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Contribution on new developments of composites materials manufactured by infusion process for their implementation in civil work

DISSERTAÇAO MESTRADO EM ENGENHARIA DE MATERIAIS.

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Dissertação orientada pelo Professor Doutor Bartolome Simonet Suau

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TITLE: CONTRIBUTION ON NEW DEVELOPMENTS OF COMPOSITES MATERIALS MANUFACTURED BY INFUSION PROCESS FOR THEIR IMPLEMENTATION IN CIVIL WORKS

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Keywords: Composite materials, VARTM, construction

SUMMARY

There are still many unknowns regarding the behavior of composite materials in the long term and in-service conditions; in particular those related to their behavior to cyclic loads, with the loss of resistance they experience over time and with their fire protection.

Composite materials result from the combination of two or more materials which, when used separately, they may not present adequate properties to be used as construction materials but, when they are well combined resulting in a material which maintain an identifiable interface surface, they constitute a new material that symbiotically merges the best properties of the original materials.

The composite materials studied in this work are constituted by two phases called fiber reinforcement and thermoset matrix. The fiber reinforcement is responsible for the mechanical performance material, providing most of its strength and stiffness. The polymeric of thermoset matrix acts as the glue of the composite material, guaranteeing the load transfer between the fibers and also between the applied loads and the composite itself. In addition to the resin, the polymeric resin often incorporates fillers and additives that may reduce production costs, improve the manufacturing process itself and improve specific properties of the final product. A clear example of it widely used in construction is the incorporation of alumina trihydrate to enhance the fireproof properties of the composite.

Today a large number of fibers and polymeric matrices presenting different characteristics are commercially available. The judicious combination of the constituent's materials has enabled the development of a wide range of products that have been used in very different structural applications, featuring several advantages when compared with traditional materials. A general overview of the potential materials having potential uses and applications in construction will be recorded in this work to discuss the general advantages and limitations over traditional materials such as wood, steel and concrete.

Unlike other materials, the manufacturing processes used to produce composites will determine their final mechanical properties because among other aspects will determine the ratio fiber to resin as well as the polymerization degree of the polymeric resin. In this way, one of the most used and potential manufacturing processes used in construction is the so-called vacuum-assisted resin transfer moulding (VARTM). One of the distinct advantages of VARTM processes is the ability to build very large parts on relatively inexpensive tooling, aspects which are of high interest in construction. In this thesis work, analysis will be focused in VARTM technology discussing their implementation for to structural components of high interest in construction. The first component is a closed structure with a monolithic laminate combination of glass and carbon fibers. As model of closed structure, a tub was been selected. The second selected component is a structural slab with a sandwich glass composite. VARTM process will be optimized in terms of cost to produce a 1:1 scale prototype. The properties of individual laminates will be tested to model and calculate using finite element theory the properties of the all laminate and the properties of the scale components in terms strength and stiffness. This study will be developed taking into account the technical code of construction as well as the main international guidelines and regulations for the application of composites in construction. Some remarks about the construction products regulation and the CE marking will be also included.

It is clear that composite offer numerous advantages over conventional structural systems in the form of higher specific stiffness and strengths but, its advantages is also lower life-cycle costs with additional benefits, such as easier installation and improved safety. For that, due its importance, the environmental impact and live cycle evaluation of the composite materials will be discussed.

Titulo: Contribuição para novos desenvolvimentos de materiais compósitos fabricados pelo processo de infusina para sua implementação em obras civis

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Palavras-chave: Materiais compósitos, VARTM, construçao

RESUMO

Ainda há muitas incógnitas sobre o comportamento de materiais compósitos a longo prazo e em condições de serviço; em particular, aqueles relacionados ao seu comportamento às cargas cíclicas, com a perda de resistência que experimentam ao longo do tempo e com a sua proteção contra incêndio.

Os materiais compósitos resultam da combinação de dois ou mais materiais que, quando usados separadamente, podem não apresentar propriedades adequadas para serem usados como materiais de construção, mas quando combinados resultam em um material que mantém uma superfície de interface identificável. material que mescla simbioticamente as melhores propriedades dos materiais originais.

Os materiais compósitos estudados neste trabalho são constituídos por duas fases denominadas de reforço de fibra e matriz termoendurecível. O reforço de fibra é responsável pelo material de desempenho mecânico, fornecendo a maior parte de sua resistência e rigidez. A matriz polimérica de termofixa atua como cola do material compósito, garantindo a transferência de carga entre as fibras e também entre as cargas aplicadas e o próprio compósito. Além da resina, a resina polimérica geralmente incorpora cargas e aditivos que podem reduzir os custos de produção, melhorar o processo de fabricação e melhorar as propriedades específicas do produto final. Um exemplo claro disso amplamente utilizado na construção é a incorporação de tri-hidrato de alumina para melhorar as propriedades à prova de fogo do compósito.

Atualmente, um grande número de fibras e matrizes poliméricas apresentando características diferentes estão comercialmente disponíveis. A combinação criteriosa dos materiais constituintes permitiu o desenvolvimento de uma ampla gama de produtos que

foram utilizados em aplicações estruturais muito diferentes, apresentando várias vantagens quando comparados com materiais tradicionais. Uma visão geral dos materiais potenciais com potenciais usos e aplicações em construção será registrada neste trabalho para discutir as vantagens e limitações gerais sobre materiais tradicionais como madeira, aço e concreto.

Ao contrário de outros materiais, os processos de fabricação usados para produzir compósitos determinarão suas propriedades mecânicas finais, porque entre outros aspectos, será determinada a relação fibra / resina, bem como o grau de polimerização da resina polimérica. Deste modo, um dos processos de fabrico mais utilizados e potenciais utilizados na construção é o denominado mouldador de transferência de resina assistida por vácuo (VARTM). Uma das vantagens distintas dos processos VARTM é a capacidade de construir peças muito grandes em ferramentas relativamente baratas, aspectos que são de grande interesse na construção. Neste trabalho de tese, a análise será focada na tecnologia VARTM discutindo sua implementação para componentes estruturais de alto interesse em construção. O primeiro componente é uma estrutura fechada com uma combinação de laminado monolítico de fibra de vidro e carbono. Como modelo de estrutura fechada foi selecionada uma banheira. O segundo componente selecionado é uma laje estrutural com um composto de vidro tipo sanduíche. O processo VARTM será otimizado em termos de custo para produzir um protótipo de escala 1: 1. As propriedades dos laminados individuais serão testadas para modelar e calcular usando a teoria dos elementos finitos as propriedades de todo o laminado e as propriedades dos componentes da escala em termos de resistência e rigidez. Este estudo será desenvolvido tendo em conta o código técnico de construção, bem como as principais diretrizes e regulamentos internacionais para a aplicação de compósitos em construção. Algumas observações sobre o regulamento de produtos de construção e a marcação CE também serão incluídas.

É claro que o composto oferece inúmeras vantagens sobre os sistemas estruturais convencionais na forma de rigidez e resistência específicas mais altas, mas suas vantagens também são menores custos de ciclo de vida com benefícios adicionais, como instalação mais fácil e segurança aprimorada. Para isso, devido à sua importância, o impacto ambiental e a avaliação do ciclo vivo dos materiais compósitos serão discutidos.

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ABBREVIATIONS AND SYMBOLOGY

AFRP (aramid fiber reinforced polymer)

BX = Biaxial (fabric)

CFRP (Carbon fiber reinforced polymer)

CTE = coefficient of thermal expansion

FEM (finite element method)

FRP (Fiber reinforced polymer)

GFRP (Glassfiber reinforced polymer)

ILSS = interlaminar shear strength

K= permeability of laminate

MRI (Magnetic resonace imaging)

P= pressure of fluid

P_{inj} = Injection pressure

PET (polyethylene terephthalate)

RTM (resin transfer molding)

TBM (Technology Business Management)

Tg = Glass transition temperature

UD = Unidirectional (fabric)

VARI (vacumm assisted resin infusion)

VARTM (vacumm assisted resin transfer molding)

Vf =Volume of fiber

Vr = Volume of resin

μ= the viscosity of the fluid

1 THESIS OBJECT

1.1 GENERAL AND SPECIFIC OBJECTIVE

There are still many unknowns regarding the behavior of composite materials in the long term and in-service conditions; in particular those related to their behavior to cyclic loads, with the loss of resistance they experience over time and with their fire protection.

The general objective of this thesis is to analyze the manufacturing process VARTM carried out for the manufacture of some typologies of parts that can be used in the field of civil works. The viability and real application of these strategies in the construction sector will be evaluated according to economic factors (cost of materials and manufacturing), mechanical capacity, easy installation.

The specific objective will focus on the analysis of 2 typologies (open and close geometry) of parts that are usually used in the construction sector. Search of raw material, mechanical capacity and viability with the proposed infusion system. Search of auxiliary material for each of the types to be implemented. Analysis and selection of infusion strategy according to the morphology of each part.

In addition, the manufacturing of a structural element (of studied type) will be carried out of one of the selected infusion strategies.

This process will be divided into:

- Parts Typologies to evaluate. Closed monolithic shape and open sandwich shape
- Selection of raw material, auxiliary material and manufacturing equipment
- Infusion strategy for each typology

Real part manufacturing:

- Characterization of raw material
- Design and structural analysis (FEM)
- Manufacturing final part

2 STATE OF THE ART

2.1 EMPLOYMENT OF COMPOSITE MATERIALS IN CONSTRUCTION

As we all know, composite materials have been implanted for years in several sectors such as aeronautics, automobiles, civil construction ... but perhaps in the latter due to regulatory restrictions, lack of knowledge on the part of professionals in the sector or sometimes due to characteristics of the material, it does not implanted as they have made materials such as steel or concrete.

But there are several types of FRP shapes that have gained a niche in some applications intended for civil works (Correia, Joao Ramôa 2015):

- Glass fiber reinforced polymer (GFRP) pultruded profiles

- FRP rebars

- FRP strengthening systems

Many of the biggest challenges that the civil engineering sector are associated with the maintenance and repair costs of buildings built with traditional materials (steel, wood, reinforced concrete).

The problems of durability associated with traditional materials have led to changes in designs, codes and standards. The growing needs for higher construction speeds and their functionalities make durability an indispensable requirement.

FRP materials combine good mechanical properties, lightness and durability even in aggressive environments, and due to this, since the 1980s, their interest in this sector has increased.

It goes back to 1948 when we found the first use of FRP materials. It was for an oil industry, and was applied in pipework and panelling for both floors and walls of offshore platforms. Behind this, other uses more in industrial buildings with very specific requirements such as resistance to aggressive environments and thermal and electromagnetic insulation. Chemical industries, paper, water treatments, electric stations, etc., are some of the most remarkable examples of its use. (Correia, Joao Ramôa 2015)

The first important appearance of the FRP materials dates from the 1950s and 1960s when 70 housing prototypes were built. Almost all of these houses were on one level and none of them exceeded the two floors. They were modular constructions and used form-active structures to overcome the low stiffness of the material. Unfortunately, these constructions were abandoned for economic reasons and due to rejection by construction professionals, perhaps due to the lack of technical information about the materials.

In the 1960s, the aeronautics sector manufactures the first advanced material made with new fibers with high strength and modulus fibers (carbon and aramid) to improve properties in both space exploration and aircraft vehicles. The high costs of these materials, meant that their use was focused specifically on this sector, abandoned any possibility of being used for construction.

In the 1970s as a result of the energy crisis, the industries responsible for the manufacture of composite materials pose alternatives to reduce costs and thus have access to new market sectors such as naval, sports, aviation ...

During the last half of the 80s, and the beginning of the 90s, due to the great technological advances carried out in the manufacturing processes of composite materials, such as pultrusion, together with the incipient increase in repairs of old structures, especially in road and highway infrastructures, makes the durability of materials one of the new concerns to face. Since then, new products manufactured with composite materials have been developed to try to satisfy these needs. Among many of them are: bars and prestress cables for internal concrete reinforcements; laminates and wraps for external reinforcement of concrete structural elements; strips, prestress cables for suspended bridges; structural profiles and cellular panels.

2.2 PROPERTIES AND CONSTITUENT MATERIALS

Composite materials are basically composed of two elements that confer different properties to the final product. One of them is the reinforcement of fibers, which is in charge of the mechanical properties of the material such as its strength and stiffness. On the other hand, there is the polymer matrix, which acts as a cohesive element of the fibers which is responsible for the transfer of charges between fibers. There are also other components such as fillers and additives that improve specific properties or improve manufacturing processes and therefore reduce costs.

The innumerable possible combinations to be made with the fibers (orientation and types), resins (types), fillers and additives gives the composite materials a competitive edge over traditional materials, due to the wide range of possible applications.

As it has been said previously, the fibers are the element that confers the structural properties to the element, being responsible for strength and stiffness in the direction of fibers. The fibers most used in the manufacture of elements in composite materials are fiberglass, carbon fiber and aramid fiber.

Fiberglass is the most used material in the construction industry due basically to its low cost and its acceptable high strength. Its weak points are its low elastic modulus, its reduced long-term strength and its sensitivity to moisture and alkaline environments. There are basically 4 types of glass fiber: E, S, AR and C. The most commonly used (80-90%) is type E for its good insulating properties. The S type has good mechanical strength but is 3-4 times more expensive than the E type. The AR type offers good properties in alkaline environments while the C type improves the properties against corrosion.

Carbon fiber is commonly used in strengthening applications due to its good properties of high tensile strength and elasticity modulus (A. Miravete. 2001). In addition, other of its competitive advantages are its low density, high fatigue and creep resistance and excellent resistance properties to external chemical agents. Its main disadvantage is its high cost associated with a production process that requires excessive energy consumption.

Aramid fiber is stronger than aramid fiber and also has better value in its elasticity modulus. It is mainly used in applications where high energy absorption (crash) is required due to its good tenacity and toughness properties. The main disadvantages are its low compressive strength, its susceptibility to stress rupture and its high sensitivity to UV radiation.

The 3 types of fiber presented above are marketed in different ways depending on their final use or their manufacturing process. We have mat (short fibers and random orientations), untwisted (roving) or twisted (yarns). These forms can lead to different types of textile products with different and simultaneous reinforcement directions.

The matrix is also responsible for carrying out load bearing tasks, particularly those associated with transverse stresses and interlaminar shear stresses. The following properties are expected from the matrix: Maintain the fibers in the correct orientation, guarantee the correct distribution of stresses between fibers, prevent fibers from buckling when subjected to compression stresses, and protect the fibers against external agents such as moisture.

The FRP polymer matrices are composed of a resin base that is usually mixed with a supplementary constituent, which causes a polymeric reaction. There are two types of polymeric resins: Thermoplastic and thermosetting.

The thermostable resins have an irreversible nature (they cannot return to their initial state). Because of this, it becomes infusible after curing and therefore cannot be reprocessed or welded. These resins have a good impregnation capacity in the fibers and good adhesive properties. They can also have low viscosity which makes it an easily processable product that improves manufacturing processes.

Due to the properties mentioned above, thermosetting resins have much more potential for civil works structures, in fact, they are the most commonly used for structural elements for this sector. The most frequent are polyester, vinyl ester, epoxy and phenolic resins. Polyester resins account for almost 75% of the production of current FRP products. They present a good balance between good mechanical, chemical and electrical properties, their dimensional stability, easy processability, great possibilities in terms of modifying their matrix with additives and low cost. Epoxy resins, for the most part, are reserved for structural applications where they need more demanding mechanical requirements in terms of strength, stiffness, service temperature and durability. The vinyl ester resin shows properties and a cost half way between the epoxy resin and the polyester resin. Finally, the great advantage of phenolic resins is their behaviour to fire exposure. It presents a similar cost to the polyester, being its dimensional stability similar. The problem with these resins can be their difficulty in reinforcing and curing.

In addition to the matrix, we have the catalyst agent, the fillers and additives. Fillers can reduce the final manufacturing costs and improve final properties, such as the fire resistance of the resin and its dimensional stability (reducing shrinkage). The fillers most used are the calcium carbonate, aluminium silicate, alumina trihydrate and calcium sulphate. These last two are used to improve fire behaviour. The additives, however, serve to achieve one of the following objectives:

- Reduction of flammability and smoke production (fire exposition)
- Antioxidant
- Reduction of shrinkage
- Reduction of voids content
- Increase in electrical conductivity
- Increase in roughness
- Reduction of the tendency to attract electric charge
- Promotion of cellular structure (foaming agents)
- Prevention of gloss, discolouration, cracking or disintegration due to UV radiation.
- Get a certain colour (pigmentation)
- Facilitate demoulding.

2.3 MAIN MANUFACTURING PROCESSES IN COMPOSITE MATERIAL STRUCTURES APPLIED TO CIVIL WORKS

When we design pieces in FRP materials, we not only have to understand that their properties depend on their components (matrix and fiber) and the composition and direction of their fibers, but also on the fiber-resin interaction (adhesion and mechanical compatibility between fibers and matrix).

