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ESEIAAT

TFG FINAL REPORT

TFG TITLE: Study of the fabrication of a monocoque structure with composites

STUDIES: Bachelor's degree in Aerospace Vehicles Engineering

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List of Acronyms

AC	Aerodynamic centre
CG	Centre of gravity
CTE	Coefficient of thermal expansion
δ	Displacement
E-glass	Electrical fibre glass
F	Force
GFRP	Glass fibre reinforced polymer
HDT	Heat deflection temperature
HTV	High temperature vulcanization(*)
I+D	Innovation and development
IBM	International Business Machines
LE	Leading edge
LITEM	[Catalan] "Laboratori d'innovació tecnològica d'estructures i materials"
OWA	Ordered weighted average
P1	Prototype 1
P2	Prototype 2
P3	Prototype 3
P4	Prototype 4
PAN	Polyacrylonitrile
PMI	Polymethacrylimide
PU	Polyurethane
PVA	Polyvinyl alcohol
RTM	Resin transfer moulding
RTV	Room temperature vulcanization(*)
S-glass	Structural fibre glass
TE	Trailing edge
TFG	[Catalan] "Treball de fi de grau"
T_g	Glass transition temperature
$T_{service}$	Service temperature
UV	Ultraviolet
WWII	World War II

(*) Vulcanization: it is an old name for cross-linking still used occasionally. [24]

Acknowledgements

I would like to thank a number of people who helped me a lot during the development of the project. To all Trencalòs Team colleagues for the support, specially to Miguel Pareja for the countless hours spent in the workshop and to Roger Serra for his implication that usually overtook the relation of mentor-student.
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Furthermore, I really thank to the Mechanical Department of the ESEIAAT for ceding the workshop where the Trencalòs' members work.
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1 Introduction

1.1 Aim

The aim of this TFG is to realise an analysis of the different methodologies that can be used while manufacturing a monocasque structure. Furthermore, this analysis is being used to fabricate specimens which would allow the evaluation of the production's viability and the specimens behaviour.

1.2 Scope

- To identify different manufacturing processes.
- Analysis of the most interesting manufacturing processes for Trencalòs.
- In-depth analysis of the chosen process that will be developed.
- Manufacturing of a prototype to get used to the chosen methodology.
- Manufacturing of two specimens following the same methodology in order to be tested.
- Manufacturing of a last specimen where the enhancements learned during the previous tasks will be introduced.

1.3 Requirements

- Only carbon, glass and aramid fibres will be considered because they are the most frequent and the delivery time, in case of running out of material, is assumable.
- According to the structural concept design of Trencalòs, the structure of the wing must be a monocoque made of composites and the thermosetting polymer used as matrix in the final parts must be epoxy, which is widely used for composites and has better mechanical properties than polyester resin.
- According to UNE EN 2374, the place of work must be:
  - Illuminated
  - Properly ventilated
  - It must be at a temperature between 15 and 30ºC
  - It must have a relative humidity between 30-75%

1.4 Justification

1.4.1 Identification of the need

In a general vision, the evolution of the industry and, especially, Aerospace industry has made the composites technology familiar to anyone, related or not to engineering manufacturing processes. In Aerospace industry, the development of composite technology has been focusing the I+D of the sector. The usage of such materials allows the industry to reduce fuel consumption, to improve efficiency and to reduce direct operating costs of aircrafts. Furthermore, to achieve economical aircraft designs, investigations of light-weight and high-temperature resistant composites materials are being developed. These investigations will also precede the next generation of high-performance aircrafts.

Composites are also used because of its good tensile strength and resistance to compression, what provides a structural strength similar to metallic alloys, but at a lighter weight –which leads to improve fuel efficiency and performance.
Having a historical view, anyone realizes that composites are a new technology. Although fibreglass is being used in aircrafts (the first one was the Boeing 707) since 1950s, until the last years, the industry has not bet the future to these materials. As can be seen in the figure 1.1, the use of composites in aviation have been growing, especially in the last 25 years. [20]

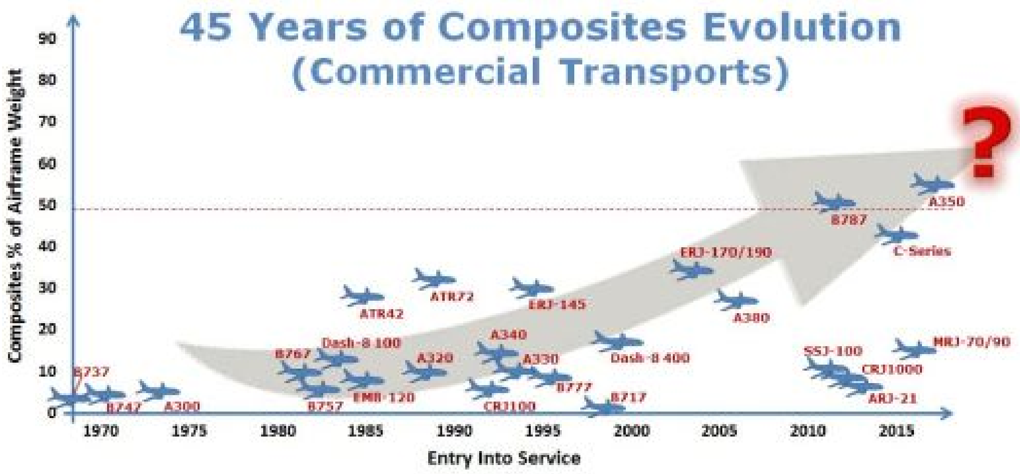


Figure 1.1: Evolution of the usage of composites in aviation. [11]

For example, only 2% of Boeing 707 (1957) weight was composites, a 12% of Boeing 777 (1994) and a 50% of 787 Dreamliner (2009), as can be seen in figure 1.2. [20]

Airbus A350-900 XWB has a similar composition, as can be seen in figure 1.3.

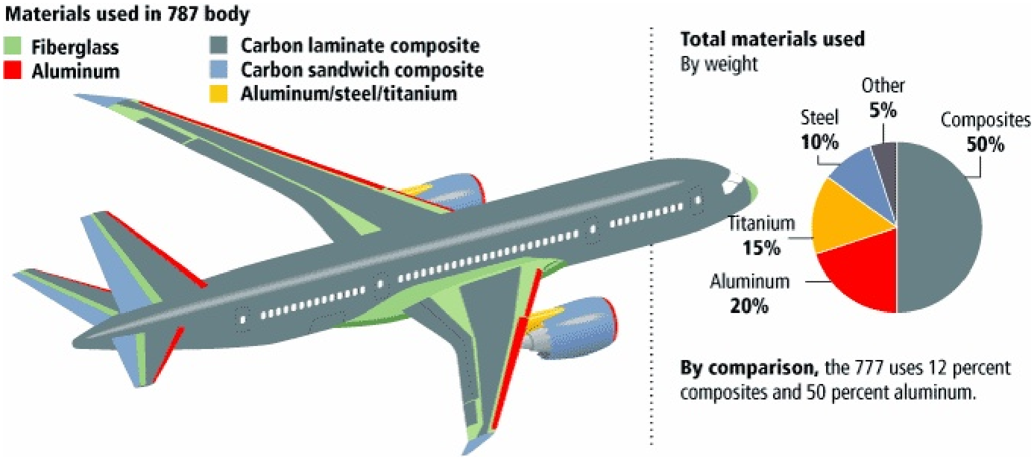


Figure 1.2: Use of composites in Boeing 787 Dreamliner. [4]

Figure 1.3: Use of composites in Airbus A350-900 XWB. [12]

What can also be seen of figures 1.2 and 1.3 is that the use of composites is not focused to a zone, as it was in previous years. Nowadays, composites are used in the whole aircraft thanks to the wide range of properties than researchers can get by modifying the composition and investigating the manufacturing processes. For the following years, new nature composites will be developed, such as ceramic matrix composites, spider silk fibres or hybrid composite steel sheets.

But, the rising use of composites requires an improvement of the manufacturing processes, where most of the difficulties may appear. Due to the complex nature of the material, it is difficult to accurately model the performance of composite-made part by computing simulation during a design phase. Then, when manufacturing them, composites are often layered on top

of each other for added strength, but this complicates the pre-manufacture testing phase, as the layers are orientated in different directions, making it difficult to predict how they will behave when are tested.
Although these difficulties, the manufacturing industry of composites are improving the results by using several manufacturing processes, lamination types and resins.

Finally, the principle disadvantage of composites is that they are new and expensive. This high cost can be related, among others reasons, to the well thought-out and intricate manufacture.
To conclude this general overview, most efforts of I+D in Aerospace industry are focused in improve the manufacturing processes.

Particularity, this study has been surged from the need of Trencalòs Team of improving the current manufacturing methodology to enlarge our know-how in radio-controlled aircrafts construction.
Trencalòs Team's conceptual design of the structure is a monocoque build with composites. This kind of structure are characterized by its closed profile and the high strength of its skin. The monocoque structure, as it is closed, give a proper response to torsion moment and, thanks to its skin, bending moment too.
Furthermore, it is possible to reach high isotropic composites by using long continue fibre laminates in different directions. What this characteristic can finally allow, faced with a determined effort applied to the compost product, is to distribute this effort in any possible direction between the matrix and the reinforcement.

1.4.2 Usefulness of the study

Commercial companies are investing huge amounts to improve the technology of manufacturing. But few of the listed processes in the state of art (section 2) fit with a low-budget project, for example Trencalòs' or LITEM's.

This project born to satisfy the need of new and advanced manufacturing processes for the radio-control aircrafts that Trencalòs design and build. This new manufacturing process will allow the Team to achieve a reduction of weight and an improvement in the performance. Up to now, Trencalòs used to build its aircrafts with low-density polymers, such as *Porexpan* or *Rohacell*[1], or balsa wood with localised composites reinforcements.

[1] An Evonik's material with very low-density and a wide range of properties.

By investigating in this methodology, Trencalòs is looking for a lighter structure that would let the Team to progress.
After a previous investigation done by the Team, it has been decided to consider only epoxy resin as matrix due to it is thoroughly used and its properties are considered to be the appropriated. It has also been decided to investigate which is the best fibre of the three most common fibre: carbon, glass or aramid.

With this TFG, this investigation goes a step further and, its main goal, has been the choice of a process that had been later executed. The criteria of election have been a good ratio between usefulness and cost (using the LITEM's technology). For that reason, this work pretends to be useful to anyone with a minimum of technology, thinking on projects' as Trencalòs or amateur groups.

1.5 Study's approach

To reach the purpose of the TFG is really important to fulfil some intermediate objectives that will mark the path that will be followed. This section does not pretend to be a preamble of the planning, it is just expected to give an slight impression of what is needed to be performed during this TFG.

Firstly, an in-depth research is really important to be able to plan all the processes. So many questions have to be answered with the data obtained from this research: What industrial processes can be performed within our possibilities? Which fibres can be used and which are their characteristics? Which are the properties of the matrix? How have to be manufactured the mould? Which are the key points to performed the best possible mould? Which products may be used to release the part from the mould? Which is the methodology to accomplish with the proper result in a final part? How can be different parts unified? All these doubts, and more that will surely appear during the research, will be answered with data and have to be sum-up before the start of the practical work.

These practical work will start preparing the plug to manufacture a mould with a good quality, which will allow the minimum hand-sand process in the mould. After the plug preparation, the mould must be manufactured and, following with the planning, the specimens will be also fabricated.

Once to this point, advantages and disadvantages of the chosen approach must be expanded.

On one hand, the advantages of this approach are the possibility of enlarging the study with practical experiences, which can be carried out in the university environment.
On the other hand, most of the information available on the net is about commercial industrialised processes. So that, an important time will be spent seeking semi-amateur data or adapting these professional methodologies to our resources.

Finally, the critical tasks are the following:

1. Build a mould that can be easily manufactured with a good superficial finish. This is important to achieve good specimens during the practical part of the work.

2. The lack of practise with the methodology can slow down the first specimen manufacturing, where the possibility to repeat the experience several times is token into account. This mishap may drag out the study, but manufacturing times are planned to absorb these circumstances that usually appear in practical procedures.

2 State of the art

The development of the state of the art has been done in order to deeply analyse and evaluate the current state of manufacturing processes that are being performed.

Many procedures can be listed: hand lay-up, pre-preg[2] forming, pressure moulding, vacuum bagging, filament winding, pultrusion, spray method, sheet moulding, bulk moulding, resin transfer moulding and, a new variation of the last one, vacuum assisted resin transfer moulding. In table 2.1, it is possible to find a comparison between them.[21]

As the elected process must fit into either Trencalòs and LITEM environment, it will be necessary to adapt some of the previous procedures to our possibilities. This is necessary because most of them use advanced machines.

Continuing analysing the manufacturing methodologies, it has been realised that the processes will depend on more parameters, such as lamination, resins and moulds.

This TFG would work on the concept of monocoque which is a structural approach whereby loads are supported through an object's external skin. The technique may also be called structural skin. In this kind of structures, longitudinal tension and compression loads are carried by the fibres, while the matrix distributes the loads between the fibres in tension and stabilizes and prevents the fibres from buckling. A sum-up of the loads carried by each one can be seen in table 2.2.

Talking about lamination concepts, it will define the behaviour against an effort and what is really important is the orientation of the fibres. If all the fibres are aligned (unidirectional lay-up), the structure would have high-strength to efforts in the fibres direction, but low resistance to others. On the other hand, a quasi-isotropic lay-up can be laminate (alienation of fibres: 0/45/-45/90). In this case, the structure carries equal loads in all four directions. To exemplify the fibres' orientation, see figure 2.1.

Other parameters can be important, such as the number of layers or the core (if it is a sandwich structure). These parameters will depend on the application. Furthermore, fibres are used to provide strength and stiffness. Some data about fibre's material are exposed in table 2.3.

The difference between carbon and graphite will be exposed. On one hand, carbon has,

[2]Pre-impregnated composite fibres where a matrix material, such as epoxy, is already present.[8]

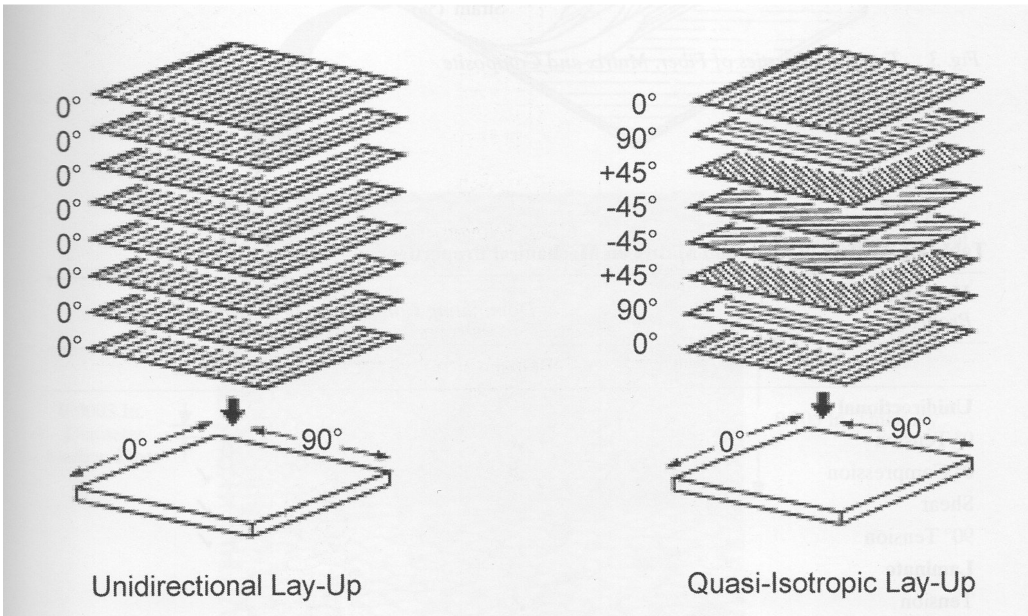


Figure 2.1: Unidirecttional and quasi-isotropic lay-up.[16]

approximately, 95% C and it has been carbonized at 980-1480ºC. On the other hand, graphite has a 99% C and it has also been carbonized but, then it has been graphitized at 1980-3040ºC [16]. After this short detail, in table 2.4 the materials have been chosen depending on the sought mechanical property.

Matrices are important for the protection from abrasion, transferation of loads between fibres and interlaminar shear strength. The most prevalent thermoset[3] resins used for composites matrices are presented in table 2.5.

Matrices for polymeric composites can be either thermosets or thermoplastics[4]. Thermosets resins usually consists of a resin and a compatible curing agent. Some consideration about a resin system must be taken in mind:

- Service temperature required for the part. T_g[5] is a good indicator. A practical rule says that $T_g = T_{service} + 100\ ^{\circ}F$.[16]
- The higher the temperature performance required, the more brittle and less damage tolerant the matrix.
- Toughened thermoset resins are available but are more expensive and their T_g's are typically lower.

