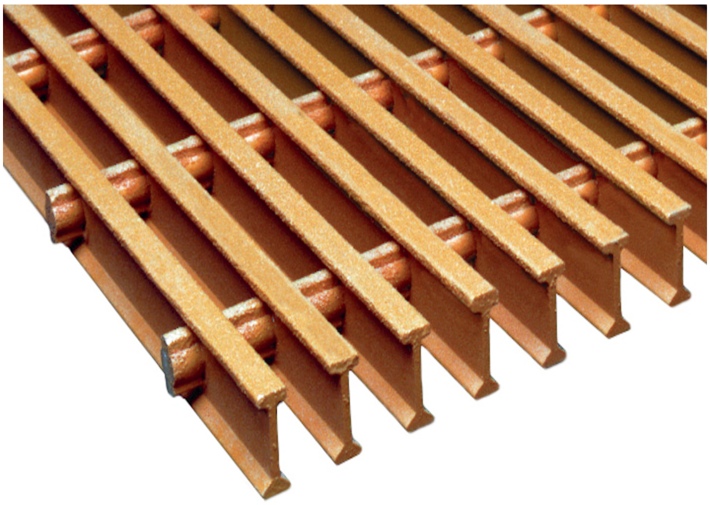

Figure 11: Pultruded GRP grating [51]

Firstly, pultrusion for grating is similar to the manufacturing process of handrail. This is what makes the process suitable for mass production. Constant pulling of fiberglass from a resin bath through a heated die allows the content of the resin to be controlled. The end product can be seen in figure [11]

Pultrusion produces a constant cross section parts for grating after which the desired length of the grating span can be cut as required. Moreover, the process directs the fibers orientation in one direction. Hence the longitudinal strength of the composite is increased. Another variant of pultrusion process is called pulforming where the composite cross-section can be slightly altered. However, pulforming is no longer a continuous process [88]. The standardised shape of composite cross-sections is an I or T shape. The pultruded rods are joined together with cross rods. This requires further post-processing, unlike molded grating.

There are various types of research done on pultrusion relating to the use of the thermo-setting polymer. Yet, the use of thermo-setting polymers in pultrusion is not extensively studied. This is because there is only a small number of thermoplastics which are suitable for the GRP pultrusion process. These thermoplastics are generally high costs. [25] argues that thermoplastics used in pultrusion process for GRP grating present an advantage not only in terms of mechanical process but also recyclability. The only downside of fiberglass-reinforced thermoplastics is its low production rate, compared to the thermosetting polymer.

2 majors pultrusion methods according to [24] are thermal pultrusion and UV pultrusion. The first method that can be used is thermal pultrusion. This method is rather traditional as it utilises a normal heat source. The other method is the UV-cured pultrusion where the thermo-setting resins are cured using ultra-violet light. The difference between the 2 methods is mainly the mechanical properties of the parts. For the UV-cured process, there is less thermal degradation in the matrix. Additionally, the curing cycles are comparatively shorter.

Another possible curing method is electron beam curing pultrusion. This method gives the best quality finished parts. However, it comes with a higher investment.

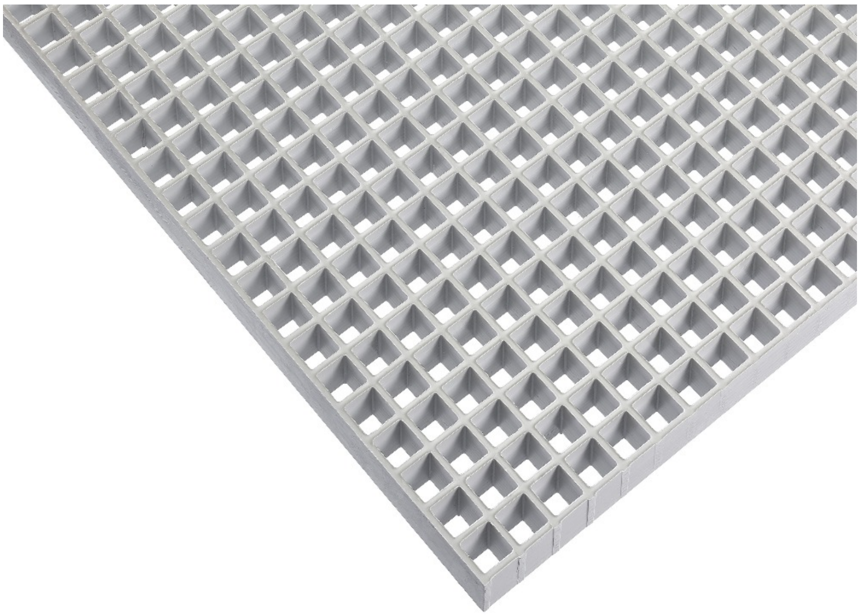

Figure 12: Molded GRP grating [51]

The molding process for molded grating is done by placing the fiber in a heated mold then the calculated amount of resins is poured into the mold. The mold gives the composite the desired grating shapes. Unlike pultruded grating, the strength of the part is not uni-directional as the fibers are not orientated in one direction [23]. Mold grating has more resin content than fiberglass [89] unlike pultruded gratings where the amount of content resin to fibers is the opposite. Figure [12] shows that there is no cross rod needed unlike grating made from pultrusion.

All in all, molding gives grating more surface options. This is essential for offshore applications. For instance, in wet surface conditions. Some manufacturers such as Lichtgitter can produce GRP grating that meets the standard of maximum anti-slipping surface R13 [51]. However, this requirement is not mentioned in DNV standards.

A common type of surface for offshore application is a meniscus top which can only be made with molded grate, seen in figure [13]. However, it is only compatible with safety shoes. Some other surface types such as integrated grit and aluminum oxide grit can also be used in wet and oily environments.

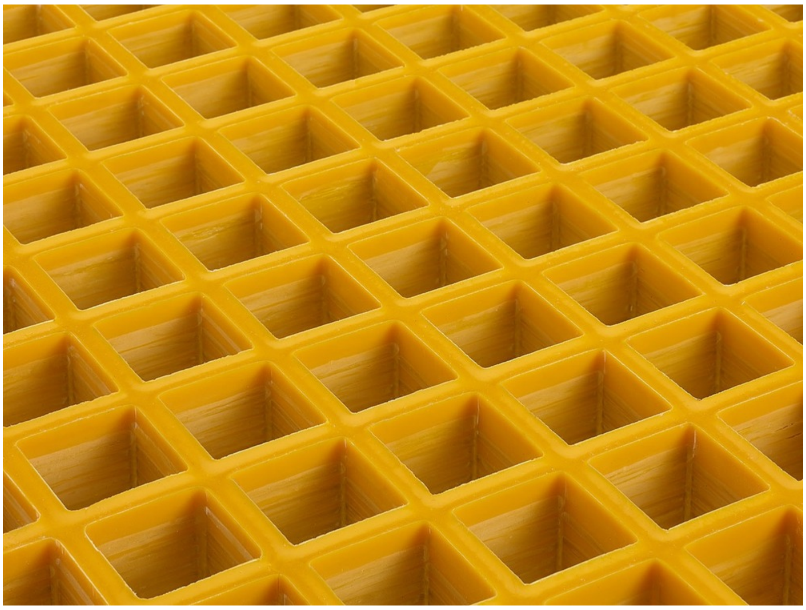

Figure 13: Grating with meniscus top [51]

The mesh shape of the molded grating is generally rectangular or square-shaped. Changing to GRP alone saves a lot of weight compared to traditional steel grating. However, the weight saving can be further increased if new designs are considered. In the next section, a performance comparison between the materials and designs is made.
According to [14], components such as low-pressure pipes, diesel storage tanks, lube and utility tanks and cable ladders/trays can be made of composites. The most common type of composite is phenol composites and the most common fibers are glass, carbon and aramid. There are also better-performing fibers such as silicon carbide, boron and aluminum oxide which would come at a higher cost.
On Davy and Bessemer platform, GRP is used in many non-structural elements. This ranges from the office equipment room, tool room, handrails, ladders on topsides and columns, gratings, fuel loading arm, drain pipe, caissons, diesel tank, lube tank and water utility tanks.
Phenol resin is used to make fire-resistant grating and modules on many platforms, including the newly installed platforms in the Gulf of Mexico. Moreover, polyester resin can be used throughout except for caisson and drain pipes where epoxy resin is used instead [15]. The most common composite used in the offshore industry is glass-reinforced epoxy as well as phenolic composites.
Components such as pipes and gratings make up a high percentage of total mass on offshore substations. In the current stage of the industry, they are made of composite materials because of their weight advantage and corrosion resistance properties. However, composite's major drawback is design flexibility as well as the high cost of raw materials and manufacturing.
HVAC vent is a good example of a component for which composite materials are not

suitable. Firstly, due to its complex shape and secondly, it does not require materials with outstanding mechanical properties. Additionally, HVAC vents are not needed in large quantities. Hence, mass production is not required. This increases the possibility of such components being made with only thermoplastics.
However, air vent only makes up a small percentage of all the non-structural elements, changing the materials to thermoplastics does not contribute to a large change in scheduled maintenance. Therefore, the grating is selected to be analysed in the following section.

In terms of assembly for offshore grating. several methods are available. the first type of securing element is called a saddle clip of M clip, seen in figure [14]. This type of fasteners can secure 2 adjacent gratings together. The bolt is drilled into the supporting metal frame below. The resulting reaction forces between the fasteners and the gratings hold every component in place.

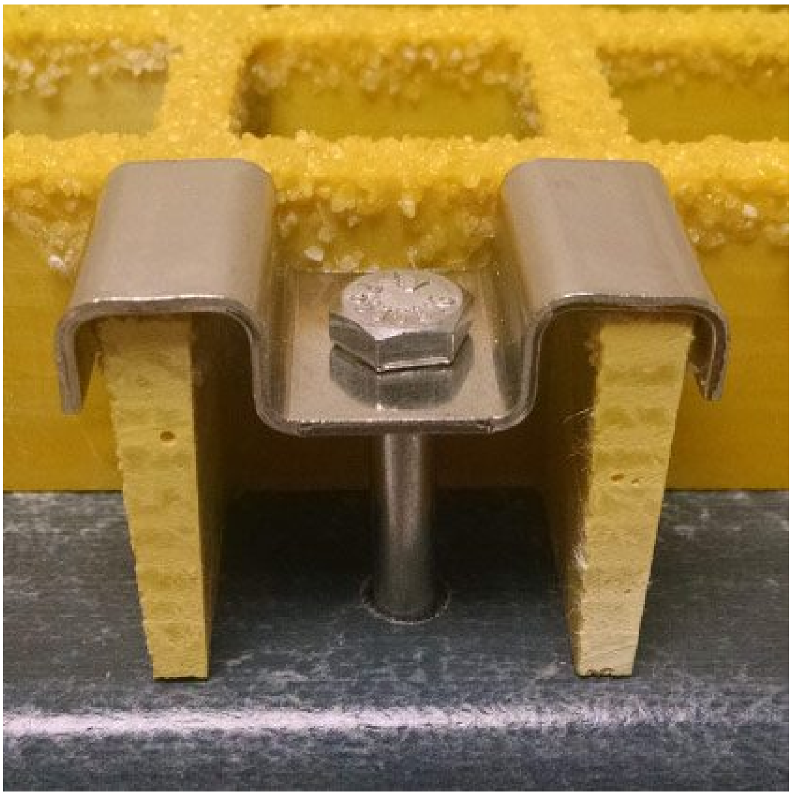

Figure 14: M clip grating fastener [31]

Another type of fastener is called a washer clip. This fastener has a disc shape which is secured in place with a bolt similar to [15. The speciality of this type of fastener is it allows an extra flat plate to be installed on top of the grating.

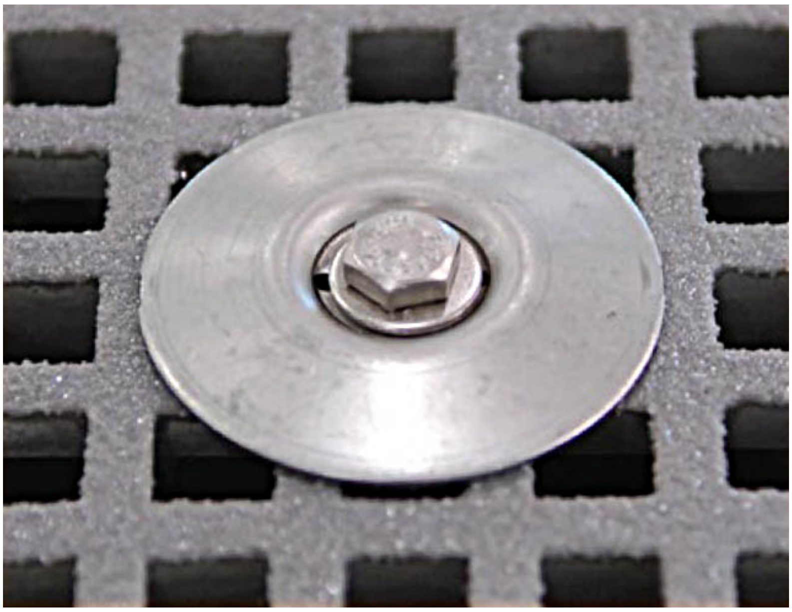

Figure 15: Washer clip grating fastener [33]

The last type of fastener can be seen in the figure [16]. It is similar to the M clip. Similar to the other types, the J clip is secured with a nut and bolt.

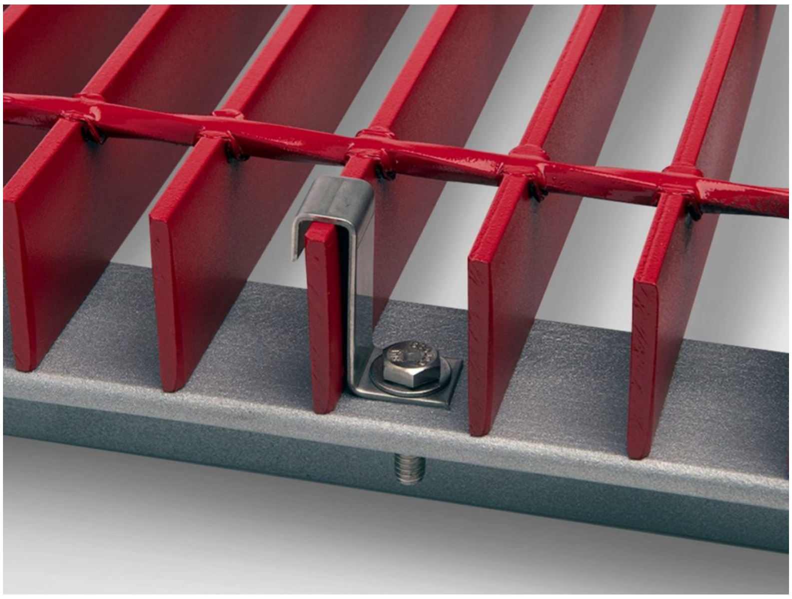

Figure 16: J clip grating fastener [32]

In all 3 types, the type of steel for the nuts and bolts have to be the same as the supporting frame. This is to ensure that galvanic corrosion cannot occur.