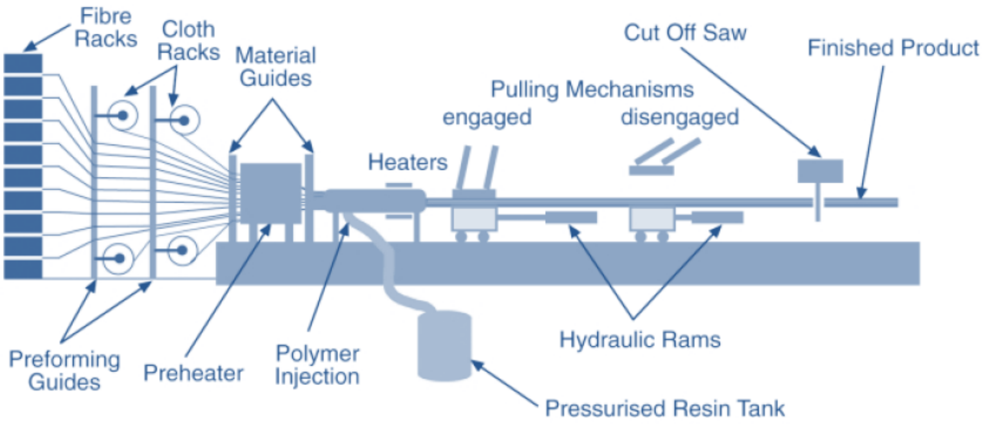
Mainly two techniques are used for the manufacture of parts for the civil engineering sector: Pultrusion and hand lay up (or wet lay-up).

2.3.1 PULTRUSION

It is a process of automatic production of continuous production of pieces with constant section. It was developed in the 1950s in the USA, producing shapes with open sections such as U and I, closed forms such as tubes, and multicellular closed-form panels. The maximum length of a profile manufactured by this technique is limited by the subsequent transport thereof. Due to the great optimization and automation of the process, this has a reduced cost which offers a best productivity / cost ratio.

It is divided into two phases. On the one hand the reinforcement (fiber), which can be presented in various forms (mats, roving ...), is impregnated with a matrix. In the second phase, matrix solidifies (cure) inside the mould together with the reinforcement, this mould having the final shape of the profile to be executed.

It is an assembly line manufacturing process, in which 6 main elements can be distinguished: 1) set of spools stacked on creels for fiber reinforcement handling, 2) preforming guides, 3) resin impregnation bath, 4) forming and curing die, 5) pulling system and 6) cutting system.



1. *Image. Example pultrusión production line. (own elaboration)*

In traditional pultrusion processes (See image 1), the fibers are impregnated in the matrix in an open bath system, just before entering the mould with the final shape, and the final excess of the fibers is eliminated when they pass through the preforming guides. In the current pultrusion machines, the fibers enter without impregnation in the mould or injection chamber, and are then impregnated by pressure (injection). This new technique allows an improvement in the uniformity of the material and in the good impregnation of the fiber (good fiber-matrix ratio). Currently, the pace of production achieved by this industry des of 2 linear meters per minute.

Main advantages:

- The production cost is very low and competitive

- The fiber-resin ratio is controlled

- Due to its fiber alignment, the final mechanical properties can be very Good

- Safety measures due to the fact that the impregnation and curing process is controlled in a closed place.

Main drawbacks:

- Only constant sections of profiles can be made. Limitation of forms

- Heating the mould can be expensive

2.3.2 HAND LAY UP-WET LAY UP

It is the pioneering process in the composite sector. It consists of the successive application of reinforcement layers (fibers) and their consequent impregnation with a polymer matrix, curing on or inside a mould that gives it the final shape, to achieve a solid FRP component. The fiber is usually impregnated with rollers or brush. This process can be improved in terms of applying temperature, pressure and / or vacuum to improve the quality of the final product.

In recent years one of the improvements of this process in the manufacture of parts for this sector is to add vacuum pressure by means of a bag, once the impregnation is finished, and apply a temperature controlled with the piece still without demoulding. By implementing these two improvements, we combine the improvement of final mechanical and thermal properties and simple manufacturing.

This process, for example, is used in the production of FRP sandwich panel. In addition, it is usual to use this type of process in situ for applications where damaged structures need to be reinforced. The main problem to be solved in this application is that the correct union between the composite reinforcement and the surface of the structural element to be reinforced is guaranteed. In most civil engineering applications, the hand-lay process is used without applying external pressure or temperature, thus curing the reinforcement at room temperature.

Main advantages:

- Easy learning and therefore not excessively qualified workforce

- Low cost of moulds (in curing at room temperature)

- Wide choice of materials (fibers and resins)

Main drawbacks:

- Very dependent on the rolling ability of the operators. Dexterity influences the number of voids.

- Operators' safety measures must be more demanding due to exposure to resins.

- The mechanical and thermal properties of the pieces are inferior to other techniques.

2.3.3 RESIN TRANSFER MOULDING (RTM)

Fabrics are laid up as a dry stack of materials. These fabrics are sometimes pre-pressed to the mould shape, and held together by a binder. These ‘preforms’ are then more easily laid into the mould tool. A second mould tool is then clamped over the first, and resin is injected into the cavity. Vacuum can also be applied to the mould cavity to assist resin in being drawn into the fabrics. This is known as Vacuum Assisted Resin Injection (VARI). Once all the fabric is wet out, the resin inlets are closed, and the laminate is allowed to cure. Both injection and cure can take place at either ambient or elevated temperature.

Main advantages:

- Good fiber-resin ratio to obtain. In addition to obtaining pieces with few pores.

- Few safety measures because the resin is confined in the mould.

- It could automate the process and thus reduce labour.

- Parts with a good finish, including both sides

Main drawbacks

- The tools used have a high cost and are also heavy due to the pressures that must be supported

- The size of pieces is limited due to the costs and the aforementioned weight

2.3.4 VACUUM ASSISTED RESIN TRANSFER MOULDING (VARTM)

It is the manufacturing process that occupies this work. Currently it is not the most used in the construction sector but for some advantages that we comment in this section and the content of the work presumes a potential development in this field.

It is a process similar to RTM but instead of using a mould and a counter-mould, we have a mould and a vacuum bag seal. As in RTM, the lamination is placed with the dry tissue. Once the lamination is finished, a release fabric or with some roughness property is placed on the surface of the piece (e.g., high roughness for subsequent adhesive operations) and the bag that encloses it. This bag is sealed on its perimeter and is only open at the resin inlets and the air vents where the vacuum pressure is applied to the part. There are more necessary components such as resin distributors, tissue aerator ... that we will see in the development of this work.

This process requires a specialization since it is necessary to carry out a preliminary study of placement of entrances, exits, distribution network of resin ... for a correct final piece impregnation.

Main advantages:

- The cost of the mould can be lower. The requirements of the mould are usually smaller because it is not subject to high pressures. The same moulds could be used as in the hand lay up or wet lay-up process.

- The sizes of pieces are not limited, being also ideal for large pieces.
- Parts with inner core can be manufactured in a single operation.

- Improved safety conditions due to non-exposure to resin

- Good fiber-resin relationships that significantly improves the mechanical conditions of the piece.

Main drawbacks

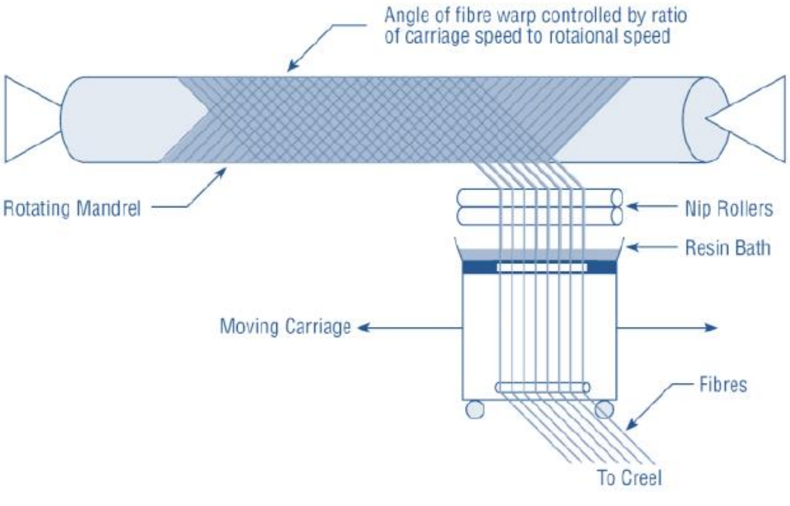
- It needs a greater specialization of the staff due to its complexity

- The resins to be used must be of low viscosity, with the consequent loss of mechanical properties

- Cost of auxiliary infusion materials that increase the cost with respect to hand lay-up-wet lay-up.

2.3.5 FILAMENT WINDING

This process is used essentially for circular or oval pieces, such as pipes or tanks. Like the pultrusion process, the reinforcements of fibre tows pass through a resin bath. Then, these fibre tows are being wound on a mandrel which in turn has a rotation movement on its axis. It needs an automatic mechanism which controls the pressure or tension of the reinforcement and the orientation of it during its placement (see image 2).



2. *Image. Filament winding. (own elaboration)*

Main advantages:

- It is a fast and economical lamination process.

- The cost of fiber as a raw material is lower, because we do not need a fabric made in the factory.

- The mechanical properties are very good due to the correct orientations of the fiber (controlled by automation) and the pressures exerted in the process.

Main drawbacks

- In this process the forms are limited to oval and circular pieces.

- You cannot place fibers in the longitudinal direction that may be necessary for some specific application

- Mandrel costs can be high

- The exterior surface, unlike the interior, does not have a good finish and therefore aesthetically is not good

2.4 APPLICATIONS-WORKS: WHY AND MATERIALS USED

Normally the FRP materials are used in two main types: As tensile components (strips, sheets, bar or cables) or as bending components (profiles, cellular or sandwich slab panels).

There are 4 main uses of these materials in the construction sector. These are: a) FRP rebars for internal reinforcements, b) Repairs and reinforcements of existing structures, c) GFRP structures d) new FRP structures.

2.4.1 FRP REBARS FOR INTERNAL REINFORCEMENTS

Bars are used to reinforce concrete structures, to which the steel bars are replaced by fiberglass bars. For the most part this application is used in concrete bridge decks located in aggressive environment to combat corrosion and thus the associated maintenance costs.

The most used rebars in the field of civil works are those manufactured by pultrusion. The typical lengths of the bars are between 10-14 meters and their most usual diameters are between 6 and 36 mm. It is normally used to reinforce concrete elements and come to replace steel bars. A decisive factor in the good adhesion between rebars and concrete is the surface of the bar. This surface must be rough.

The main advantage is his low density (1/6-1/4 less than steel). This makes the operations of placing and transporting them considerably easier Unlike GFRP bars, CFRP bars and AFRP bars have negative thermal expansion coefficients in the axial direction. Finally, one should note that for high temperature variations, the high thermal expansion coefficient in the transverse direction may cause the longitudinal separation between the FRP bar and concrete, especially if the concrete cover is low.

The FRP bars present linear elastic behaviour up to failure with very high tensile strength. The elasticity modulus of FRP bars is very dependent on the type of fibre. In GFRP bars is only about 20-30% that of Steel.

Due to the low properties of elastic modulus and strength in compression, these elements are not usually used in elements that work in compression as pillars for example. The shear resistance of FRP bars depends mainly on the properties of the resin, although this property can be improved by placing fibers or tissue in the transverse direction.

Another typical characteristic of these materials transferred to the bars is their resistance to corrosion and their electromagnetic transparency. Finally, to say that the mechanical properties at high temperatures decrease considerably, so it must be taken into account its use in places with fire resistance requirements.

The main applications of the FRP bars have been to replace traditional steel bars in reinforced concrete. Above all, this has been carried out in structures located in coastal areas, due to the corrosion suffered by steel in these environments. In addition to these places, it is also located in buildings or structures that require insulation properties to electromagnetic fields such as MRI facilities.

An example of the use of GFRP bars was in the soft eye tunnel in Belgium. In this example, a drilling technology was used that used reinforcements with GFRP rods while drilling the stone. This choice of material resulted in cost savings and high construction times, but is also in line with the high safety standards today involved in construction sites. These materials were chosen for the following aspects.

• Corrosion Resistance: GFRP is a durable material which is not affected by corrosion. Therefore, GFRP bars/anchors can be used also for example as part of the final lining in a tunnel supporting the structure during its whole life span. No excessive measurements for the protection of the anchor against corrosion are required as is necessary with steel anchors.

• High Tensile Strength: GFRP bars can bear very high tensile loads. The commonly used fibre bars in the construction industry have a breaking load which is nearly double as high as the one of a steel bars with same diameter.

• Cuttability: GFRP material can be cut with working tools like saws, pilling/drilling equipment and TBM tools. This avoids damages to cutter heads and does not delay the work progress as piling or cutting through GFRP bars is unproblematic. The fibre bars are split in small pieces which do not harm slurry pipes.

• Low Weight: The weight of a GFRP bar is only a fourth of its steel counterpart, having the same dimensions. Combined with the flexibility of the bars this allows an easy installation even in confined working space or where the support of lifting equipment is not available

2.4.2 REPAIRS AND REINFORCEMENTS OF EXISTING STRUCTURES

It is normally used to reinforce existing reinforced concrete structures. These structures, mainly due to reasons of corrosion on the reinforcing steel, have reduced their mechanical properties, with which, the CFRP come to perform a job similar to that performed by structural steel. It began using reinforcing beams for bridges and columns, and currently, it is already established in the sector of housing rehabilitation as a consolidated reinforcement technique.

There are two types of techniques used to reinforce these existing structures. On the one hand wet layup system cured in situ, and on the other pre-curated adhesive parts on the existing structure.

Wet layup system consists of a mat, unidirectional or multi-axial dry material which is impregnated on the surface to be reinforced. These reinforcing elements are usually made of reinforced concrete, which reinforced steel is damaged and does not fulfil its structural function. The impregnated piece heals in the same place of the work, something that we have to take into account, since it will have to heal at room temperature and humidity. Sometimes these elements can come pre-curated from the factory, which requires an application of temperature on site to reach the curing of the piece.

The systems of plates or profiles precured, usually are elements manufactured by means of techniques of pultrusion that adhesived on the element to reinforce.

The use of these elements began to develop in the 1980s. Numerous are the examples of its use, its use being currently standardized. They are consolidated techniques. The main advantages of its use are very high tensile strength, high elasticity modulus (with carbon fiber), high deformation capacity, low self-weight (not increasing the own weight on the old structure), non-corrodibility, and the great variety of shapes and reinforcement geometries.

2.4.3 GFRP PULTRUDED PROFILES

Basically, the pultruded profiles of composite materials have been limited to copying both the shapes and all the metrics of standard profiles made of steel and aluminium.

Currently, pultrusion profiles are used in many structural applications. Despite this, they present some disadvantages with respect to their counterparts in traditional materials, such as their susceptibility to compression loads and impact loads. Faults of this type occur in the wings of both the beams and the columns before the failure of the material. In addition, to the main advantage low density, its main characteristic is the great mechanical capacity in the longitudinal direction of the profile.

Another aspect to highlight is its linear elastic stress-strain relation to breakage which contrasts with the ductile behaviour of the steel and the low modulus of elasticity in the composite profiles in 15-20% of the steel. The low modulus of elasticity is associated with an increment of the deformability of the structure, for which the shear deformation may also give an important contribution, especially in non-slender elements.

Competitive advantages with respect to profiles manufactured in traditional materials:

- Under weight
- High strength-to-weight and stiffness-to-weight ratio
- High fatigue strength
- Thermal insulation and electromagnetic transparency
- Easy transportation and handling on site
- Low maintenance cost
- Resistance to corrosion in terms of durability

The main disadvantages are:

• Low elastic modulus which increases the deformation and the maximum deflection required by the construction regulations

• Its fragile nature

• His behaviour in front of fire due to the flammability, heat and smoke relay. Also, for its low mechanical performance at high temperatures

• Lack of specific regulations

• Initial investment costs.

2.4.3.1 EXAMPLES OF APPLICATION OF THE PULTRUDED PROFILES

The first applications of pultruded GFRP profiles did not have a main structure function, but secondary structures or non-structural elements that met requirements of low weight, durability in environments susceptible to corrosion or with requirements of electromagnetic transparency.

The GFRP pultrusion profiling industry has created a wide range of secondary structures and non-structural elements. In spite of this, in recent years profiles have been used for their application as the main structure in some examples of infrastructures, especially pedestrian and vehicular bridges.

2.4.3.2 PULTRUDED PROFILES IN BRIDGES

The first pedestrian bridge entirely made of composite was made in 1992. It was the Aberfeldy bridge, which had 131 meters long cable-stayed and consisted of ACCS panels suspended from GFRP towers erected by aramid cables.

Another example of a bridge, this time of vehicles, was the bonds Mill Lift Bridge, which was also the first bridge of vehicles built entirely by pultruded profiles of GFRP in 1994. It was also built with panels such as the Aberfeldy bridge, supported by longitudinal girders. made in GFRP pultruded profiles. The greatest competitive advantage of the use of these materials was their low weight. It is a lift bridge, which requires a mechanical lifting system. The low weight of the structure meant a considerable saving both in lifting machinery and in energy costs of its daily use.

Already in 1997, a pedestrian bridge built in two parts in Pontresina, Switzerland. These were two individual trusses that connected a part of the shore with a central point of a river. Each truss was 12.5 meters long. One of the openings had all the joints adhesively bonded, while the other had bolting. This bridge was manufactured and assembled entirely in the workshop, which meant a considerable improvement economically and in terms of quality control. This bridge was designed to be removed every year at the end of winter, and to be reinstalled once the risk of flooding has passed.

Again, in this case the weight is one of the important factors, since the process of transfer of the integral bridge is done in a 4-hour operation with the help of a helicopter. In addition to the weight, its high resistance to corrosion was another factor in the choice of these materials.