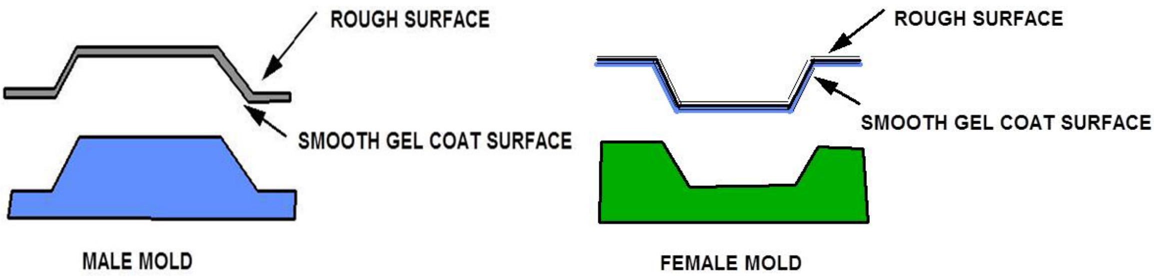
[3]It is a prepolymer material that cures irreversibly. The cure may be induced by heat, through a chemical reaction or suitable irradiation.[13]

[4]It is a polymer that becomes pliable or moldable above a specific temperature and solidifies upon cooling.[13]

[5]Temperature where a polymer changes from a rigid glassy solid into a softer, semi-flexible material. At this point, the polymer structure is still intact but the cross-links are no longer locked in position.[16]

- High-temperature resins are also costlier and more difficult to process.
- The following factors should be considered: pot-life or working life, shelf life, viscosity and cure time.

To conclude with the state of the art, moulds will be introduced. There are male and female moulds (see figure 2.2).



(a) Male (b) Female

Figure 2.2: Differents types of moulds.[6]

On one hand, a male or positivity mould is the cheapest, it is quicker to construct, but the part is fabricated over its outer surface –which will produce a rough outer surface that requires laborious finishing.
On the other hand, a female or cavity mould is costlier, but offers numerous advantages for medium to large production runs. Every part emerges with a smooth outer surface. Furthermore, this type of mould lends themselves to use with core materials because the outer skin is always smooth regardless of how inconsistently the core is used inside the part. Finally, if liquid resins are used, it is also recommended to use female moulds.
Although these differences, a process may need both types, such as compression moulding.[5]

PROCESS	ADVANTAGES	DISADVANTAGES
Hand Lay-up	- Low tools costs - Versatile	- High time - Air bubbles can appear - Disorientation of fibres - Inconsistency
Pre-preg forming (machine)	- Orientation of the fibres can be changed - Consistency - High productivity	- Only if there are costumers the process can be continuous - Limited shelf life - Delamination
Pressure moulding	- Wide range of shapes - Integrate parts - Consistency - Structural stability - Relatively simple	- High cost of machine - Time to heat up, time to cool down and time of curing - Expensive moulds - No intricate parts - Large volume
Vacuum bagging	- Simple design - Any combination of fibre and matrix - A cheap mould can be useful - Good quality	- It cannot be heated up too much - Breeder cloth has to be replaced frequently - Low pressure allowed (maximum of 1 atm) - Slowest speed - Inconsistency
Filament winding (machine)	- Existing textile processes are used - Quick and easy to handle packages - Parts can have be huge	- Spinning speed is limited due to: + Resin penetration and splashing + Traveller speed and yarn breakage - Curing by heat is not easy to apply - Only cylindrical shape products
Pultrusion (machine)	- Automated processes - High speed - Versatile cross-section shape - Continuous reinforcements	- Die can be easily messed up - Die process is expensive - Mainly thermoset matrix
Spray method	- Continuous process - Any materials can be used as mould - Errors can be easily re-sprayed	- Slow and inconsistent - No fibre orientation control - Only one side finished - Environmentally unfriendly
Sheet moulding (machine)	- High productivity thus inexpensive - Consistency	- Low volume fraction - Only boards can be manufactured
Bulk moulding (machine)	- Highest volume fraction for short fibre reinforced composites (50%) - Good mechanical properties - Inserts and attachments can be introduced	- High temperature and pressure - Random fibre orientation - Not for intricate parts - Staple fibres only
Resin transfer moulding (machine)	- Good surface finish on both sides - Selective reinforcement and accurate fibre management are achievable - Uniformity of thickness and fibre loadings, uniform shrinkage - Inserts may be incorporated into mouldings - Tooling costs comparatively low - Only low pressure injection is used - Low volatile emission during processing - Process can be automated, resulting in higher production rates - Ability to mould complex structural and hollow shapes - Ability to achieve laminate thickness from 0,5mm to 90mm	- Waste of material - High curing time - Hard for intricate parts

Table 2.1: Comparison of composite manufacturing processes [21]

Mechanical Property	*Dominating Composite Constituent*	
	Fiber	**Matrix**
Unidirectional		
0º Tension	X	
0º Compression	X	X
Shear		X
90º Tension		X
Laminate		
Tension	X	
Compression	X	X
In-Plane shear	X	
Interlaminar shear		X

Table 2.2: Effect of fibre and matrix on mechanical properties. [16]

Fiber	**Density** (kg/m^3)	**Tensile strength (MPa)**	**Elastic modulus (GPa)**	**Strain to failure (%)**	**CTE** [$x10^{-6}$] **(m/m/K)**
E-glass	1,44	3,45	75	4,8	5,04
S-glass	1,47	4,48	87	5,6	2,34
Aramid (Kevlar 49)	0,83	3,79	70	2,8	-1,98
Carbon (AS4)	1,04	3,65	227	1,5	-0,36
Carbon (IM7)	1,03	5,03	283	1,8	-0,36
Graphite (P100)	1,25	2,41	738	0,3	-0,3

Table 2.3: Properties of high strength fibres.[16]

Mechanical property	**E-Glass**	**S-Glass**	**Aramid**	**Carbon**
Tensile strength	X	*(Possible)*		
Tensile modulus				X
Compression strength			*(Avoided)*	X
Compression modulus	*(Avoided)*			X
Density	4th choice	3rd choice	1st choice	2nd choice
CTE	Positive	Positive	Negative	Negative
Impact strength			X	*(Avoided)*

Table 2.4: Chosen fibres depending on the sought mechanical property.[16]

Polyesters	Used extensively in commercial applications. Relatively inexpensive with processing flexibility. Used for continuous and discontinuous composites.
Vinyl esters	Similar to polyesters but are tougher and have better moisture resistance.
Epoxies	High performance matrix systems for primarily continuous fiber composites. Can be used at temperatures up to 120-135ºC.
Bismaleimides	High temperature resin matrices for use in the temperature range of 135-175ºC with epoxy-like processing. Requires elevated temperature post cure.
Polyimides	Very high temperature resin systems for use at 290-315ºC. Very difficult to process.
Phenolics	High temperature resin systems with good smoke and fire resistance. Used extensively for aircraft interiors. Can be difficult to process.

Table 2.5: Relative characteristics of composite resin matrices.[16]

3 Approach and alternatives selection

3.1 Matrix

As said previously in this TFG, matrix of composites materials gives continuity between fibres, transmits the forces to the fibres and supports some shear tensions. In this section, epoxy resins –which are the matrix that has been used– are explained.

The following factors should be considered when choosing a matrix material:

1. **Pot-life or working life:** time period that a matrix has when the handling characteristics remain suitable for the intended use. A long pot-life is desired to processes that use unreinforced resin, such as filament winding, RTM and pultrusion. A short pot-life requires frequent resin bath changes and increased scrapped material. A short pot-life can also negatively affect the quality of the part in a wet process by decreasing fibre wet-out.

2. **Shelf life:** length of time a matrix material can be stored for under certain environmental conditions while meeting all performance and handling requirements. Pre-pregs can be frozen for 6 to 12 months, while resin and curing agent (which are in different containers) can along their shelf life to two years.

3. **Viscosity:** its resistance to flow. Normally the lower the viscosity, the easier it is to process and better the wetability [6] of the matrix to fibre.

4. **Cure time:** (*Thermoset resins*) the time it takes for the cross-linking reactions to take place. Typically, $higher - T_g$ resins require longer cure times. Epoxies generally have cure times of 2 to 6 hours at elevated temperature. A post-cure may not be required for some matrices. Therefore, elimination of post-cure requirements should be avoided. Curing temperatures can range from 120°C to 175°C for epoxies.

In this TFG, epoxy resins have been used because of its good properties, which will be explained next in this section.

Epoxy resins are characterized by their good mechanical properties and the presence of the three-member ring epoxy group (sometimes called the oxirane group) which is where crosslinking occurs in epoxies and which gives epoxy polymers many of their characteristic properties. This epoxy group can be attached directly to another organic group. Epoxy groups

[6] Ability of a liquid to maintain contact with a solid surface.

are characterized by the epoxy ring (see figure 3.1), the epoxy group and the glycidyl group (see figure 3.2).

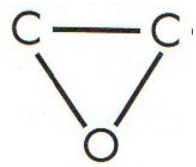


Figure 3.1: Epoxy ring.[15]

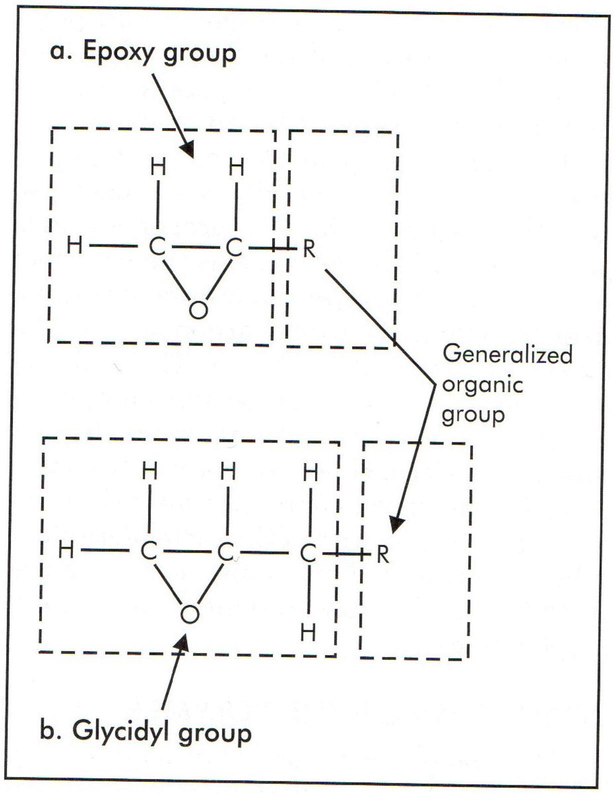


Figure 3.2: Epoxy and glycidyl group.[15]

Manufacturers usually add epoxy groups to other polymers (or monomers) to improve the final product properties. Furthermore, hydroxyl (OH) is usually added to the final result to improve, for example, the adhesivity of the final polymer.

Processing parameters

Active site on polymer

Epoxy groups is the site where crosslinking occurs in epoxy resins. This site is usually at the ends of polymer chain, never in the middle of the chain because the epoxy ring only has one attachment point.

Type of crosslinking reaction

The reaction is based upon the opening of the epoxy ring by a reactive group on the end of another molecule, called the hardener. It has active groups (like the amines [NH_2]) on both ends, what allows the hardener to react with two epoxy groups on two different molecules, linking the two molecules together. For example in amine, the nitrogen of the hardener seeks the slightly positive carbon in the epoxy ring. The nitrogen loses a hydrogen molecule, as it forms the bond with carbon. The hydrogen will bond to the oxygen that was part of the epoxy ring. This procedure is shown in figure 3.3.

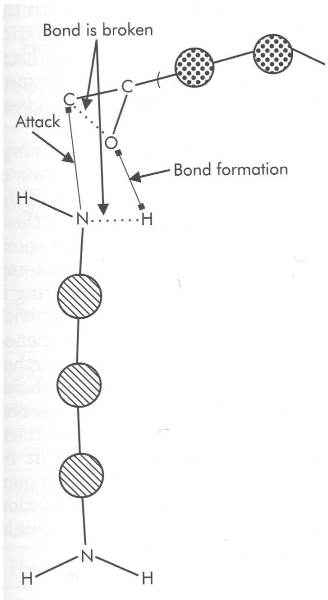


Figure 3.3: Epoxy curing reaction with amine hardeners.[15]

By-products of the cure reactions

Neither curing reaction results in by-product, what greatly simplifies the curing reactions because no care needs to be taken for eliminating the by-products.

Reactive agent to begin cure

For epoxies, several types of reactive groups will open the epoxy ring and start the crosslinking sequence. The most common reactive groups for this purpose are amines, amides, acids, phenols, analines, sulphides and other molecules that with a simple reaction can form one of these reactive groups. Each type can affect the curing characteristics and final part properties. The molecules that have reactive groups used to cure epoxies are called hardeners or curing agents. Usually, the manufacturers that sell the epoxies have chosen the best hardener for each epoxy.

Amount of hardener

In simple epoxy systems the resin and the hardener are mixed in roughly equal proportions. However, in more sophisticated systems and especially where properties need to be optimized, the number of active sides on the epoxy and on the hardener, as well as the molecular weight of both need to be carefully considered when deciding how much of each component to mix together. As the reactive agent choice, the manufacturer usually supplies the relation of the parts.

Toxicity of uncured reactants

Some uncured epoxy resins and some hardeners are known to cause skin irritation. To avoid the direct contact, plastic or rubber gloves should be worn. Another problem is the potential toxicity of vapours or liquids if ingested. Fortunately, most of the epoxy resins and hardeners have low vapour pressures. Nevertheless, precautions, such as masks or respirators, may be appropriate.

Use of solvents/diluents

Solvents have been used with epoxy resins to obtain thinning and easier fibre wet-out, but the environmental problems associated with them have forced their elimination in most cases. However, if high-molecular-weight epoxy resins are used, possibly to reduce the brittleness that comes with high crosslink density, the pre-cured epoxy resin will likely be a solid. In these cases, solvents can be added to provide the capability to wet-out the reinforcement or mix easily with a filler. These solvents are removed from the finished parts.

Volatiles from the system

Most epoxy resins and hardeners have low vapour pressures and are inherently low in emitted volatiles. However, if solvents are used or if the resin or the hardener is heated, the volatility will increase.

Fibre wet-out/viscosity

Epoxies generally have high viscosities. Therefore, fibre wet-out is much more difficult. There are methods of reducing the viscosity. One method is to combine different epoxies, but they must be checked carefully for compatibility. Another method is heating the resin before it its applied to the resin, but the curing reaction also begins when the resin is heated, which may significantly shorten the pot life or working time. Continuing with the third and last method, epoxy resin can be diluted with solvent to reduce its viscosity, but the solvent must be removed prior or during the cure. Finally, a low-viscosity resin helps prevent unwanted solidification of the polymer, which can occur upon prolonged storage when the freezing point if a resin in at or below room temperature.

Cure temperatures

- RTV: some epoxies will cure at room temperatures, initiated merely by the mixing of the resin and the hardener.
- HTV: most epoxies are cured at elevated temperatures to facilitate the movement of the resins and the hardeners. The performance of the polymer is often related to the cure temperature. Therefore, epoxies used at high temperatures need to be cured at even higher temperatures. The common epoxies used in composites cure at 121ºC, while high-temperature epoxies cure at 177ºC.

Accelerators, promoters and catalysts

Despite the use of accelerators, promoters and catalysts in epoxies is less common; some acid act as accelerators by reacting with the epoxy ring to make it easier to open, or some basic act as accelerators by reacting with the hardener to make it more effective attacking agent.

Cure rates

Epoxies cures are usually several hours long, even when heated. A typical profile for a commercial (using autoclave[7]) epoxy curing would be the shown in figure 3.4. The resin/fibre system is heated to about 54ºC where it is held at temperature for an hour. This allows the system to equilibrate and gives uniform curing. The system is then further heated to about 179ºC and held for about two hours to complete the cure. The cure rates and temperatures depend on both the resin and the hardener and are suggested by the resin manufacturer.

Pot life

The long curing times of epoxies and the need to heat the materials provides for long pot life in most epoxy systems. Those epoxies that cure at room temperature will, of course, have a shorter pot life than high-temperature-cure epoxies. Usually this is not a problem as even in the RTV systems the pot life is sufficient for most manufacturing processes.

[7]Pressure vessels used to process parts and materials which require exposure to elevated pressure and temperature.

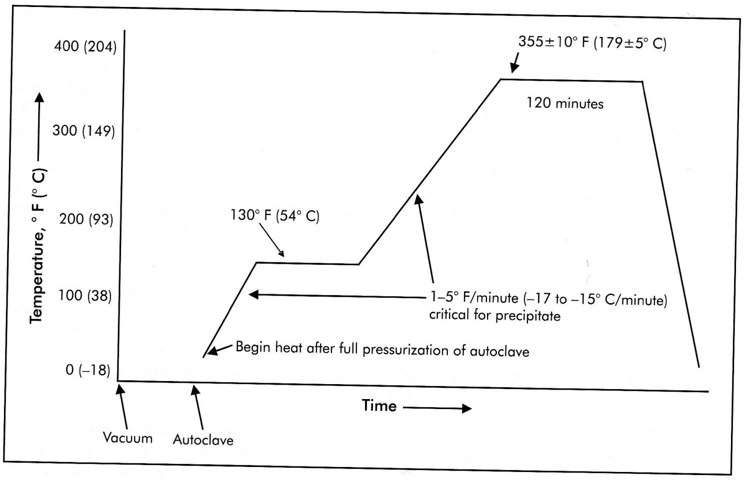


Figure 3.4: Typical curing profile for an epoxy.[15]

Use of inhibitors

The long cure times, relatively stable pot life, lack of peroxide initiators in the curing system and general need for curing make the use of the inhibitors unnecessary in most epoxy systems.