3.5 The alternative to composites

As mentioned, water and UV degradation plays an important role in determining materials for offshore applications. Additionally, manufacturability is an equally important factor in realising the designs.

For non-structural elements, qualitative and quantitative properties are equally important for the selection criteria. This becomes evident for grating as it is a component that involves a weight-bearing function.
There are many other non-structural components on an offshore substation that can be made with an alternative material to steel and do not require the strength-to-weight ratio of GRPs. However, some of these components have complex shapes which is not suitable to be made with GRP. GRP has design and processing limitations that can be solved with thermoplastics.

3.5.1 *Thermoplastics Degradation*

Thermoplastics are used in many different components due to their mechanical properties and costs. They can be processed by various manufacturing methods. In the offshore industry, thermoplastics are subjected to degradation like all other materials.
Similar to glass-reinforced polymers, thermoplastics degrade in the presence of seawater and UV radiation. The degradation of polymers changes their mechanical properties which leads to more frequent maintenance.
Under UV radiation, the degradation mechanism of thermoplastics is photo-oxidation [56]. UV lights catalyze photo-oxidative reactions causing polymers' bonds to break down [59]. Another degradation mechanism of thermoplastics is hydrolysis. This phenomenon occurs when water molecule breaks down the chemical bonds of polymer. This alters the mechanical properties of the polymer which eventually causes mass erosion.
The total degradation rate of polymer is both, the rate of UV degradation and hydrolysis. The total degradation rate of thermoplastics is temperature dependent as temperature increases, bond energy is also weakened. As a consequence, the degradation rate due to UV radiation is slower for fully submerged thermoplastics as the sea water absorbs heat [56]. The rate of UV degradation is further reduced with an increasing submerged depth. Yet, the total degradation level remains relatively the same because the rate of degradation due to hydrolysis is increased with the submerged depth [60].
UV exposure affects the fatigue behaviour of thermoplastics due to chain scission and post-crosslinking [59]. This happens especially for low-density polyethylene which is categorised as a bulk semi-crystalline polymer.
Furthermore, some thermoplastics can undergo chemical degradation in marine environments as well. This is the case for cellulose acetate [58].
All in all, photo-oxidation and hydrolysis are the main degradation mechanism. Another mechanism is chemical reaction but this depends on the chemical composition of the polymers.
Ions in seawater interact with the chain causing bond breaking. The result is a reduction in molecular weight and length on a local scale and surface cracks on a global scale.

When the polymer is subjected to both seawater and UV light. The degradation would occur at a higher rate. The UV light aids the formation of free radicals in the polymer. The electron pairs in the chain can react with oxygen in water, causing chain degeneration. However, like many other polymers, when it is subject to humidity, a hydrolysis reaction occurs. [66]

3.5.2 *Offshore Thermoplastics*

In most applications, thermoplastics are used as a resin in a composite. The combination between fibers and matrix material improves the strength-to-weight ratio as well as fatigue resistance. For offshore, thermoplastics give better corrosion resistance compared to metallic materials. [65]. Common thermoplastics offshore that are used to make the composite are PolyEthylene (PE), Polypropylene (PP), Polyamide (PA), PolyVinylidene DiFluoride (PVDF), and PolyEther Ether Ketone (PEEK) [63]. In addition, some composites also have healing properties [62]. Composite of a magnetic polyamide-6 (PA-6) nano-composite film could undergo a self-healing process when exposed to microwave heating.

Acrylonitrile styrene acrylate (ASA) is a thermoplastic commonly used for outdoor applications due to its ability to resist UV radiation.

A set of strategies can be implemented to protect thermoplastics from degradation. First is to use a UV stabilizer additive which prevents the chain from unwanted reaction [67]. The second is to adjust the chemical structure of the polymer to improve degradation resistance. By introducing a crosslinking agent, the stability of the polymer can be improved it reduces the chance of hydrolysis and photo-oxidation. [67]. A physical method to prevent degradation is to use an extra coating layer which serves as a barrier between the subjected conditions and the polymer.[67]

From the literature review, it is apparent that reinforced polymer has superior mechanical properties compared to thermoplastics. However, in the case of non-structural elements, the advantage of design flexibility outweighs the strength of the reinforced polymer.

ASA is a thermoplastic that is commonly used in additive manufacturing, specifically fused deposition modelling. [36]. Its chemical composition consists of co-polymer between acrylonitrile, styrene, and alkyl acrylate elastomer.

The main composition of the 3 is butyl acrylate [37]. These 3 co-polymers gives ASA its overall advantages over other types of polymer in terms of manufacturability and physical properties

According to CEFAN, an important factor to take into account during the printing process of ASA parts is the printing temperature. By adjusting the temperature, the mechanical properties of the end products can be enhanced or diminished. [36].

The specific mechanical property that is greatly affected by the printing temperature is tensile strength. However, additive manufacturing is relatively new. Therefore, the

effect of the printing temperature of ASA is not as well documented compared to another polymer such as ABS (acrylonitrile butadiene styrene)
As mentioned, the superior mechanical properties of the 3 co-polymers give ASA great weather resistance compared to its alternative polymers like ABS.
The fact that ASA contains a saturated acrylate elastomer instead of butadiene which is unsaturated gives ASA superior resistance to outdoor weather conditions than ABS. Additionally, from this chemical composition, ASA has higher heat stability and impact strength. Thus, ASA is chosen to be used in many offshore applications.
The current application of ASA is as a protective layer for telecommunication components [37]. Another variant of ASA is also made to improve its current physical properties. ASA can be combined with ethylene acrylic and reinforced with nano-sized carbon to increase its strength. Some modifiers such as PVC can be mixed to improve impact strength [38]. However, The combination of ASA and PVC is not manufactured for the market yet.
All in all, various polymers come from the same family as ABS depending on its modifier. The size of the filler will eventually affect the additive manufacturability that ASA originally had.

3.5.3 *Manufacturing process of thermoplastics*

Considering the non-structural elements mentioned in the previous section, Their manufacturing processes as polymers are explored in this section. It is worth mentioning that there are other manufacturing methods of polymer. This section compares the viability of the alternative materials to GRP. All in all, a comparison in terms of design flexibility is clarified. There are various ways of processing thermoplastics depending on the end product.
The 2 main manufacturing methods of polymers for non-structures are injection molding and thermoforming. Additive manufacturing is currently at the experimental stage with the Cefan department of Navantia.

Injection molding

Figure 17: An example: insert molded part

The most common manufacturing method for a component with a relatively complex design is injection molding. it has a fast cycle time and low production cost. The low cost of production comes from the fact that injection molding can be automated. Therefore a large number of personnel are not needed during operations.

High heat and pressure are used as the operating condition of the injection molding process. This allows intricate mold design to be used as a molten polymer can be injected with ease.

This manufacturing process is available for many types of polymers and low post-processing is required as the molds usually have very low tolerance. Moreover, in some cases, inserts can be Incorporated by insert molding, as seen in figure [17]. In addition, the filler can be mixed with the parts to enhance strength and ease the molding process by altering the molten polymer's mechanical properties.

However, intricate mold design comes with a high cost of investment. Such costs involve testing, set-up operation and mold designs [61]. Before the actual production process begins, prototypes have to be made and tested. Furthermore, parts with sharp edges lead to low product quality with injection molding. The draft angle should be created in the mold for ejection and constant wall thickness has to be ensured to avoid shrinkage.

Thermo-forming

Thermoforming is a manufacturing method which is suitable for producing large components. It is suitable for all polymer types. However, the design of the parts created is relatively less complex compared to injection molding.

However, thermoforming is relying on a heating and pressing basis which does not allow parts with large thicknesses. The raw material is only limited to sheets. In thermoforming, failure can occur when the sheets have uneven thickness. This lead to shrinkage that weakens the final product. [52]

The cost of the thermoforming process mainly depends on the materials [53]. Material distribution on the mold is not the only factor that affects the quality of the final product. In [52], oxygen transmission rate also plays a part in the manufacturing process.
Deeper research into polymer chemical structure finds that the amorphous structure of the polymer is more suitable for thermoforming processes than semi-crystalline polymer. The thermoforming process requires a large temperature range around the melting point which semi-crystalline structure polymers do not have ([52]).
As mentioned earlier, the main challenge of the thermoforming process is unequal thinning which results in warping. The analysis is usually done by comparing the measured oxygen transfer rate to the expected rate.
Another variation of thermoforming is to use a non-fixed die (multi-point thermoforming). This increases parts' complexity and accuracy as it can manipulate the surface elasticity of the polymer. [54]
The mechanical properties of the polymer after thermoforming are relatively unchanged. [55] argues that the surface and bulk properties of polymers are unchanged after thermoforming process in a vacuum. Moreover, heating surface treatment can be done to further enhance the stiffness of the parts by increasing the level of crystallinity in the polymer. Lastly, only a small percentage of shrinkage is detected in thermoformed multilayer films.

Additive manufacturing: 3D printing

Traditionally, additive manufacturing is used for prototyping as it is relatively quick, accurate and low costs for prototypes. In the Cefan department of Navantia, additive manufacturing is used to conduct experiments on many non-structural elements for offshore applications. These components include grating, HVAC vents, door panels. An entire bathroom including a shower in figure [45] can be seen in the appendix. This bathroom is 3D printed with polylactic acid (PLA) in a single run. Extra accessories such as a door, mirror, and showerhead are assembled into the module later. Some of these components are now already in use offshore. Grating made from ASA can be seen in figure [44] in the appendix.
Additive manufacturing is entirely automated. Thus, labour costs and human errors are greatly mitigated. Moreover, it allows designers to tailor the design of parts to their function with computer-aided design programs. Moreover, it can produce complex shapes due to the degree of freedom of the nozzle. Result products have little waste materials which makes additive manufacturing attractive for the renewable energy sector. [68]
In terms of costs, additive manufacturing has no set-up costs like other manufacturing processes. This is because its set-up costs are not fixed regardless of the number of products produced like other manufacturing methods.[40]
The emission from manufacturing processes all around the world take up to 76 % of all the emissions from industries [44]. Due to its less material waste during production. Additive manufacturing has a promising outlook in the future, not only in the offshore industry.

Even though there is very little material wasted, the downside of additive manufacturing is that compatible materials are limited. The selection of material that suits the function of the final products has to be confirmed via the material selection process. Furthermore, regardless of the ability to produce an entire final product in a single process, the production time can take up many hours with complex parts.This makes additive manufacturing a less desirable choice for mass production. [69]

In the offshore industry, there are many possibilities for additive manufacturing. However, this depends on the selected material as well as overall costs in the supply chain.

4 CASE STUDY: OFFSHORE GRATING

Figure 18: Offshore grating [86]

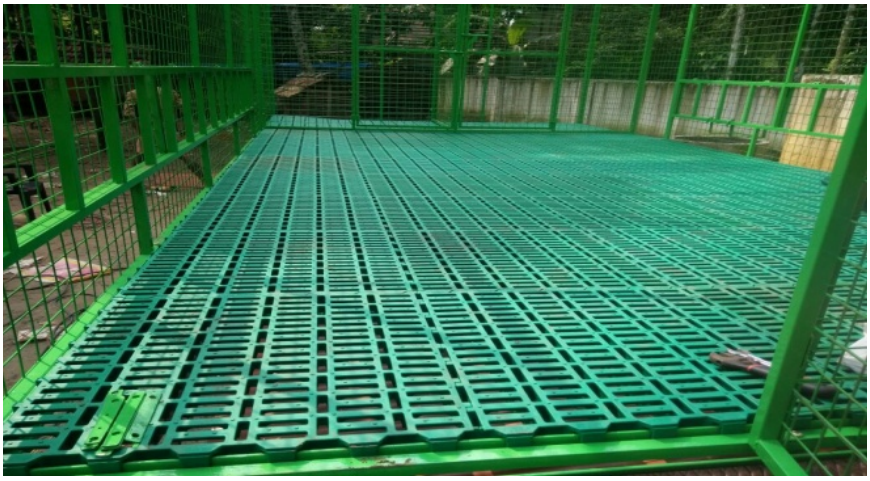

Figure 19: Agricultural grating[87]

4.1 Polymer grating

Research into the existing use of polymer grating is done to determine the level of design novelty. The finding shows that the use of polypropylene slat floors is found in the agricultural industry.

The functions of slat floors in agricultural and offshore industry are relatively similar. Both have to be able to bear weight and are required to be corrosion-resistant. However, the main purpose of slat floors in the agricultural industry is hygiene related. In addition, the design for weight-bearing capacity for animals is entirely different for humans due to EU legislation that has to be followed [64].

The majority of the polypropylene slats in agriculture are produced by injection molding. Unlike the offshore industry, weight saving is not the main concern because due to accessibility. As a result, Other variations of materials such as concrete is used.
Even though the functions and conditions between the two industries are similar. The objective is to investigate the validity of polymers in the offshore industry. There are not many non-structural components that are subjected to small loads and are also mass-produced. Total weight of grating can be one of the heaviest non-structural components on an offshore substation.
Considering a thermoplastic such as ASA (Acrylonitrile Styrene Acrylate), the cost of injection molding become increasingly expensive with the level of design complexity. Additionally, the difficulty of removing parts from the mold can affect the dimensions of the components [82].

4.1.1 *Why honeycomb structure ?*

There are many possible designs for weight- saving. The honeycomb structure has a relatively high strength-to-weight ratio. Generally in a sandwich structure, the honeycomb structure is located between 2 face sheets (parts B and C) seen in figure [20]. The top and bottom face sheets are laminated to the core of the honeycomb.