Also, in 1997, the Kolding pedestrian bridge was built in Denmark. It was the first bridge manufactured in composite, in crossing the railway line. All the materials used in the manufacture of this bridge were GFRP. The purpose of choosing these materials, and also to emphasize that everything was done with them resides in avoiding an electromagnetic interference with the railway electrification. All the assembly was done in the factory, and its assembly on site was carried out in 3-night sessions (18 hours total), which avoided excessive traffic interruption. The weight of these materials was key in its speed of assembly on site, in addition to lower costs and save energy.

In Lleida another bridge was built in 2001. It crossed a road, a railway line and the new road that would house the high-speed train (AVE). It is a 38-meter structure consisting of a double-tied arch. All the pieces were manufactured with composite profiles and their joints were made by bolted using stainless steel. The total weight of the bridge was 19 tons, this meant a quick installation in only 3 hours. Like its predecessors, it was assembled in the factory. Its great competitive advantages were its low weight, which benefited its assembly and its non-electromagnetic interference.

2.4.3.3 BUILDINGS

In 1999, the Eyecatcher building was built. It was a milestone in the construction of a building with composite materials. It was the tallest building, consisting of GFRP pultrusion profiles and adhesive joints. There are three trapezoidal structures made with these profiles. Like the walkways and bridges of the previous section, almost the entire structure was pre-assembled in the factory due to its low weight. The construction of the building only lasted 3 days, since everything was pre-assembled. The façade was built in sandwich panels 50 mm thick, made with glass fiber and inner core that worked as thermal and acoustic insulation. The low thermal conductivity of the profiles meant that it was not necessary to place a thermal bridge for thermal insulation.

2.4.3.4 REHABILITATION

In addition to the previous applications, one of the fields where the composite materials have intervened is in the rehabilitation of buildings or structures made of traditional materials (mainly concrete). Composite materials today represent a more than consolidated alternative in this field. But not only rehabilitates with the best-known commercial reinforcements, but also replace traditional elements with composite elements. For example, many of the bridges of traditional materials are being replaced by the deck system. This type of panels considerably reduces the weight of the bridge itself, its durability, fatigue strength, easy maintenance and quick installation, with the latter impacting on the minimum interruption of the traffic and its low energy consumption.

Another lesser known application of these materials is the replacement of wooden floors in old buildings. This is the case of Wörlitz castle in Germany. It was decided to replace the degraded soil using pultruded GFRP beams, which were riveted and adhesive onto existing elements. Its main advantage was the low weight, since the previous structure was not prepared to assume higher own weights. Also, avoiding thermal bridges in the wall junctions.

2.4.4 NEW FRP STRUCTURES

Normally composite materials are combined with traditional materials, and singular pieces are executed which do not follow standard forms. This, perhaps, is the current trend of composites, which implies a detailed study of the structure to be made, the design and materials chosen and, lastly, the manufacturing.

As an example, we have pedestrian bridge of 45 m in length executed in carbon fiber located in the Casa de Campo of Madrid (Rodriguez Lopez, Beatriz 2012). This footbridge in stands out for its low weight and its ease of assembly, for which only one crane was needed. In this case its design is not important, but what is a milestone in the landscape of civil architecture, and as a reference for its characteristics for the possible use of architects. The project consists of pieces in the shape of a "U" that add some others as if it were a Roman bridge, to which to give them consistency and tension to compression is placed as an interior finish prefabricated concrete pieces in the form of "U".

In July 2004, a vehicular overpass of 46 meters of light was completed on the Cantábrico highway in the Tamón (Carreño) - Otur (Luarca) section in the Vegarrozadas-Soto del Barco sub-section, very close to the Asturias Airport (Rodriguez Lopez, Beatriz 2012). The peculiarity of this work is that its resistant structure is formed entirely by composite materials. This overpass has been the result of the Iberoeka "Pumacom" project, started in 2003. A fundamental aspect in the development of this work has been the resolution of the bridge beams, made of carbon fiber / epoxy on a block of polyurethane. It was done by hand lay up (wet with brushes and roller) and a subsequent compaction with vacuum bag. Another of the most interesting challenges from the point of view of the materials consisted in the union between the beams in carbon / epoxy and polyurethane with the board made of concrete with a very light assembly formed by bars of diameter 16 mm separated every 20 cm. The material selected for the connectors of both structural elements was an AR fiberglass composite material manufactured by pultrusion. It's the longest bridge made of composite materials

2.5 ADVANTAGES, DISADVANTAGES AND CHALLENGES OF COMPOSITE MATERIALS IN CONSTRUCTION

The choice of materials can be used in the construction industry according to numerous technical and economic criteria. It is for this reason that the most used composites, in this field, are based on polyester resins and glass fibers, because they are the ones that achieve a better quality / price ratio. However, compared to traditionally used materials, the compounds have certain, but also certain drawbacks, which, in some cases, can be remedied, but it is necessary to know well to know how to deal with the choice of said materials.

Next, they are going to list, in a schematic way, the main advantages and disadvantages that composites have to be applied in the field of civil works.

Main advantages

- Lightness, since its densities range between 1700 and 2300 Kg/m3. This also generates the advantages derived from the low weight that prefabricated elements would have with these products: economy and ease of transportation, economy and ease of handling and assembly and, finally, reduction of loads on structures. All these factors imply a considerable cost saving, starting with the transportation fuel, following its easy handling and energy saving in the movements of the pieces, and finally in the saving of material in the main structure by considerably reducing the loads of the building.

- Excellent behaviour against environmental corrosion, which makes it very suitable for coastal and maritime applications, applications in aggressive environments with virtually no maintenance.

- One of its main advantages are its high mechanical properties to traction, compression, bending and shear. You just have to choose the right fiber and resin choice, and then the most suitable laminate configuration for each application.

- Its mouldability allows access to complex shapes for easy reproduction of constructive elements (rehabilitation), integration of functions (structural, closure, insulation, finishing ...) with the use of numerous manufacturing techniques. In addition, with that freedom of forms, it confers an attraction more towards the architectural tendency of organic forms.

- Possibility of moulding in large pieces with few limitations and applications difficult to execute with traditional materials. The only limitation in this sense is the final transport of the piece.

- They do not present interference to electromagnetic waves, so they are suitable materials for communications buildings and transmissions.

- Low thermal conductivity, which makes them ideal for solving thermal insulation problems. In fact, they are widely used today in facade sandwich panels and roofs.

- Inert to water and chemical agents, which causes them to be used massively in the storage, distribution and transport facilities of chemical products and dangerous goods

-Excellent electrical insulators, which make them recommendable for storage, distribution and transport installations in the electrical industry, achieving the elimination of insulators.

Main disadvantages:

- High cost of raw material. These costs can be cushioned by choosing fiberglass and polyester resins, but not always the technical requirements advise it. In addition, with a suitable design that takes advantage of its lightness, economy of transport, handling and assembly, reduction of loads, almost null maintenance, elimination of painting and integration of functions, can be a cost-effective constructive element in comparison with other conventional elements.

- Ignorance of composite materials, both in regard to the lack of training of future technicians and workers, and lack of information in general about their characteristics and application possibilities.

- Lack of regulation of use or technical regulations, which gives insecurity for its design and calculation. In addition to needing people and specialized tools in the area of structural calculation of elements made with these materials.

- Lack of information on its durability, since it is very young materials, little used so far, so the architect, overwhelmed by his ten-year responsibility, prefers not to risk.
- Behaviour to fire. Although its behaviour against fire is not bad (depending on the choice of resins and fillers), there is still a long way to go to improve its mechanical properties at high temperatures, fumes, gases ...

- They are difficult to recycle materials, however, the most recent research is achieving very important advances, for example: they are subjected to mechanical treatments and subsequent crushing to be used as a load in other composites or construction materials.

- Lack of mentalization between users and technicians. All this together with traditional conservatism in the construction sector, makes it very difficult to introduce new materials or new technologies, if they do not bring an economic benefit for the builder.

Challenges of composite materials.

2.5.1.1 DURABILITY OF FRP MATERIALS

Compared with traditional materials, there is proven evidence of the best properties of composite materials against aggressive external agents of the environment. This property has been observed over a long period of time in examples such as boats, piping, storage tanks and many other applications for oil, chemical, water treatment industries ...

Despite this proven improvement of durability properties, one of the reasons that the use of GFRP pultrusion profiles has not been standardized is precisely the lack of comprehensive and validated data on durability, since in civil works it has to be guaranteed at least 50 years of service life of the structure. The composite materials used in civil works require a deep investigation in aspects such as moisture / solution, thermal effects, ultraviolet radiation, alkalinity, creep / relaxation, fatigue and fire.

2.5.1.2 SUSTAINABILITY OF FRP MATERIALS

To talk about the sustainability of a material, it would be necessary to analyse all the phases of life of a material, from its manufacturing phase, its service life and its end of cycle. The first thing that we have to analyse in the manufacturing phase of these materials is their energy for production and the amount of waste generated in said process. In its second phase (service life) the necessary maintenance. Finally, at the end of its cycle several factors need to be taken into account such as reuse, recycling...

In terms of energy, when manufacturing GFRP profiles in comparison with their steel and aluminium counterparts, they consume ¼ and 1/6 of energy respectively (Fernanda Margarido. 2015). However, when it comes to profiles made with carbon fiber, this energy consumption increases considerably due to the large amount needed for the production of these fibers.

During their service life, FRP offer a competitive advantage over other traditional materials with their reduction in maintenance work due to their improved durability against environmental agents. In addition, its low thermal conductivity influences the consequent energy savings in buildings.

The end of the cycle of composite materials is the most limited factor with respect to sustainability. This is mainly due to the no-reuse of the thermosetting resin used in manufacturing processes. There are not many possible alternatives with the final waste. At present, as recycling processes of these resins we have three groups: the first one, the recycling of machining, which consists of reducing the size of the scraps (this process involves an expenditure of energy in said shredding). The second is the chemical process and finally the thermal recycling techniques which with a pyrolysis incineration process try to separate the fiber matrix to proceed with its reuse. This last process leads to very high energy costs compared to the first recycling method.

In the future, it may be possible for FRP materials to become as sustainable as traditional materials such as concrete and steel. This depends on the success in the development of thermoplastic resins for its application in this sector due to its characteristic of reproducibility.

2.5.1.3 FIRE BEHAVIOUR OF FRP MATERIALS

With respect to fire, the main factors to be taken into account of the materials used in construction are avoiding fire deflagration, flame spread and effective smoke production and spreading. In addition to this, it is also important the resistance and the time required in the material during a fire before the structure collapses.

In all these fields the materials have a long way to improve to find the most suitable matrix for this field. As a competitive advantage, it should be noted that composite materials have an excellent property as a thermal insulator, which gives them an important mission to slow down the spread of fire from room to room.

3 PARTS TYPOLOGIES TO EVALUATE. CLOSED MONOLITHIC SHAPE AND OPEN SANDWICH SHAPE

In this section we will describe the two types of pieces chosen for development of this work. The choice has been made, thinking of two antagonistic morphologies and that are susceptible to be transferred to the field of construction**.**

3.1 CLOSED MONOLITHIC SHAPE

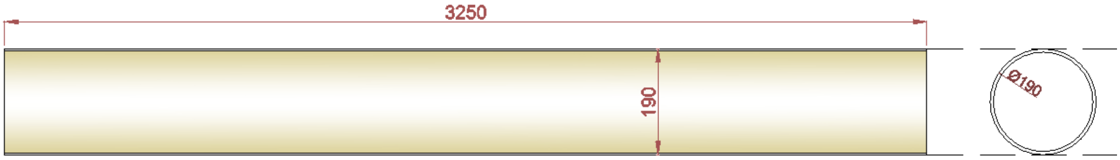
In the field of the manufacture of composite pieces, it is well known the difficulty of the manufacture of monolithic pieces with closed form. This morphology of parts is almost relegated to manufacturing processes by pultrusion and filament winding. These manufacturing techniques ensure the correct alignment of fibers. However, as we have seen in previous sections, in the case of filament winding, the orientation of fibers in the longitudinal direction of the piece is difficult to reach, which limits some applications of these elements. Quite the opposite happens to the pultrusion process, which assures fiber orientations in direction 0, but does not manage to place fibers in other directions.

This project intends to carry out the manufacture of this piece morphology by infusion techniques, which is rarely used for the manufacture of this type of pieces due to its difficulty of rolling and the complexity of its moulds.

The tubular shape is widely used in the field of construction. It is usually a hollow piece of metal that is characterized by having a round outline and two open ends. In construction it is usually made of quality alloy steel, to present a good performance in the face of great traction, compression and shear, as well as to allow the transmission of heat and current, and to be "relatively" light.

They have excellent properties to support static loads, not only with respect to buckling, biaxial bending and torsion, but also in aspects related to the global design of elements. Not only cylindrical hollow profiles are used to transport a fluid, but also the excellent properties of this morphology with respect to the efforts of compression, torsion and bending in all directions

Geometry (See image 3):



3. *Image. Part Geometry. (own elaboration)*

This tubular shape will have a laminate thickness of approximately 6 mm.

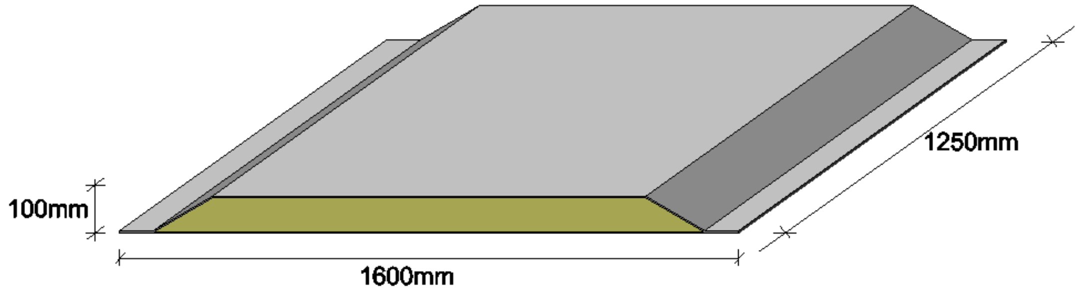
3.2 OPEN SANDWICH SHAPE

The other type to be implemented is an open sandwich type morphology. This typology, in the construction sector, is mainly used in roofs and façades, which makes it a secondary structural element. But in our case, we will use this same morphology to create a structural element that could serve as a slab (example, deck panel in bridges).

Normally, the pre-slabs are prefabricated concrete elements used as permanent formwork, which later supports the concrete poured in situ, in such a way that it significantly eliminates the use of formwork, formwork and other temporary support elements, which greatly facilitates the execution of works by traditional methods.

This morphology (see image 4) consists of two monolithic supports (only fiber and resin) and a central part of sandwich panel (two monolithic sides and foam between them). The foam of the piece manages to give inertia to the piece to save material and weight costs.

In addition, said core will have cut the edges with an angle of 45-60 ° which favours the correct transmission of loads and avoids stress concentrations



4. Image. Part Geometry. (own elaboration)

4 MATERIALS, EQUIPMENT AND PROCEDURE

4.1 Selection of raw material, auxiliary material and manufacturing equipment

4.1.1 CLOSED MONOLITHIC SHAPE

4.1.1.1 Raw material

In this case, and as mentioned at the beginning of this work, a combination of carbon fibers and fiberglass will be used for this type of piece.

- Carbon fiber: Unidirectional fabrics 600 gr/m2 (U-C-600)

- Fiberglass: Biaxial fabric ±45 450 gr/m2 (X-E-450)

A thermosetting and infusion epoxy resin will be used as matrix. This has an appropriate viscosity for the manufacturing process to be carried out and a curing of 8 hours at 60 °C.

4.1.1.2 Auxiliary material

As auxiliary materials we will have:

- Peel ply (Comploflex150). This fabric has the function of demoulding the resin distribution network of the outer skin of the piece, as well as absorbing part of the resin when internal pressure is added to the impregnated part.

- Resin distribution network. It is used to correctly distribute the resin through the laminate and accelerate the impregnation process creating preferred channels.

- Vacuum bag: It is responsible for confining the laminate to create an interior vacuum.

- Coremat: It is a tissue of absorption, aeration and retention of resin. It is usually placed to direct the resin and also to perform the barrier function so that the resin does not reach the vacuum pump easily.

- Sealing putty: to seal the edges of the mould and avoid vacuum leaks and consequent leakage of resin during the process

- Polyethylene tube. It serves to channel the resin from the container to the laminate

- Valves and plastic Ts. Valves to close-open the resin passage through the tubes and the Ts serve to divide the pipe network.

4.1.1.3 Manufacturing equipment

- Vacuum pump. It is the team in charge of generating the vacuum in the mould. (See image 5)

5. *Image. Vacuum equipment (taken from www.vacmobiles.com)*

- Pneumatic compressor equipment: Provides air inside the rubber tube to generate the pressure after the impregnated

- Air heater: Electric heating equipment, which provides the necessary temperature for curing part.

4.1.2 OPEN SANDWICH SHAPE

4.1.2.1 Raw material

In this case, only fiberglass is used as reinforcement of the piece and also, as mentioned in the previous section, an inner foam will be available to obtain inertia.

- Fiberglass: Unidirectional fabric ±45 1000 gr/m2 (U-E-1000)

- Foam: PET 80Kg/m3 core. 100mm thickness. This should be grooved on both sides and perforated, thus creating preferential resin channels both horizontally and vertically.

- A thermosetting and infusion vinilester resin will be used as matrix. This has an appropriate viscosity for the manufacturing process to be carried out.

With the choice of only glass fiber in the laminate and the choice of vinilester resin, the cost of raw material is considerably reduced.