Use of fillers

Epoxy composites rarely contain fillers. This arises from the generally high performance requirements placed on epoxy parts. This high performance is often highly weight sensitive, meaning that epoxy composites is used where mechanical and physical properties are to be at maximum and weight a minimum. These performance factors usually outweigh the cost advantages that can be obtained from using fillers. Most common advantages are: extended pot life, lowered exotherm, resistance to thermal shock, reduced shrinkage, improved ability to machine the composite part, improved abrasion resistance, increased compressive strength, increased density, improved arc resistance, increased electrical conductivity, increased viscosity and improved self-lubricating properties.

Degree of cure

The slow cure rate of epoxy resins suggests that post-curing might be important as a method of getting more efficient use of the moulds. Post-curing is done by removing the part from the mould after considerable curing has taken place so that the part is dimensionally stable, and then placing the part into an oven where it is given an extended additional curing time at an elevated temperature. This is done to improve the part's physical and mechanical properties.

Shrinkage

During the moulding process, low shrinkage is occurred in epoxies. Low shrinkage improves moulding capabilities, especially for parts in which dimensional tolerances are critical.

In table 3.1, a sum-up of the processing parameters explained above is exposed.

Processing parameter	Epoxy
Active site on polymer	Epoxy ring
Type of crosslinking reaction	Ring opening
By-products of the cure reaction	None
Reactive agent to begin cure	Hardeners (usually a bi-functional short polymer)
Amount of hardener or initiator	Usually 1:1 with polymer
Toxicity of uncured reactants	Some are skin irritants and possible carcinogens
Use of solvents/diluents	Less frequent
Volatiles from the system	Low
Fibre wet-out/viscosity	Generally high viscosities and wet-out more difficult
Cure temperatures	Mostly elevated, some at room temperature
Accelerators, promoters and catalysts	Not common
Cure rates	Generally moderate to long
Pot life	Adjustable from minutes to hours
Use of inhibitors	Rare (none)
Use of fillers	Occasionally
Degree of cure	Post-curing not uncommon
Shrinkage	Low

Table 3.1: Epoxy crosslinking parameters. [15]

Properties

Adhesion

The creation of the OH group during the crosslinking reaction and the possible presence of OH groups in the body of polymer give epoxy resins the superior ability to adhere to many surfaces. Possibly, the most important aspect of adhesion in epoxy composites is the bond strength between epoxy matrix and the reinforcement fibres. This strong bonding is seen in many of the properties of composites including strength, stiffness, creep resistance and solvent resistance.

Shear strength

The composite property most closely identified with the bond strength between the resin and the fibre is the composite's shear strength. This is one of the key reasons why epoxies are used in high-performance composites.

Fatigue resistance

Fatigue resistance is a measure of how a material performs with repeated forced movements over long periods of time. This failure is often the result of breakdown of the bonds between the resin and the fibre. Fatigue also depends on the ability of the matrix to withstand repeated flexing. Although epoxies can be quite stiff, indicating poor elongation, some types have good elongation while still maintaining many of the most important strength and stiffness properties.

Strength/Stiffness

The strength and stiffness properties of composites products are chiefly dependent on the reinforcement. Even considering the effects of fibre and the fibre-matrix bond, the matrix strength and stiffness have some relevance to the strength and stiffness of the composite. Epoxies are generally stronger and stiffer than most of the competitive resins, especially polyester thermosets.

Creep resistance

Creep is the gradual movement of a material under long-term loads. This movement is usually a stretching or sliding of the material. It is strongly controlled by the presence of fibre reinforcement that have almost no creep under normal environmental conditions. However, because the matrix has the responsibility of holding the fibres in place, when fibres are not continuous in the part, a slippage in the matrix can result in movement of the fibres or creep. Therefore, matrix stiffness under load is important in these cases and epoxies are known to have excellent resistance to this internal motion. Normally, two important factors affect the amount of matrix creep. The crosslink density and the stiffness of the polymer backbone itself. If epoxies are strongly crosslinked, they can become slightly superior to polyesters.

Toughness

With epoxies, higher crosslinking can be achieved through the use of multifunctional reactants and more aggressive curing conditions, including higher temperatures and longer curing times. As with other thermosets, toughness eventually reaches a maximum value after which the rigidity of the highly crosslinked structure leads to brittleness.

Thermal stability

Two important factors strongly affect the thermal stability of epoxy composites. One factor is the extent of crosslinking –the higher the density of crosslinking, the higher the thermal stability. The second important factor is the basic nature of the polymer chain. For instance, the HDTs of various epoxies show that aromatics have higher thermal properties than aliphatics.

Electrical resistance
Epoxies are the preferred resin for composites used in electrical applications. This is both a function of performance and cost. Furthermore, epoxies have a low conductivity and a high dielectric strength.

Water absorption resistance
The aromatic content of most epoxies helps them resist water absorption. However, countering that is the presence of the OH groups, which have an affinity for water, will absorb water molecules. The net result of these two opposing forces is that water absorption is only moderate in epoxies.

Solvent resistance
The majority of solvents are reasonably resisted, leading to a characterization of the solvent resistance of epoxies as good.

UV resistance
The high aromatic content common in epoxies is not a good UV light resistance. The bond between the aromatic group and the molecule to which it is attached have about the same energy level as UV light. This results in excitation of the bond electrons and subsequent rupture of the bond.

Flammability resistance
The aromatic materials tend to char rather than burn freely, which is seen as a reduction in both the ability of the material to be ignited and the rate at which the material burns.

Smoke
The smoke is quite hard and can be emitted in large amounts even though burning is not vigorous.

In table 3.2, a sum-up of the epoxy properties explained above is exposed.

The requirement of using epoxy is clearly a right decision because its adhesion properties, shear strength and stiffness are excellent. The matrix needs to transmit efforts to the reinforcements and, in addition, may support some shear strength. Another excellent properties that are really interesting in wings is the fatigue resistance. A common flight has vibrations on the wings and perturbations during the flight act as punctual forces, not

Property	Epoxy
Adhesion	Excellent
Shear strength (fibre-matrix bond)	Excellent
Fatigue resistance	Excellent
Strength/Stiffness	Excellent
Creep resistance	Moderate to good
Toughness	Poor to good
Thermal stability	Good
Electrical resistance	Excellent
Water absorption resistance	Moderate
Solvent resistance	Good
UV resistance	Poor to moderate
Flammability resistance	Poor to moderate
Smoke	Moderately dense
Cost	Moderate

Table 3.2: Epoxy properties. [15]

permanent. Therefore, if the matrix is resistant to fatigue, the structure will be more efficient during a longer period of time.

Sandwich structure

Composite structures can be made lighter and at lower cost by forming a sandwich construction in which the core material is bonded between the composite laminate faces. However, the complexity is also increased. The most important part of manufacturing a sandwich structure is the bonding of the core material to the face plates. This is done with an adhesive film that is placed between the face plates and the core. That adhesive must be strong enough to transfer the load from applied forces onto the face sheets and to resist debonding from the surface of the core.

In the TFG case, both surfaces have used sandwich structure. It is a *Rohacell* thin layer that helps supporting the compression efforts on the upper surface –which would promote the appearance of local buckling– and gives robustness in both surface. This solution gives extra inertia to the structure by separating the layers of fibreglass. It should be clear understood that, theoretically, *Rohacell* does not provide extra endurance, it is just used to separate the layers of fibreglass.

Rohacell is a PMI-based structural foam that has been used in fibre-composite technology for more than 30 years. It has excellent mechanical properties over a wide temperature range, even at low densities. It also has high temperature resistance up to 220°C and unique compressive creep behaviour for processing up to 180°C and 0,7 MPa. Finally, it has excellent dynamic strength.[1]

An scheme of the skin sandwich can be seen in figure 4.5.

3.2 Fibres

Fibres are used to provide strength and stiffness to the material. In table 2.3, properties of the most used fibres are presented.
A requirement of this TFG is to consider only glass, carbon and aramid fibres. This is a proper consideration because they are the most used fibres which guarantee a reliable behaviour and an affordable price. Besides, many data are available thanks to numerous studies made since the second half of the 20th century.

3.2.1 Glass fibres

Fibreglass is, by far, the dominant reinforcement material in terms of usage. This dominance is due to the combination of its low price and excellent properties. Furthermore, fibreglass has been used since the WWII, so loads of data and know-how is available in the net, possibly more data than any other kind of reinforcement.

The raw materials of fibreglass are silica sand (SiO_2) and various subcomponents, such as limestone and boric acid, and some minor ingredients, such as clay, coal and fluorspar.

Different types of glass fibres are available in the market: E-glass, S-glass, C-glass and quartz. The most common are E-glass and S-glass, which are explained below.

- *E-glass fibres:* they were originally used when strength and high electrical resistivity were required. Because of their good strength properties and low cost, E-glass fibres are the most common type of fibreglass used in composites. They have a high-density, low-modulus fibre, good corrosion resistance and good handling characteristics.

- *S-glass fibres:* they are approximately 35% higher in strength than E-glass and have better retention of mechanical properties at elevated temperatures. S-glass is preferred in advanced composite applications where fibreglass is used rather than one of other high-performance reinforcements like carbon or aramid. They have a higher-strength fibre, used in filament-wound pressure vessels and solid rocket motor casings.

Talking about properties, fibreglass is easy to shape (with moulding), it is light, not susceptible to water logging or corrosion and the overall cost of manufacture GFRP is often less than the other materials. Furthermore, GFRP usually allows a significant reduction in the number of the parts.

3.2.2 Carbon fibres

The demand for reinforcement fibres with strength and stiffness higher than those of glass fibres has led to the development of carbon fibres, which finally occur at 1950s. Today, carbon fibre has among the highest specific strength and highest specific modulus of any material.

Carbon fibres base materials are PAN, pitch or rayon (to a lesser extend). All materials have high carbon concentrations relative to other atoms and can be converted into graphite materials.

The internal structure of carbon fibre –see figure 3.5– is now discussed. The plates stack upon each other to form a three-dimensional structure. They are oriented within the fibre so that the long axis of the fibre is the same direction as the long axis of the plates. Hence, when the fibres are pulled in tension, the force is pulling against the ring structures of the plates. These rings are formed by strong covalent bonds so the resistance against the tensile force is strong. The ring structure is also dimensionally stable, thus adding even more strength in the fibre axis direction and significantly improving the stiffness. However, in the cross-fibre direction there are weak Van der Waals bonds that form to hold the stacked rings in place.

Continuing, carbon fibres are available in a variety of grades from many different manufacturers and the existence of three major types of carbon fibres (PAN-based, pitch-based and rayon-based) further complicates the evaluation.

- For *PAN-based fibres*, both strength and stiffness increase going from standard modulus to intermediate modulus. However, when going from intermediate modulus to ultra-high

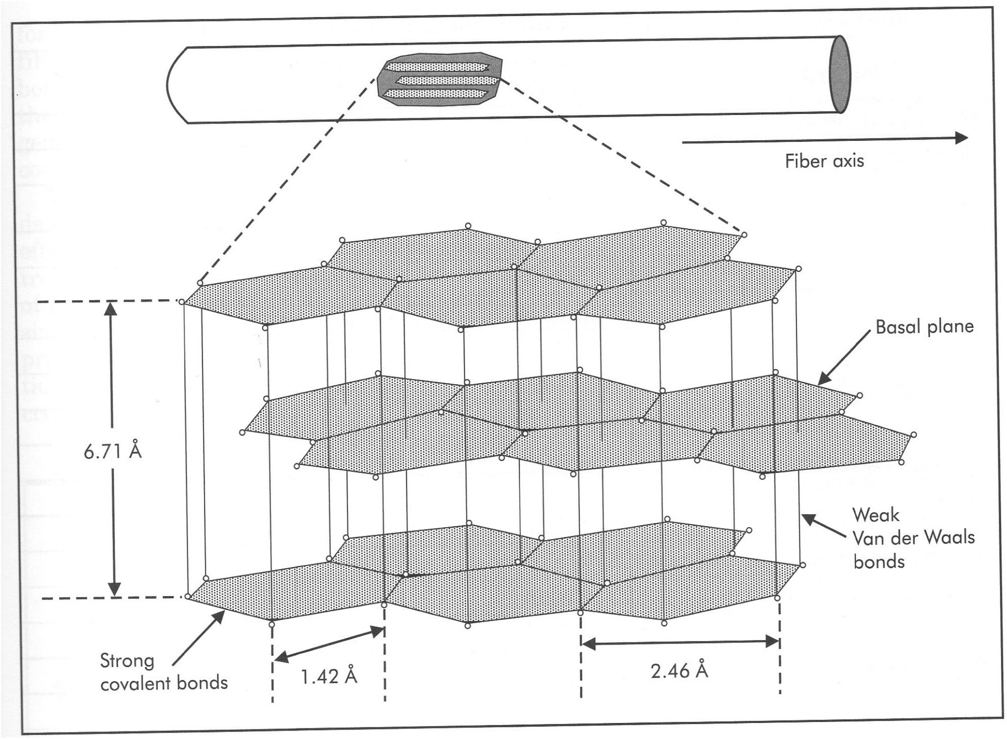


Figure 3.5: 3D representation of carbon fibre structure.[15]

modulus, the strength goes down and the modulus goes up. The optimization of modulus is generally a function of the temperature. In general, PAN-based fibres are more commonly sold in the marketplace.

- For *pitch-based fibres*, the trade-off is not as dramatic, at least within the range of products currently in production. However, the elongation for pitch-based fibres is generally lower than for PAN-based fibres. Therefore, pitch-based fibres are being used in applications where both strength and modulus are critical, and the lower elongation is not a problem.

Although mechanical properties like tensile strength and modulus are the most important in carbon fibres, thermal properties are becoming increasingly important. For almost all materials, the CTE is positive because the increased motion of the molecules at higher temperatures will increase the size of the sample, but carbon fibre are the rare exception to this rule. They have a negative CTE indicating that as the temperature goes up, the sample gets smaller. Another thermal property of great importance is the thermal conductivity. Pitch-based carbon fibres have high thermal conductivity, surpassing that of most metals.
Carbon fibres are structurally very efficient and have an excellent resistance. Besides, carbon fibres are moderately good conductors of electricity. Furthermore, they are elastic to failure at normal temperatures, which renders them creep resistant and not susceptible to fatigue.

However, carbon fibres have some short-comings. They are brittle, have a low impact resistance and low break extension, relatively low compressive strength and a small coefficient of linear expansion, which is a benefit except that it might complicate processing. Besides, carbon fibres can suffer of galvanic corrosion if the fibres are in direct contact with aluminium. Finally, they are expensive. For that reason, they are only used in aircraft control surfaces, in some parts of fuselage and in aircraft structural part such as doors and landing gear assemblies.

3.2.3 Aramid fibres

Aramid fibres are an extremely tough organic fibres. Their structure is wholly aromatic with amides as linkage. Therefore, the strength and the stiffness are high, the polymer is highly polar and, so that, there are significant intermolecular bonds which increase the strength and the stiffness.

Several procedures are needed in order to get fibres because the polymer is difficult to dissolve. However, in contrast with glass and carbon fibres –which have sizing coated onto their surfaces–, aramid fibres often do not require sizing. This is possible because aramid fibres are tough and not, therefore, subject to the same incidental processing damage that occurs with glass and carbon fibres.

Three grades of aramid fibres are available: Kevlar 29 (high toughness), Kevlar 49 (high modulus) and Kevlar 149 (ultra-high modulus). The difference between the grades are determined by processing conditions, which generally give more crystallinity to the higher-modulus fibres.

Talking about properties, aramid fibres are less dense than fibreglass and carbon fibres, and intermediate in strength and stiffness between glass and carbon fibres. Therefore, the specific strength of the aramids is quite high, roughly comparable to the specific strength of carbon fibres. Finally, the specific modulus of aramids is higher than glass but not as high as the outstanding specific modulus of carbon.
The elongations of aramid fibres are much higher than either fibreglass or carbon fibre. That elongation, plus the excellent tensile strength, results in high toughness for aramid fibres that the other fibres do not offer. This toughness is one of the most important properties and leads to the majority of applications in which aramid reinforced composites are used.

The failure of aramid fibres is unique. When they fail, the fibres break into small fibrils, which are like fibres within the fibre. Therefore, aramid fibres fail by a series of fibril failures rather than a brittle failure like carbon and glass fibres. However, the fibrils do not have the same resistance to compression forces as do glass and carbon fibres. Therefore, in general, aramid fibres are rarely used when compressive force resistance is important.

Finally, aramid fibres suffer a rapid deterioration when they are exposed to sun light. But, the most important positive property is impact damage prevention.

3.2.4 Decision of fibre used in the TFG

An OWA analysis –see table 3.3– have been performed in order to chose the fibre reinforcement that will be used in the monocoque structure.
In this analysis some mechanical properties, manufacturing facilities, data available and price. A higher weight is given to price, manufacturing facilities and data available because the aim of the TFG is to manufacture a monocoque structure.