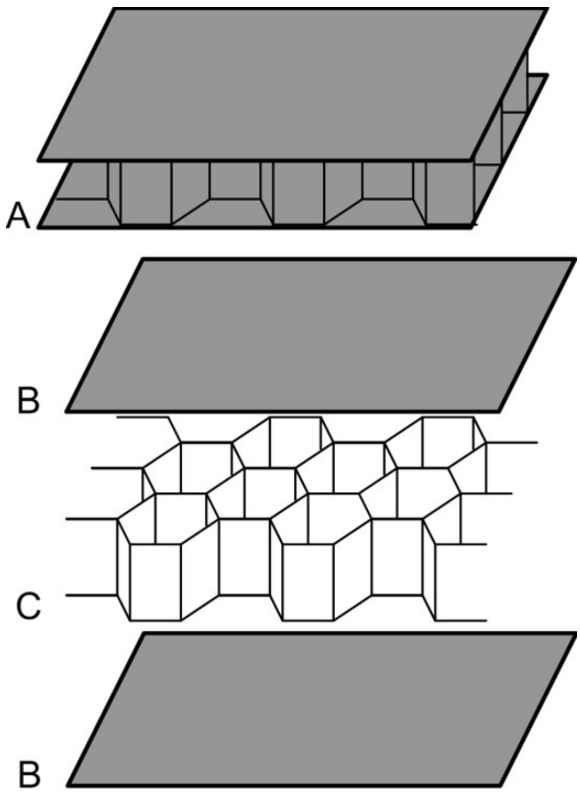

Figure 20: Honeycomb in a sandwich structure [45]

Honeycomb traditionally has a regular hexagonal shape. However, the cell parameter

can be adjusted according to the design requirement. The weight saving of a sandwich structure comes from the hollow cells of the honeycomb. This weight is relative to the weight of a solid beam [46] as it is also called bulk density.
The bulk density of a honeycomb structure has a range between 0.08 g/cm3 to 0.15 g/cm3[47]. Such weight-bearing capacity requires less material which in turn saves more manufacturing costs. The use of honeycomb structure can be seen in many industries where weight saving is crucial. Whether it be aerospace, transportation or construction industry.
Furthermore, the honeycomb structure also has a soundproofing property. honeycomb core in a metamaterial can be designed such that negative sound refraction is achieved[48]. The mechanical properties of a honeycomb are sensitive to its geometry. Equivalent bending stress in transversal and axial directions is affected by a change in cell length and wall thickness Section 4 gives a detailed mathematical explanation.
The interest in investigating the potential of honeycomb grating is further supported by the validity of additive manufacturing. The manufacturing method allows multiple materials to be integrated into one structure. Such a combination can greatly improve the mechanical properties by increasing the impact energy and compressive force [49].
It is mentioned in [50] that 3-dimensional woven honeycomb fabric improves the shear and tensile strength of a sandwich composite. This is because de-lamination cannot occur. Undoubtedly, not only the material choices but also the manufacturing method influences the mechanical properties of a honeycomb.
The geometry of a honeycomb is explored further in the next section. The proposal to manufacture grating by thermoplastics gives an outlook on the possible future of the offshore renewable industry.

4.1.2 *Material selection process*

Both quantitative and qualitative selection criteria are needed for thermoplastics in an offshore application. The criteria ensure functions as well as safety. The concerns regarding safety issues are pinpointed by following the standard of a classification society.
Fire safety is explained under section 6.4.3 of the DNV Offshore substation standard [83]. It is stated that except for the insulation in the refrigerated compartment, the materials used have to be non-combustible. This requirement is essential for the material selection process as some thermoplastics are flammable. The specification of each structural element varies according to its fire safety class in the fire safety document DNV-OS-D301 [71].
There are 4 fire division classes in total. Class H division has the same requirements as class A but with an addition of fire testing methods. These 2 divisions are formed by decks and bulkheads. Class B division is formed by ceilings or linings. It is a division which is less critical than A and H classes. Lastly, class C is relatively least critical of all.

This division is made of approved non-combustible materials which do not need to meet the requirement of flame passage nor the temperature rise limit.
In the document for thermoplastics composite pipe [84], the detail regarding accelerated UV exposure testing is given. Results between accelerated and natural exposure to UV radiation should be evaluated. DNV states that service experience documents can be used to demonstrate UV resistance. However, for the element of interest, only testing can be done to demonstrate the resistance.
Next, under section 5.15, guidance regarding chemical degradation is given. Low levels of hydrolysis and oxidation have to be ensured. Evaluation of mechanical properties after chemical reactions should be conducted. Furthermore, the depletion of additives used to prevent chemical reactions should be estimated.
DNV allows the use of documented evidence to prove the material resistance to chemical resistance as an alternative to experimental evaluations. Lastly, the usage of the thermoplastics has to be agreed upon by both parties (the manufacturer and the purchaser).
Furthermore,the design temperature is also mentioned in section 6.14. The document states the importance of the maximum and minimum operating temperature as well as the glass transition temperature of the matrix. This applies to the case of grating. Material selection has to ensure the operating temperature is below the glass transition temperature.
Grating is one of many components that are currently being experimented with different polymers by Cefan. The grating function involves a small load. This makes it a suitable component for design validation .
The main interest from Cefan is to experiment with thermoplastics that can be processed by additive manufacturing. They have several thermoplastics proposed for experiments. These polymers are 2 variants of polycarbonate (PC), Polyphenylene sulfide (PPS) and Acrylonitrile Styrene Acrylate (ASA). The material selection will be done using the CES Edupack program. The result will be cross-checked with CEFAN's proposal.
In the first stage, glass transition temperature is the determining factor in filtering out unsuitable thermoplastics. The chosen value is 100 $°C$. The rest of the criteria are according to fire safety, manufacturing process, and environmental resistance.

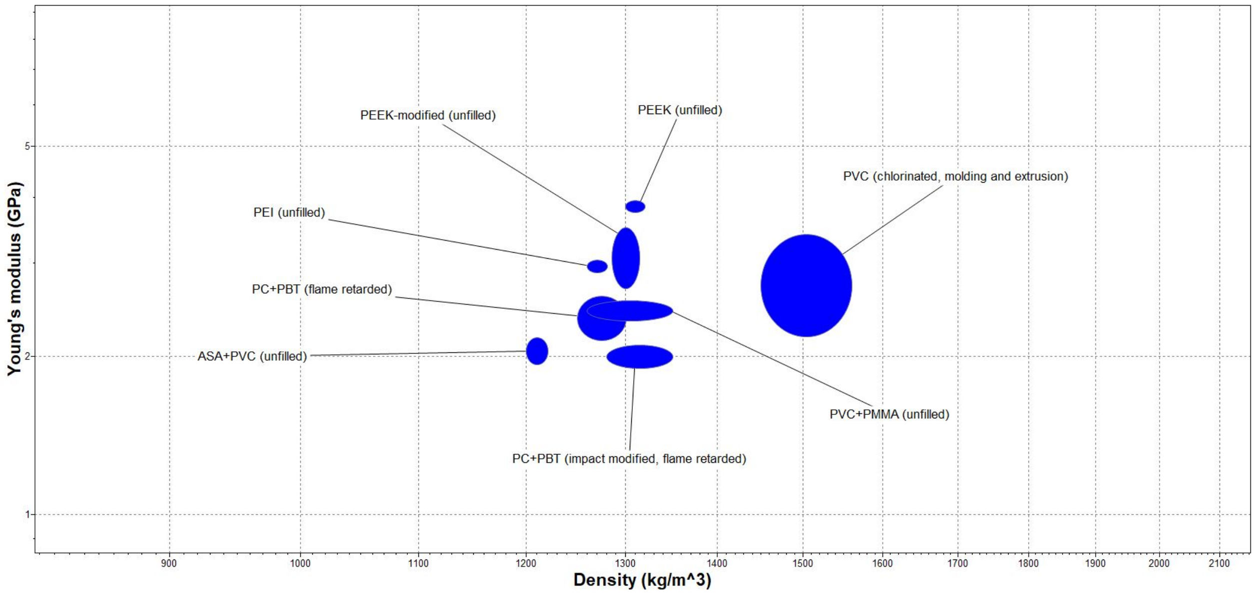

Figure 21: Thermoplastics selection: Stage 1

In the second stage, the goal is to find the best strength-to-cost ratio.
Finally, the same materials as the CEFAN proposals are shown. These materials are then selected in terms of costs since they all pass the same selection criteria.

Table 2: Qualitative criteria

Properties	Qualitative criteria
UV resistance	Excellent
Salt water resistance	Excellent
Flammability	Self-distinquish, non-flammable
Polymer injection molding	Excellent, acceptable
Polymer extrusion	Excellent, acceptable

Table 3: Quantitative criteria

Properties	Quantitative criteria
E	1.9
K_c	14
E_{flex}	60
$T_g(°C)$	100

Out of 3947 materials on the database, 3 materials base have passed. One of which has another variation, making 4 materials in total.

The properties and costs of each are given in the table below.

Table 4: Lists of polymers and their properties

Properties	ASA(INEOS)	ASA+PVC(new)	PC+BCT	PVC+PMMA
E	2.3	1.93	2.15	2.34
σ_y	-	43.4	50	32.8
σ_T	-	44	42	44.1
$\mathcal{E}$	9	40	50	35
E_{flex}	70	62.1	73	71
ρ	1.07	1.2	1.25	1.26
T_g	100	90	172	90
Cost estimate [€ per kg]	5	3.02	4.65	3.35

As the focus is on non-structural elements, quantitative properties such as Young's modulus and ultimate tensile strengths can be considered a second priority to qualitative properties. The use of composites offshore as a structural component has not been extensively studied due to safety concerns. Even though the material properties of many composites are known, an important factor that raises doubts is water absorption as it causes unpredictable failures.

The design of structural elements is entirely possible but it comes with a higher cost of design and analysis.

4.2 Analytical calculation: Honeycomb structure

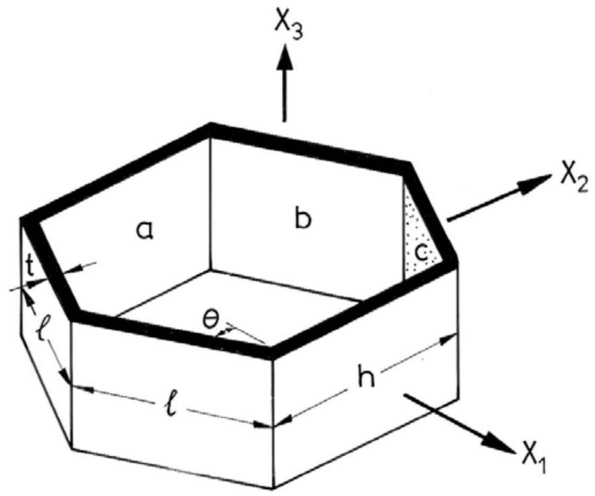

Figure 22: Hexagonal honeycomb cell diagram [1]

Table 5: Parameters: Honeycomb analytical optimisation

Parameters	**Value**	**Unit**
Honeycomb internal angle	30	degree
Grate length	330	mm
Grate width	330	mm
Core depth	20	mm
Cell length (l)	22	mm
Cell width (h)	22	mm
Distributed load	25	kN/m^2
Geometrical factor (t/l)	0.27	-
E_{ASA}	2300	N/mm^2
G_{ASA}	800	N/mm^2

4.2.1 *Hexagonal honeycomb*

Both plate and beam bending theories can be used to estimate the maximum grating deflection. The theorem selection depends on the geometry of the object of interest. For grating, it is clear that plate bending is more suitable. On the other hand,when beam theory is used, shear bending components can be added to the total deflection . Since grating is not a solid plate. Equivalent stiffness in the transverse direction has to be calculated. The dimensions are defined according to assumptions made for the derivations of analytical equations .
A distributed load is defined according to the Lichgitter data sheet [51]. The load is applied on 2 proposed designs. 1) Regular hexagonal honeycomb design 2) Square honeycomb. The latter design is the traditional grating pattern. [85]

Equivalent Young's modulus

The equivalent Young's modulus in x_3 direction is related to the relative density of the structure to the material which is used to make the structure.

$$\boxed{\frac{E^*}{E_s} = \left\{ \frac{\frac{h}{l} + 2}{2(\frac{h}{l} + sin(\theta)) \cdot cos(\theta)} \right\} \left\{ \frac{t}{l} \right\} = \frac{\rho_c^*}{\rho_s}} \tag{2}$$

For a hexagonal unit cell, the term in the bracket relates to the surface area projected to plane x_3. In the case of a regular hexagon where $l = h$, the term is simplified to 1.1547 as the angle θ is exactly 30 degrees [1].

Equivalent Shear modulus

The derivation for equivalent shear modulus requires 2 theorems under an important assumption that the cell thickness is much smaller than the cell length. $t << l$ This is to

ensure the hypothesis of uniform stress along the cell wall [39]
The first theorem (12) applies the theory of minimum potential energy to find the upper bound of the equivalent shear modulus.

$$\frac{1}{2} \cdot G_{13}^{*} \cdot \gamma_{13}^{*} \cdot V^{*} \leq \frac{1}{2} \Sigma \left(G_s \cdot \gamma_i^2 \cdot V_i \right) \qquad i = a, b, c \tag{3}$$

The second theorem applies stress equilibrium to define the lower bound of shear modulus.

$$\frac{1}{2} \cdot \frac{\tau^2}{G_{13}^{*}} \cdot V \leq \frac{1}{2} \Sigma \left(\frac{\tau_i^2}{G_s} \cdot V_i \right) \qquad i = a, b, c \tag{4}$$

After simplification, the relationship between the honeycomb equivalent shear modulus and the solid shear modulus is given below.

$$\frac{G_{13}^{*}}{G_s} \geq \frac{cos(\theta)}{\frac{h}{l} + sin(\theta)} \cdot \left(\frac{t}{l} \right) \tag{5}$$

$$\frac{G_{23}^{*}}{G_s} \geq \frac{\frac{h}{l} + sin(\theta)}{\left(1 + \frac{2h}{l}\right) cos(\theta)} \cdot \left(\frac{t}{l} \right) \tag{6}$$

$$\boxed{G_{13} = G_{23} = \frac{1}{\sqrt{3}} G_s \left(\frac{t}{l} \right)} \tag{7}$$

For a regular hexagonal cell shape where $l = h$, it can be confirmed that the upper and the lower boundary coincide.

Deflection

The deflection of a grating contains two components; shear bending and pure bending. Since plate bending theory is used to model the offshore grating, only equivalent stiffness is required. The maximum deflection occurs in the middle of the plate.

Maximum deflection

The coefficient α can be found in the table by calculating the aspect ratio of the plate. Since the length b and L are the same, the aspect ratio is 1. The value of alpha according to [85] is found to be 0.0444.

$$\boxed{\delta_{max} = \frac{-\alpha \cdot q \cdot b^3}{E^{*} \cdot t^3}} \tag{8}$$

4.2.2 *Square pattern honeycomb*

The minimum potential energy is used to determine an expression for equivalent shear modulus for a square cell honeycomb. Since it is known that when $l = h$, the upper and lower bound will coincide. the expression for direction 23 is omitted.

Shear modulus

$$\begin{aligned} &\frac{1}{2} G_{13}^{*} \cdot \gamma_{13}^{2} \cdot h \cdot l \cdot C \\ &= \frac{1}{2} G_s \cdot \gamma_{13}^{2} \cdot t \cdot l \cdot C \end{aligned} \tag{9}$$

Minimum potential energy theory

$$\boxed{\frac{G_{13}^{*}}{G_s} = \frac{t}{h}} \tag{10}$$

This grating design can be mathematically interpreted as a square structure. The comparison is to validate that the hexagonal shape structure provides superior mechanical properties to the traditional square shape.