As auxiliary materials we will have:

- Peel ply. This fabric has the function of demoulding the resin distribution network of the outer skin of the piece.

- Resin distribution network. It is used to correctly distribute the resin through the laminate and accelerate the impregnation process creating preferred channels.

- Vacuum bag: It is responsible for confining the laminate to create an interior vacuum.

- Sealing tape: It is used to seal the perimeter of the bag and thus create a tightness and reach a vacuum.

- Diadrain: It is a flat resin or vacuum channel. It consists of a three-dimensional polyester filament core structure wrapped in a non-woven polyester sleeve. It functions as resin supply channel or vacuum channel in vacuum infusion process.

- Coremat: It is a tissue of absorption, aeration and retention of resin. It is usually placed to direct the resin and also to perform the barrier function so that the resin does not reach the vacuum pump easily.

- Polyethylene tube. It serves to channel the resin from the container to the laminate

- Valves and plastic Ts. Valves to close-open the resin passage through the tubes and the Ts serve to divide the pipe network.

4.1.2.2 Manufacturing equipment

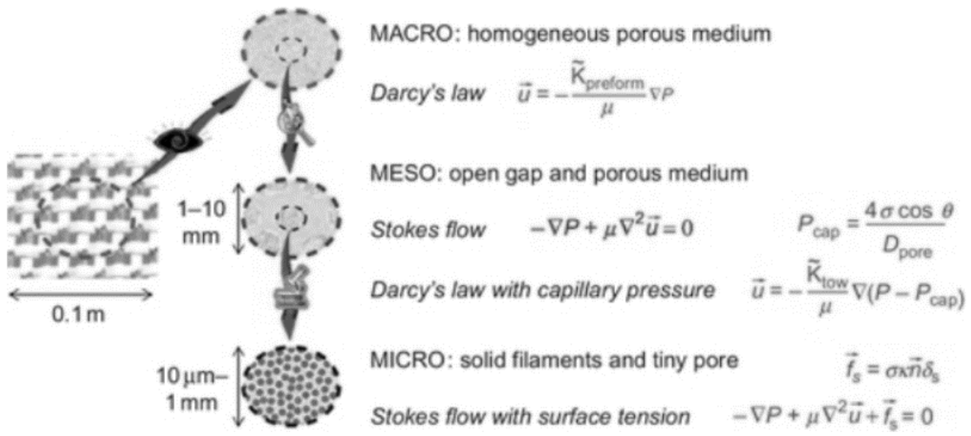
- Vacuum pump. It is the team in charge of generating the vacuum in the mould.

4.2 Procedure. Infusion strategy for each typology

In the manufacturing process, an important aspect to take into account is the impregnation time of the laminate, which affects the final cost. In addition, we have to avoid fiber misalignments and voids, which have a negative impact on the final mechanical properties.

In this work a basic approximation of simulation of impregnation of the laminate is made assuming several principles (Park, C.H. (2015)). First of all, it is based on a model of continuous fiber-reinforced composites processing. Secondly, we take into account that the resin flow can be considered as Newtonian flow, and also through fiber reinforcement as a Newtonian flow in porous medium. There are several calculation or flow modelling processes depending on your observation scale. We will consider for this work the macroscopic scale where Darcy's law is applied to describe the resin flow in the fibrous medium of which flow conductance is represented by permeability.

Darcy's law, in the macroscopic observation scale, is used to analyse both the global resin flow in the mould, and its resin inlets and vents positioning to optimize the infusion process. (See image 6)



6. *Image. Different scales in textile reinforcements and corresponding Flow characteristics. (Park, C.H. 2015)*

The equation that governs this macroscopic scale is:

$$\vec{u}_D = -\frac{\tilde{K}}{\mu}\nabla P$$

Where u_D is Darcy's velocity or volume averaged fluid velocity, K is the permeability, µ the viscosity of the fluid and P the pressure of this.

Permeability is a key parameter to determinate the resin velocity. Normally this permeability is calculated by means of relevant tests that give us permeability data in the three directions or axes of the tissue (Kx, Ky, Kz). But there is also an approximation by theoretical calculation which expresses a relationship between permeability and fiber volume fraction. This is represented by the Kozeny-Carman equation (Carman, 1927).

$$K_{ij} = \frac{d_f^2}{16k_{ij}}\frac{(1-V_f)^3}{V_f^2}$$

If we also obviate the transverse impregnation direction (Kz), this equation is simplified. And we will also place a channel distribution in the width part, only have a value of permeability Kx (Only parts with constant width).

Next consideration, let's make an estimate that the injection pressure is constant (vacuum). When the viscosity remains constant during the process, even in the case of a prescribed constant pressure P_{inj}, the filling time is obtained by a straightforward integration over the total length of the mould L and can be expressed as (M. Deléglise [a] 2011):

$$t_{\text{inj}} = \frac{1}{2}\frac{\phi\mu}{KP_{\text{inj}}}L^2$$

If our geometry and laminate were complex and very variable, we would need numerical simulation (Boccard et al., 1995). Finite difference method (FDM) with moving grids was used to obtain pressure field at each time step during the computation.

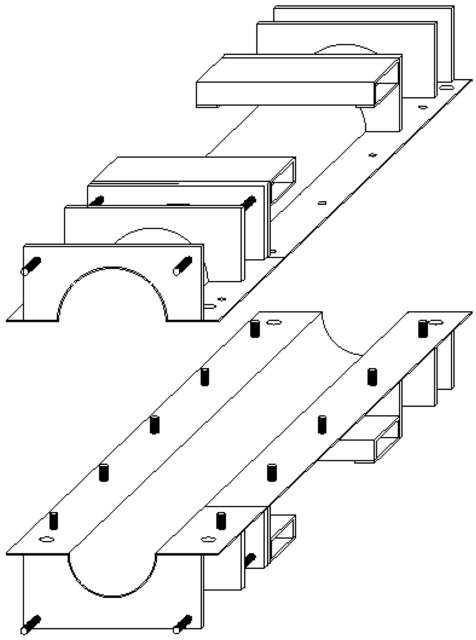
Before starting with the procedure and with the infusion strategy, it is necessary to define or specify some piece requirements. For example, for the case of the tube, we will try to respect the external diameter of the piece, therefore the good part face will be the external one. The inside face of the piece will not be relevant. For the case of the sandwich panel, the face with the largest flat surface will be the mould surface. (See image 7)

7. Image. Section part (sandwich panel). Own elaboration

4.2.1 CLOSED MONOLITHIC SHAPE

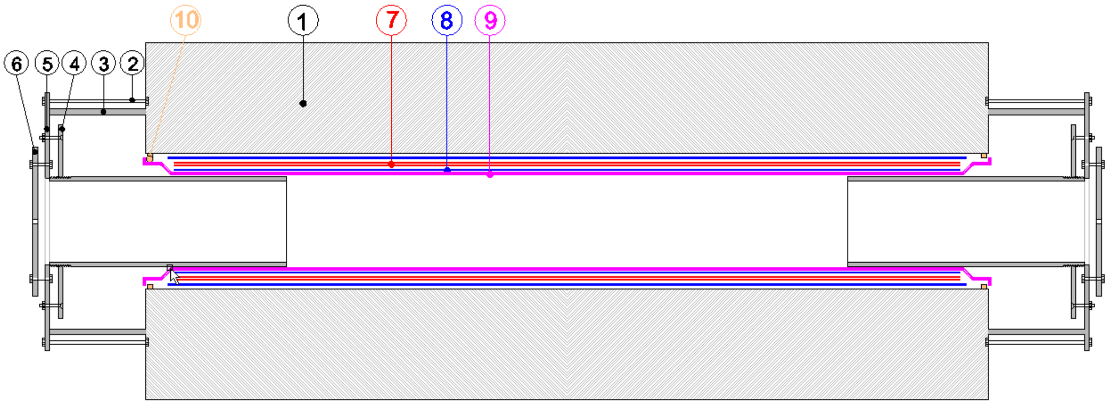
To define the infusion strategy and the procedure, first we must know the part and mould geometry and the laminate of the element.

For the case of the tube, we start from a metal mould of two semi-cylindrical halves, which join to form the tube. (see image 8). The mould is formed by a thick metal tube to which stiffening ribs are placed, and then machined with the exact shape of the tube.



8. *Image. Tube mould. Own elaboration*

These two semi-moulds are joined to form the tube and are closed at the sides with a system of closing plates. The laminate is confined in the tool, inside the tube the bag, creating the vacuum.(see image 9)



9. *Image. General scheme. Own elaboration*

1. Mould; 2. Joining part to mould; 3. Centering bushing; 4. A Plate (Threaded on threaded bushing); 5. B Plate (Centering tube in mould); 6. C Plate; 7. Laminate; 8. Peel ply and resin distribution; 9. Vacuum bag; 10. Sealing tape;

The lamination carried out on the piece is described in the table below.

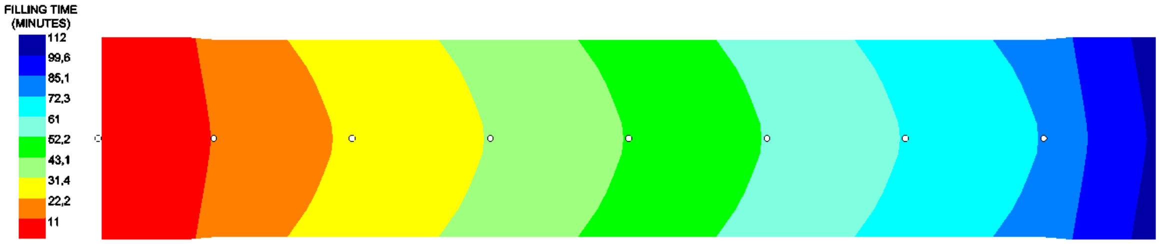
	FIBER
LAYER 1	X-E 450
LAYER 2	U-C 600
LAYER 3	X-E 450
LAYER 4	U-C 600
LAYER 5	X-E 450
LAYER 6	U-C 600
LAYER 7	X-E 450
LAYER 8	U-C 600
LAYER 9	X-E 450
LAYER 10	U-C 600
LAYER 11	X-E 450
LAYER 12	U-C 600
LAYER 13	X-E 450
LAYER 14	U-C 600
LAYER 15	X-E 450

10. *Table. Tube laminate. Own elaboration*

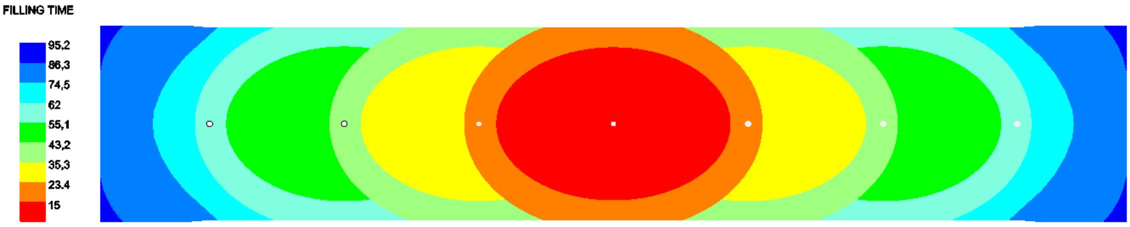
Due to the thickness of the laminate and the length, it has been thought to place 8 equidistant resin inlets and perform an infusion strategy progressively. It means that a resin entrance will not be opened without guaranteeing that the laminated part up to that entrance contains the amount of resin that corresponds it.

As explained in the initial section, an approximation of the infusion strategy is performed by means of numerical calculation methods, and the calculation is represented by means of schematic drawings that help us observe the process of impregnation of the piece.

In the lower scheme we see two infusion strategies carried out in the tube. The complete development of laminate is represented. On the one hand, the first strategy (see Image 11) with the entrance of resin on one side and progressively opening each of the entrances to reach the vacuum outlet at the opposite end. On the other hand (see image 12), we fear the beginning of the infusion from the central entrance and two empty exits (one at each end). Also, in this last case the resin entrances are opening progressively.



11. Image. Case 1. Own elaboration



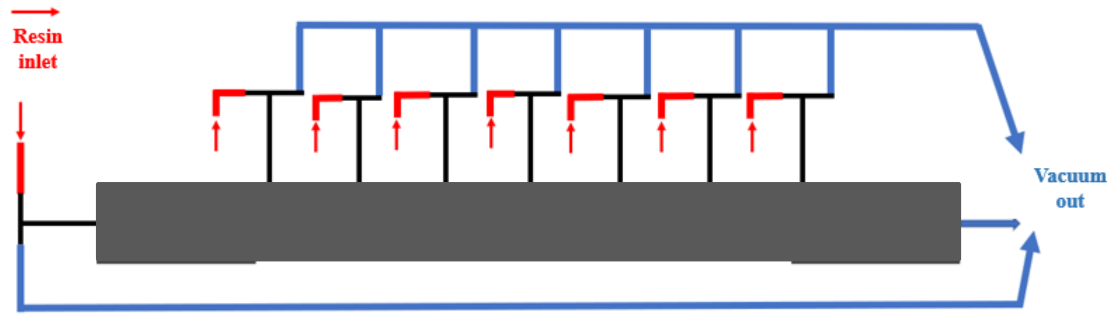
12. Image. Case 2. Own elaboration

Observing both strategies, the infusion strategy is chosen from one end to the other due to the more homogeneous impregnation that it achieves.

The first resin inlet will be made from one end of the tube. This decision is made based on a factor, the resin inputs of the tool, except the first, do not have a resin distribution channel, it is only an injection point, this makes the resin reach the bottom of the tube. later, however, from the top, quickly reach the nearby resin entrances. If we open a resin inlet without the bottom part being impregnated, it can derive in areas of laminate without resin or with air occlusions which derivates in weak parts.

The progressive resin entries are due to the length of the piece. Partial polymerizations may occur in the part during the process, or the resin front may cure before reaching the end of the part.

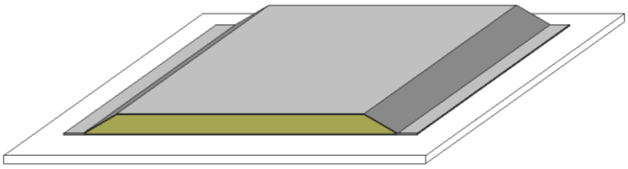
In addition, to help the resin flow, the resin inlets themselves, before introducing resin into the laminate, will function as vents. When the resin reaches each exit-entry, the vacuum will be closed and all successive exits will be maintained. Said resin inlets should not be opened until the resin consumption up to that point is satisfactory, since this could cause parts of the laminate to have interior air. (See image 13)



13. *Image. Tube infusion strategy . Own elaboration*

4.2.2 OPEN SANDWICH SHAPE

In the case of the sandwich panel, the mould is much simpler, since if we have as a requirement that the largest flat surface of the piece is mould face (so that the surface does not present irregularities and is as flat as possible), we only need a mould with a flat, smooth and non-porous surface to ensure the correct posterior vacuum. The vacuum will be made with the help of the sealed bag around the perimeter of the tool. (See image 14)

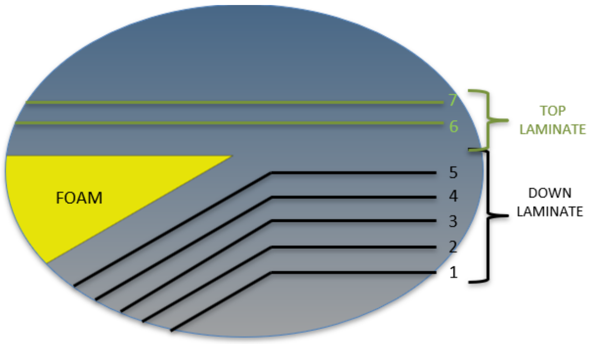


14. *Image. Open sandwich mould. Own elaboration*

Laminate (see table 15 and image 16):

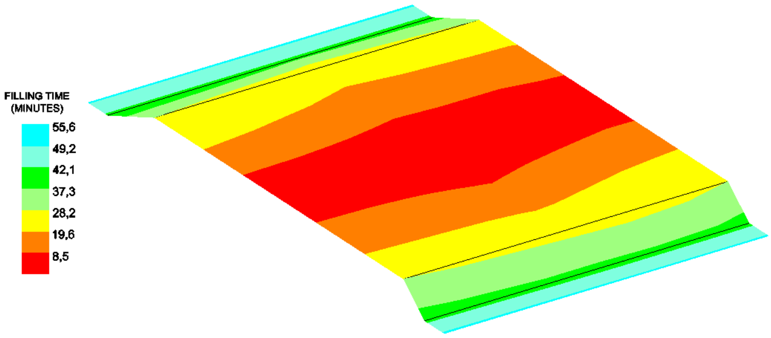
	FIBER	ORIENTATION	ZONE 1 (COMPLETE)	ZONE 2 (REINFORCEMENT)
LAYER 1	U-E 1000	0	X	
LAYER 2	U-E 1000	0	X	
LAYER 3	U-E 1000	0		X
LAYER 4	U-E 1000	0		X
LAYER 5	U-E 1000	0		X
LAYER 6	U-E 1000	0	X	
LAYER 7	U-E 1000	0	X	

15. *Table Laminate. Own elaboration*

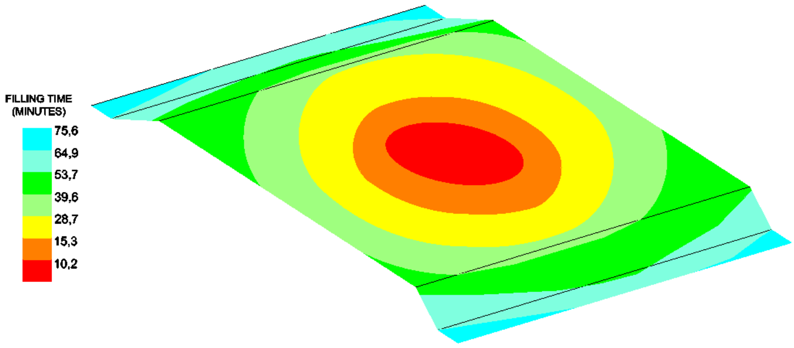


16. *Image Laminate scheme. Symmetrical laminate. Own elaboration*

As in the case of the tube, two infusion strategies are approximated by numerical calculation. Both are presented with a central point of resin entry; the difference is that in the first case (See image 17) is placed resin supply channel (diadrain) which causes the resin to flow from one end to another at the first instant and the resin front advance more parallel to the end.