		Weight	Glass fibre		Carbon fibre		Aramid fibre	
Criteria		g	p	$p \cdot g$	p	$p \cdot g$	p	$p \cdot g$
Mechanical properties	*Density*	40	1	40	2	80	3	120
	Tensile strength	30	3	90	1	30	2	60
	Elastic modulus	30	2	60	3	90	1	30
	Strain to failure	20	3	60	1	20	2	40
	Impact strength	30	2	60	1	30	3	90
Manufacturing facilities		70	3	210	2	140	1	70
Data available		60	3	180	2	120	1	60
Price		80	3	240	1	80	2	160
Sum		360		940		590		630
OWA				**0,87**		**0,55**		**0,58**

Table 3.3: OWA analysis for the internal structure of the fuselage.

As can be seen in the table 3.3, fibreglass is the most favourable fibre to be used because of its manufacturing facilities, its available data on the net and, majority, its low price.

3.3 Processes

Thank to the research done in the lasts decades of the 20th century, the industry of composites had improved the processes of manufacturing and work with this materials. Some of these improvements are based in big manufacturing processes, which are out of these TFG's scope. But some others are in a smaller scale which favours to used them in a quotidian way.
In this section, two ply collation methods and two curing processes will be exposed. On one hand, the ply collation methods are the hand lay-up method and the spray method. On the other hand, curing processes are the vacuum bagging and the compression moulding.

Before getting into the bulk of this section, it is considered to explain that pre-pregs have not been used because if they are stored at room temperature, they would lose properties.

3.3.1 Ply collation

Play collation is the method how the fibres are presented into the part. Two processes have been considered, the hand lay-up and the spray method.
When the resin is added at about the same time the fibres are placed into the mould, these processes are called *wet*.
Furthermore, when the mould is single-sided and is not covered by a second rigid mould part during cure –although it might be covered by a flexible sheet– is called *open moulding*.

Hand lay-up

Hand lay-up is the most labour intensive method but the most economical. Lay-up parts can be of almost any size and shape. In fact, it is the method of choice for some parts that, usually because of high complexity of shape, can only be made by this method. If only few parts of any design are to be made, lay-up is usually the most effective method of manufacture. Furthermore, the resins, which can be a wide range, should be stored within the temperature range, which is usually moderately narrow (about 25°C).

In normal practice, the resin is mixed with the hardener and, if necessary, fillers and other additives are also added in the same mixer. To improve wetting, the upper surface of gel coat (or mould if it is not used) can be pre-wetted with a thin layer of resin before the reinforcements are placed in the mould.
There are two ways of placing and wetting the reinforcements. On one hand, it is possible to place them first and to wet them later. On the other hand, it is possible to wet the reinforcements external to the mould and then transferred into the mould and smoothed.

Full wet-out and coverage of all the reinforcements is done by rolling the resin into the reinforcements. Small hand-held rollers with ridged surfaces have proven to be excellent tools. By rolling, the resin is distributed evenly over the reinforcements. In fibreglass reinforcements, when them are being wetted, a change in colour is noted as the resin is absorbed. Thus aiding in monitoring the wet-out process. For a scheme of hand lay-up process, see figure 3.6.

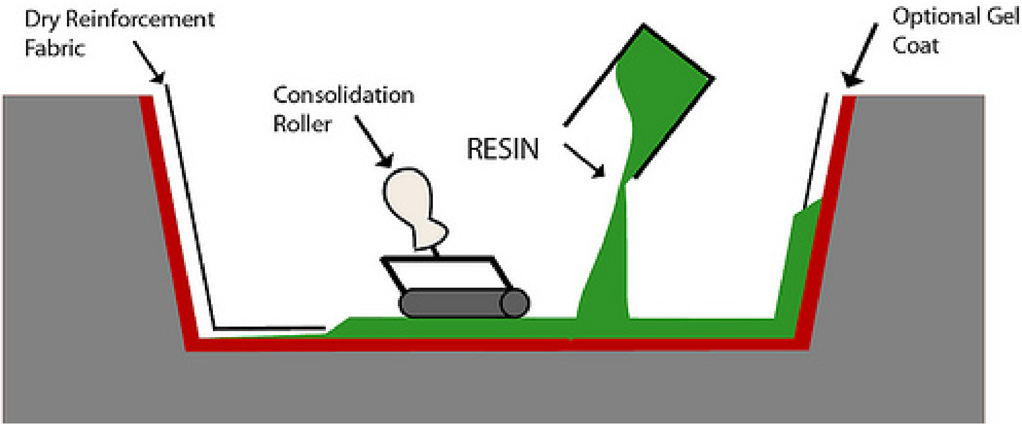


Figure 3.6: Hand lay-up method scheme. [7]

Continuing with the lay-up ply collation method, curing processes can be done at room temperature or at elevated temperatures. In both cases, one important point that must be considered is exotherms because they can damage the part or cause safety issues. In order to avoid them, the composite layer cannot be too thick. Alternatively, if the layer is too thin, proper curing may not occur.

If one layer of reinforcement and resin is not sufficient for the structure of the final part, as it is often the case, additional reinforcements layers and resin may be added after the previous layer is cured. It is desired that chemical bonds form between the first and the second layer. This can be accomplished when the resins in the two layers are the same. Also, adding the second layer to the structure before the first layer is nearly but not totally cured permits the softness of the primary layer to facilitate the formation of bonds. Despite composites of any thickness can be made by applying this method, the thickness of each layer should be controlled within the range defined for acceptable cure. If the resin has wax, it should be sanded before applying the secondary layer.

Even with the greatest care during the lay-up process, air is inevitably trapped between the layers. Experienced workers have seen that better parts can be made if some of the air is removed after the lay-up and before the part is cured. This process of air evacuation is called debulking.[15]

Spray method

The advantage of spray-up over lay-up for most parts is simply the speed with which the fibre and the resin can be applied to the mould. The disadvantages are the special spraying equipment required, the more limited choice of resins, the inability to control the direction of the fibres, the high air pollution because of spraying the resin, and higher skill level needed by operator. Furthermore, the choices of resin are more limited because resin's viscosity must be more carefully controlled to ensure that spraying can be done appropriately.

Spraying equipment is quite special. The fibres are brought into the chopper as roving and then chopped, so that, they fall into the stream of resin just after the nozzle. This means that the chopped fibres are entrained with the resin and together are sprayed into the mould. Furthermore, some training for the spray-up operator is required, especially since the uniformity of fibre placement is critical to the performance of the part. In figure 3.7, a scheme of spray-up can be seen.

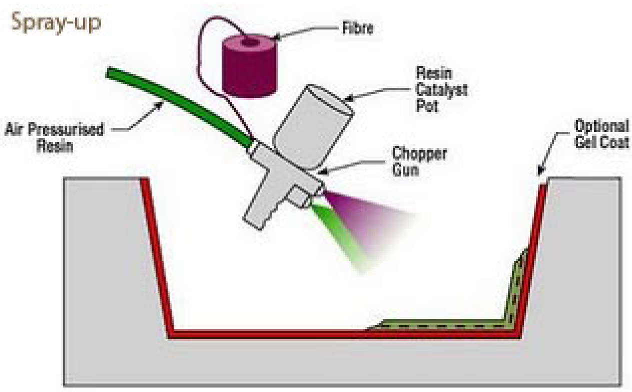


Figure 3.7: Spray-up method scheme. [2]

On one hand, the length of the chopped fibre should be short to ease of spraying and coverage into tight areas of the mould. But for best mechanical properties and ease of chopping, the length should be long. So that, not an standard size is promoted.

After the fibres and resin are sprayed into the mould, a roller is used to make sure the resin fully wets the fibre bundles. Finally, curing in spray-up is the same as curing in lay-up. [15]

3.3.2 Curing processes

Usually, curing processes are based in a machine that allows that cure. In industrialized processes, it is really common the use of an autoclave to favour the pressure and temperature conditions needed in certain methods.
In this section, vacuum bagging and compression moulding are presented.

Vacuum bagging

Applying a vacuum, especially during cure when the resin is less viscous, has different benefits when manufacturing composites parts.
First of all, it can be used as a debulking process (up to four plies). Secondly, volatiles that may be present in the resin are removed. These volatiles may include residual solvents; others may have been absorbed into the resin when it was stirred to formulate it with the hardener.
Finally, another benefit is the movement of resin during the curing stage as a result of the nature of the bagging system. The molten resin is encouraged to move between the layers and into an absorbent layer in the bagging system. This resin absorption causes a moderate loss of resin that increases the fibre-resin ratio and reduces the total weight without significantly reducing the mechanical properties of the composite.

Different material are used in vacuum bagging process (see figure 3.8):

- Peel ply or release film are used to provide a simple method of pulling all the bagging system off the part after curing. Typically, Teflon sheet or Teflon-coated glass fabric.
- Bleeder is used to absorb the excess of resin. It is important to have good absorption qualities and does not compact under the pressure of an autoclave.
- Breather material acts as a distribution for the air (vacuum) and for escaping volatiles and gasses. If the resin absorption is carefully controlled, the bleeder material can serve as breather.
- Vacuum valve with a resin trap placed in the vacuum line to protect the pump from the resin.
- A sealant material which is to form an airtight seal with the vacuum bag. It must withstand the temperatures experienced during the cure.
- Lay the vacuum bag over the assembly and push the vacuum valve stem through the bag. The vacuum bag is then pressed onto the sealant to create an airtight seal all around.

Following with the vacuum bagging process, some common problems can be identified:[15]

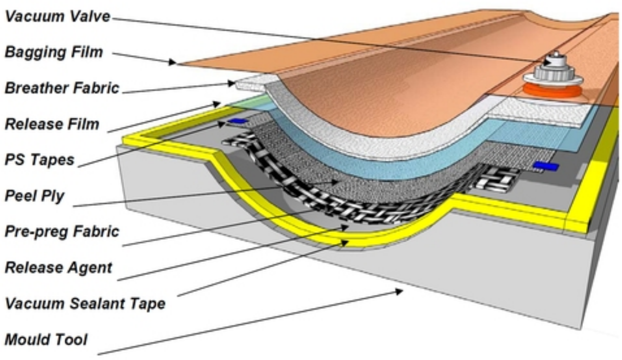
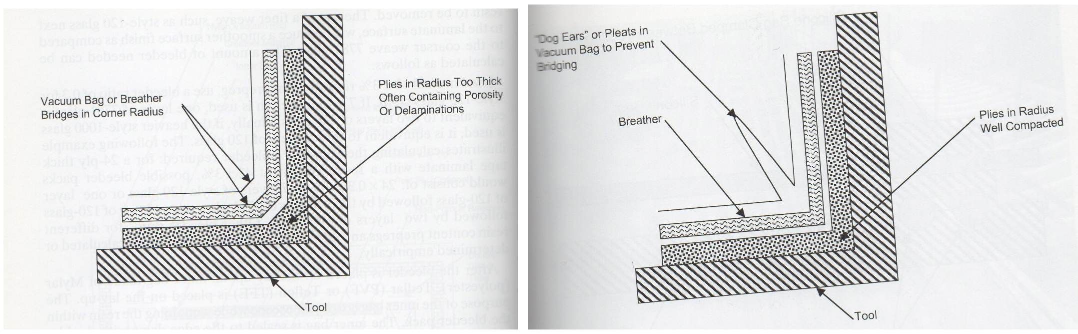


Figure 3.8: Vacuum bagging scheme.[3]

- The vacuum should be carefully monitored during this period to ensure that there are no air leaks.
- Bag breakage is catastrophic because it is often not detected until after the part is has been cured and, therefore, it is too late to remedy.
- Bridging occurs when the shape of the part, that is the shape of the mould that makes the part, does not allow the vacuum bagging materials to press against all the part's surface. Therefore, these non-pressed areas are not properly compressed. Good bagging techniques, such as pleats intentionally put into areas where bridges may occur allow enough excess film to be present for bag conformity against the part's surface. (see figure 3.9).
- The easiest path for resin to take during curing is along the direction of the fibres (edge bleed). However, the direction in which the moulder would like the resin to move is perpendicular to the plane of fibres (face bleed). Therefore, a technique to encourage resin movement in the perpendicular direction and to prevent leakage is to include resin dam around the perimeter of the bagging assembly and, simultaneously, sufficient bleeder is placed normal to fibres' plane. Finally, when resin starving occurs, there is insufficient resin to fully wet the fibres and therefore loads cannot be transferred properly from matrix to the reinforcements.

Finally, after the bagging system has been assembled, and the part has been debulked, the resin needs to be cured. Two tasks must be accomplished during the cure. The first is curing and that is done by heating or pressuring the part. The other is to reduce void content, which is done, in part, by debulking during the cure. As a guide, the inter-laminar shear strength reduces about a 7% for each 1% of void content present up to a maximum of about 4%. A reasonable goal for void content in the finished laminate is a 0,5% or less.
Vacuum also helps by consolidating the laminate's layers. This was noted in a study of shear



(a) Without *dog ears* (b) With *dog ears*

Figure 3.9: *Dog ears* scheme. [16]

strength for two parts, one cured with a vacuum and another cured without. The shear strength increased by a 20% in the part moulded with a vacuum.

Following a video published in an internet forum, a basic and extremely efficient method of creating vacuum bags have been discovered.[14]
It basically consist on sealing an anti-adherent film by following the expected geometry of the bag with a soldering iron.

The quality of the bag had been proved to ensure that this trick is a good option to achieve our goal. Its results were very satisfactory, reaching a maximum of 0,97 atmospheres of vacuum and it takes approximately 14 minutes to decrease the vacuum to 0,5 atmospheres. When the vacuum pump is activated again, in 30 seconds, 0,96 atmospheres are achieved. In a practical situation, doing cycles of 3 minute where the pump is running and 12 minutes where it is not running, a pretty reasonable vacuum process would be achieved. The work of the vacuum pump is needed to take about three hours which is the time that epoxy resin needs for lasting its first curing. Then, the part would be let reposing for almost a day to ensure the complete curing of the part.

Compression moulding

There are two possibilities of compression moulding that can be developed in a quotidian environment. The first alternative is a method that use four moulds (a male and female for each surfaces) and the second alternative, use a balloon (which only needs two females for both surfaces).

On one hand, the method that use four moulds is used in industrialized processes, compression moulding is made with special equipment, which is not possible to use in this

TFG. For that reason, other ways to produce the pressure will be used. For instance, dumbbells and other heavy objects may be used (see figure 3.10).

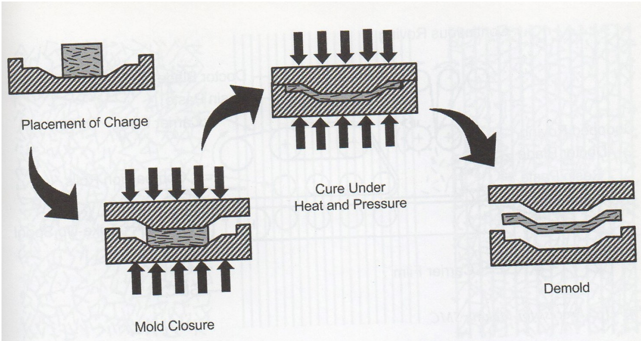


Figure 3.10: Compression moulding of thermosets. [16]

Compression-moulded parts should have relatively few changes in depth and must not be too narrow. However, in industrialized processes, compression moulding is widely extended and it is used for large and small parts.
The process of lay-up is the same as in vacuum bagging (either lay-up or spray-up method). This process is done in a female mould, as in vacuum bagging. However, a male mould may be need for compress the laminate part. This part should be smaller because the layers take up a space.[15]

This quotidian method can have huge problems, such as not enough weight to make the pressure to the part or not adequate thickness of the layers to fill the gap between moulds. Furthermore, four moulds must be manufactured.

On the other hand, the method that uses a balloon is a handmade process that has been studied through videos in the net [14]. People in their home use this method to produce little aircraft composite parts. All the effort of the structure will be hold by the composite. It is not possible to introduce reinforcements such as beams or ribs because the balloon will not fill the entire part of the mould.

This technique is used to produce all the shape in only one curing (upper and lower surface). For achieving this goal is really important that the two female moulds completely fit together. Furthermore, in one edge, it is necessary to make a hollow space where the neck of swelled balloon would completely fit.
The balloon should be handmade and a little bit larger than the planform of the wing. This margin is not known, so some practices should be performed.

The ply collation should be applied at the two moulds –upper and lower surface– at the same time. After this step, they should be fitted together and, rapidly, the balloon should be introduced and swelled. For a better performance, it is preferred that the balloon would be larger, because it is swelled maximum to the exact shape of the part, but if it is not big enough, the method would not work because no compression would be done.

The balloon compression moulding has been rejected because a balsa wood beam will strengthen the structure and, in the LE and the TE, small balsa wood profiles will help giving shape to the wing. With the balloon technique, no strengthen parts as the exposed before are allowed, because the swelled balloon could not reach the whole surface.

3.3.3 Decision

According to Trencalòs' and LITEM's possibilities, it has been chosen these two methodologies:

- **Hand lay-up:** this ply collation method has been chosen because spray-up method has more disadvantages. Basically, it has two big issues. Firstly, it is not possible to oriented the fibres as one's choice. Secondly, it is needed a certain tooling (a compress-air gun) and express chopped fibres.
- **Vacuum bagging:** this curing process has been chosen because if compression moulding was selected, it demands two extra moulds for part (one for upper surface and another for lower surface). Besides, the impossibility to introduce easily the internal structure makes dismissing the balloon the easy decision.