Young's modulus

From expression (2), the equivalent stiffness in x_3 direction for a square pattern is directly related to its cell wall thickness t. The term in the bracket of the equation [2] is reduced to 1.5. The equivalent stiffness of the square honeycomb in X_3 direction is as following.

$$\boxed{\frac{E_3^{*}}{E_s} = 1.5 \cdot \left(\frac{t}{l}\right)} \tag{11}$$

4.2.3 *Result comparison*

Assumptions

1. The same wall thickness t
2. The same cell length l
3. The same material
4. The same grating dimension
5. the cell wall thickness t is much smaller than cell wall length l

Table 6: Comparison: Square vs Hexagonal honeycomb core

Mechanical properties	**Hexagonal**	**Square**
E_3^*/E_s	0.31	0. 41
G_3^*/G_s	0.16	0.27
Maximum deflection [mm]	2.27E-03	1.75E-03

A hexagonal honeycomb is more prone to shear stress compared to a square honeycomb of the same wall length. The hexagonal shape is slightly less stiff than the square in the out-of-plane direction.
For the application of grating, the load is predominantly inducing bending deflection. Since the stiffness of the hexagonal shape is lower than the square. Performance comparison must be done in terms of the percentage difference between mass and deflection.
In other words, it is essential to compare the load resistance per given mass. The investigation will be done in detail with numerical analysis in the next section.

4.3 Numerical calculation: Honeycomb structure

A list of assumptions for each honeycomb type is shown below. The assumptions allow problem size reduction and hence save the computational time. The goal of this numerical analysis is to validate each design in terms of strength-to-weight ratio.
The assumption given in [39] such that θ equals 0 and l is $\frac{h}{2}$. Ansys design modeller is the selected program for modelling and analysis of the designs according to the assumptions [5].
For the models, the cell thickness (t) is 6 mm, cell length (l) of 22 mm and cell depth (C) of 20 mm. The span is 330 by 330 mm. These dimensions ensure uniform stress along the cell wall. The aspect ratios $\frac{l}{C}$ is 0.3 and the ratio of $\frac{t}{l}$ is 0.27.
In terms of boundary conditions, the model is fixed on 4 sides. These figures are shown in the appendix [42] [43]. A distributed load of 25kN/m2 [51]is applied on the top surface to seek the total maximum deflection. Acrylonitrile Styrene Acrylate (ASA) is selected as the material for the simulation. Its mechanical properties are assigned manually into Ansys Workbench. The mesh convergence study is initiated with a mesh size of 1 mm and the volume as well as the mass of each model is calculated by Ansys.

4.3.1 *Quality of mesh*

There are 3 ways to check the quality of mesh elements. In this case, Q4 is automatically selected by Ansys.
Jacobian ratio is the measurement of element distortion by comparing the specific mesh element to the ideal element. If the element of interest matches with the ideal element, the jacobian ratio is 1. It can be seen in the appendix that all the elements in both

designs have a very small deviation from 1. For the square honeycomb's mesh, the average Jacobian is 0.9907 and 0.9998 for the hexagonal design. Given the simplicity of the parts, the values of Jacobian being close to 1 is expected.
Aspect Ratio is always equal to or more than 1. It is the ratio between the 2 lengths from the midpoint across the element. If the ratio is 1 then the element is a perfect square. 1.0145 is the average value of the hexagonal part. For the square honeycomb part, the average ratio is 1.039
Skewness is found by subtracting 90 degrees by the angle found between the intersection between the lines from the midpoint of each side of the element. If the angle found is 90 degrees, the resulting skewness is 0.

4.3.2 *Hexagonal honeycomb*

Table 7: FEA results: Hexagonal honeycomb

Mesh size [mm]	Nodes number	Element number	Total deflection [mm]
4	15660	12960	2.0431
3	24336	21168	2.063
2.5	35154	31104	2.086
2	52470	47520	2.102
1.9	62424	57024	2.106

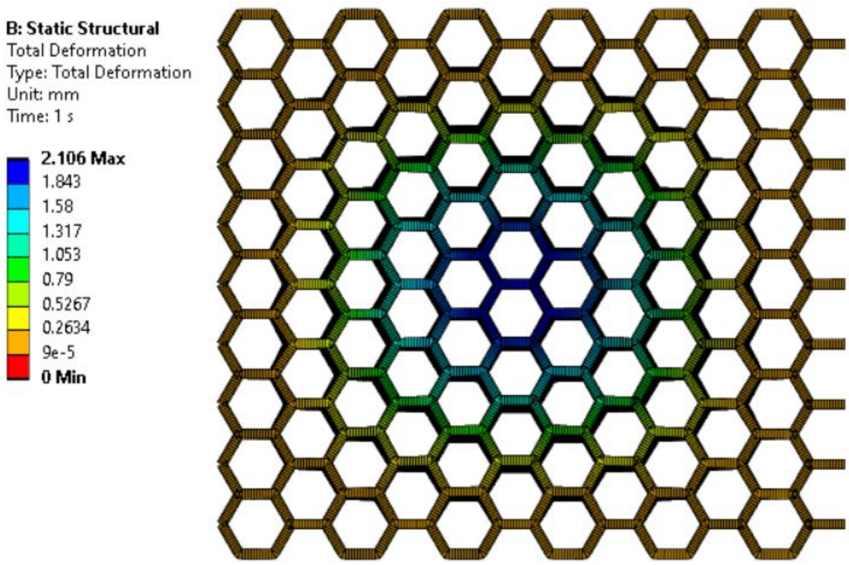

Figure 23: Total deflection (Top view): Hexagonal honeycomb

4.3.3 *Square pattern honeycomb*

Table 8: FEA results: Adjacent square honeycomb

Mesh size [mm]	Nodes number	Element number	Total deflection [mm]
4.5	18080	14336	1.631
4	27840	23040	1.676
3.5	32480	27648	1.678
3	45312	39424	1.706
2.9	49408	43008	1.721
2.6	55584	49152	1.722

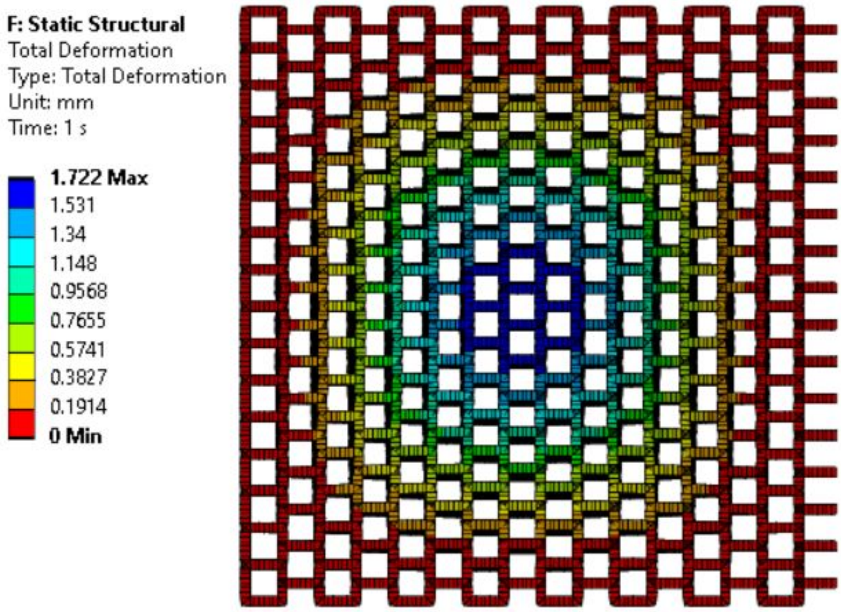

Figure 24: Total deflection (Top view): Adjacent square honeycomb

4.3.4 *Results comparison*

Table 9: Honeycomb performance comparison

	Hexagonal	Adjacent square
Mass [kg]	1.2203	2.1694
Total deflection [mm]	2.1065	1.7220
Mass%	0	77.78%
Deflection %	0	-18.25%
Strain %	1.3%	1.0%

As seen in the table [9], the percentage mass difference is much greater than the percentage deflection difference. Assuming the maximum deflection is not reached, it can be concluded that the hexagonal design is superior. On the other hand, supposed the maximum deflection is reached, small geometry adjustments would make the hexagonal honeycomb an adequate design. The geometry adjustment can be either reducing cell wall length (l) or increasing core depth (C) and cell wall thickness (t). All in all, resources allocated to optimising the honeycomb design could be an opportunity for offshore wind energy companies. It is best to compare the total costs during lifespan before making any allocation into design and manufacturing.

Results of the analytical calculations are based on an empirical formulation which is accurate for regular shapes. However, in the case of irregular cell lengths, the calculation will only be an approximation.

4.4 Performance of GRP vs thermoplastics

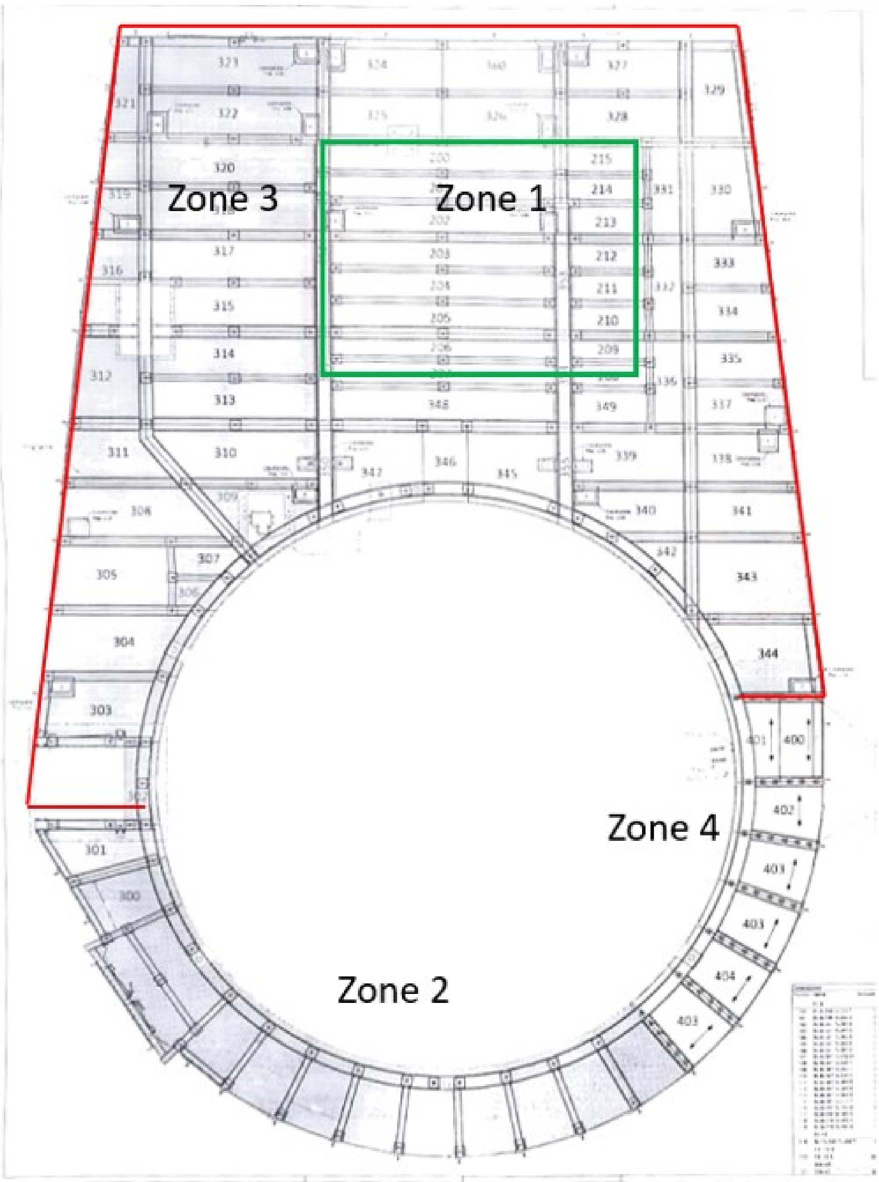

Figure 25: Monopile transition piece of Vineyard wind project

A drawing from Lichgitter for the Vineyard project is shown in [25]. The drawing shows a transition piece of a monopile where the majority of the grating is made from composite material, specifically glass fiber reinforced isophthalic resin.
There are 4 different zones with different loading cases. Grating from zone 1 to zone 3 is made of composite material, whilst grating in zone 4 is made of steel.
Zone 1 is the laydown area where the operational load is the highest. Zone 2 is the ball-proof area. The term 'ball proof' signifies the fact that the mesh size of the grate is small enough to prevent dropped objects from falling through the open grates. However, the specific mesh dimension for zone 2 is not given in the drawings. Lastly, zone 3 is made of composite and has micro mesh grating. it is made for the function of personnel on the

transition piece.

From the manual, the load applied on zone 2 and zone 3 are identical. The only difference is in the mesh design. The drawing gives the total surface area of the 3 zones.

It is clear from the material data that thermoplastics are less stiff compared to GRP. A shorter span for ASA grating is required to have the same percentage of maximum deflection as GRP grating. Moreover, a shorter span requires more supporting frames which are usually made of steel.

However since the density of ASA is 1.07 g/cm^3 which is almost half of glass epoxy composite at $1.8g/cm^3$, the thickness of grating can be increased to compensate for its stiffness.

In the analysis, the thickness of the grating is considered to be a standard thickness. Many manufacturers produce GRP grating up to 40mm which means that an optimum dimension between grating thickness and span can be calculated. This optimum point gives the best total weight-saving performance for ASA grating compared to GRP grating.

The independent factor that dictates this optimum point is the maximum deflection at mid-span. DNV does not specify this requirement. It is only up to an agreement between the grating manufacturers and the offshore wind company.

In the next section, a challenge of recycling GRP shows that thermoplastic is becoming a more attractive choice both in terms of sustainability as well as costs.

5 OUTLOOK OF GRP

The future of offshore renewable energy depends on economic factors. the costs involved in generating the output have to be minimal to make wind energy competitive with other sources of energy, let alone profitable.
To analyse the costs in the supply chain of non-structural elements. grating is used as an example. However, pinpointing the costs in number is inaccurate because factors such as inflation, and taxes play a role in the net calculation. This entirely depends from country to country.
A perspective on the industry from the engineering and economic point of view is linked to the supply chain. In this section, the outlook of the industry from a material point of view is discussed.