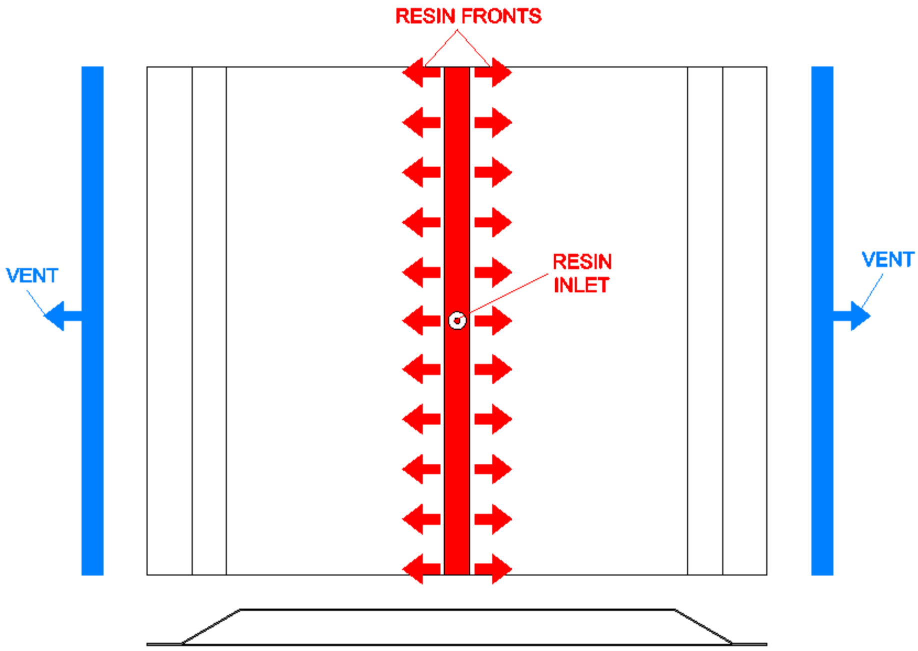


17. *Image. Infusion strategy central channel. Own elaboration*

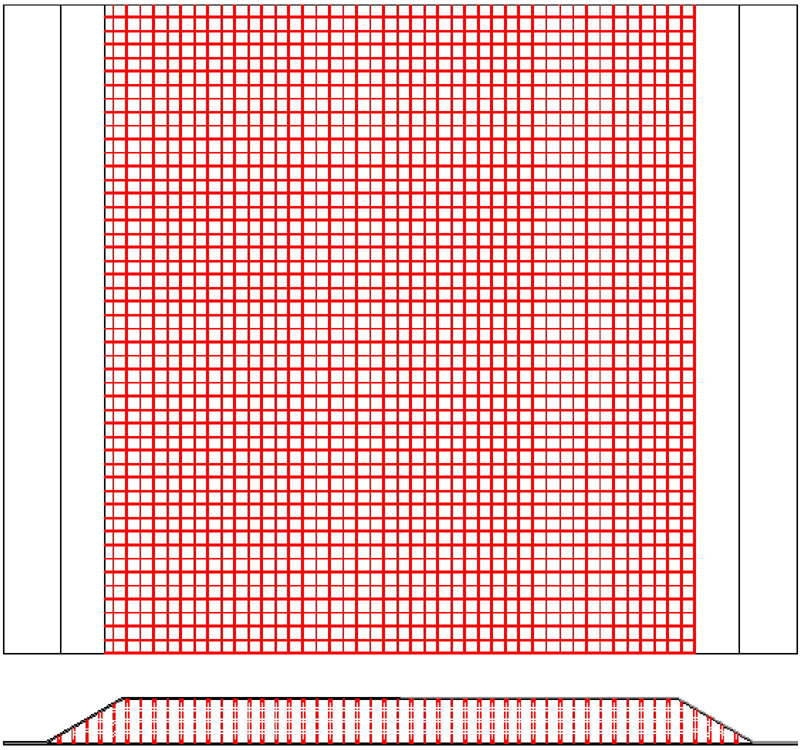


18. *Image. Infusion strategy injection point. Own elaboration*

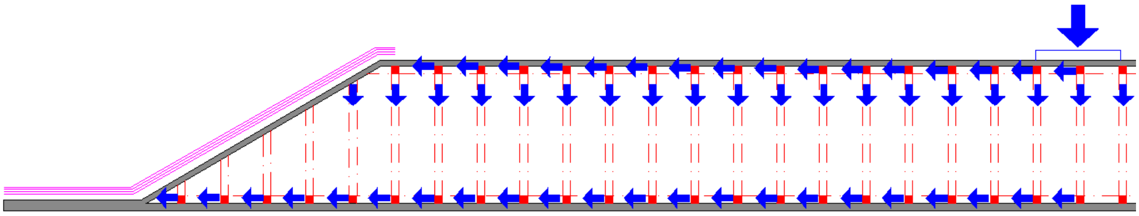
For the infusion strategy, a central resin entry system has been chosen, aided by a resin distribution channel, and two vents, one at each end of the piece. With this we achieve that there are two resin fronts as homogeneous as possible. The resin inlet is only placed on the upper surface, we need to drill the core so that the resin reaches the mould face laminate.(See images 19, 20 and 21)



19. *Image. Panel Infusion strategy. Own elaboration*



20. *Image Foam channels scheme. Own elaboration*



21. *Image Infusion strategy. Red: Foam channels; Blue: Resin direction; Pink: resin distribution mesh. Own elaboration*

5 CHARACTERIZATION AND MECHANICAL PROPERTIES OF THE MATERIALS

5.1 CLOSED MONOLITHIC SHAPE

This section shows the results of mechanical and thermal properties obtained for the materials of the present piece, as well as the analytical estimation of properties and their validation.

5.1.1 Raw material

The selected resin is a bicomponent epoxy resin. Next, the data sheet properties of the resin used are shown. (See image 22)

Mechanical properties of pure resin

Systems				
Cure		24 hrs 40 °C	16 hrs 60 °C	8 hrs 80 °C
Tension				
Modulus of elasticity	N/mm†	3290	3110	2800
Maximum resistance	N/mm†	73	74	74
Resistance at break		69	71	70
Elongation at max. resistance	%	3.2	4.2	5.4
Elongation at break	%	3.4	5.1	6.0
Flexion				
Modulus of elasticity	N/mm†	3250	3150	2800
Maximum resistance	N/mm†	115	116	117
Elongation at max. resistance	%	4.4	5.3	6.2
Charpy impact strength				
Resilience	KJ/m†	17	39	21
Glass Transition				
Tg 1 Onset		71	89	103
Tg 1 Onset maximum				101

Tests carried out on samples of pure cast resin, without prior degassing, between steel plates.
Measures undertaken according to the following norms :
Tension: NF T 51-034
Flexion : NF T 51-001
Charpy impact strength: NF T 51-035
Glass transition DSC : ISO 11357-2 : 1999 -5°C t o 180°C under nitrogen gaz
Tg1 or Onset : 1st point at 20 °C/mn
Tg1 maximum or Onset : second passage

22. *Image. Resin properties Datasheet. Own elaboration*

2 types of fiber are selected:

- Carbon fiber: Unidirectional fabrics 600 gr/m2 (U-C-600) (50 K)

- Fiberglass: Biaxial fabric ±45 450 gr/m2 (X-E-450)

Next, the properties of dry fiber belonging to carbon fabric are shown. No mechanical data are available in the manufacturer's data sheet of the biaxial E fiberglass. (See image 23)

	SI	US
Tensile Strength	4137 MPa	600 ksi
Tensile Modulus	242 GPa	35 msi
Electrical Resistivity	0.00155 ohm-cm	0.00061 ohm-in
Density	1.81 g/cc	0.065 lb/in3
Fiber Diameter	7.2 microns	0.283 mils
Carbon Content	95%	
Yield	267 m/kg	397 ft/lb
Spool Weight	5.5 kg, 11 kg	12 lb, 24 lb
Spool Length	1500 m, 3000 m	1640 yd, 3280 yd

23. *Image. Carbon fiber UD 50 K mechanical properties. Own elaboration*

5.1.2 Results of the raw material characterization tests

This section shows the results of the tests carried out and according to what regulations have been carried out (Structural Design of Polymer Composites. Eurocomp design code and Handbook, Luigi Ascione 2016 and American Composites Manufacturers Association. (2016)):

• Traction elastic module (UNE-EN ISO 527-4)

• Compression elastic module (ISO 14126)

• Shear elastic modulus (UNE-EN ISO 14129)

• Tensile strength (UNE-EN ISO 527-4)

• Compression resistance (ISO 14126)

• Cutting resistance (UNE-EN ISO 14129)

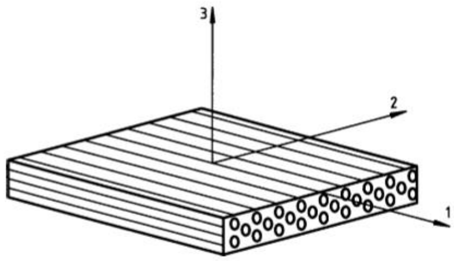
• ILSS (ISO 14130)

• Fiber Volume (EN2564)

• Tg (ISO 6721)

• CTE (ISO 11359: 1999)

These tests are carried out for the two main directions of the sheet: fiber direction and direction of the resin. The following figure shows the axes of the sheet, where the direction 1 is that of the fiber and the direction 2, the perpendicular in the plane of the sheet (commonly called the direction of the resin).(See image 24)



24. *Image. Layer axes. Own elaboration*

For the design allowances in composite material the B-Value will be used. The obtaining of this value is detailed in "MIL-HDBK-17-1F" and its meaning is "B-Basis (or B-Value) - A statistically-based material property; to 95% lower confidence bound on the tenth percentile of a specified population of measurements. Also, at 95% lower tolerance bound for the upper 90% of a specified population. " That is, 90% of the resistance measurements are above this value with a confidence level of 95%.
The B-Value is calculated as follows:

$$B = \bar{x} - k_B \cdot s$$

Where:

$\bar{x}$ is the average resistance of the samples taken.

s is the standard deviation

k_B is a factor obtained from the following table (obtained from "MIL-HDBK-17-1F") based on the number (n) of test pieces tested. (See table 25)

N = 2 - 137							
n	k_B	n	k_B	n	k_B	n	k_B
2	20.581	36	1.725	70	1.582	104	1.522
3	6.157	37	1.718	71	1.579	105	1.521
4	4.163	38	1.711	72	1.577	106	1.519
5	3.408	39	1.704	73	1.575	107	1.518
6	3.007	40	1.698	74	1.572	108	1.517
7	2.756	41	1.692	75	1.570	109	1.516
8	2.583	42	1.686	76	1.568	110	1.515
9	2.454	43	1.680	77	1.566	111	1.513
10	2.355	44	1.675	78	1.564	112	1.512
11	2.276	45	1.669	79	1.562	113	1.511
12	2.211	46	1.664	80	1.560	114	1.510
13	2.156	47	1.660	81	1.558	115	1.509
14	2.109	48	1.655	82	1.556	116	1.508
15	2.069	49	1.650	83	1.554	117	1.507
16	2.034	50	1.646	84	1.552	118	1.506
17	2.002	51	1.642	85	1.551	119	1.505
18	1.974	52	1.638	86	1.549	120	1.504
19	1.949	53	1.634	87	1.547	121	1.503
20	1.927	54	1.630	88	1.545	122	1.502
21	1.906	55	1.626	89	1.544	123	1.501
22	1.887	56	1.623	90	1.542	124	1.500
23	1.870	57	1.619	91	1.540	125	1.499
24	1.854	58	1.616	92	1.539	126	1.498
25	1.839	59	1.613	93	1.537	127	1.497
26	1.825	60	1.609	94	1.536	128	1.496
27	1.812	61	1.606	95	1.534	129	1.495
28	1.800	62	1.603	96	1.533	130	1.494
29	1.789	63	1.600	97	1.531	131	1.493
30	1.778	64	1.597	98	1.530	132	1.492
31	1.768	65	1.595	99	1.529	133	1.492
32	1.758	66	1.592	100	1.527	134	1.491
33	1.749	67	1.589	101	1.526	135	1.490
34	1.741	68	1.587	102	1.525	136	1.489
35	1.733	69	1.584	103	1.523	137	1.488

25. *Image. Table for obtaining the KB coefficient according to the number of test pieces tested (n). Own elaboration*

For the Young and Poisson module values, the means obtained from the tests will be used as design values.

The testing campaign is focused on 3 material configurations.(See table 26)

MATERIAL	FIBER	RESIN
MATERIAL 1	Carbon fiber UD 600	Epoxy
MATERIAL 2	Glass fiber BX 450 E-glass	Epoxy

26. *Table Materials test. Own elaboration*

5.1.3 Material 1

The following tables show the results obtained in the tests for material 1: (See tables 27)

test	X_T (MPa)	v_{12}	E_{1T} (GPa)
P01	1242	0.41	122,970
P02	1428	0.3	122,960
P03	1447	0.33	121,300
Average	1369.1	0.34	122,407
Standard deviation	113.3	0.06	0,961
characteristic resistance	671.7		

Table Material 1: 0° tensile test results

Test	Y_T (MPa)	E_{2T} (GPa)
P01	38	8
P02	38	8
P03	35	8
Average	37	8
Standard deviation	1.7	0
Characteristic resistance	26.3	

Table Material 1: 90° tensile test results

Test	Y_c (MPa)	E_{2c} (GPa)	ILSS (MPa)
P01	731	112,88	58
P02	692	110,15	61
P03	655	103,93	57
Average	692	108,921	58,64
Standard deviation	38	4,587	2,1
Characteristic resistance	458		

Table Material 1: 0° compression test results

Test	X_C (MPa)	E_{1C} (GPa)
P01	140	8,4
P02	134	9,94
P03	125	9,85
Average	132,9	9,369
Standard deviation	7,5	0,864
Characteristic resistance	86,4	

Table Material 1: 90° compression test results

Test	Vf (%)	Vr (%)	Vo (%)	ρ (Kg/m3)
P01	64,80*	38.37**	-2.46	1,582
P02	64,24*	39.09**	-2.63	1,58
P03	63,86*	38.43**	-1.6	1,566
Average	64,3	38.6	-2.22	1,58
Standard deviation	0,5	0,4	0,5	0,009

Table Material 1: Test results Volume of fiber

Test	Tg (ºC)
P01	105,97
P02	105,65
P03	106
Average	105,9
Standard deviation	0,2

Table Material 1: Tg test results

Test	CTEx (µm/m ºC)	CTEy (µm/m ºC)
P01	-3,1 / 1,6	
P02		36,3

Table Material 1: CTE test results

Test	S_{12} (MPa)	G_{12} (GPa)
P01	33.18	5,75
P02	31.62	5,51
P03	37.55	5,67
Average	34	5,642
Standard deviation	3,1	0,564
Characteristic resistance	15,1	

Table Material 1: IPS shear test results

27. Image. Material 1. Test results. Own elaboration

* Considering a carbon fiber density of 1.81 g / cm3 obtained from the technical data sheet of the manufacturer's website. Reference 1.

** Considering a 100g mixture of resin (density 1.159 g / cm3 per technical sheet) with 27 g of catalyst (density 1.01 g / cm3 per technical sheet). Reference 4.

5.1.4 Material 2

The following tables show the results obtained in the tests for material 3 (see tables 28):

Test	X_T (MPa)	ν_{12}	E_{1T} (GPa)
P01	473	0,16	26,910
P02	455	0,17	27,150
P03	472	0,17	27,510
Average	466,6	0,17	27,188
Standard deviation	10,1	0,01	0,302
Characteristic resistance	404,3		

Table Material 3: 0° tensile test results

Test	Y_T (MPa)	E_{2T} (GPa)
P01	543	22
P02	563	20
P03	570	21
Average	558,5	20,984
Standard deviation	14	1
Characteristic resistance	472,3	

Table Material 3: 90° tensile test results

Test	Y_c (MPa)	E_{2c} (GPa)	ILSS (MPa)
P01	304	29,080	48
P02	346	30,080	49
P03	382	29,880	45
Average	342,5	29,676	47,30
Standard deviation	39,0	0,529	2,1
Characteristic resistance	102,1		

Table Material 3: 0° compression test results

Test	X_C (MPa)	E_{1C} (GPa)	ILSS (MPa)
P01	339	28,990	44
P02	434	29,940	46
P03	383	29,770	47
Average	383,4	29,563	45,65
Standard deviation	47,5	0,506	1,5
Characteristic resistance	90,7		

Table Material 3: 90° compression test results

Test	Vf (%)	Vr (%)	Vo (%)	ρ (Kg/m3)
P01	57,29*	46,13**	-3,43	1,98
P02	57,87*	46,06**	-3,93	1,994
P03	57,97*	45,19**	-3,17	1,987
Average	57,7	45,8	-3,510	1,99
Standard deviation	0,4	0,5	0,4	0,007

Table Material 3: Test results Volume of fiber

Test	Tg (ºC)
P01	104,51
P02	104
P03	104,85
Average	104,5
Standard deviation	0,4

Table Material 3: Tg test results

Test	CTEx (µm/m ºC)	CTEy (µm/m ºC)
P01	10,6	
P02		14,5

Table Material 3: CTE test results

Test	S_{12} (MPa)	G_{12} (GPa)
P01	66,94	4,410
P02	66,52	4,400
P03	70,12	4,530
Average	67,8	4,446
Standard deviation	2,0	0,072
Characteristic resistance	55,7	

Table Material 3: IPS shear test results

28. Image. Material 3. Test Results. Own elaboration

* Considering a fiberglass density of 2.57 g / cm3 obtained as a typical value of the design guide for composite materials of the European Commission. Reference 3.