4 Proposed solution development

4.1 Plug

One of the primary keys to succeed in mould construction is a proper preparation of the plug, which is the *original* used to create the female mould. Any imperfections in the plug surface will be transferred to the mould, and then to the future parts made from it. For that reason, the plug needs to reach a finish at least as good as the desired finish of the parts are going to be produced.
The preferable surface finish for the plug would be a polished high-quality finish, free from any porosity or scratches. In order to achieve an acceptable mould surface, it is far more effective to remove defects from the plug surface than attempting to remove defects from the mould surface.

In the case of this TFG, an expanded polystyrene wing of 600 mm of span and 240 mm of chord has been coated with modelling clay in order to achieve a continuous and high-quality surface. The original wing can be observed in figure 4.1. In order to make easier the work, it has been only used the main wing profile, avoiding the flap section. So that, the effective plug measures 600 mm long per 190 mm wide.

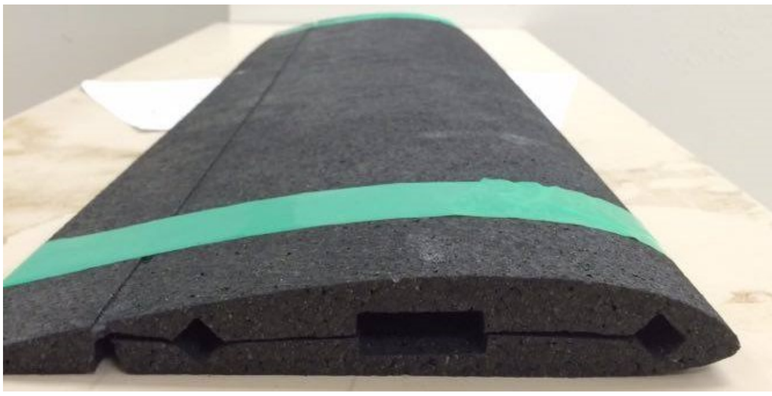


Figure 4.1: Original expanded polystyrene wing.

To reach the highest quality in the plug preparation, different thin layers of modelling clay have been applied, and subsequently hand-sanded, in order to avoid all the potholes and irregularities present in the expanded polystyrene. It is important not to use too many clay because the profile form must be invariable.
During the clay appliance, some imperfections must be avoided by applying more clay and hand-sanded it. To show examples of these defects, see figure 4.2.

(a) (b) (c)

Figure 4.2: Examples of imperfactions in the plug.

In figure 4.3, an example of modelling clay application can be seen. In the first region, marked with the number 1 in the figure, only one coat of clay has been applied. In the second region, marked with a 2, two coats has been applied. And, in the region marked with a 3, three coats.
It can be observed the smoothly change in colour and, if it was possible to touch the part, a smoother surface is achieved in the region 3. Finally, the number of clay's coats is not defined. As bigger the coats, highest the final quality of the plug.

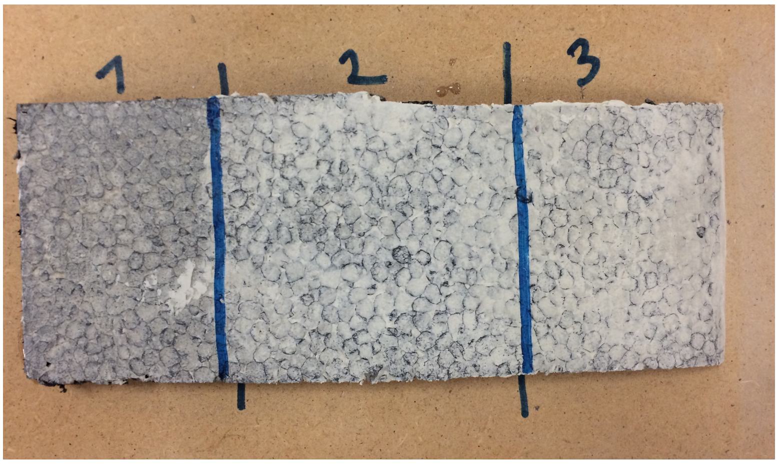


Figure 4.3: Example of clay's coats in plug finish definition.

To achieve a good results, different weight of hand-sanding paper have been used. Firstly, a 180; followed by a 240 and, then, by a 600. If a high quality is wanted, a 840 hand-sanding paper should also be used.

4.2 Mould Construction

Of all the advantages offered by composite materials, their ability to be moulded to complex shapes is perhaps the most popular. In order to be moulded time after time, it is really important to fabricate a mould that allows repeating as many times as want the same geometry. Furthermore, moulded parts emerge perfectly shaped every time and require little post-finishing work.

As explained on the state of the art (section 2), there are male and female moulds. The use of one or other mould is strongly related to the chosen process. For instance, either type of mould can be used for vacuum bagging, but female moulds are usually easier to seal while achieving good surfacing characteristics. But compression moulds are sometimes made by using both a male and a female form. So that, the key is to think about the intended use of the finished part and what type of mould will be needed.

When selecting the materials with which the mould will be manufactured and the method of construction, it is important to take into account such things as the length of the production run (in the TFG case, four specimens) and the desired quality of the surface finish on the part. Other things to be consider include technique specific modifications to the mould in order to aid in procedures like vacuum bagging and compression moulding. Langer flanges are worth incorporating to make both procedures easier.

Nearly all composite materials can be utilized in mould construction, but the part requirements often don't justify the expense of more exotic materials. In the TFG case, polyester resin, polyester gel coat, fibreglass of 210 gr/m^2, fibreglass mat of 300 gr/m^2 and sand have been used.

Using a good tooling gel coat had also aided greatly in achieving a top-notch mould surface. Fibreglass has been used to give the first and last shape to the mould, while mat offers a quick build-up, along with uniform strength and stiffness. To conclude,PU will be used to create a good thickness of mould in order to be easily transported and give stability.

Polyester based resin and gel coat have been used because are cheaper than epoxy (which has been used in the parts manufacturing). Besides, mat cannot be used with epoxies because it is not compatible.

Due to the softness of the gel coat, it is important to reinforce the mould with fibreglass and mat. The use of fibreglass gives a smooth and detailed finish. Besides, the first layer of fibreglass has to be carefully looked after to reach a finish loyal to the plug.

How is the mould released from the plug and subsequent parts from the mould have also impacted on the overall design and construction. The first factor to consider is the draft

angle[8]. A mould with zero draft has sides perpendicular to the bottom; with positive draft, thanks to the sides are wider at the top, parts will easily pop out of the mould; with negative draft, parts are impossible to remove from the mould.
To make easier the operation of releasing the part from the mould, it is possible to drill holes through the mould and bond an air fitting to the back. It will also be necessary to ensure that the resin does not contaminate the air line (holes can be filled with clay or similar material). Then, when the part is ready to release, just let the air come inside through the holes.
Furthermore, to ease the releasing action, wax has been used. The application method is really important in order to avoid globs in the final part.

Finally, the chemical behaviour between components has to be taken in care. It is really important to ensure that the gel coat and the resin are compatible, and both with the releasing agents too.

Step by step mould construction

About the mould construction could be said the same than in the plug. The quality has to reach the highest possible, because its quality will be the final quality of the part. For this reason, a strict method is detailed below.

1. Using modelling clay, the surface of the plug is treated.
2. The plug is mounted onto the tooling created specially for this process. A delimiting plane has allowed to align the LE with the TE. Furthermore, four wooden plates have been used in order to form a box around the delimiting plane, which is also made of wood, in which a rectangle of the wing dimensions have been cut. The draft angle has been zero.
3. A mould release agent was needed to be applied to the plug. This is a critical step, since it would allow to separate the mould from the plug once the materials used to construct the mould have cured. If the mould does not release properly from the plug, the mould and the plug could be damaged. The release agent that has been used is parting wax and PVA. Generally four coats of wax are applied with a half-an-hour wait in between the second and the third coats. After the final application has dried and it has been buffed, the PVA can be sprayed –or painted– onto the plug. The PVA should be applied in three thin mist coats and allowed to dry for 20-25 minutes.

[8] Angle of the sides of the mould compared to its base.

4. Before starting the lay-up of the mould, parting flanges or dams must be added to the plug along the parting planes. This is the form which divides the mould segments during construction. This form is removed once one side has been moulded. Like the plug itself, these parting flanges are constructed of the least expensive materials that would support the curing fibreglass later. In the TFG case, only one section is being build, so that no parting flanges have been used.

5. Any locating keys or dowels for re-aligning the segments of a multiple-piece mould should be added to the parting flanges.

6. Cover the plug with gel coat. Although the surface coat can be applied with a brush, a more uniform result will be achieved by spraying it. Gel coats and other surface coat materials are too thick to be sprayed with normal equipment, so special gravity-feed *cup* must be utilized. In the TFG case, it has been applied with a brush.

7. Carefully, place the fibreglass of 210 gr/m^2 to give shape to the mould. Use the gel coat to fix the reinforcement. It is critical to stabilize the first layer of reinforcement within an hour an a half to 5 hours (at room environment). The first layer of reinforcement is also the most critical layer in the mould to lay down without trapping air bubbles. The main advice here is to wait and begin the process when the coat within the 5-hour window of opportunity. It will save time and money and it also helps to prevent heat distortion in polyester moulds.

8. When the first reinforcement layer is cool to touch, place the fibreglass mat of 300 gr/m^2 and coat it with polymer resin. The remaining layers can be added fairly quickly to this stabilized surface without much fear of thermal distortion, but do not exceed 3-4 layers at a time. Do not cut the chopped strand mat, tear it into manageable chunks.

9. Using a natural bristle brush, pre-wet the surface with properly catalysed resin, then place the fibreglass of 210 gr/m^2 on the plug. The reinforcement has soaked up much of the resin, but white spots indicate more resin is needed. Once again, begin by butting pre-cut strips into the angles where the parting dam meet the plug. In figure 4.4, it can be seen a mould resting up to this point.

10. To gain thickness on the mould and make it more stable and easy to handle, PU has been used.

11. Release wedges can be used to help coax the mould off the plug. These plastic wedges should be used in place of screwdrivers and putty knives because they would not chip the mould surface. Insert the wedges around the perimeter of the mould and gently tap them

into place, progressing evenly around the edges. Special air-injection release wedges can also be used for stubborn parts. Slowly the two should be separated. If the problems still persist, light blows with a rubber mallet can send vibrations through the mould causing the separation.

Figure 4.4: Mould image before the aplication of PU.

Mould preparation

Once the mould is separated from the plug, clean and inspect its surface. The residue of PVA mould release agent should be washed off with warm water. Dry the surface and look for any serious defects. Critical problems have actually to be ground out and resurfaced. Furthermore, the surface should already be very smooth. Typically, the mould release agents leave a light texture behind, but this can be quickly removed.

4.3 Pre-process considerations

A pretty repetitive fact about composites is the stress on the difficulty of manufacturing. Basically, for two reasons: the cost and the amount of work that is necessary to support.
For these reasons, it is really important to ensure that the following hesitations are already thought and planned.

- Which will be the cutting process of raw materials?

- Which lay-up process will be followed?
- How is the curing process? (Parts with the same cure-cycle should cure together for reducing times and costs)
- With which liquid mould release agent would be the mould coated?
- Which are the tools requirements to shape the materials?
- What are the materials specification?
- Manufacturing work instructions:
  - Location and orientation of the cut pieces of materials on the tools
  - Curing method and conditions in the autoclaves (or room)

Based in the information found in the literature, the detailed process have been described –step by step– in section 4.4.

4.4 In-depth process analysis

4.4.1 Conceptual design of the structure

As it has been explained and defined in the objectives of this TFG, the goal is to experiment with monocoque structure's construction. To achieve that purpose, how should be the structure to support a certain effort has not taken into account.
Even so, some theoretical considerations have been thought in order to perform the most complete skin sandwich possible (with core and reinforcements with different characteristics). In this section, these considerations –or structural concept design– are exposed.

Skin sandwich

To help understanding the configuration, it is possible to see an scheme of it in figure 4.5.

Firstly, fibreglass has been used for its lower cost and its good mechanical properties. Two sheets of fibreglass of 80 gr/m^2 will be used. Inside these two layers, *Rohacell* and carbon fibre are also used. On one hand, *Rohacell* is used to separate the two layers of fibreglass, what would let the structure adquire some inertia (a basic parameter in the structural design). This high-performance foam is not continuous in the x axis to avoid failure in flight. When this material collapses, a crack is transmitted to the whole sheet. By separating the different

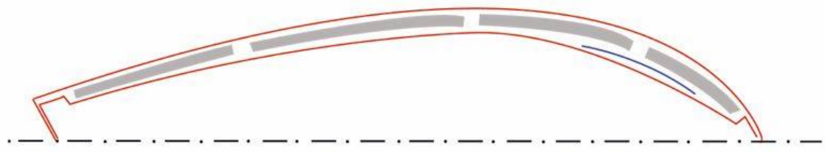


Figure 4.5: Scheme of the skin sandwich. In red, fibreglass; blue, carbon fibre; grey, *Rohacell*.

sheets –which will be more narrow–, the crack would be stopped at the edge of the collapsed region and it would not make collapse the whole structure.
Secondly, the unidirectional carbon fibre that is placed in the maximum thickness helps in the absorption of axial efforts in the most requested region of the wing (the classic airfoils have a suction peak in the LE which creates a much bigger lift in this zone).

Finally, both upper and lower surfaces have the same configuration in order to be structural symmetrical.

Internal structure

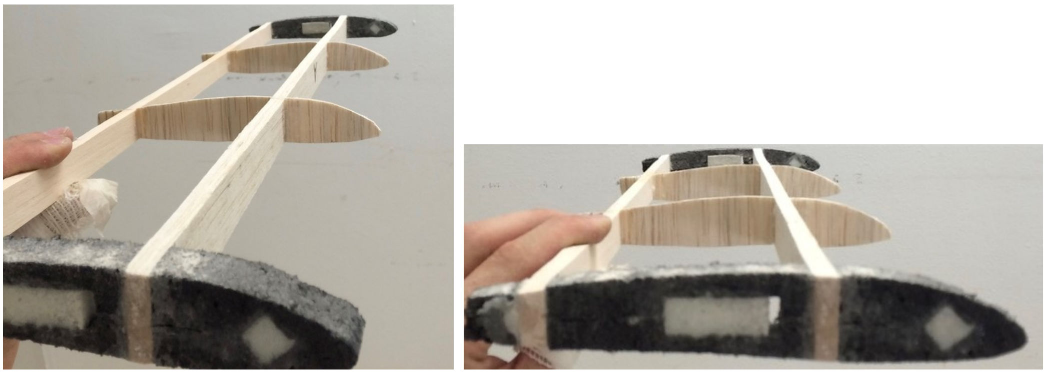
Besides the sandwich structure, a balsa-wood-made internal structure helps supporting shear strength (acting as a conventional beam and ribs). The first balsa wood beam have been located at, approximately, 30% of the chord. This location is not improvized because, in classic airfoils, the CG is near this percentage and, furthermore, the AC –a fictitious point where Aerodynamic forces are applied– is commonly located at 25% of the chord. This two points characterized the two origin of forces. Therefore, a structure that helps transmitting the effort on the z_{body} axis in such a critical point is needed.

The internal structure, as it can be seen in figure 4.6, is formed by two balsa wood beams of $8-10$ mm thickness which simulates the walls of a torsion box and, both, transmit and support shear tension. Furthermore, this configuration is more pleased to unify in detachable wings. Besides the beams, some balsa wood ribs of $0,5$ mm are added to help transmitting the shear tension and, the number of ribs used, defines the behaviour against buckling. In other words, the last defines the free length between supports that should limit –in more or less efficiency– the local buckling of upper surface against compression. Furthermore, balsa wood ribs are used to keep the shape of the wing, to help transmitting the shear between both surfaces and to reduce the bifurcation load (P_{cr}).

The use of this two balsa wood reinforcements aims achieving a lighter structure with a

better behaviour during the performance.
Balsa wood have been chosen because its good shear strength, its high fatigue endurance and its good temperature range. Furthermore, it has a low cost and it can be easily bonded and easily finished.

In figure 4.6, about the edges, the structure is reinforced with foam to absorb extra punctual reaction created in the supports during the tests.



(a) (b)

Figure 4.6: Internal structure.

4.4.2 Step by step explanation of the process

To understand how have been the wings build, in the following list all the steps of the process can be found.

1. Preparation of the workspace and materials: to clean the workshop, to cut the fibres and the core material at the exact size and the epoxy dose (resin and hardener separately). Theoretically, matrix corresponds to 40% of the total weight of the part and reinforcement, the resting 60%. To achieve that percentage and to ensure that all the surface is covered by the epoxy, the same mass of reinforcement will be prepared of epoxy (50%-50%). In order to reached a better precision, instead of mass percentage, we have worked in volume percentage (directly measured from a syringe. Inside the 50% of matrix, it is taken into account the hardener (30% volume) and the resin (70% volume). These doses have been to be confirmed with the density of each ones and of each resin (it has been used two different epoxies).