5.1 GRP market outlook

The impact of glass-reinforced polymer on the environment can be assessed through a life cycle assessment. The assessment includes all the stages from production to disposal or in the more specific term, cradle to grave. The impacts of glass-reinforced polymer production range from climate change due to emission, and soil acidification to contamination of fresh water. [28]
To gain an insight into the supply chain of the glass-reinforced polymer. The source of raw materials has to be investigated. Silica, sand and Borate are geological materials. These materials are used to make the reinforcing material for the composite. Finally, the environmental effects of glass-reinforced polymers can be evaluated and a strategy for disposal, recycling and reuse can be made. This will reduce overall environmental impacts if not during the manufacturing process.

5.2 Glass Reinforced Plastic Market Overview

The importance of understanding the market is to predict the future supply chain of composite materials. The industry has to be examined from a bigger picture which is from the relationship between supply and demand. In this section, the economic aspects of glass-reinforced polymer are outlined. The research does not limit its analysis only to the offshore industry but all the industries involving the use of composites. The market data ranges from the aerospace industry to transportation as well as oil and gas.
There are various sources of data for market analysis.The market of glass-reinforced plastic will reach 13.04 billion euros by 2027 (not adjusted to inflation) [16] . With a compound annual growth rate (CAGR) of 6.3 % during 2022-2027.
A specific detail about which type of composite will be in favour by the industry is given in the report [16]. It is estimated that polyester and epoxy resins will dominate the

glass-reinforced polymer market. The main drive for the demand for GRP comes from an increasing need for composites for non-structural components such as interior and exterior wall panels and possibly offshore grating.
In 2021, the level of composite production in Europe increased by 19% relative to the year before. this makes up around 3 million metric tons of composites. Moreover, the statistic shows that short-fiber composites have the majority of the market share [17]
Another market study estimated a rather more aggressive growth of 8.4% between the 10 years from 2023 to 2033. However, the market valuation is different. This is because of factors taken into account for the analysis. [22] predicts that the market will be valued at roughly 37 billion euros in 2033 from 17 billion euros in 2023.
Arguably, the difference in figures between the sources comes from an inelastic demand for composite materials that have superior mechanical and physical properties to steel. Secondly, the relatively overestimated figure from [22] is due to the fact that figures from other industries are taken into account. The other industries mentioned refers to those that are highly dependent on composites such as the automotive and aerospace industry.
Moreover, the growth of the GRP market is further accelerated by sustainability awareness. Industries in Europe are adjusting to the regulations imposed to cut down carbon emissions. For instance, using GRP in the automotive industry will help cut down the emissions due to its lightweight property which saves more fuel.
Lastly, advancement in manufacturing technology for producing composite parts allows lower production costs which makes composites become a more attractive option for many end users. A clear example of this is the improvement of molding technology that has high efficiency and low downtime.
On the other hand, several factors hinder the growth of the GRP market. This is due to the challenge of recycling. Recycling glass fiber is a health hazard and separation of glass fibers from resin is known to be difficult. Nonetheless, the possibility of recycling is not 0.
In the next section. GRP piping is investigated. It is a well-studied composite component which involved in many industries and not only offshore. This makes GRP pipe a good representation of the niche market of GRP components.

5.2.1 *GRP pipes market*

A large section of the GRP market is taken by glass-reinforced plastic piping. The section takes up to approximately 4.6 billion euros in 2020 according to [74].
The compound annual growth rate is slightly estimated lower than the whole market at 4.5 % from 2021 to 2027. The main drive for this growth is due to the demand for GRP's superior mechanical properties as well as the growing energy and chemical industries.
Thermo-setting polymer is the major type of resin that dominates the GRP piping market.
A significant portion of this currently goes to the oil and gas industry.
GRP pipes are used not only to transport chemical fluids but also to supply fresh drinking

water as well as wastewater. There is a large variety of GRP pipes in the market thanks to its manufacturing process, the thermal property and stiffness can be slightly adjusted from the fiber orientation and the curing process. This gives the end-users flexible options to select. The most common types of resins are epoxy and polyester. The forecast by types of resins is shown in figure [26].

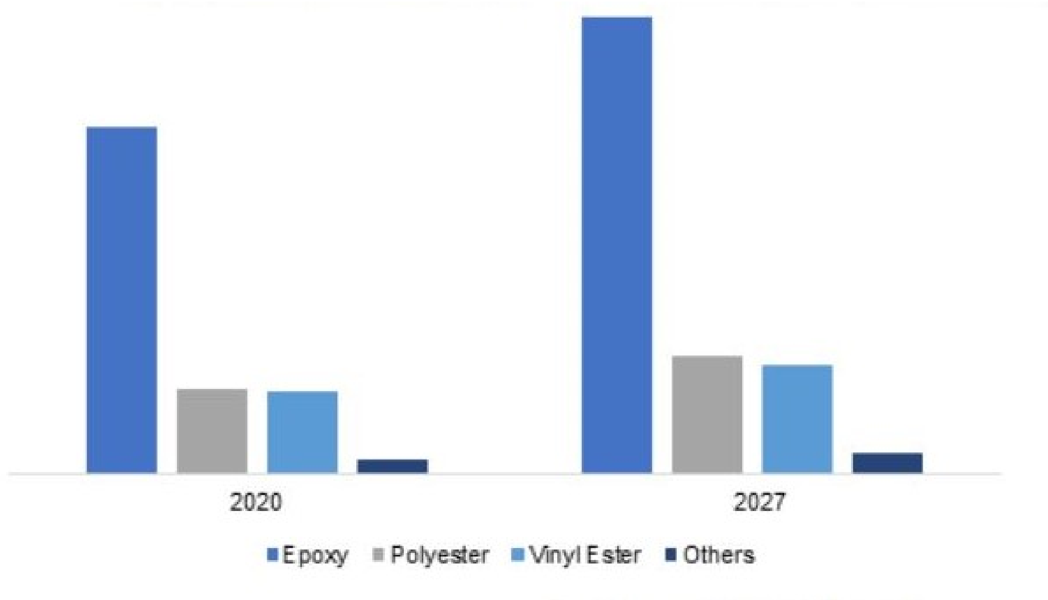

Figure 26: Global glass reinforced plastic piping market, by resin (in us million) [74]

The growth of epoxy resin-based composite is almost the same rate as the GRP piping market as a whole at 4.3%. Since epoxy resin-based composite is the most common of all. Statistical research is done and shows that 3.2 billion euros of the piping market alone goes to this type of resin. Water plays an essential part in many industries. it is expected that global consumption will be up to 21 % for all the treatment of wastewater. Wastewater is a by-product of cooling and manufacturing in industries such as pharmaceuticals and mining. According to the prediction, a portion of the revenue from the market of 1.6 billion euros will be held by Europe in 2027. GRP pipes in Europe are demanded by many chemical companies. Furthermore, as mentioned, the development of urban areas and higher populations would add to higher consumption and economic growth in general.

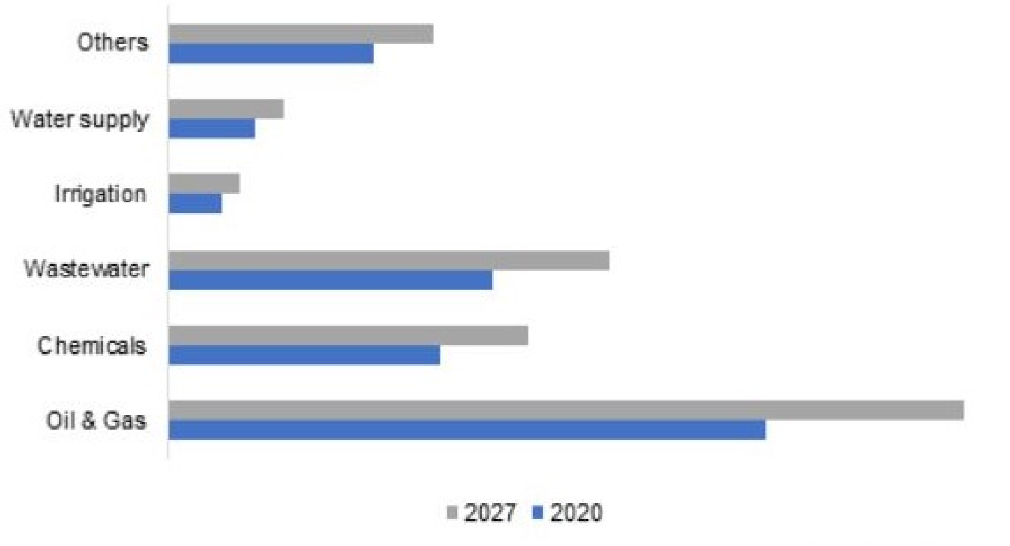

Figure 27: Global glass reinforced plastics piping market, by application [74]

The speculated driver for the growth of the piping market is similar to the GRP market as a whole. Piping is a solution to sustainable 'green building' where ductile metal pipes are substituted. This is confirmed by a statistic from UNO that the global population in the metropolitan areas are predicted to double by 2040 compared to the rural, countryside areas. Additionally, the imposed emission limits further urge the use of sustainable and long life span infrastructures. Figure [27] shows the industries in which GRP pipes are in high demand. The highest volume is allocated to the oil and gas industry which is followed by wastewater.

Apart from the rise of the need for sustainable infrastructure. The report of the piping marking also shows an increasing trend in the North American oil and gas energy sector. A large sum of the demand in this sector goes to an emerging technology of horizontal drilling. A technology which spurs the production of hydrocarbon in the US market. The list of pipe functions goes on in the oil and gas industry from exploration, and transportation to refinery. Therefore, it is undoubted that the advancement of other industries has a direct impact on the demand for composite components.

Many developing countries are now considering biofuel as an alternative to hydrocarbons and another source of energy as it is easily accessible. This further supports the need for fluid-transporting components which explains the GRP piping market size prediction in 2027.

A factor that resists the expansion of the GRP piping market is regulations. From country to country, different rules monitor the production and use of composite pipes. Examples of such authorities are the European Council and the Organisation for Standardization (ISO). These organisations are responsible for setting the guidelines for production and safety standards. For the composite pipes that are used in the water and food industries.

Health regulations have to be followed. The inner lining of the pipes must be made with a certain type of lining that is non-toxic and 'food-safe'.
Many of these regulations deter new manufacturers from entering the market. In addition, GRP piping manufacturing requires high capital investment which makes the market supplies more inelastic. On the other hand, imposing stricter regulations can in turn increase the demand for GRP pipes. For instance, regulations for production companies to decontaminate wastewater cause a spike in demand for GRP piping in many water treatment facilities.
Similar to any other composite parts, the production of GRP pipes has a challenge in recycling waste materials. Many local authorities have a limit to landfill disposal which can in turn limit production. Moreover, the nature of the manufacturing process of GRP pipes is 'made to stock' and not 'made to order' basis which means the manufacturers are highly sensitive to the volatile price of the raw materials.

5.3 Offshore renewable outlook

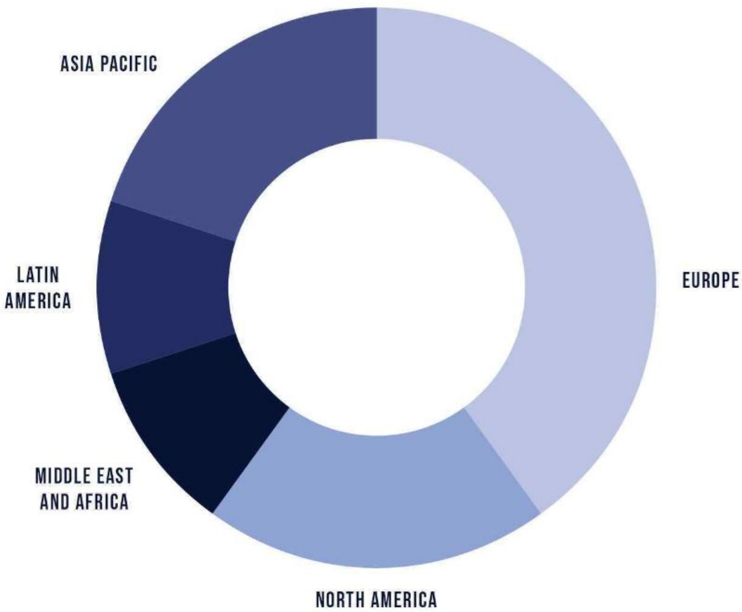

Figure 28: Offshore wind energy market share by region, 2021 [73]

The use of offshore composite materials has a direct correlation to the capacity of renewable energy output. the estimation of the offshore wind energy market size provides information about related industries and the factors that impact the market.
The market analysis contains different categories for wind turbines. First, the division is done according to water depth. There are 3 main regions, shallow, transitional and deep water. Next, the division is done by output level, below 3 MW, between 3 to 5 MW and above 5MW. The forecast period is between 2022 to 2030. The current most profitable

water zone for offshore wind turbines is in the shallow region. this is because of the ease of installation, maintenance and power transportation. However, the deep water region has a higher power production potential. Larger turbines can be built in deep water with floating technology. This allows companies to harvest more energy at a higher initial investment.
The market size for offshore wind energy is 25.1 billion euros in 2021. This value is estimated to increase to 118.5 billion euros in 2030 with a compound annual growth rate of 19% during the period. [73]
Offshore renewable energy is one of the most promising sources of sustainable energy for the future. The industry is relatively new and has the potential to create jobs and employment that can benefit a country's economy.
As of 2021, there are around 40 developing projects in the United States. In addition, Europe has new installations that are capable of a total of 19.1 GW both offshore and onshore combined in 2022. This is an improvement of 4 % compared to the previous year. Even though the target was aimed at 12 % to balance the emission. [72]
Currently, the UK has the strongest output from offshore wind energy in the world. This level of competition is healthy for the advancement of more efficient energy. Yet, the costs of operation and maintenance are still very high compared to onshore wind energy. It can be seen in figure [28] that Europe has the biggest portion out of all the industry.