** Considering a 100g mixture of resin (density 1.159 g / cm3 per technical sheet) with 27 g of catalyst (density 1.01 g / cm3 per technical sheet). Reference 4.

Summary of test results (See tables 29 and 30):

Test	UD CARBON	BIAXIAL GLASS
E_{1T} (GPa)	122.407	27.188
E_{1C} (GPa)	108.920	29.676
E_{2T} (GPa)	8.000	20.984
E_{2C} (GPa)	9.369	29.563
G_{12} (GPa)	5.642	4.446
Vf (%)	63.6	57.7
Tg (ºC)	105.9	104.5
CTE_X (10^{-6}/ºC)	-3.1/1.6	10.6
CTE_Y (10^{-6}/ºC)	36.3	14.5

29. Table Results of tests of the average values obtained. Own elaboration

Test	UD CARBON		BIAXIAL GLASS	
	Average	Charact.	Average	Charact.
X_T (GPa)	1369.1	671.7	466.6	404.3
X_C (GPa)	692	458	342.5	102.1
Y_T (GPa)	37	26.3	558.5	472.3
Y_C (GPa)	132,9	86,4	383.4	90.7
S_{12} (GPa)	34	15.1	67.8	55.7
ILSS X(MPa)	58.64	45.8	47.3	34.5
ILSS Y(MPa)	No	No	45.65	36.2

30. Table Test results of the mean and characteristic resistance values. Own elaboration

5.1.5 Prototype tests. Result of type lamination characterization tests

In addition to the characterization tests of the material, it is convenient to carry out the tests for the characterization of the type laminate. These tests have been carried out according to the following regulations:

• Traction elastic module (UNE-EN ISO 527-4)

• Compression elastic module (ISO 14126)

• Tensile strength (UNE-EN ISO 527-4)

• Compression resistance (ISO 14126)

• ILSS (ISO 14130)

• Vf (EN 2564)

• Tg (ISO 6721)

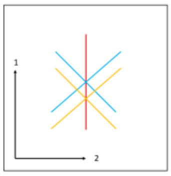
The laminate to be tested is shown in the following table 31:

Layer	Orientation	Material
1	45	Biaxial Glass
2	0	UD Carbon
3	45	Biaxial Glass
4	0	UD Carbon
5	45	Biaxial Glass
6	0	UD Carbon
7	45	Biaxial Glass
8	0	UD Carbon
9	45	Biaxial Glass
10	0	UD Carbon
11	45	Biaxial Glass
12	0	UD Carbon
13	45	Biaxial Glass
14	0	UD Carbon
15	45	Biaxial Glass

31. *Table Stacking sequence for characterization tests of laminate type. Own elaboration*

These tests are carried out for the two main directions of the laminate, which will be defined as follows: (See image 32)

- Direction 1: It will coincide with the main direction of the unidirectional sheets.
- Direction 2: Orthogonal to address 1 in the plane.



32. *Image. Schematic of the main directions of the laminate with respect to the orientation of the fibers (carbon fiber UD in red). Own elaboration*

Since these tests are not focused to use the values obtained as design values, but for property validation, characteristic values will not be obtained but only average values.

Test results (See table 33)

Test	X_T (MPa)	E_{1T} (GPa)	ILSS (MPa)	Tg (ºC)	Vf (%)	CTEx µm/(m ºC)
Traction 0	986	87.55				
Traction 90	161	13.55				
Compression 0	514	79.3				
Compression 90	253	12.77				
ILSS 0			51.34			
Tg				*		
Vf					**	
CTEx						2.5

33. Table Type laminate: Test results. Own elaboration

* Not performed because it is not possible to test specimens of the thickness of the laminate on available DMA equipment.

** According to formulas

5.2 OPEN SANDWICH SHAPE

5.2.1 Raw material

The selected resin is a bicomponent vinylester resin. Next, the data sheet properties of the resin used are shown. (See table 34)

Mechanical characteristics of set pure resin (***)(Typical values)

Characteristics	*Value*	*Unit*	*Method*
HDT	95	℃	ASTM D 648
Tg	123	℃	DIN 53445
Tensile strength	81	MPa	ASTM D 638
Tensile elastic modulus	4,1	GPa	ASTM D 638
Tensile elongation	3,5	%	ASTM D 638
Barcol hardness	48	--	ASTM D 2583

(***) Catalysis: 100 g Resin + 1.50 g MEKP 50
24 hours at room temperature + 2 hours at 100℃

34. Table Resin properties. Own elaboration

1 type of fiber are selected:

- UD Fiberglass 1000gr/m2: E-glass

No mechanical data are available in the manufacturer's data sheet of the UD E fiberglass.

5.2.2 Results of the raw material characterization tests

This section shows the results of the tests carried out and according to what regulations have been made:

• Traction elastic module (UNE-EN ISO 527-4)

• Compression elastic module (ISO 14126)

• Shear elastic modulus (UNE-EN ISO 14129)

• Tensile strength (UNE-EN ISO 527-4)

• Compression resistance (ISO 14126)

• Cutting resistance (UNE-EN ISO 14129)

• ILSS (ISO 14130)

• Pin Bearing (EN ISO 13706-2)

• Fiber Volume (EN2564)

• Tg (ISO 6721)

Like the tube, the tests run for both directions. The design admissible B-value will also be used and this will be determined analogously to the tube.

For the Young and Poisson modulus values, the means obtained from the tests will be used as design values. Finally, the tests are carried out for material, quasi unidirectional fiberglass + vinylester.

The following table 35 shows a summary of the tests carried out for the material:

MATERIAL	TRACTION	COMPRESSION	SHEAR	ILSS	BEARING	Vf	Tg
QUASI UD	X	X		X	X	X	X

35. Table Test for the material. Own elaboration

With this test campaign all the necessary variables are obtained to carry out the structural simulations of the material used in manufacturing. At the design level there are one material, quasi unidirectional fiberglass. For the quasi unidirectional fiberglass, a unidirectional tape approach will be made.

The results obtained in the tests are shown in the following tables: (See tables 36,37,38,39,40 and 41)

TEST	X_T (MPa)	ν_{12}	E_{1T} (GPa)
P1-01-1	777	0.17	36.08
P1-01-2	705	0.22	34.24
P1-01-3	727	0.25	34.29
P1-01-4	745	0.22	32.08
P1-01-5	711	0.23	34.55
P1-02-1	699	0.23	33.89
P1-02-2	604	0.22	35.93
P1-02-3	653	0.21	35.82
P1-02-4	711	0.22	33.23
P1-02-5	655	0.2	34.51
P1-03-1	671	0.25	31.22
P1-03-2	701	0.27	35.51
P1-03-3	778	0.2	33.58
P1-03-4	789	0.21	36.72
P1-03-5	748	0.24	37.31
Average	709.8	0.22	34.56
Standard deviation	51.8		
Characteristic resistance	602.7		

36. Table Material 1: 0º tensile test results. Own elaboration

Tests	Y_T (MPa)	ν_{21}	E_{2T} (GPa)
P1-04-1	57	0.06	12.69
P1-04-2	62	0.09	13.76
P1-04-3	67	0.08	13.03
P1-04-4	63	0.08	12.39
P1-04-5	62	0.09	13.3
Average	62.1	0.08	13.03

Standard deviation	3.6		
Characteristic resistance	54.7		

37. *Table Material 1: 90º tensile test results*

Test	**Y_c (MPa)**	**E_{2C} (GPa)**	**ILSS (MPa)**
P2-01-4			17
P2-01-5			14
P2-01-6			15
P2-01-7			13
P2-01-8			14
P2-01-9	141	15.85	
P2-01-10	127	14.56	
P2-01-11	135	19.69	
P2-01-12	140	15.6	
P2-01-13	146	16.22	
P2-02-4			15
P2-02-5			11
P2-02-6			11
P2-02-7			12
P2-02-8			16
P2-02-9	122	15.6	
P2-02-10	140	18.61	
P2-02-11	138	18.85	
P2-02-12	132	17.78	
P2-02-13	123	18	
P2-03-4			11
P2-03-5			17
P2-03-6			15
P2-03-7			15
P2-03-8			17
P2-03-9	156	18.52	
P2-03-10	136	21.13	
P2-03-11	152	16.03	
P2-03-12	127	15.16	
P2-03-13	127	18.6	
Average	135.8	17.25	14.04
Standard deviation	10.1		
Characteristic resistance	114.8		

38. *Table Material 1: 90º compression test results. Own elaboration*

TEST	**X_C (MPa)**	**E_{1C} (GPa)**	**ILSS (MPa)**
P2-04-4			57

P2-04-5			58
P2-04-6			56
P2-04-7			51
P2-04-8			44
P2-04-9	332	35.74	
P2-04-10	282	33.21	
P2-04-11	297	34.74	
P2-04-12	398	37.08	
P2-04-13	341	36.14	
P2-05-4			54
P2-05-5			51
P2-05-6			55
P2-05-7			62
P2-05-8			54
P2-05-9	359	36.98	55
P2-05-10	326	37.15	
P2-05-11	339	36.22	
P2-05-12	300	37.6	
P2-05-13	357	36.75	
P2-06-4			60
P2-06-5			50
P2-06-6			57
P2-06-7			51
P2-06-8			50
P2-06-9	308	38.87	
P2-06-10	327	37.84	
P2-06-11	310	39.62	
P2-06-12	308	37.79	
P2-06-13	354	37.13	
Average	327.9	36.83	53.81
Standard deviation	30.1		
Characteristic resistance	265.8		

39. *Table Material 1: 0º compression test results. Own elaboration*

TEST	**$\sigma_{BEARING}$ (MPa)**
P3-01-1	347
P3-01-2	260
P3-01-3	354
P3-01-4	326
P3-01-5	289
P3-02-1	337
P3-02-2	341

P3-02-3	346
P3-02-4	276
P3-02-5	300
P3-03-1	283
P3-03-2	316
P3-03-3	296
P3-03-4	322
P3-03-5	282
Average	310.3
Standard deviation	30.0
Characteristic resistance	248.3

40. *Table Material 1: Test results pin bearing at 0º. Own elaboration*

TESTS	**$\sigma_{BEARING}$ (MPa)**
P3-01-1	210
P3-01-2	200
P3-01-3	198
P3-01-4	206
P3-01-5	195
P3-02-1	210
P3-02-2	201
P3-02-3	213
P3-02-4	192
P3-02-5	180
P3-03-1	208
P3-03-2	210
P3-03-3	210
P3-03-4	187
P3-03-5	201
Average	201.2
Standard deviation	9.6
Characteristic resistance	181.2

41. *Table Material 1: 90º pin bearing test results. Own elaboration*

The results of the fiber volume tests are shown below. These tests have been carried out in accordance with the regulations (EN2564). (See table 42)

Test	% fiber volume	% resin volume
1	55.7	44.3
2	54.5	45.5
3	56.7	43.3
4	56.3	43.7

5	57.6	42.4
6	60.3	39.7

42. Table Result of fiber volume tests. Own elaboration

The results of the Tg-onset tests are shown below. These tests have been carried out in accordance with the regulations (ISO 6721). The following table shows the results of Tg-onset according to the curing conditions. (See table 43)

Temperature (ºC)	Time (hour)	Tg-onset (ºC)
60	10	105.21
65	8	104.68
60	8	120.66
70	6	110.55
65	6	101.00

43. Table Tg-onset test results. Own elaboration

6 DESIGN AND STRUCTURAL ANALYSIS MODELS

6.1 CLOSED MONOLITHIC SHAPE

This chapter shows the structural analysis for the composite tube. This analysis will be carried out using a finite element model with the help of Altair's Hyperworks software package.

6.1.1 FEM MODEL

In this chapter the real configuration of the structure is modelled and its behaviour is analysed before the imposed loads, in order to verify its resistant capacity. For this purpose, a resistance analysis of the tube will be carried out.

In the different sections of this chapter, the necessary constituent parts for the realization of the FEM model will be exposed and later the resistance analysis will be carried out. The constituent parts of the FEM model are:

1. Mesh of the parts of which the model consists

2. Models materials

3. Contour conditions

4. Applied load

5. Loading cases

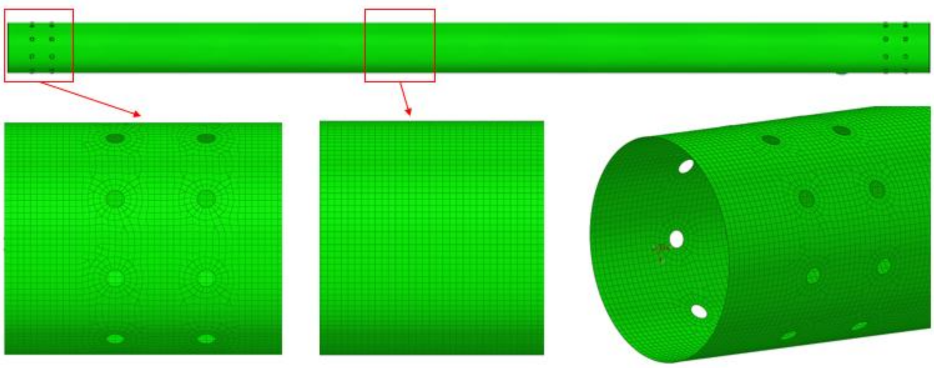
6.1.1.1 Mesh of the parts of which the model consists.

The FEM model of the tubes consists of the following parts:

- Composite tube:
- Laminate type

For the union of the tube with the structure that supports it, it has been thought that it is formed by two rows of structural rivets at each end. These rivets will join the inside face of the composite tube with a cylindrical piece of steel which will join a larger structure. The calculation of the specific joint has not been made, since a real test of union with the rivets and the laminate in question would have to be carried out.

To correctly collect the curvature of the tube and to give maximum precision to the results without penalizing excessively the calculation time, an element size of 5mm is selected. The composite tube is modelled using 2D Shell elements. Below are images of the mesh of the tube. (See image 44)



44. *Image. General views of the composite tube mesh. Own elaboration*

For the generation of the laminate, the elements that make up each of the fabrics are selected. For the death of the fabrics is considered a 5mm offset between fabrics.

6.1.1.2 Models materials

- Composite Unidirectional Carbon Fiber. This material is modelled using a MAT8 card. This card applies to orthotropic materials applied to 2D elements. The modulus of elasticity data is needed in the two directions of the plane, the Poisson's coefficient and the three shear modulus. These data are obtained from the chapter of characterization of materials. (See table 45)

Carbono UD + Epoxy (Vf = 60%)	
E1	115665 MPa
E2	8684 MPa
G12	5642 MPa
v12	0.34

45. *Table Values elastic properties of UD + Epoxy Carbon sheet. Own elaboration*

For the resistance analysis, the Tsai-Hill failure criterion will be used. For this, it is necessary to know the resistance values in the different directions, both traction and compression. The Tsai-Hill criterion consists of the following equation:

$$Tsai - Hill = \frac{{\sigma_{11}}^2}{{S_{11}}^2} - \frac{\sigma_{11} \cdot \sigma_{22}}{{S_{11}}^2} + \frac{{\sigma_{22}}^2}{{S_{22}}^2} + \frac{{\sigma_{12}}^2}{{S_{12}}^2} \geq 1$$

Where:

- S_{11}^{+} is the tensile strength in the 0º direction.
- S_{11}^{-} is the resistance to compression in the 0º direction.
- S_{22}^{+} is the tensile strength in 90º direction.
- S_{22}^{-} is the resistance to compression in the 90º direction.
- S_{12} is the shear resistance.

The value that is introduced in the criterion depends on the tensions that appear in the element, so that:

- If $\sigma_{11} \geq 0$; then $S_{11} = S_{11}^{+}$
- If $\sigma_{11} < 0$; then $S_{11} = S_{11}^{-}$
- If $\sigma_{22} \geq 0$; then $S_{22} = S_{22}^{+}$
- If $\sigma_{22} < 0$; then $S_{22} = S_{22}^{-}$

The resistance criterion will be that the reserve factor associated with the Tsai-Hill criterion is greater than 2. This translates into:

$$reserve\ factor = \frac{1}{\sqrt{Tsai\_Hill}}$$

Again, the resistance values are obtained from the tests and can be found in chapter 5. (See table 46)

STRENGHT	X1t (MPa)	X1c (MPa)	X2t (MPa)	X2c (MPa)	S12 (MPa)
	671.7	458	26.3	86.4	15.1

46. *Table UD + Epoxy carbon sheet resistance values. Own elaboration*

For the other fiber type, the same calculation criteria as the previous laminate are modelled and used.