2. It is really important to place both moulds in the workspace in order to cut the bleeder film and the absorption blanket of the exact size. If the vacuum process works properly

and the state of these two components is optimal, the final percentage of the part would be 60% reinforcement and 40% matrix.

3. To protect the tables used with newspapers' sheets and place the non-sticky film –which will be used to build the vacuum bag– and the moulds. Furthermore, it is important to place the vacuum equipment in a position that would let all the workers perform their job without disturbing and near enough to create the vacuum efficiently.

4. To coat the surface of the mould with three or four layers of wax and three or four more of PVA. Before the appliance of a new layer, carefully ensure that the anterior layer is dry.

5. **Beginning of the lay-up process.** To locate the first fibreglass layer on the mould with the orientation chosen (0º/90º or 45º/-45º) and painted with epoxy properly mixed. It is recommended to have absorptive paper, surplus of non-sticky film and a glass with solvent in order to keep the workspace and the tools clean. To avoid air bubbles, the application of the epoxy must be from the centre to the edges, firstly to LE and TE and secondly to the lateral edges. Finally, an excess of epoxy will be applied in these edges to make sure that, during the vacuum process, the form of the wing is perfectly achieved.

6. Afterwards, *Rohacell* is placed not really close to LE nor TE to avoid air's entrance when the surplus would be cut. Above *Rohacell*, and at the maximum thickness of the airfoil, a thin and narrow unidirectional carbon fibre is placed.

7. The final fibreglass layer is placed and painted. The application methodology is the same as the one explained in the step 5. **End of the lay-up process.**

8. The lay-up process is performed again for the other mould. As explained before, the mould have to place exactly in the same position for the lay-up and the vacuum process. This esteem is thought to a more comfortable experience.

9. The room temperature and relative pressure are written down.

10. **Beginning of vacuum process.** A square hole is cut in the non-sticky film to introduce the mouthpiece and in a region of the mould with no curvature and out of the final part shape. Then, the bleeder film and the absorption blanket are fitted in the mould.

11. With a soldering iron, the bag is closed with the aid of guides that help making pressure between the two folds of the non-sticky film.

12. The mouthpiece, the security chamber and the pump are connected and the vacuum is carefully created. With the hands, the workers have to guarantee that the shape is perfectly achieved with the vacuum bag. In section 4.4.3, the equipment needed for the vacuum process is explained.

13. It is needed to be sure that no air's leak appear and that the vacuum process reaches, at least, 10 minutes losing half of the pressure (from approximately 1 to $0,5$ atm). In figure 4.7, the vacuum environment is shown.

(a) Upper surface part (b) Both moulds

Figure 4.7: Vacuum bagging methodology.

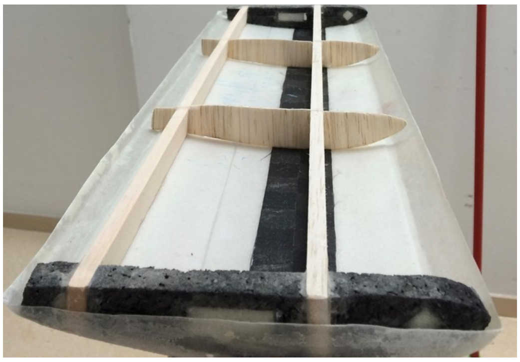
14. The process must work during three or three and a half hours performing cycles of 5 minutes ON and 10 minutes OFF. Once the process is finished, the part will be resting for 12 to 24 hours more at room temperature. In section 4.4.4, the influence of the temperature is discussed. **End of the vacuum process**.

15. Upper and lower surfaces are released and the quality of the parts is evaluated. At this point, it has to be decided if the lamination process should repeated or not. In addition, the skin sandwiches are weight.

16. The internal structure is cut and hand-sanded to fit perfectly in the wing. Each wing must be corresponded for a unique hand-sanded structure. The contact between the surface and the intern structure must be guaranteed.

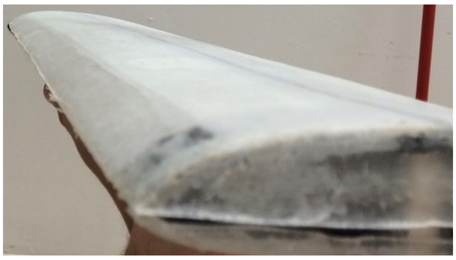
17. Using epoxy 30min –which means that in 30 minutes is hardened, but not cured yet–, the upper surface and the internal structure are glued. Once the epoxy has cured, the surplus of skin sandwich is cut for both parts (upper and lower surfaces). Then, the lower surface is glued. See figure 4.8 and figure 4.9.

(a) Curing process with weights

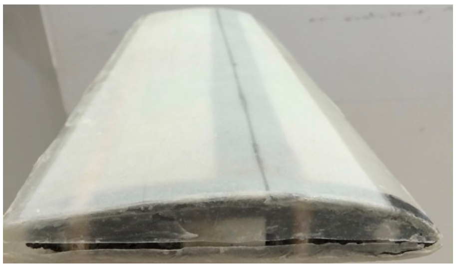


(b) Result after the curing process

Figure 4.8: Internal structure during the wing assembly.



(a) Continuity in LE is extremely needed



(b) Whole wing

Figure 4.9: Wing aspect after glued both surfaces to the internal structure.

18. To close the wing, fibreglass has been also used in the LE, TE and lateral edges. The continuity has to be extremely achieved in LE zone. If other kind of fibres would be used for improving some mechanical properties of the wing, now is the moment. For instance, carbon-Kevlar should be used for the LE. (See figure 4.10)

19. Let the wing repose and, after some hours (or days), possible tools for guaranteeing the alienation of edges are removed and the wing weighted. See figure 4.11.

20. Finally, some post-processes should be performed (painting, assembly systems, servos...)

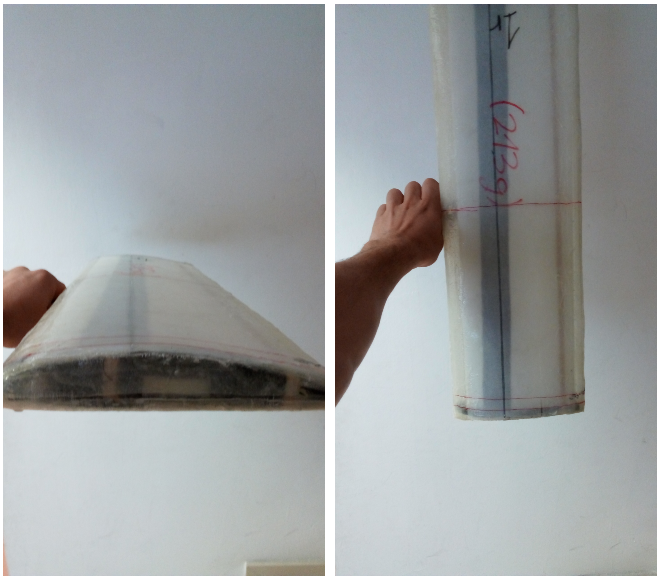


Figure 4.10: Wing aspect after closing the gaps in LE and TE.

Figure 4.11: Wing resting after fibreglass is glued.

4.4.3 Vacuum equipment

For the vacuum process, it has been used: (see figure 4.12)

- **Mouthpiece:** part that surrounds the film. It must be really fitted through the small square hole to avoid air's leaks.
- **Tubes:** are used to connect the three mains parts. A mechanical gadget is at the ends in order to ensure that it does not leave the other part during the process.
- **Filter:** is a tank where litter, majority epoxy, is stopped in its way to the pump, what helps maintaining the pump in optimal conditions.

- **Pump:** machine that creates the vacuum pressure. As better the pump, a larger continuous vacuum cycle –in mode ON– can be performed. If the pump is not so good, a programmer timer could be used to automatise the process.

(a) Mouthpiece (b) Filter (c) Pump

Figure 4.12: Vacuum equipment

4.4.4 Influence of temperature in curing epoxy

Just as a comment, thanks to the figure 4.13 and extrapolating the tendency to all temperatures, it can easily be concluded that a higher room temperature would make the epoxy curing faster, giving less time to laminate and create a proper vacuum.

4.5 Post-process considerations

The essentials of the methodology of manufacturing are already explained. But, for future references, data about the following topics should be kept for each specimen:

- Orientation of fibres
- Raw materials used
- Autoclave cure cycle
- Clean room environmental parameters

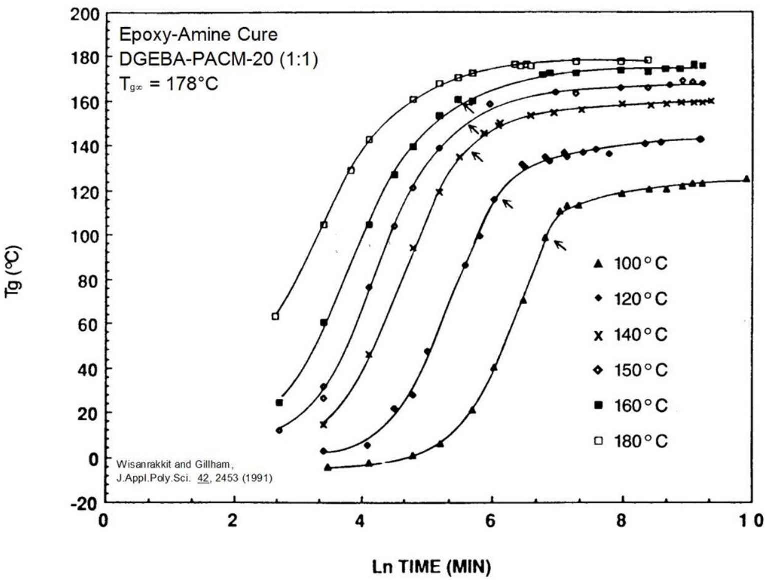


Figure 4.13: T_g of epoxy at different environtment conditions. [19]

- Routine manufacturing process data
- Quality assurance records for problems faced during manufacturing process
- Results of tests of the specimen should be kept

These data is kept in order to identify the behaviour of each modification and to extract conclusions once the specimens have been tested.

4.6 Standard of tests

In order to get some values of the specimens, a test on two supports and a distributed load. As it is shown in figure 4.14, the test uses, firstly, a traction machine for controlling the displacement and applying a continuous load. Secondly, it uses a load cell of 10 kN. The capacity of the load cell is important to avoid the noise in low loads measurements. Typically, loads between 1% and 5% of the maximum measurement can be deeply affected by electrical noise.

To capture both data, it has been used the traction machine software and catman Easy software [9].

For simulating a distributed load, a piece of wood (200 mm x 40 mm) that is pushed by the traction machine.

[9]An IBM software of data acquisition.

Figure 4.14: Montage of the tests

Finally, the relation of load and displacement has been plotted in order to find the load that the first mode of buckling appears (P_{cr}) and the system stiffness matrix (K). In the case of this TFG, the last matrix is just a value that is obtained directly using the following expression in the lineal region of the graph:

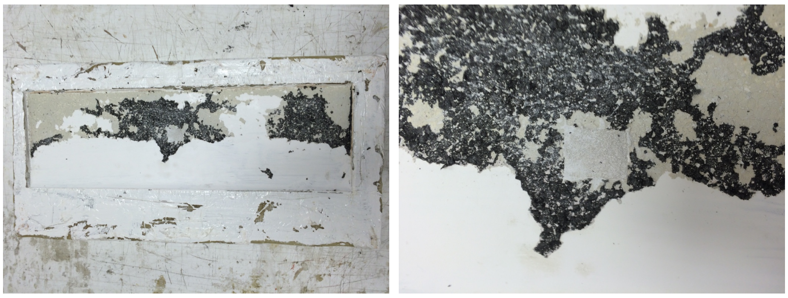
$$K = \frac{F}{\delta} \tag{4.1}$$

In addition, in Annex I, all tests are presented..

5 Results

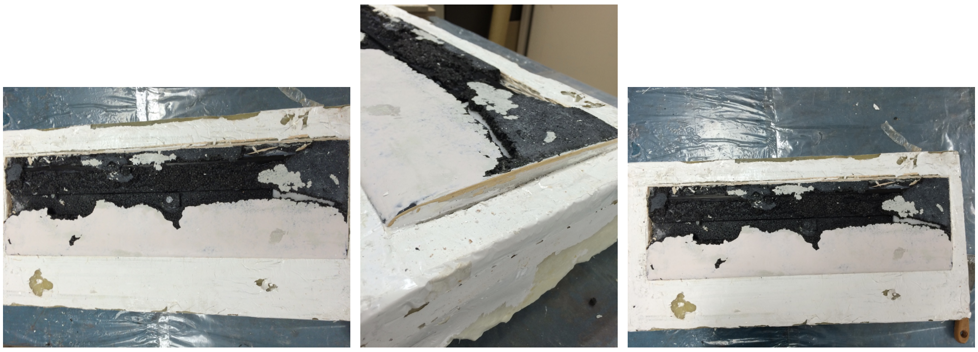
5.1 Interaction plug-mould

Due to the inoperative PVA and wax, the realising action of moulds from plug have been really hard. Firstly, both moulds were curing in the same curing box, what has complicated a lot the separation of both moulds. Secondly, the plug was weaker than the interaction plug-mould and it has been destroyed. Figures 5.1 and 5.2 show this problem.



(a) (b)

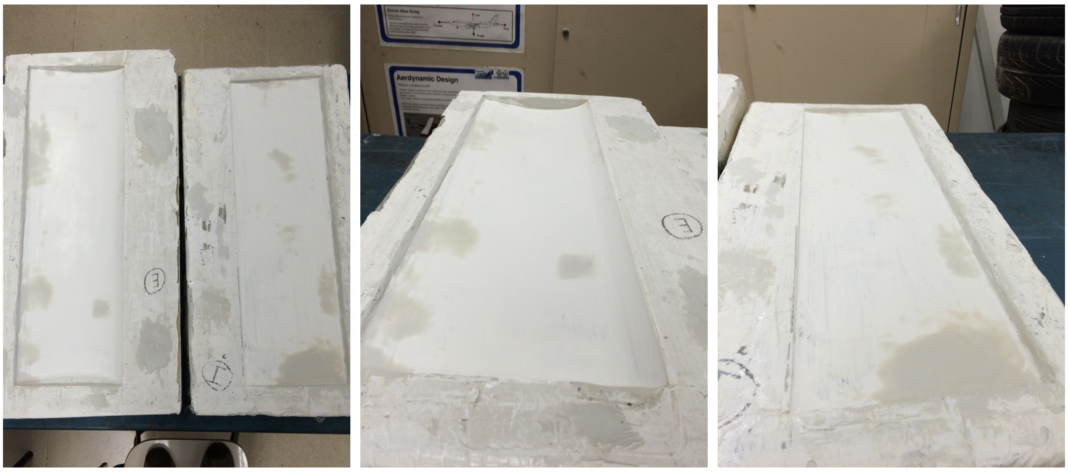
Figure 5.1: Lower surface mould after separation.



(a) (b) (c)

Figure 5.2: Upper surface mould after separation.

After some post-process, the mould have achieved a good quality, as it is shown in figure 5.3.



(a) Both moulds (b) Upper surface mould (c) Lower surface mould

Figure 5.3: Final moulds images.

5.2 First specimen

Considerations of lamination process

In table 5.1, it can be observed the details of the lamination of the first specimen's skin sandwich. In this case, the epoxy used is one of fast curing (in half an hour the texture was viscous enough to stop the lamination). The densities of the epoxy components are shown in table 5.2.

Taking into account the densities above, the percentage –in volume– of resin and hardener are 69,7% and 30,3% respectively.

Process' analysis

- **Epoxy's quantity used:** it have been used a 50% extra of epoxy for each skin sandwich.
- **Vacuum bagging:** both moulds have bent due to the gaseous nature of PU. This problem have been repared by increasing the quantity of PU in order to reduce the gas inside PU chains. The difference in height of the moulds have caused that the vacuum bag have suffered more than expected. Thanks to the fast curing of epoxy, the attempts to create a proper vacuum inside the bag have been enough to cure the skin sandwich.
- **Mould treatment:** before the lamination process, five coats of wax and three of PVA have been applied to the mould. The combination of both realising agents have made appear a white coat. In specimen 2, only PVA have been applied. After the process, the

Temperature	24,8°C
Relative humidity	40%
Compliance of UNE EN 2374	Yes
Upper surface reinforcement weight	Fibreglass = 30 g Carbon fibre = 2 g *Rohacell* = 6 g
Lower surface reinforcement weight	Fibreglass = 31 g Carbon fibre = 2 g *Rohacell* = 6 g
Orientation of fibreglass	0°/90°
Epoxy's proportions (of one dose)	Resin = 23 mL Hardener = 11,5 mL
Workers	Oriol Chandre Roger Serra Miguel Pareja Gurinder Saran Sergio Logrosán

Table 5.1: Considerations for the first specimen.

ρ_{resin}	1,15 g/cm^3 = 1,15 g/mL
$\rho_{hardener}$	1 g/cm^3 = 1 g/mL

Table 5.2: Densities used in the first speciment (fast-curing epoxy).