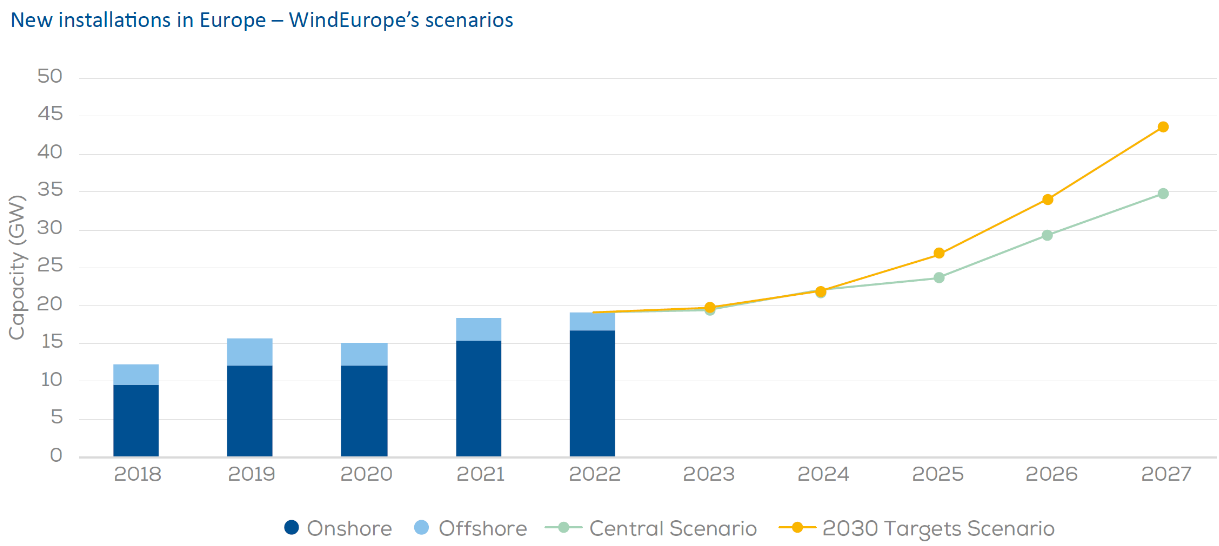

Figure 29: The wind energy capacity in Europe [72]

In figure [29], it can be seen onshore wind has a majority of the output capacity. The target scenario of the future is rather ambitious and substitution for composite materials is only part of the whole picture.
Currently, Europe has the largest market in the world. The growth of this market is expected to grow even larger in the upcoming years. An organisation like the European

Wind Initiative aids technological development to ease the installation and improve the wind infrastructure further. With the ongoing research on installation and transportation methods, the size of the blades and the height of the tower will be larger in the future.
Undoubtedly, Europe is currently having the largest market energy for offshore wind but the fastest growing market is in Asia Pacific. The contribution of China, India and Japan gives their market a higher compound annual growth rate than Europe. This creates competition between the 2 markets which will further drive technology development.
Thus, to respond to the global demand for more sustainable energy, the development of technology to make sustainable energy accessible to all is crucial.
Sectors that are involved in the supply chain of offshore renewable energy can be located by the related industries and personnel needed to establish a wind farm. The actions of these stakeholders can affect each other directly and indirectly.
In the future, the industry is inclined towards floating wind turbines as larger blades are capable of higher output. However, this is viable only if the profit can be made. larger blades present a transportation challenge. Special transportation methods have to be arranged which are usually an expensive one-time occasion.
Overall, with composite materials, the costs of transportation can be reduced regardless of the assembly method. This is because less fuel is required to move a lighter mass. Moreover, on sight assembling technique can eliminate the need for special transport, as seen in figure [30] below.

Figure 30: Special transportation of turbine blades

New technology can mean a more complex design that requires suitable materials such as polymer. Such support from government agencies makes the possibility of neutralising emission levels more hopeful but at this stage, we are far from complete.

There are many possible locations for wind farm installation in the world. For instance, the US has enough coastal areas that can generate 2000 GW. Additionally, China has the biggest output from offshore wind in Asia. With an estimated of around 18,000km available coastline for production.
This data gets attention from many investors but the process of verifying takes time. Moreover, not only in the US but areas in developing continents such as South America and Africa draw the interest of many investors. It is apparent that it entirely depends on the accessibility of the technology to make renewable energy a solution.

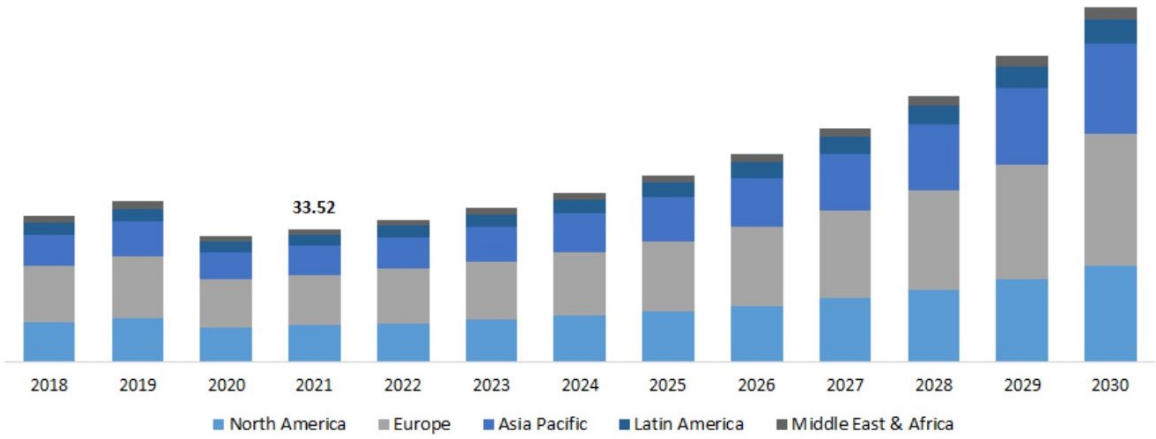

Figure 31: Offshore wind energy market size by region 2018-2030 [20]

A figure from another market report shows a slightly different result. According to [20] the global market value in 2021 is at 30.7 billion euros. During the forecast period of 8 years, the market value is targeted to grow at a CAGR of 12.1%. A slight drop can be seen in the figure [31] between the years 2019 and 2020 due to the pandemic.
The demand for sustainable energy to lower carbon emissions is the main drive of this market growth. The growth is accelerated by governments' support and public investment to achieve the carbon emission limit by 2050.
This increase in the yearly output of renewable energy has to go from 25% per year to 86 % to reach the Paris Agreement according to the international renewable energy agency. However, other sources of renewable energy can contribute to this objective. Solar and tidal energy have a promising future and they can take up to half of global energy production by 2050
The offshore wind industry is very sensitive to a change in schedule. The forecast period includes the impact of the pandemic which shows the reduced level of consumption during the lockdown period. This negatively impacted the supply chain and therefore most projects have been delayed as a consequence.
In conclusion, the revenue of the offshore wind energy market is approximated to be 82.4 billion euros in 2030.
Apart from offshore wind turbines, tidal energy is an alternative sustainable source that

can contribute to total renewable energy in the future. By 2050, the waves and tides can provide a capacity of up to 337 GW where 1/3 of this capacity is in Europe according to Ocean Energy Europe [21]. this means that 10% of Energy demanded in Europe can be covered by this source of energy. Therefore, relying on offshore wind turbine energy alone in the hope of reducing emissions is unrealistic.
Several forecasts show that by 2030 total production capacity will be around 323 GW where the majority of this power production comes from onshore.

5.4 Recyclability

Recycling of GRP components is foreseen to increase regardless of the reduction in the production rate. A large part of these GRP components comes from the construction of buildings, where there is the most waste produced. The next biggest sector that generates the composite waste is electronics and transportation. Each type of industry and the waste produced can be seen in figure [32].
The ultimate goal of the renewable energy sector is to aid the reduction of carbon emissions. at this stage, the main challenge of the GRP pultrusion process is to recycle the by-products created from the manufacturing process. due to such difficulty of recycling, these by-products end up at landfills [26]

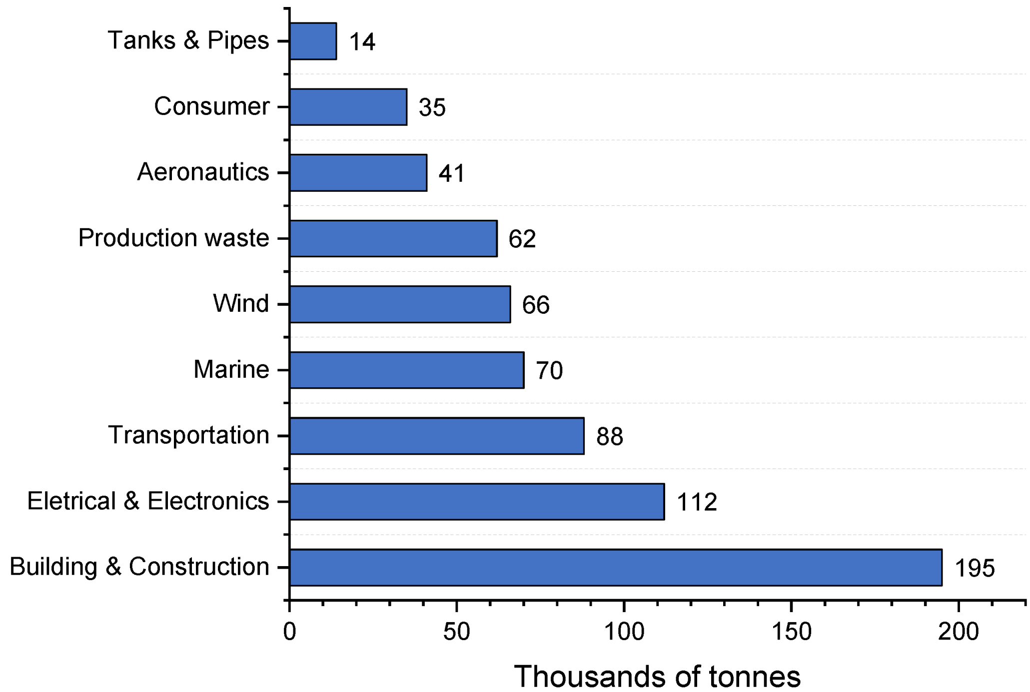

Figure 32: Composite materials recycling [18]

According to [29], a new method of coatings for GRP parts has been studied and successfully created. These composite parts are made by using 'end of life' glass fiber which has been mechanically recycled.

The samples of these composites are used as an example in the proposal for new industrial guidelines for coatings. Hence, it is apparent that there is a possibility to avoid landfill disposal of the glass-reinforced composite when the end of service life is reached.
On the other hand, the urge to tackle the recycling challenge leads to a proposal to use the manufacturing by-products as reinforcing materials. Substituting the waste products into polyester-based mortars as sand aggregates and replacing the filler are new solutions. The result is improved mechanical properties of the polymer mortars.[26]
A recycling challenge of GRP leads to an experiment with an alternative reinforcing fiber. It has shown that ramie fiber presents an advantage to glass fiber as it contributes to a lower environmental impact, more specifically less ozone depletion [27]. In terms of costs. ramie is a natural fiber which does not require processing like silica to make glass fiber.

Besides the advantage in terms of the level of environmental impact, the mechanical properties of composites made from ramie fiber are not well documented. Thus, it becomes increasingly important in the future that composites from natural fibers are studied in detail.

The knowledge developed from experimenting with natural fiber will, in turn, reduce the manufacturing costs which makes such composites more available in the future.
Surprisingly, according to [18], sustainable wind energy is speculated as one of the highest waste producers as well. Approximately 2.5 million tonnes to be produced in the future. The low service life of the blades can become a challenge when they are to be replaced. The blade composition of 17% carbon fiber does not allow a full recycling process. Moreover, it is estimated that around 66000 tones of thermo-setting composites will be generated in 2025. This comes from the blades alone. Hence, to take into account all the non-structural components on a substation, the figure is much higher.
The contradiction between a 'sustainable' source of energy and the materials used is clear. It is crucial to develop a solid method for recycling composite materials to separate the fiber from the resin or to mechanically digest the fiber and the resin altogether. The landfill is not the solution to the cause of the problem. It is merely a temporary solution to an inevitable need for recycling.
Focusing on bio-based GRP is essential to tackle the problems relating to the recycling of waste products. At the current stage, the industry is only at the experimental stage of innovating bio-based GRP. All the stakeholders in the composite industry have a responsibility to limit and reduce their footprint levels.
In developing countries, concerns over carbon footprint are arguably not the most urgent priority. Therefore, it is an important task for researchers and pioneers to develop a more accessible technology for all.

6 CONCLUSION

The thesis is qualitative research on the use of composite materials in the offshore industry. A major drawback of composite is recyclability and manufacturing processes. A large portion of the weight on a substation or any offshore structure is gratings and handrails. These components present an area for cost-savings by substituting the original material. The study finds a new potential for thermoplastic applications due to their mechanical properties. Acrylonitrile Styrene Acrylate is one of the thermoplastics of interest due to its weather durability and suitability with additive manufacturing. These properties give ASA an advantage over other thermoplastics such as Polycarbonate and Polyphenylene sulfide. After having an understanding of GRP and its corrosion mechanism, design validation between the hexagonal pattern and square pattern is done for grating with analytical and numerical analysis. For square grating, the result shows 77.8% increases in mass and only 18.9% less deflection. Hence, It is clear that the honeycomb design presents a great weight-saving capability. All in all, the derivations are proved to be accurate as the deflection from the equations derived is similar to the results obtained from Ansys.
Undoubtedly, classification societies influence the design requirement for each component of a substation. For non-structural elements, the most important criterion is fire safety. Cable trays reflect this importance from their function of supporting power cables. The materials selected from CES Edupack passed all the environmental criteria. However, only ASA and PC are shown to have excellent processability.
Looking at the bigger picture, the sustainability of energy production has to be considered beyond the operation period. The real challenge of using composite material comes when the end-of-life is reached. Most composites used in many industries are made of thermosetting resin. This prevents glass fibers from being separated from the resin to be recycled or reused. This is because thermo-setting polymers cannot be reheated like thermoplastics. Therefore, an outlook in a composite material is to consider bio-fiber or thermoplastic resin which comes at a higher cost. Lastly, the physical properties of thermoplastics open many possibilities in the offshore industry. Yet, the window to offset the level of emission is narrowing. The study of using alternative materials can only contribute to a small portion of sustainability. The future of composite materials are depending on the technology for the manufacturing process and the end of life processing.