- Composite Biaxial Glass fiber (See table 47 and 48)

Glass Biaxial + Epoxy (Vf = 60%)	
E1	28433 MPa
E2	25274 MPa
G12	4446 MPa
v12	0.17

47.

48.

47. *Table Values Elastic properties of sheet Biaxial Glass + Epoxy. Own elaboration*

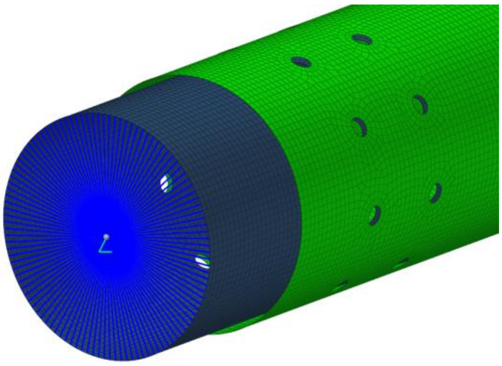
STRENGHT	X1t (MPa)	X1c (MPa)	X2t (MPa)	X2c (MPa)	S12 (MPa)
	404.3	102.4	472.3	90.7	55.72

48. *Table Biaxial + Epoxy glass resistance values. Own elaboration*

6.1.1.3 Contour conditions

For boundary conditions it is necessary to restrict the movements of the structure as rigid solid. For this, at one end of the metal bushing an RBE2 element (rigid solid) is created, which will have the centre of the circumference as independent node and the nodes of the end contour of the bushing as dependent nodes. The independent node of this RBE2 is restricted to all degrees of freedom. In this way the movement is restricted as a rigid solid of the structure.

Additionally, to ensure that the load is always introduced in the direction of the axis of the structure and does not deviate, it is necessary to introduce boundary conditions at the opposite end. The method is exactly the same as the one shown above to restrict the movement of the structure: generate an element RBE2 whose dependent nodes are the end elements of the metal bushing while the independent node is located on the axis of the structure. This independent node is restricted in all directions except the longitudinal movement of the tube, so that compression-traction can be applied, but misalignment of the structure resulting from the applied load cannot occur. (See image 49)



49. Image. Boundary conditions. Restriction of movement in extreme as rigid solid. Own elaboration

6.1.1.4 Applied load

A type load is arranged for the piece. The service / work load will be 285 KN (short-term load <3 minutes). This load will be multiplied by 1.5 to obtain the last load of the structure, Fult = 427.5 KN

The way of applying the load will be by means of a point load in the longitudinal direction of the structure applied in the independent node of the RBE2, whose longitudinal degree of freedom was not restricted. The direction of the load will vary depending on the case in question, that is, traction or compression.

6.1.1.5 Loading cases

In this analysis, 3 load cases are studied:

1) Ultimate load to compression. Static linear analysis. Verification of the strength of the structure before the required load.

2) Buckling to ultimate load compression. Linear stability analysis. Verification of the stability of the structure (no appearance of buckling)

3) Last load to traction. Static linear analysis. Verification of the strength of the structure before the required load.

6.1.2 FEM RESULTS

In this chapter we present the results obtained in the FEM analysis of the one load case studied.

For linear static load case, the following resistance analyses are carried out:

• Resistance analysis of the composite tube

The reserve factor in composite tubing must be greater than 2. For the case of linear stability, the following analysis is carried out:

• Buckling self-value. You must verify a buckling eigenvalue greater than 2.

In addition, the maximum displacements obtained in linear static load cases will be shown.

6.1.2.1 Resistance analysis. Ultimate compression load

<u>Composite tube. Laminated area type</u>

Due to the symmetry of revolution and the homogeneity of the laminate in this zone, the tensions are uniform throughout the type zone and, therefore, the reserve factor will be the same at any point.

Because it is a compression in the longitudinal direction, the most requested fabrics will be unidirectional carbon and, therefore, the critical reserve factor is found in these fabrics.

Next, the summary table 50 is shown with the reserve factors obtained for each fabric. (See image 51)

Layer	Material	Orientation	Reserve factor
1	Biaxial Glass	45	3.52
3	UD Carbon	0	2.48
5	Biaxial Glass	45	3.53
7	UD Carbon	0	2.50
9	Biaxial Glass	45	3.50
11	UD Carbon	0	2.51
13	Biaxial Glass	45	3.43
15	UD Carbon	0	2.51
17	Biaxial Glass	45	3.27
19	UD Carbon	0	2.45
21	Biaxial Glass	45	3.05
23	UD Carbon	0	2.32
25	Biaxial Glass	45	2.86
27	UD Carbon	0	2.20
29	Biaxial Glass	45	2.69

50. *Table Laminate type. Ultimate load to compression. Reserve factors of tube fabrics. Own elaboration*

51. *Image Laminate type. Ultimate load to compression. Reserve factor in critical fabric (Ply 27) Own elaboration*

6.1.2.2 Stability analysis. Ultimate compression load

In this section, the stability of the structure is evaluated globally before compression loading. In this case, the load introduced is the ultimate compression load. For the structure to meet the stability requirements, it must be satisfied that the eigenvalues resulting from the calculation are greater than 2 (Self-value 1 would mean that the load introduced is just the buckling load, then the eigenvalue greater than two would imply a reserve factor before buckling of 2).

Next, the first 3 eigenvalues obtained are shown. (See table 52)

Self-value	Value
1	6.45
2	6.59
3	7.14

52. Table Stability. Ultimate load to compression. Eigenvalues. Own elaboration

Composite tube. Laminated area type

Due to the symmetry of revolution and the homogeneity of the laminate, the tensions are uniform throughout the type zone and, therefore, the reserve factor will be the same at any point.

Because it is a compression in the longitudinal direction, the most requested fabrics will be unidirectional carbon and, therefore, the critical reserve factor is found in these fabrics. Next, the summary table is shown with the reserve factors obtained for each fabric. (See table 53 and image 54)

Layer	Material	Orientation	Reserve factor
1	Biaxial Glass	45	5.38
3	UD Carbon	0	3.66
5	Biaxial Glass	45	5.39
7	UD Carbon	0	3.68
9	Biaxial Glass	45	5.41
11	UD Carbon	0	3.70
13	Biaxial Glass	45	5.42
15	UD Carbon	0	3.72
17	Biaxial Glass	45	5.42
19	UD Carbon	0	3.57
21	Biaxial Glass	45	5.43
23	UD Carbon	0	3.37
25	Biaxial Glass	45	5.43
27	UD Carbon	0	3.18
29	Biaxial Glass	45	5.30

53. Table Ultimate load to traction. Factors of reserve the fabrics of the tube in laminated zone type. Own elaboration

54. *Image Ultimate load to traction. Reserve factor in critical fabric (Ply 27). Own elaboration*

6.1.2.3 Summary of results (See table 55)

LOAD CASE	ZONE	MINIMUM RESERVE FACTOR
COMPRESSION	LAMINATE TYPE	2.20
BUCKLING COMPRESSION	GLOBAL	6.45
TRACTION	LAMINATE TYPE	3.18

55. *Table Summary of results. Own elaboration*

6.2 OPEN SANDWICH SHAPE

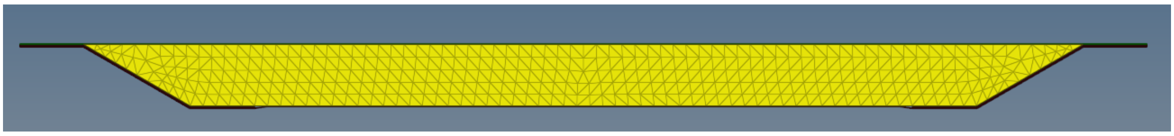
6.2.1 FEM MODEL

In this chapter the real configuration of the structure is modelled and its behaviour is analysed before the imposed loads, in order to verify its resistant capacity. For this purpose, a resistance analysis of the panel sandwich will be carried out.

6.2.1.1 Mesh of the parts of which the model consists.

The FEM model of the panel consists of the one only part.

To correctly collect the corners and chamfers of the panel and to give maximum precision to the results without penalizing excessively the calculation time, an element size of 5mm is selected just like the one selected for the case of the tube. The composite sandwich panel is modelled using 2D Shell elements. Next, meshing images are shown. (See image 56)



56. *Image Panel sandwich mesh. Own elaboration*

6.2.1.2 Models materials

- Composite Unidirectional Glass Fiber. This material is modelled using a MAT8 card. This card applies to orthotropic materials applied to 2D elements. The modulus of elasticity data is needed in the two directions of the plane, the Poisson's coefficient and the three shear modulus. These data are obtained from the chapter of characterization of materials. (see tables 57, 58 and 59)

Elastic value of composite	E_X (MPa)	E_Y	G_{xy} (MPa)
	34560	13030	4460

57. *Table Composite panel values. Own elaboration*

Strenght values of composite	σXX traction (MPa)	σYY traction (MPa)	σXX compression (MPa)	σYY compression (MPa)	IPSS (MPa)	ILSS (MPa)
	600	55	-260	-115	55	40

58. *Table Strenght values panel composite. Own elaboration*

Core strenght values	Main variables of influence	E Foam (MPa)	Requirement τ (MPa)	Compression requirement σ (MPa)
	Foam	65	0,5	-0,8

59. *Table Foam properties. Own elaboration*

6.2.1.3 Contour conditions

The contour conditions of the panel differ to the case of the tube. In this case, two lines of nodes are fixed at the monolithic ends of the panel. This line of nodes only has vertical movements impeded, that is, it is as if the piece was supported by its monolithic parts and with a load on it that prevents it from moving in z. If you can move in the other axes.

6.2.1.4 Applied load

As loads, two types will be used:

- Limit state of service, where the maximum admissible arrow will be verified. By regulation for elements of this type is set at l / 200. Being l = 1.6 meters, the maximum allowable arrow is 8mm. The load to be supported by the element will be 750 Kg / m2.

- Last load to bear. It is estimated that the service load is increased by a coefficient of 1.5. In this case it is 1125 Kg / m2.

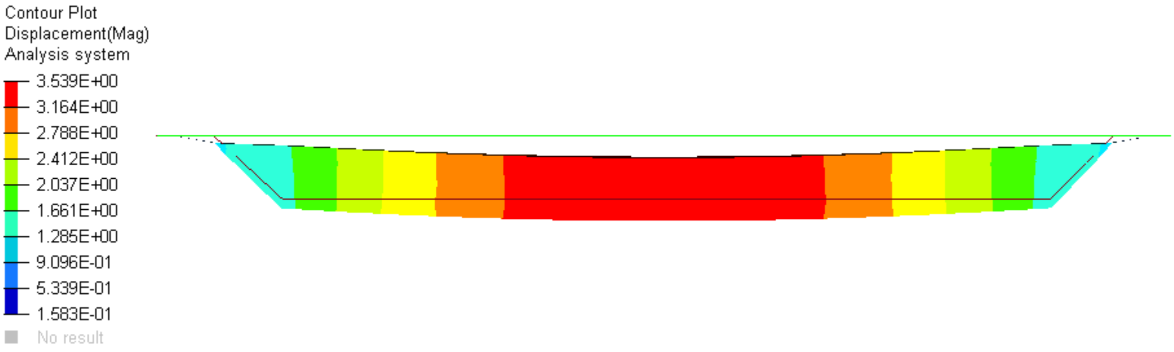
6.2.2 FEM RESULTS

This chapter describes the results obtained in the FEM analysis of the load cases studied. For linear static load cases the following resistance analyses are performed: (See table 60 and image 61)

- Panel resistance analysis

LIMIT STATE OF SERVICE			ULTIMATE LOAD	
CASE	**WEIGHT**	**DISPLACEMENT**	**COMPOSITE RESERVE FACTOR**	**FOAM RESERVE FACTOR**
CASE 1	29.75 Kg	3.6 mm	5.4	2.94
Load		750 Kg /m2	1125 Kg / m2	

60. *Table FEM RESULTS. Own elaboration*



61. *Image Panel vertical displacement. Own elaboration*

As can be seen in the table 60, the piece with this laminate fulfils both last load requirements and service limit state requirements.

7 PROTOTYPES MANUFACTURING

Once the materials, part design, material characterization and FEM simulation have been defined, the manufacture of both parts is carried out.

7.1 CLOSED MONOLITHIC SHAPE

7.1.1 Preparation of mould and auxiliaries

The first operation to be performed will be the internal cleaning of the mould, as well as the fixing plates that are part of it, membranes and all auxiliary accessories that are part of the manufacturing process.

Once clean and dry all these elements will be applied with a clean rag, five layers of mould release to the mould, as the system of auxiliary accessories, in those areas that will be in contact with the piece to be laminated. Allow a minimum of 10 minutes to dry between layers of release agent.

7.1.2 Lay-up

Before the lamination (See image 63), the fabric patterns are prepared.

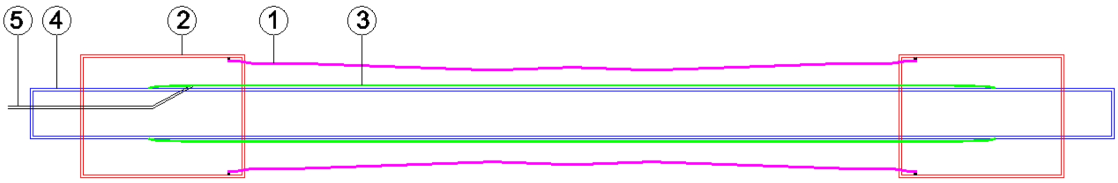
To help the lamination, we use a tool composed of several elements:

- Metal tube: It helps us to maintain the longitudinally and rigidity of the laminate

- Metal bushes: They help us to the lay-up and later to centering laminate in the mould by the end

- Plastic mandrel: It serves to help the rolling action. It is inflated like a camera and offers a consistency to wind the fabric

- Vacuum bag: It is sealed by the inside of the metal cap and is responsible for maintaining the vacuum in the laminate to perform the infusion (See image 62)



62. Image Diagram of tool for laminate. 1-infusion bag; 2-metallic cap; 3-mandrel; 4-Metal profile; 5-air inlet pressure. Own elaboration

On this previous tool, elements with this order are rolled up:

1-Infusion mesh; 2-Peel ply; 3-Biaxial Glass; 4-UD Carbon fiber; 5-Biaxial Glass; 6-UD Carbon fiber; 7-Biaxial Glass; 8-UD Carbon fiber; 9-Biaxial Glass; 10-UD Carbon fiber; 11-Biaxial Glass; 12-UD Carbon fiber; 13-Biaxial Glass; 14-UD Carbon fiber; 3-Biaxial Glass; 15-UD Carbon fiber; 16-Biaxial Glass; 17-UD Carbon fiber; 18-Biaxial Glass; 19-Peel ply ; 20-Infusión mesh (See image 63)

63 Image. Carbon lamination and final peel ply and infusion mesh. Own elaboration

7.1.3 Positioning in mould, closure and infusion

Next, place the laminated piece on the mould, ensuring that the end of the laminate reaches the end of the mould. We proceed to remove the lay-up tool aid from the inside of our tube. (See image 64)

64. *Image Lamination on tool.*

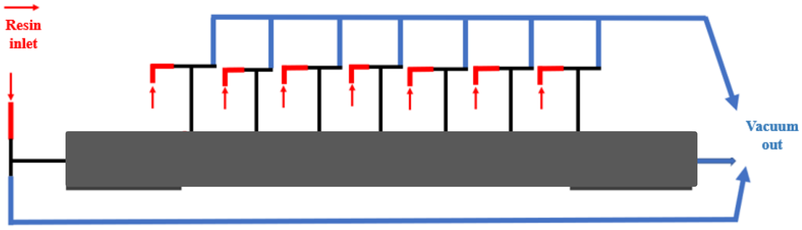
The upper part of the mould is placed, paying special attention so that the laminate is not pinched between both parts. Lower the mould by matching the 4 threaded rods that serve as a guide. Once closed, place the two centering diagonally (one at each end) and tighten the mould closing screws. The centering are removed.

We place the bushings that ensure the centricity of the bushing with respect to the mould and the tube and ensure that both bushes share the same axis.

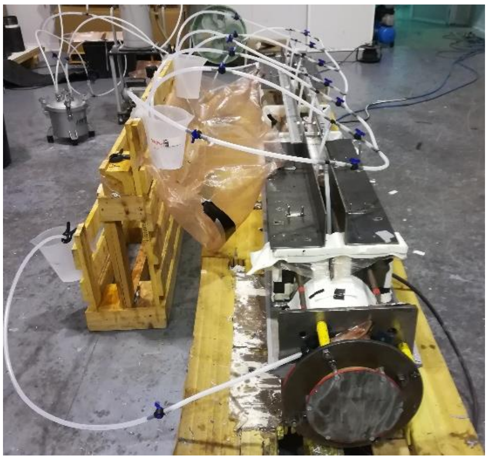
Finally, the mould is closed at the ends with the help of these clamping plates. Before starting the infusion, two vacuum bags (one at each end) must be made, which will be our resin inlet and outlet.

All the joints of the mould will be sealed with sealing putty to avoid loss of vacuum.