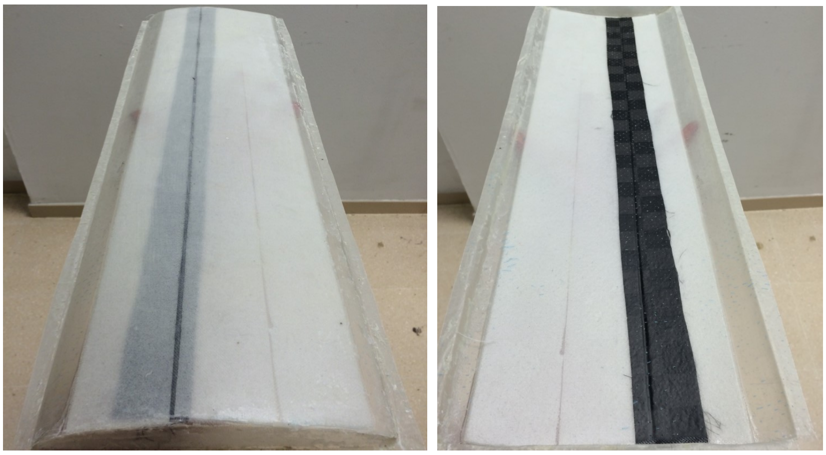
mould surface have good conditions to future laminations.

Tests

It has been considered that it is a proper skin sandwich, so that, the rest of the wing is added to them. As it can be seen in figures 5.4 and 5.5, the surface quality of the specimen is really fine.

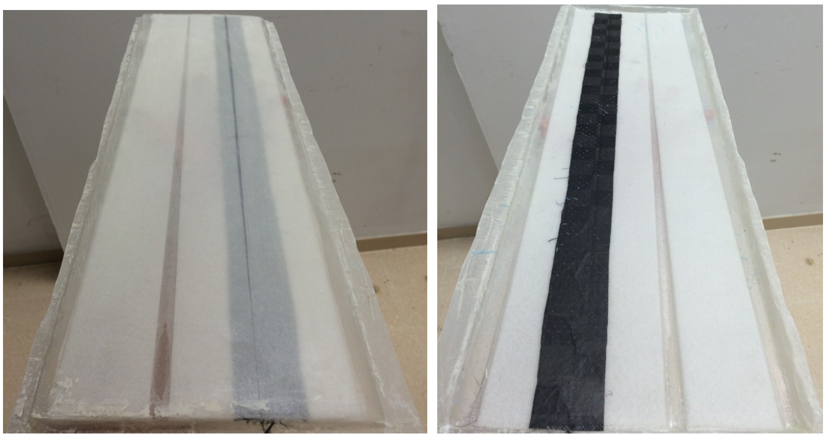
In table 5.3 and figure 5.6, the final characteristics of the specimen are presented. According to the final percentages (in terms of mass), the bleed film and the absorption blanket have work properly, reaching an optimal result.

The behaviour of the specimen has been as expected. It has collapsed due to buckling effects, so that, the P_{cr} has the same value than F: $431,66\ N$. As it can be seen the graph,



(a) Exterior surface (b) Interior surface

Figure 5.4: Upper surface (first specimen).



(a) Exterior surface (b) Interior surface

Figure 5.5: Lower surface (first specimen).

before the final collapsing of the specimen, there are 2 small losses of load. They can be originated by a relocation of some parts or by a starting damaging process of epoxy.
The structure collapses at the mentioned load but it is not a fragile fracture, so that, it would support a longer load cycle by decreasing little by little the load. Apparently, the internal structure remains intact. The wrinkle –that shows where the buckling effect is produced– is originated in the LE and with an orientation of 45º.

In table 5.4, the ultimate tensile strength, the bifurcation force (P_{cr}) and the K value are presented. Furthermore, in figure 5.7, the mechanism of failure can be seen.

For calculating the moment equivalence have been followed the equation 5.1.

Skin sandwich final weight	131 g 59% reinforcement 41% matrix
Number of ribs	1
Final wing weight	213 g
Distance between supports (y)	560 mm
Final load supported (F)	431,66 N
Total displacement (δ)	10,79 mm
Moment equivalence at collapse	60,43 Nm

Table 5.3: Sum-up results for the first specimen.

$$\frac{F}{2} \times \frac{y}{2} = M \tag{5.1}$$

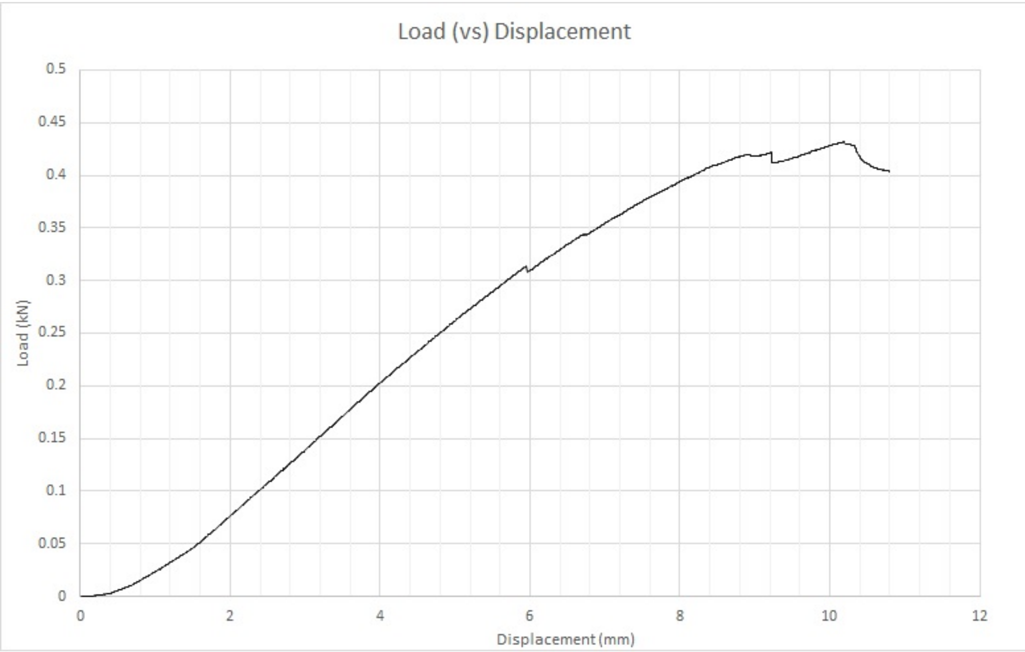


Figure 5.6: Load (vs) Displacement of the first specimen.

P_{cr}	431,66 N
K	40005 N/m

Table 5.4: First specimen's key values.

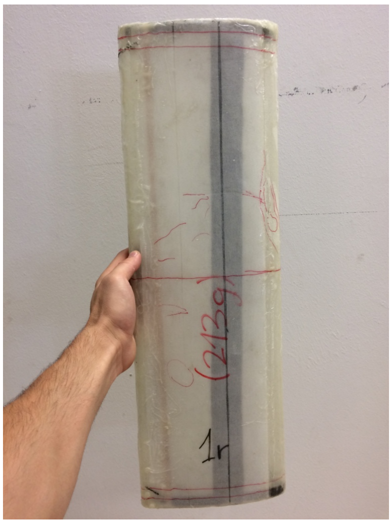


Figure 5.7: Mechanism of failure of the first specimen.

5.3 Second specimen

Considerations of lamination process

In table 5.5, it can be observed the details of the lamination of the second specimen's skin sandwich. In this case, the epoxy used is one of normal curing (it might take three hours to acquire viscosity and almost a day to a complete curing). The densities of the epoxy components are shown in table 5.6.

Taking into account the densities above, the percentage –in volume– of resin and hardener are 73,53% and 26,47% respectively.

Process' analysis

- **Epoxy's quantity used:** it have been used the exact quantity of epoxy planned for each skin sandwich.
- **Vacuum bagging:** both moulds have bent, again, due to the gaseous nature of PU. This problem have been repaired by adding concrete to the PU. The new epoxy offers more time for laminate and preparing the vacuum process. A programmer clock have been used to automatise the process. Stages of 5' ON and 10' OFF have been performed properly for a total of 4 hours. When the pump is working, a maximum of $0,98$ atm of

Temperature	24,0ºC
Relative humidity	39%
Compliance of UNE EN 2374	Yes
Upper surface reinforcement weight	Fibreglass = 32 g Carbon fibre = 2 g *Rohacell* = 7 g
Lower surface reinforcement weight	Fibreglass = 30 g Carbon fibre = 2 g *Rohacell* = 6 g
Orientation of fibreglass	0º/90º
Epoxy's proportions (of one dose)	Resin = 22,63 mL Hardener = 8,83 mL
Workers	Oriol Chandre Càndia Muñoz Albert Herrando Gurinder Saran

Table 5.5: Considerations for the second specimen.

ρ_{resin}	1,3 g/cm^3 = 1,3 g/mL
$\rho_{hardener}$	1,2 g/cm^3 = 1,2 g/mL

Table 5.6: Densities used in the second speciment (normal-curing epoxy).

vacuum is created and it has descended to $0,5$ *atm* before the pump works again.

- **Mould treatment:** before the lamination process, five coats of PVA have been applied to the mould. This change have been enough to avoid the appearance of a white layer. From now on, only PVA have been applied. After the process, the mould surface have good conditions to future laminations.

After some hours of rest, the resin may not cure as expected. To confirm the percentages of resin and hardener, some tests are performed. Some samples are let them curing and, after four hours, the texture of each sample is verified. In table 5.7, the results are presented.

For the following processes, the proportion of 65% resin and 35% hardener is selected.

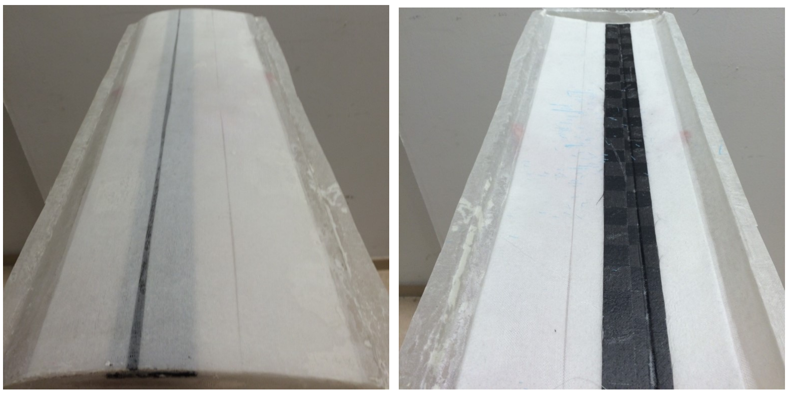
Tests

It has been considered that it is a proper skin sandwich, so that, the rest of the wing is added to them. As it can be seen in figures 5.8 and 5.9, the quality is highly correct. There

Percentage (in weight	Texture after 4 hours
70% Resin 30% Hardener	Almost solid
65% Resin 35% Hardener	Pretty viscous (the sample cannot almost drip)
60% Resin 40% Hardener	Viscous fluid
55% Resin 45% Hardener	Little viscous fluid (the sample starts dripping with some difficulties)
50% Resin 50% Hardener	Little viscous fluid
45% Resin 55% Hardener	Just starting to acquire viscosity (the sample drips with no much difficulties)
40% Resin 60% Hardener	Just starting to acquire viscosity

Table 5.7: Samples of different percentages of epoxy's components.

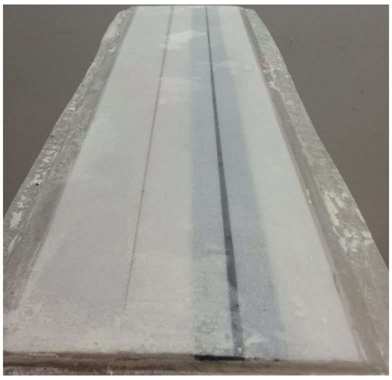
are some parts that have not the same appearance than others, but it can be dust particles or a first layer of moulds' clay.



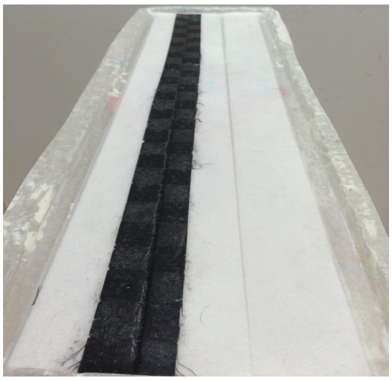
(a) Exterior surface (b) Interior surface

Figure 5.8: Upper surface (second specimen).

In table 5.8 and figure 5.10, the final characteristics of the specimen are presented. According to the final percentages (in terms of mass), the bleed film and the absorption blanket have work properly, reaching an optimal result.



(a) Exterior surface



(b) Interior surface

Figure 5.9: Lower surface (second specimen).

This specimen has the same behaviour against the load as the first specimen. So that, the hypothesis –that a weak point of the structure was the buckling mode– was correct. In this case, the graph presents some irregularities by decreasing load's values in determined points. Again, the reasons of them could be a relocating of internal structure. The value of K is quite similar and the use of two ribs seemed to not affect. The reason why this growth is so small could caused by the deformation of the foam used in the edges of the wings was bigger in one case than in the other. For example, if in the second specimen, the foam has compressed more than in the first specimen, then the value calculated of K is lower than the real value.
As the previous specimen, the structure has not failed suddenly and the internal structural seems to remain intact. The failure is produced at the edges of the wood piece that reproduces a distributed load. Furthermore, this fracture is in the x_{body} axis sense (from LE to TE). As it is not the expected wrinkle during a flight (which should be 45º or in the y_{body} direction), if this specimen was flying, it might not collapsed yet.

In table 5.9, the ultimate tensile strength, the bifurcation force (P_{cr}) and the K value are presented. Furthermore, in figure 5.11, the mechanism of failure can be seen.

5.3 Second specimen

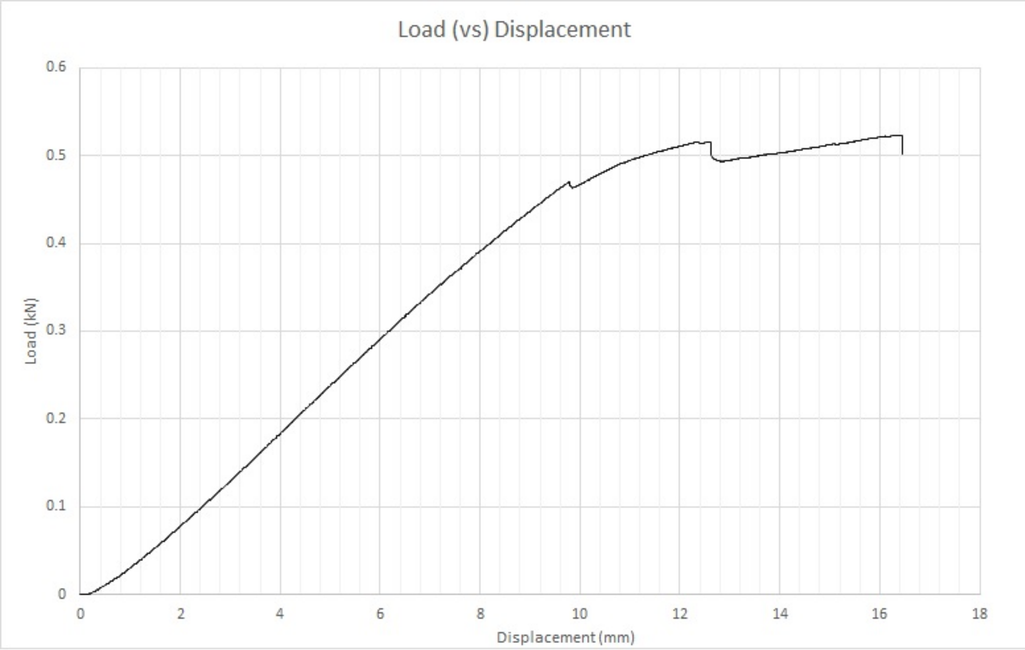


Figure 5.10: Load (vs) Displacement of the second specimen.

Figure 5.11: Mechanism of failure of the second specimen.

Skin sandwich final weight	111 g 72,1% reinforcement 27,9% matrix
Number of ribs	2
Final wing weight	192 g
Distance between supports (y)	560 mm
Final load supported (F)	523,36 N
Total displacement (δ)	12,40 mm
Moment equivalence at collapse	73,27 Nm

Table 5.8: Sum-up results for the second specimen.

P_{cr}	523,36 N
K	42206 N/m

Table 5.9: Second specimen's key values.

5.4 Third specimen

Considerations of lamination process

In table 5.10, it can be observed the details of the lamination of the third specimen's skin sandwich. As in the second specimen, the epoxy used is one of normal curing . The densities of the epoxy components are shown in table 5.6.

Taking into account these densities and the sample of table 5.7, the percentage –in volume– of resin and hardener are 66,8% and 33,2% respectively.

Process' analysis

- **Epoxy's quantity used:** it have been used the exact quantity of epoxy planned for each skin sandwich.

- **Vacuum bagging:** the soldering action have been hard to perform because the vacuum bag is the same for the two previous specimens. It is reached a maximum of $0,96\ atm$ but it descends quite easily to $0,9\ atm$. However, it holds up to 10' arriving to a minimum of $0,46\ atm$ (which it is considered as acceptable due to the problems in creating a better vacuum process). It seems that the pump is suffering more than usual (the oil may be changed), so that the vacuum cycle is reduced to 1' ON and 10' OFF, done manually during three hours.