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APPENDICES

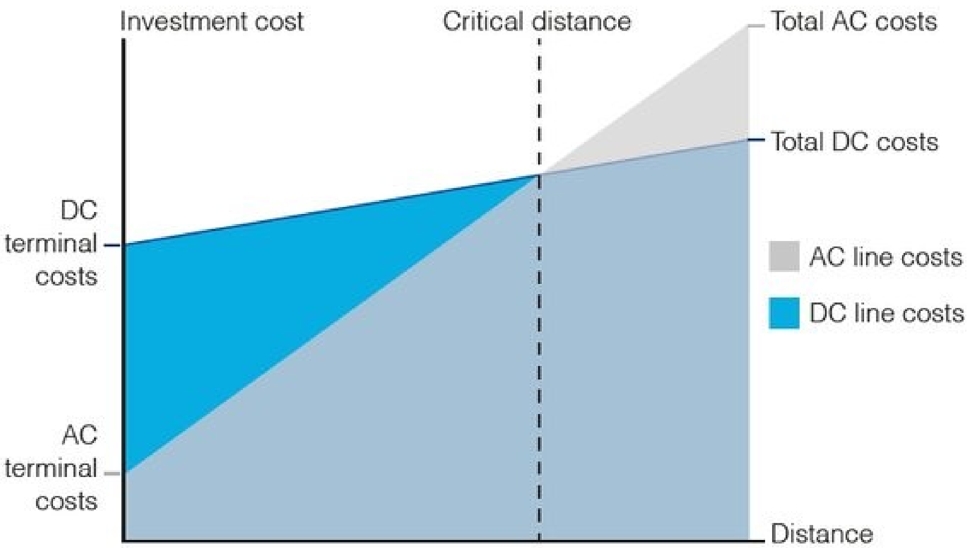

Figure 33: Costs difference between AC and DC due to distance [30]

$$\frac{1}{2} \cdot G^*_{13} \cdot \gamma^*_{13} \cdot V^* \leq \frac{1}{2}\Sigma \left(G_s \cdot \gamma_i^2 \cdot V_i\right) \qquad i = a, b, c \tag{12}$$

The second theorem applies stress equilibrium in order to define the lower bound of shear modulus.

$$\frac{1}{2} \cdot \frac{\tau^2}{G^*_{13}} \cdot V \leq \frac{1}{2}\Sigma \left(\frac{\tau_i^2}{G_s} \cdot V_i\right) \qquad i = a, b, c \tag{13}$$

Cell unit volume

$$\begin{aligned} V^* &= [h \cdot lcos(\theta) + lsin(\theta) \cdot lcos(\theta)] \cdot C \\ &= [h + lsin(\theta)] \cdot lcos(\theta) \cdot C \end{aligned} \tag{14}$$

Cell wall volume

$$\begin{aligned} V_a &= h \cdot t \cdot C \\ V_b &= V_c = l \cdot t \cdot C \end{aligned} \tag{15}$$

Shear direction 13

$$\begin{aligned}\gamma_a &= 0\\ \gamma_b &= \gamma_{13} \cdot cos(\theta)\\ \gamma_c &= \gamma_{13} \cdot cos(\theta)\end{aligned} \tag{16}$$

The same procedure is repeat for shear direction 23. The shear strains on each cell wall are defined below.

Shear direction 23

$$\begin{aligned}\gamma_a &= \gamma_{23}\\ \gamma_b &= \gamma_{23} sin(\theta)\\ \gamma_c &= \gamma_{23} sin(\theta)\end{aligned} \tag{17}$$

The minimum potential energy is used again to determine an expression for equivalent shear modulus for square cell honeycomb. Since it is known that when $l = h$, the upper and lower bound will coincide. the expression for direction 23 is omitted.

Unit cell volume

$$V^* = h \cdot l \cdot C \tag{18}$$

Cell wall volume

$$V_a = V_b = t \cdot l \cdot C \tag{19}$$

Shear modulus

$$\begin{aligned}\gamma_a &= 0\\ \gamma_b &= \gamma_{13}\end{aligned} \tag{20}$$

$$\begin{aligned}&\frac{1}{2} G_{13}^* \cdot \gamma_{13}^2 \cdot h \cdot l \cdot C\\ &= \frac{1}{2} G_s \cdot \gamma_{13}^2 \cdot t \cdot l \cdot C\end{aligned} \tag{21}$$

Minimum potential energy theory

$$\boxed{\frac{G_{13}^*}{G_s} = \frac{t}{h}} \tag{22}$$

The current grating design can be mathematically interpreted as a square honeycomb structure. this section is to validate the fact that hexagonal shape structure provide superior mechanical properties to the traditional square shape.

Young's modulus

From expression (2), the equivalent stiffness in x_3 direction for square honeycomb is directly related to its cell wall thickness t. Logically, if $t = l$, the plate becomes solid. Therefore, the following expression is obtained.