As explained in chapter 3 (See image 65), a progressive infusion strategy has been developed with 8 resin inlets and 9 air outlets. The air outlets close as the resin reaches that point. The exits do not open until the minimum resin volume that must have passed up to that point is assured. Before starting, vacuum is made with all open vents except the first one. It is checked that the vacuum is below -0.9 bar and stabilized when the vacuum is cut off for 5 minutes. Once this is verified, the infusion is carried out. (See image 66)



65. *Image. Tube infusion strategy. Own elaboration*



66. *Image Infusion process.*

The consumption of resin for each entry must be the following (See table 67):

Entry Nº	1	2	3	4	5	6	7	8
Quantity gr	2.100	1.905	1.905	1.905	1.905	1.905	1.905	2.100

67. *Table. Resin quantities for entry (grams). Own elaboration*

The times to which the resin entrance opens have been (see table 68):

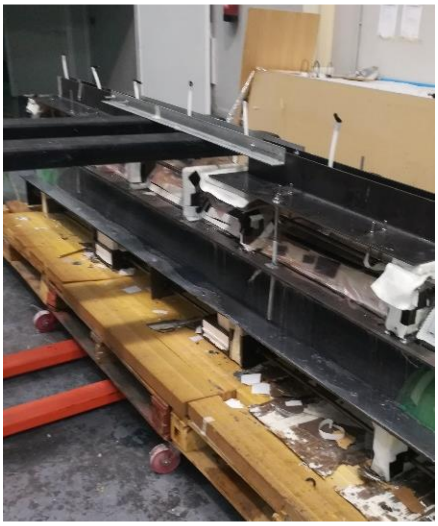
Entry Nº	1	2	3	4	5	6	7	8
Time (minutes)	0	8	25	38	55	71	90	118

68. *Table Times resin entries. Own elaboration*

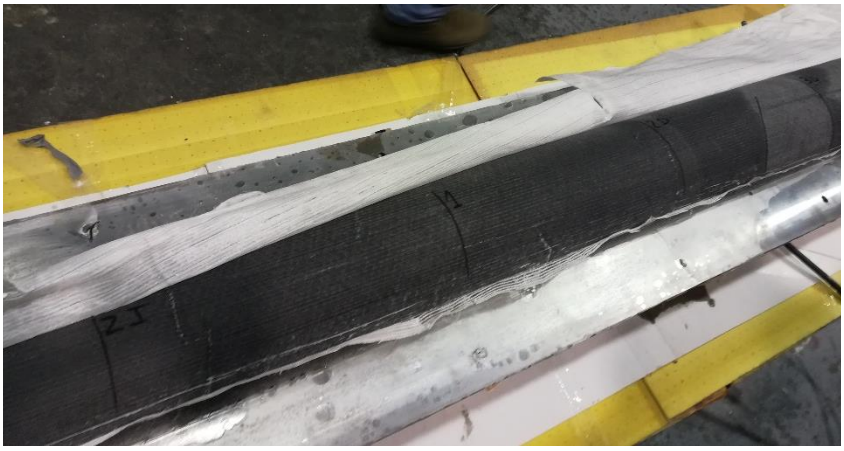
The infusion ends at 135 minutes. Once finished, all vents are opened (this is done to let out the excess resin when the mandrel is tightened), and 2.5 bars of pressure is applied with the inner mandrel and the compaction bags at the ends.

The curing is carried out with the mandrel pressure, for 16 hours at 60 ° C.

Once the curing time is completed, and the mould at room temperature, the piece is removed from the mould. (See images 69 and 70)



69. *Image Demoulding*



70. *Image Demoulding part 2*

7.2 OPEN SANDWICH SHAPE

7.2.1 Preparation of mould

For this type of piece, the preparation of useful is much simpler, since it is only the preparation of a flat surface, smooth and without pores or holes. Like the tubular piece, the tool will be cleaned and 5 layers of release agent will be applied with a layer to layer separation of approximately 10 minutes.

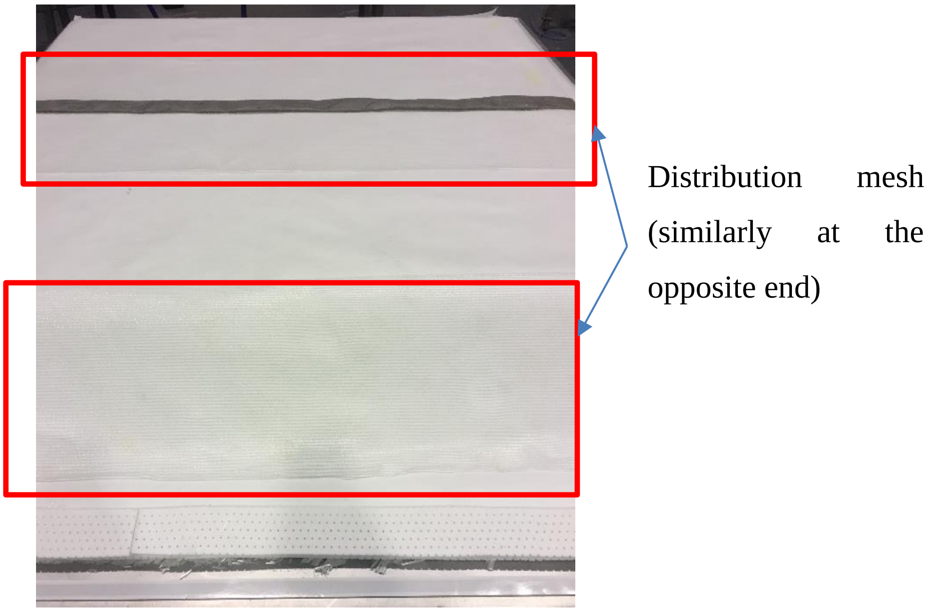
7.2.2 Lay-up

Before starting the lamination, all the layers of fiber must be previously cut in patterns and properly identified. In this case, in addition to the fiber, the inner foam has to be cut, both in size and in the realization of the chamfers with the corresponding angle.

The laminating (see image 71), in this case is also simpler than in the case of the tubular piece, because the lamination is made directly to the mould and this being a flat surface. The rolling sequence will be carried out according to chapter 3.

71. *Image Lay-up sandwich panel*

Once the installation of glass fiber sheets has been completed, the infusion aids must be placed. First, the peel-ply is placed. On this, the resin distribution mesh is placed. This must be placed only on specific sites, since the core has grooves on both the top and the bottom. The network will be placed in the central part just below the distribution channel (diadrain) to eliminate air from the entrance, and at the end of the foam continuing through the monolithic part of the laminate. (see image 72)



72. *Image Panel sandwich. Location distribution mesh*

Once placed red and peel ply the fabric is placed aerator of the ends (for the vents), and the bag is sealed with sealing putty at the edges.

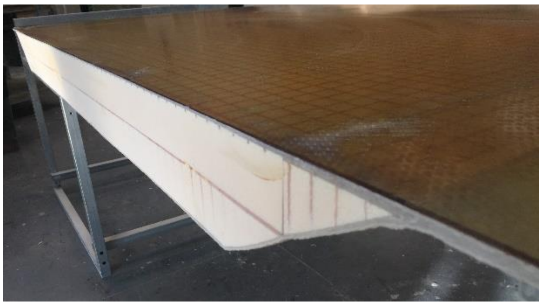
7.2.3 Infusion

Like the tube, it is checked that the vacuum is below -0.9 bar and stabilized when the vacuum is cut off for 5 minutes. Once this is verified, the infusion is carried out. (see image 73)

73. *Image Infusion strategy panel sandwich*

The central resin inlet is opened and the resin is distributed through the channel (diadrain). It is divided into two resin fronts that are balanced with each other and almost parallel to the entrance channel. The infusion is done in 45 minutes, with the resin consumption of 12.1 Kgs of resin. Once this is finished, the resin inlet is cut and the piece is cured with vacuum for 8 hours at 60 ° C. (See images 74 and 75)

74. *Image Final cured part*



75. *Image Final cured part. Lateral section*

8 GENERAL DISCUSSION OF RESULTS

8.1 CLOSED MONOLITHIC SHAPE

The results of weight and volume of resin fiber of the tube are shown below. As you can see, the final weight of the piece approximates its theoretical weight but is 940 grams below. This affects its fiber-resin volume, which is finally 62.24-37.76% respectively (the theoretical volume was 60-40%). Even so the proportion obtained can have good mechanical properties and has had good impregnation. (See table 76)

The resin delay may be due to the fact that when the pressure mandrel exerts 2 bars, the resin tends to exit through the vents. It can also be due to the loss of vacuum at some point which causes the resin to escape where the air leak is located.

			theoretical		Real	
Part real Weight (Kg)	**Part theoretical Weight (Kg)**	**Fibre weight real (Kg)**	**Fiber volume (%)**	**Resin volume (%)**	**Fiber volume (%)**	**Resin volume (%)**
25.16	26.1	15.66	60	40	62.24	37.76

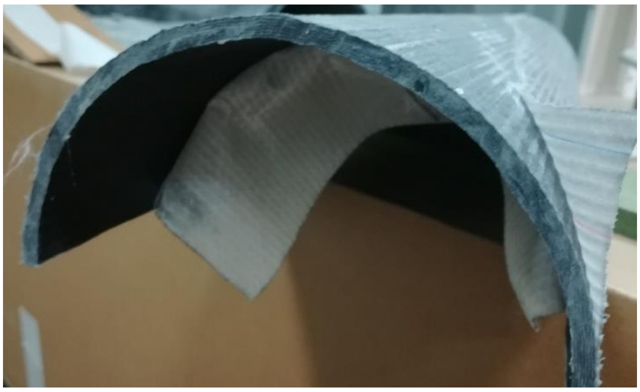
76. Tube results (volume fibre-resin; weight. Own elaboration

Regarding the infusion time of the piece, the real time exceeds the calculation time by 23 minutes. This can be due to numerous factors among which can be due imperfections of the laminate and its auxiliaries, vacuum losses that decrease the speed of the resin front flow, resin temperature (depending on the temperature can increase or decrease its speed). (See table 77)

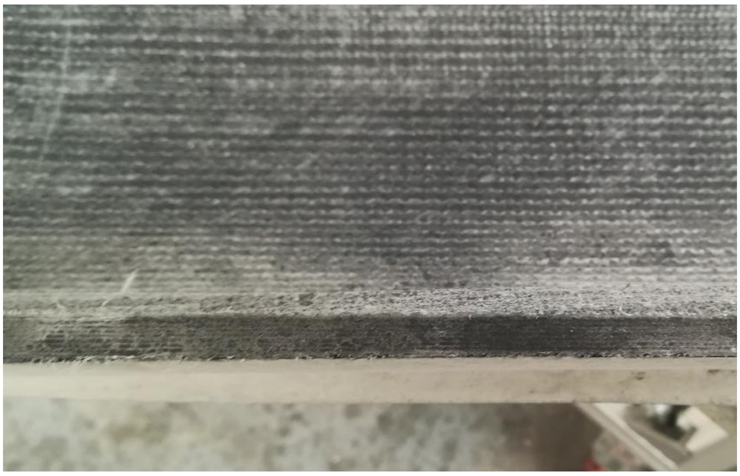
Infusion real time (min)	Infusión theoretical time (min)
135	112

77. Table Infusion times tube. Own elaboration

Cuttings are made in the piece both longitudinally and transversally to be able to observe if there are dry areas or delamination. As can be seen in both cuts, the laminate seems to have no resin-free parts and good laminar compaction. (See tables 78 and 79)

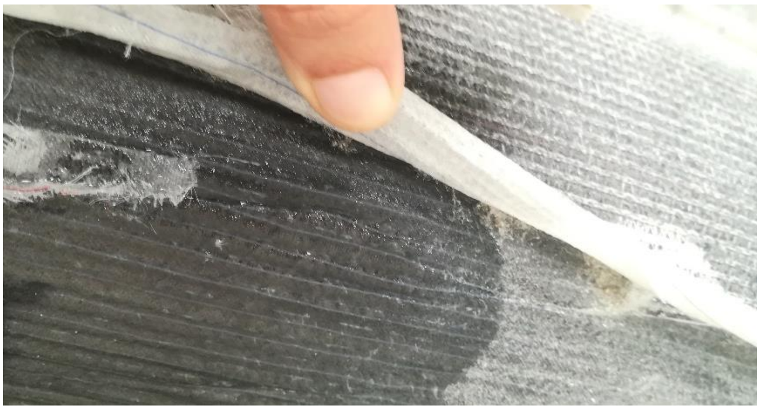


78. *Image Cross section*



79. *Image Longitudinal section*

There are both outer and inner surface parts that have folds of cloth. These folds are due to lamination imperfections. The diameter of dry rolled tube was greater than that of the mould itself, with which the fabric wrinkled in some points to be introduced into the tool.



80. *Image Superficial folds*

Observing at the surface, compaction and fiber volume results, it can be deduced that the laminate can meet the mechanical requirements calculated by FEM simulation. A suitable compaction and impregnation is observed with the naked eye and except for the folds, the fiber orientation has not deviated from its initial composition. (See image 80)

The auxiliary materials used for the process have not had a high cost and the time spent (except for improving the rolling), could be suitable to carry out this piece in series. The infusion-impregnated process could always be improved by introducing resin with the help of a resin injector. It eliminates resin preparation times and reduces mould impregnation times

8.2 OPEN SANDWICH SHAPE

In the lower tables (See table 81), as in the case of the tube, the weights of fiber, foam, piece and fiber-resin volumes obtained are presented. In this case, the volume of theoretical versus real fiber-resin, differ in opposite way to the case of the tube. In this case the volume is 54.2-45.78%, with which there is an excess of resin in the piece. In principle we should not worry too much as it approaches the theoretical percentage and because the foam was grooved and a lot of resin is in these channels. In addition, the foam absorbs resin since it is a porous material. To get a more accurate fiber-resin volume, it would be necessary to take several witnesses from several zones and remove the foam and resin from the channels.

				theoretical		Real	
Part real Weight (Kg)	**Foam Weight (Kg)**	**Part theretical Weight (Kg)**	**Fibre weight real (Kg)**	**Fiber volume (%)**	**Resin volume (%)**	**Fiber volume (%)**	**Resin volume (%)**
35.26	13.2	33.13	11.96	60	40	54.22	45.78

81. *Table Panel results (volume fibre-resin; weight). Own elaboration*

As for the infusion times, the actual impregnation time is reduced by 10 minutes with respect to the simulation time. This reduction is due to the fact that in the simulation the grooves / channels of the core were not considered, nor the perforations, which distributed the resin more quickly and achieved the rapid impregnation of the fabrics. (See table 82)

Infusion real time (min)	Infusión theoretical time (min)
45	55.6

82. *Table Infusion times panel. Own elaboration*

On the upper surface of the panel, at the upper corners of the chamfer, since these are angles or concave surfaces, these are conducive to creating lamination folds when vacuuming the piece (See image 83). These wrinkles are impregnated and remain as superficial folds in positive. These folds negatively affect the correct transmission of stresses in the fiber due to the misalignment of these, and in addition to an accumulation of resin that causes its mechanical properties to decrease. In order to correct this, a profile or membrane with the same shape that would act as a gripper should have been placed in these corners to avoid "cloth clamping".

83. *Image Superficial folds*

A cut is made in the piece so that the core-laminated interface and the corner of the chamfer can be observed. The compaction of the fibers and the impregnated one seems correct and no cavities of air without resin or delamination are observed. In addition, the channels or perforations of the core are also observed well filled with resin. (See image 84)

84. *Image Panel section*

Due to the raw material and auxiliary materials used, the manufacturing cost is relatively inexpensive. The process itself could have improvements to adapt this process to manufacture long series as introduction of resin injection machines to shorten impregnation times, as well as use of reusable silicone membranes instead of vacuum bag.

9 CONCLUSIONS

The introduction of composite materials in the construction and infrastructure sector is increasing. There is an increasing demand from the industry for materials that have better mechanical properties and that reduce costs both in the construction phase of the building and in its useful life (maintenance). Characteristics that we have seen that gather these materials and that place them in the best placed materials to unseat some traditional materials in the future.

The variety of fibers, resins, fillers, offered by the market, means that the designer or architect can have a wide range to cover the specific needs for each application. In addition, there are already many companies specialized in the design and manufacture of composite materials, which offer the sector the possibility of making almost any design for any final application, selecting the materials and the ideal manufacturing system. In addition, there are more and more tools that simulate the loading conditions and the mechanical properties of the piece (FEM) or resin infusion processes (SIMULATION).

In this work you can see the mechanical properties obtained by the materials, their design process and the manufacture of the final piece. VARTM processes offer these mechanical properties and are therefore possible to be a manufacturing process aimed at the manufacture of large parts for the construction sector due to their low cost- high mechanical properties. These costs could still be adjusted more with manufacturing improvements, such as the use of reusable membranes (in elements of high production rate), heating moulds, resin injection machines (to reduce manufacturing times).

However, there are several important drawbacks where composite manufacturers have to work. In the short term, improve the resistance of these materials against the effect of fire. Although there are already several products (fillers, skin coats) to meet these fire requirements, they have not yet achieved that the composite materials have sufficient mechanical capacity to withstand high temperatures, which makes these materials relegated to the background. structural or applications where fire is not a requirement.

In the long term, one of the problems that these materials have, especially those made with thermosetting resins, is their recycling. Currently, there is more regulation in the construction sector about the recycling of environmental impact and life cycle evaluation of materials. Due to the environmental impact that the extraction of materials generates in the environment, and the possible lack of resources in the future, new regulations are being implemented in Europe and the world aimed at depositing used materials that can be reused in the sector. construction, even if they are secondary elements.

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