$$\boxed{\frac{E_3^*}{E_s} = \frac{t}{l}} \tag{23}$$

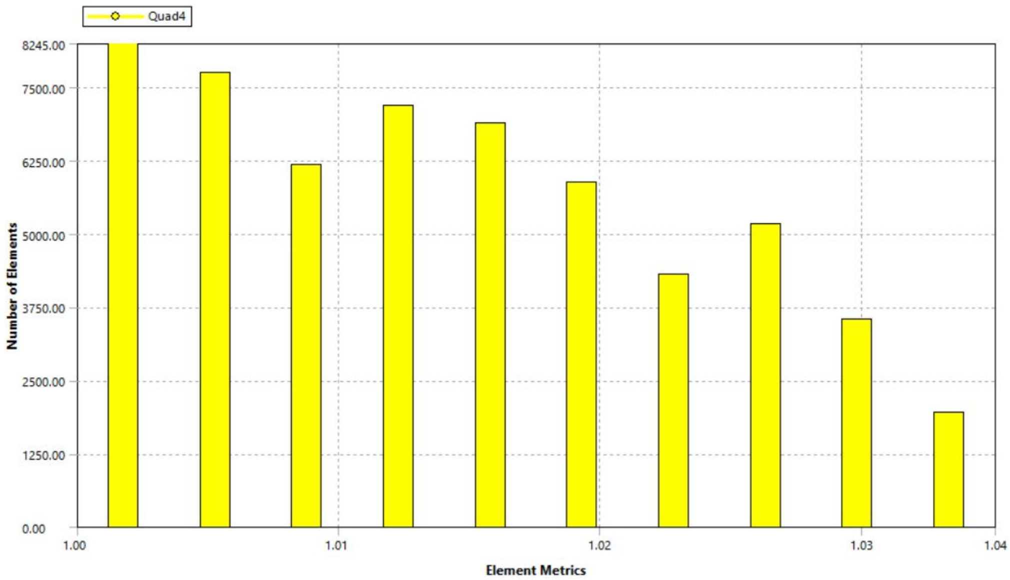

Figure 34: Aspect ratio of the hexagonal grating

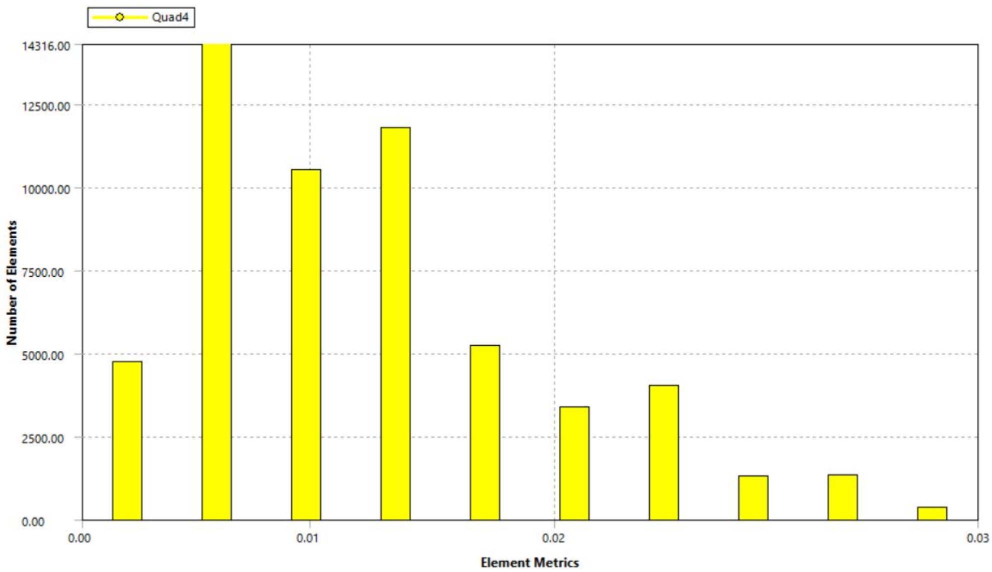

Figure 35: Skewness of the hexagonal grating

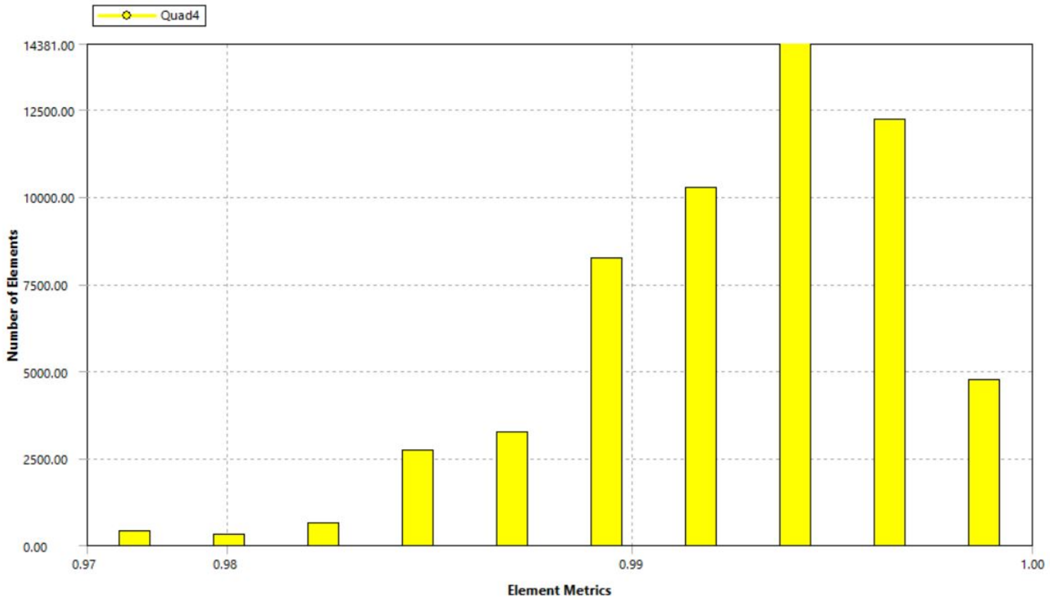

Figure 36: Jacobian of the hexagonal grating

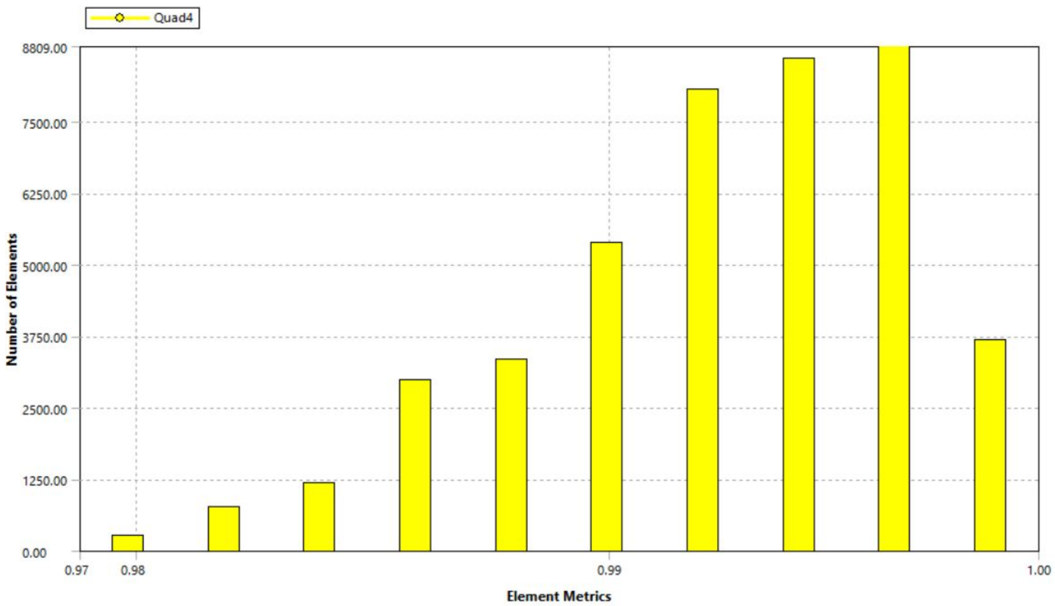

Figure 37: Jacobian of the square grating

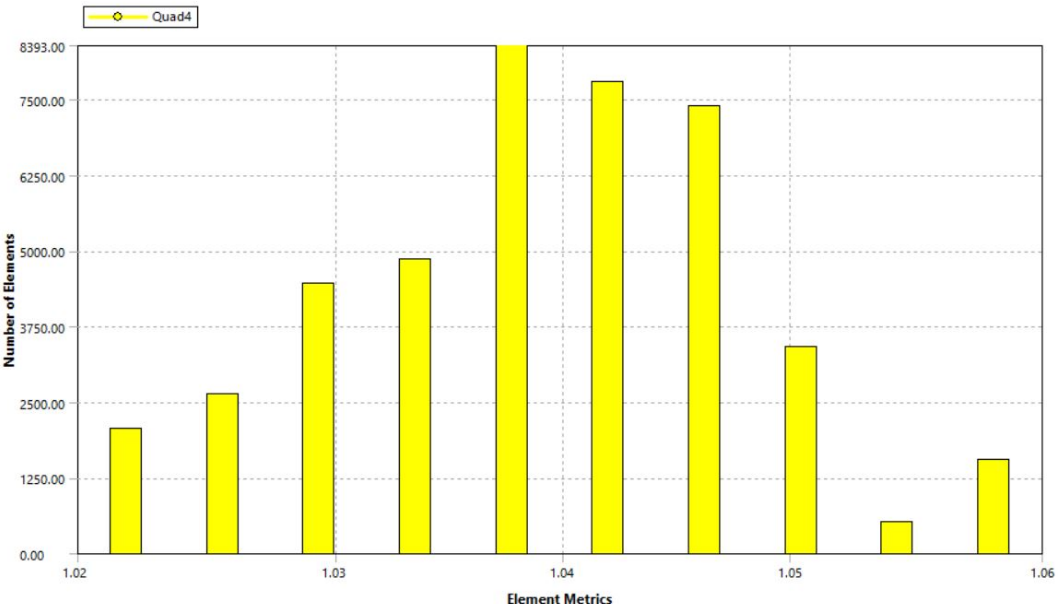

Figure 38: Aspect ratio of the square grating

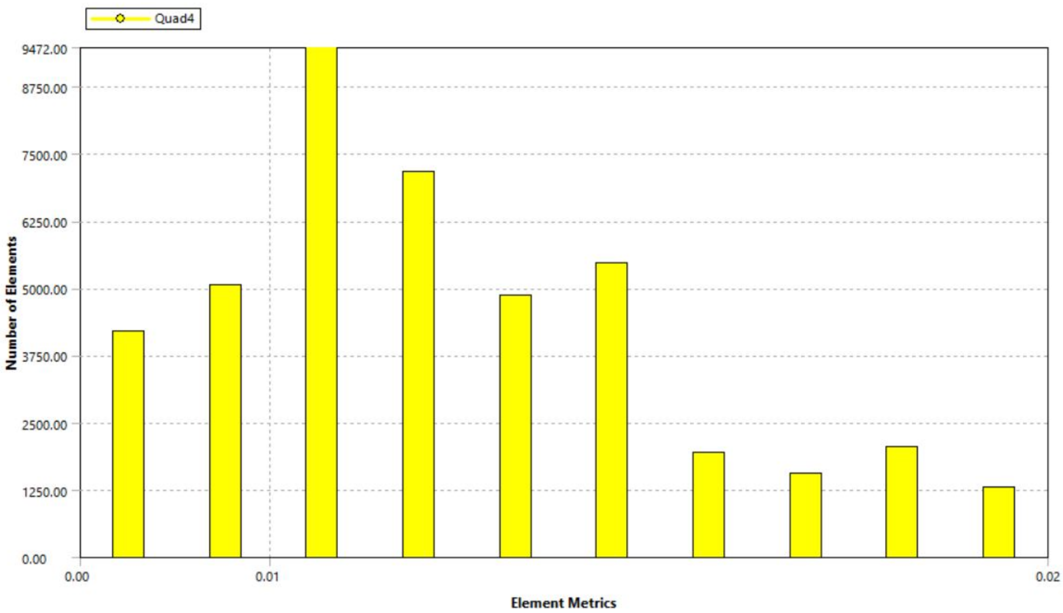

Figure 39: Skewness of the square grating

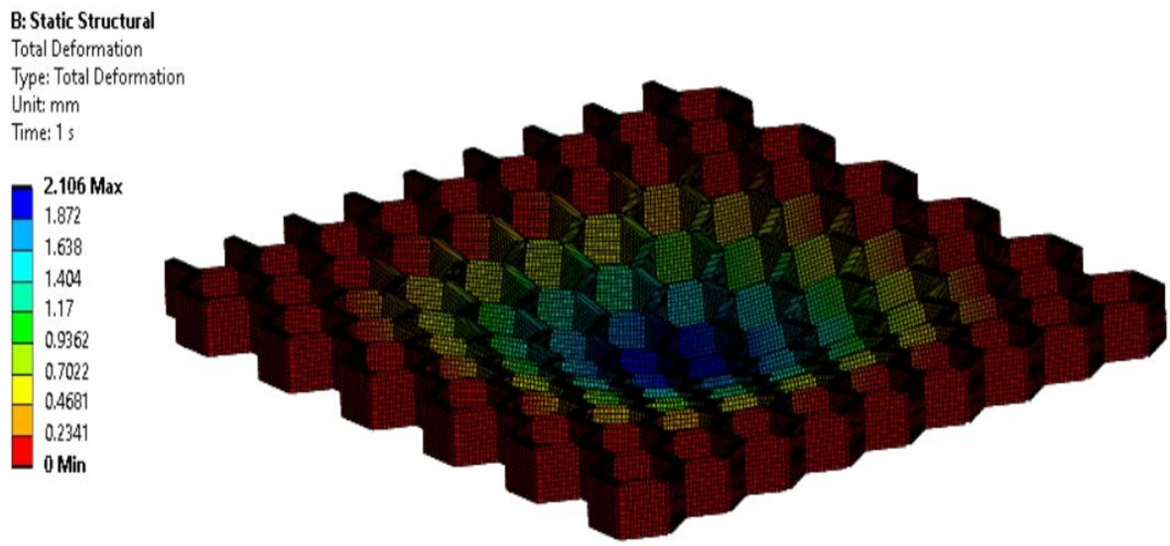

Figure 40: Total deflection (Isometric view): Hexagonal grating

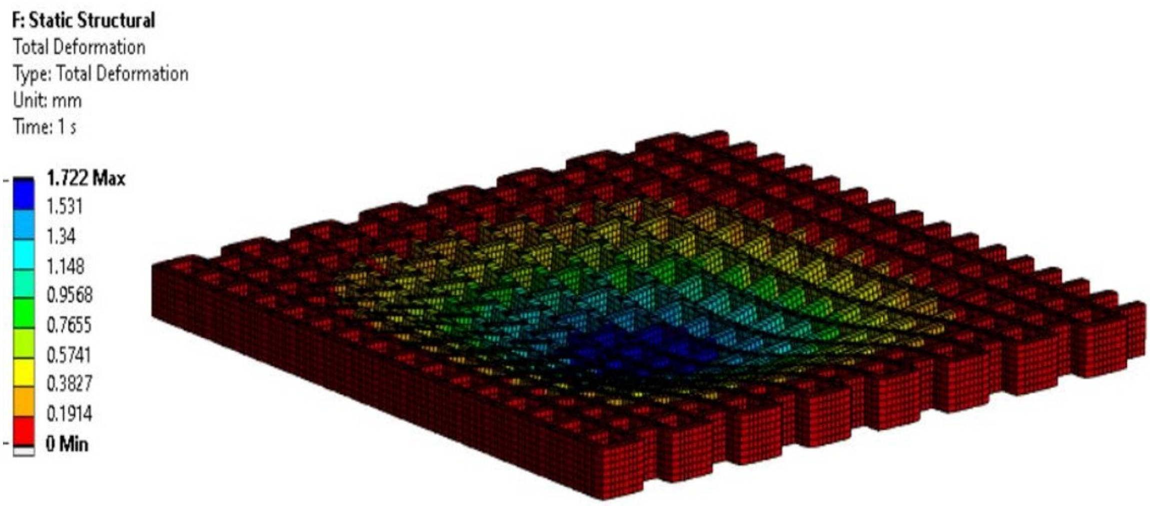

Figure 41: Total deflection (Isometric view): Square grating

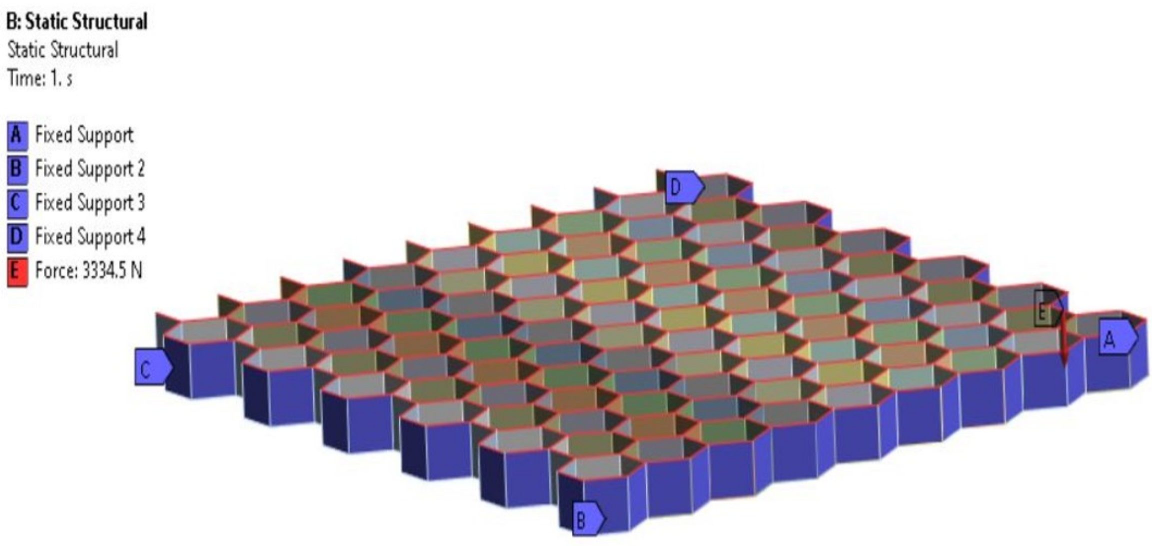

Figure 42: Boundary conditions of the hexagonal grating

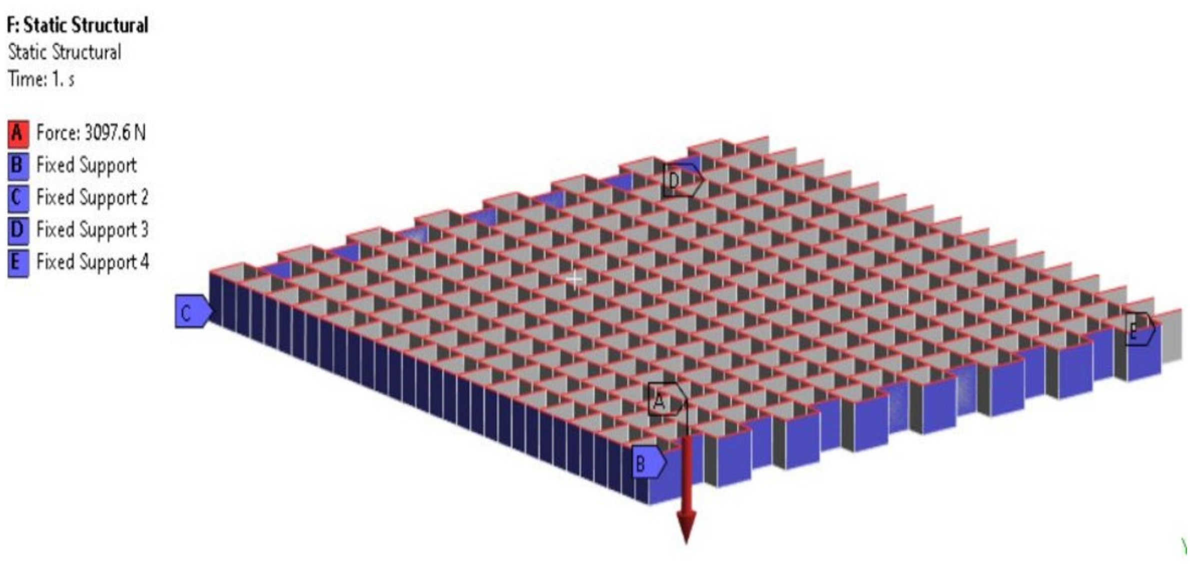

Figure 43: Boundary conditions of the square grating

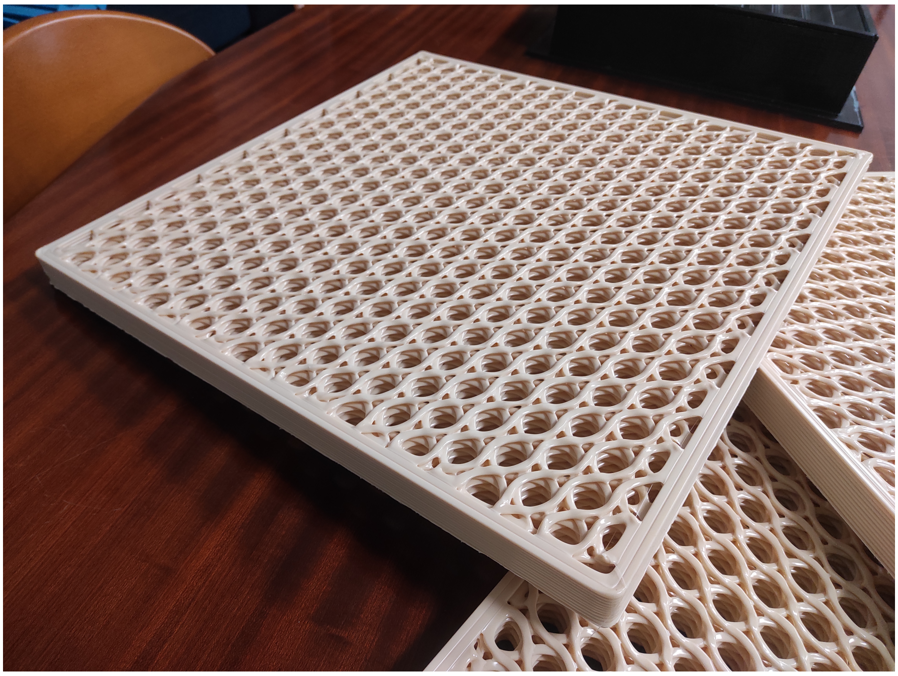

Figure 44: CEFAN Acrylonitrile Styrene Acrylate grate prototype

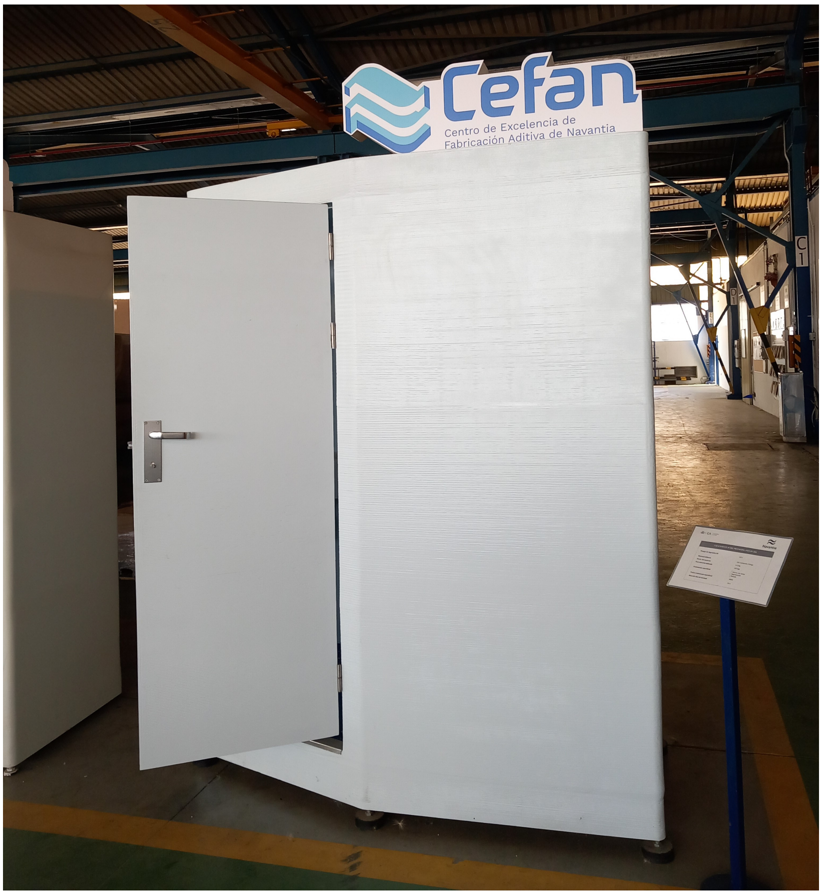

Figure 45: Cefan: 3D printed bathroom

Structural category 1)	Principles for determination of structural category
Special	Structural parts where failure will have substantial consequences and which are subject to a stress condition that may increase the probability of a brittle fracture 2)
Primary	Structural parts where failure will have substantial consequences.
Secondary	Structural parts where failure will be without significant consequence.
Determination of structural categories are given in the various DNV unit specific standards.	
Complex joints, triaxial or biaxial stress patterns will increase the possibility for brittle fracture	

Table 10: Offshore structural categories