Temperature	25,2ºC
Relative humidity	42%
Compliance of UNE EN 2374	Yes
Upper surface reinforcement weight	Fibreglass = 28 g Carbon fibre = 3 g *Rohacell* = 6 g
Lower surface reinforcement weight	Fibreglass = 26 g Carbon fibre = 3 g *Rohacell* = 6 g
Orientation of fibreglass	45º/-45º
Epoxy's proportions (of one dose)	Resin = 19 mL Hardener = 10,23 mL
Workers	Oriol Chandre Joan Altimira

Table 5.10: Considerations for the third specimen.

- **Mould treatment:** before the lamination process, five coats of PVA have been applied to the mould. The concrete is extremely useful for supporting the vacuum pressure, but PU deforms and the surface of the mould acquire some irregularities. It has been decided to perform another cycle, but these moulds may probably out of service.

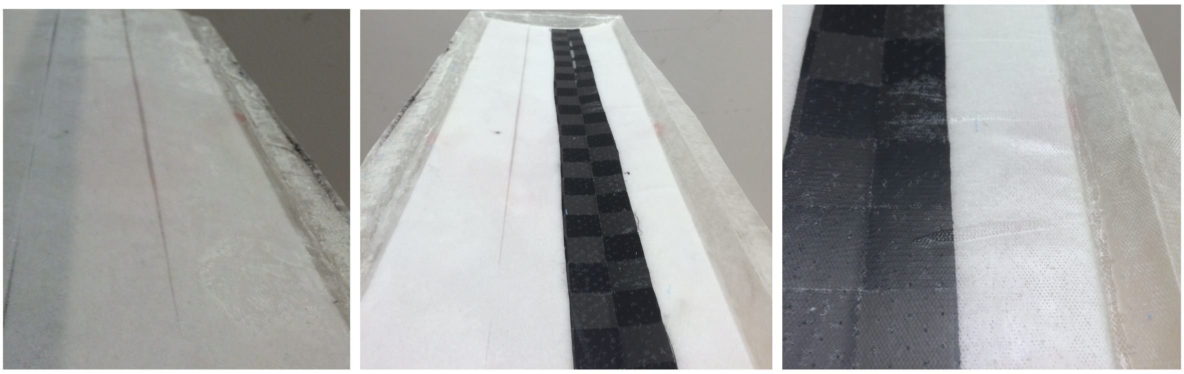
Tests

Due to the problems of vacuum process and in the moulds deformation, the final result of this specimen is not correct and the wing will not be constructed. As it can be seen in figures 5.12 and 5.13, air bubbles are present in all surfaces. The quality is much lower than quality of the first and second specimen. It is highly alarming the quality of the lower surface, which has much lower curvature.

In table 5.11, the final characteristics of the specimen are presented. According to the final percentages (in terms of mass), the bleed film and the absorption blanket have work properly, reaching an optimal result.

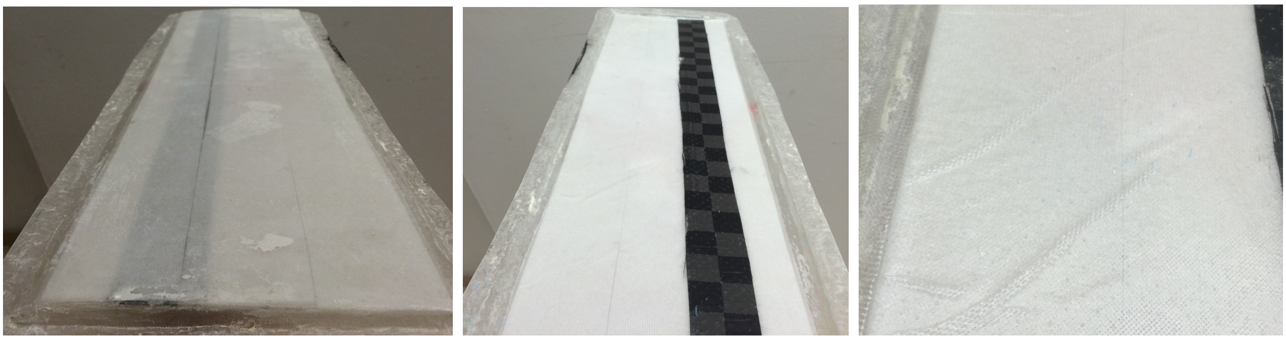
Skin sandwich final weight	122 g 60,66% reinforcement 39,34% matrix

Table 5.11: Sum-up results for the third specimen.



(a) Exterior surface (b) Interior surface (c) Zoom at an air bubble

Figure 5.12: Upper surface (third specimen).



(a) Exterior surface (b) Interior surface (c) Zoom at an air bubble

Figure 5.13: Lower surface (third specimen).

5.5 Fourth specimen

Considerations of lamination process

In table 5.12, it can be observed the details of the lamination of the fourth specimen's skin sandwich. As in the second and third specimen, the epoxy used is one of normal curing . The densities of the epoxy components are shown in table 5.6.

As it is the last specimen, the percentage of epoxy will be the same as the one with better results that, with this epoxy, is the second specimen: 73,53% resin and 26,47% hardener.

Process' analysis

- **Epoxy's quantity used:** it have been used a 50% extra quantity of epoxy because a bigger excess of epoxy have been used in the edges in order to ensure good results.
- **Vacuum bagging:** although the oil of the pump have been changed, it has been decided

Temperature	25,5ºC
Relative humidity	44%
Compliance of UNE EN 2374	Yes
Upper surface reinforcement weight	Fibreglass = 36 g Carbon fibre = 2 g *Rohacell* = 9 g
Lower surface reinforcement weight	Fibreglass = 32 g Carbon fibre = 2 g *Rohacell* = 5 g
Orientation of fibreglass	0º/90º
Epoxy's proportions (of one dose)	Resin = 26,58 mL Hardener = 10,35 mL
Workers	Oriol Chandre Gurinder Saran Joan Altimira

Table 5.12: Considerations for the fourth specimen.

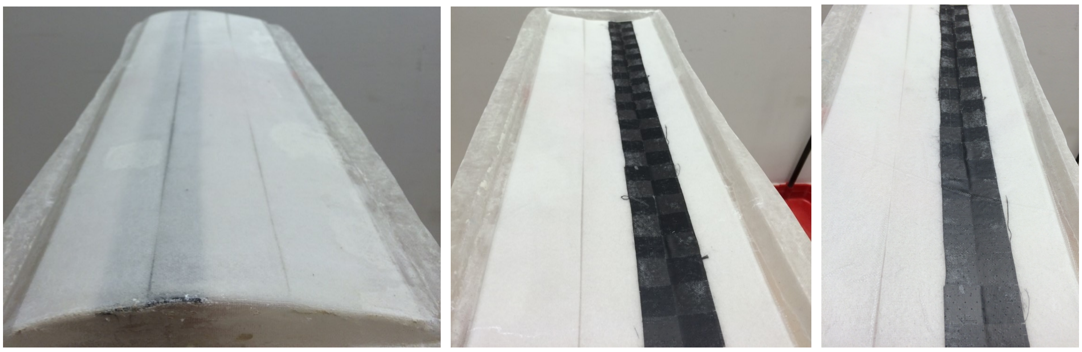
to perform a manual vacuum process. It is sought that *Rohacell* contacts and glues to the fibres, so that three stages of vacuum process have been done in 3 hours and a half. During one hour, the cycles have been 4' ON and 6' OFF (reaching a maximum of $0,96$ *atm* and a minimum of $0,46$ *atm*). Then, for 1 hour and 15 minutes, the cycles have been 3' ON and 5' OFF (reaching a maximum of $0,96$ *atm* and a minimum of $0,54$ *atm*). This variation have been in order to increase the minimum pressure and let the pump rest. The final stage has been one of 1 hour and 15 minutes again, with cycles of 2' ON and 4' OFF (reaching a maximum of $0,96$ *atm* and a minimum of $0,64$ *atm*). The bag has been replaced for a new one.

- **Mould treatment:** before the lamination process, four coats of PVA have been applied to the mould. As it had been said for the third specimen, the moulds were not at a good condition to perform a good vacuum process.

Tests

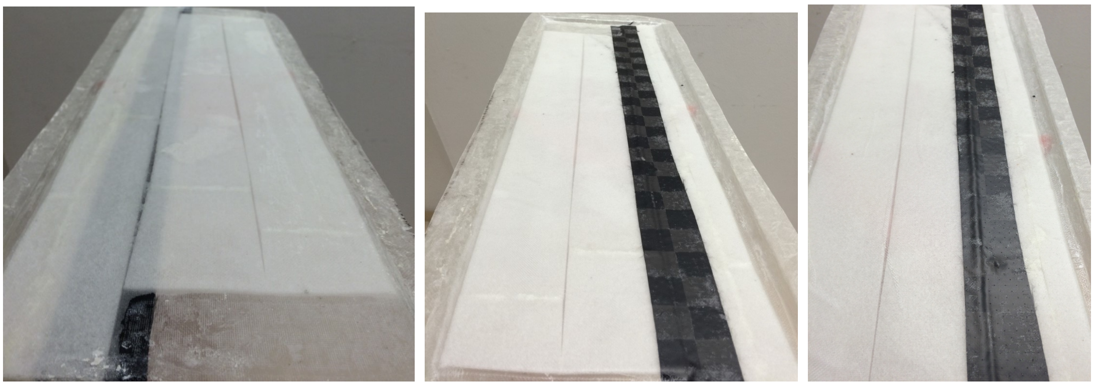
Although the aspect in the deformed mould seemed to be pretty correct, once the parts are released from the mould, air bubbles are created.
The only surface that are not okay is the exterior of the upper surface (the one which has more curvature). As it can be seen in figures 5.14 and 5.15, appearently the result is acceptable, except for the mentioned surface. This specimen has less *Rohacell* in the lower surface because

it were ended earlier than expected.



(a) Exterior surface (b) Interior surface (c) Zoom at an air bubble

Figure 5.14: Upper surface (fourth specimen).



(a) Exterior surface (b) Interior surface (c) Zoom at an air bubble

Figure 5.15: Lower surface (fourth specimen).

In table 5.13, the final characteristics of the specimen are presented. According to the final percentages (in terms of mass), the bleed film and the absorption blanket have work properly, reaching an optimal result.

Skin sandwich final weight	133 g 70,68% reinforcement 29,32% matrix

Table 5.13: Sum-up results for the fourth specimen.

5.6 Mould resistance

After four laminating processes, the mould are not in optimal conditions. In fact, the last two specimens can be affected by the mould state and it could be one of the reason of why the vacuum process have failed. The final state of the moulds can be seen in figures 5.16 and 5.17. As can be easily seen, the mould have been damaged during the last cycle.

Figure 5.16: Final state of moulds.

Figure 5.17: Detailed view of the mould surface.

6 Budget of the TFG

In this section, the budget of the TFG has been calculated. Almost all the products had to be bought, so that the price is strongly accurated. [22] [17].
Furthermore, the price per hour of a novel engineer has been considered of 20,00 €/h. [9].
Finally, the prices of *Rohacell* and the pump are approximated. The first have been provided by Evonik but the type of *Rohacell* used may not be the same as which they have priced.
Then, the second hand pump price, should contrasted with other offers.

CONCEPT	PRICE PER UNIT	UNITS	PRICE
Polyester gel coat (1kg)	13,12€	1	13,12€
Polyester resin 300 gr/m^2 (1kg)	10,70€	1	10,70€
Fibreglass mat 300 gr/m^2 (€/m^2)	4,31€	2	8,62€
Fibreglass 80 gr/m^2 (€/m^2)	5,12€	6	30,72€
Fibreglass 210 gr/m^2 (€/m^2)	7,30€	3	21,90€
PVA (1 kg)	7,06€	1	7,06€
Parting wax (1,5 kg)	21,66€	1	21,66€
Polyester filler	11,72€	1	11,72€
Epoxy resin (1 kg)	17,75€	1,5	26,63€
Unidirectional carbon fibre	10,85€	2	21,70€
Tubular vacuum bag	19,96€	2	39,92€
Bleeder film (€/m^2)	8,80€	2	17,60€
Absorption blanket 150 gr/m^2 (€/m^2)	3,90€	2	7,80€
Closing clay (10-roll box)	48,40€	1	48,40€
Abedul wood	22,56€	1	22,56€
Laser cut (€/min)	0,581€	20	11,62€
Balsa wood	22,35€	1	22,35€
Compacted wood	5,10€	1	5,10€
Rohacell A (€/m^2)	38,02€	2	76,04€
PU	3,95€	2	7,90€
Programmable clock	19,95€	1	19,95€
Clock with temperature and relative pressure sensors	21,00€	1	21,00€
Gloves (box of 100u)	8,12€	1	8,12€
Face mask 3M	6,05€	2	12,10€
Protection glasses	10,48€	2	20,96€
Brushes	0,35€	8	2,80€
Vacuum pump (Second hand)	164,76€	1	164,76€
Personal fees (€/h)	20,00€	600	12.000,00€
TOTAL			**12.682,82€**

Table 6.1: Budget of the TFG

7 Environmental impact study

In this section, general composites environmental issues have been treated. Then, from the materials used in the TFG construction part, *Rohacell* and epoxy resins are added to the environmental analysis.

Besides the important politics that have been made in the last decades in order to make more environmental-friendly industries, what means less contaminants agents emitted to the air and a better treatment of materials in their end of life, the composites' industry is now entering to the end of the end-of-life of the first-used composites materials. For that reason, environmental legislation will mandate engineering composite materials to be properly recovered and recycled in a near future.
Extensive research and development is being done to develop better recyclable composites and recycling technologies for composite materials. This will contribute to the sustainable development of composites industry.

As a general argument, composites' lighter weight allow a lower environmental load when they are transported or used in transport application. Besides, composites are more corrosion-resistance, which let that the parts will last longer.

Distancing from the direct operating advantages of composites, conventionally produced composite materials are made from petroleum based resins and fibres –which are non-degradable. This fact becomes a significant problem when most composites end up in a landfill once the life cycle of a composite comes to an end.
Motivated for the growing ideological trend of green engineering, significant research are being conducted in biodegradable composite materials, which are made of natural fibres.

Talking of **fibreglass**, it is produced by using less energy and is used in products which result in less carbon emissions. Furthermore, research has lead to methods such as grinding, incineration and pyrolysis. But, recycled fibreglass have been effective in reducing shrinkage in concrete thereby increasing its durability. Also, recycled fibreglass can be used as filler in resin, which can increase mechanical properties in certain applications.[10]

Related to **carbon fibres**, research has been conducted to extract the high value carbon fibres from end-of-life components, with the goal to use them for creating other carbon fibre composites. Furthermore, recycled carbon fibres are used in bulk moulding components, phone cases or laptop shells, among others.[10]

Talking of ***Rohacell***, it is non-hazardous, not governed by any particular safety regulations and non-water-polluting. Besides, it can be disposed of in accordance with local ordinances but it cannot be materially recycled. If possible, incinerate in a common combustion plant instead of land-filling as a disposal method.[18]

Related to **epoxy resin**, a technology called *Recyclamine* enables the recovery of the epoxy thermoset resin as its thermoplastic counterpart. With *Recyclamine* cured resins, potentially all components of a composite are recoverable. Unfortunately, this technilogy is not commerciable yet. So that, for now, pyrolysis –which burns away everything except for the fibre reinforcements– looks like the only real recycling method.[23]

8 Planning

The idea is to keep iterating possible solutions while the methodology is practised. The structural simulations that will be done with *Abaqus* will define the structural design, but some intermediate designs should be tested in order to correlate the simulations with the reality. Finally, to obtain useful results, only one variable of design should be analysed every test.

8.1 Brief description of the future tasks

NOTE: Tasks in sections 8.1 and 8.2 will be treated as classified. The chronological relation between tasks can be easily seen in the figure 8.1.

- **Mould constructions**
  - **Aerodynamic design:**
    If a new wing is wanted to be constructed, the airfoil used, the planform of the wing and geometrical parameters of the wing such as dihedral angle, swept angle or taper ratio must be define. However, using an already designed wing is also an option.
  - **Mould fabrication:**
    New moulds should be constructed. Two work stations and concrete (for the base) will be used.
- **Vacuum bagging iteration**
  - To prove different *Rohacell* sizes to define the optimal for reproducing the airfoil's curvature.
  - To combine different orientation of fibres (0º/90º and 45º/-45º) to corroborate its effects in th final results.
  - To reduce fibreglass weight and test the especimen to verify its behaviour.
  - To compare results of *Rohacell* core sandwiches with balsa wood core sandwiches. It should be compared in terms of loads supported, values of K and weight.
- **Wing assembly**
  - To iterate the number of balsa wood ribs and their thickness. They should be emptied anyway.
  - To improve the joining system for upper and lower surfaces. Maybe, some tooling should be designed and constructed.

  - To create an assembly system between different wing's sections. The two-beam system should be used.

- **Alternatives to vacuum process**
  The following question should be answered: "Is possible to manufacture an entire wing by using balloon method [10], adding the internal structure *a posteriori*?"

8.2 Detailed relation between future tasks

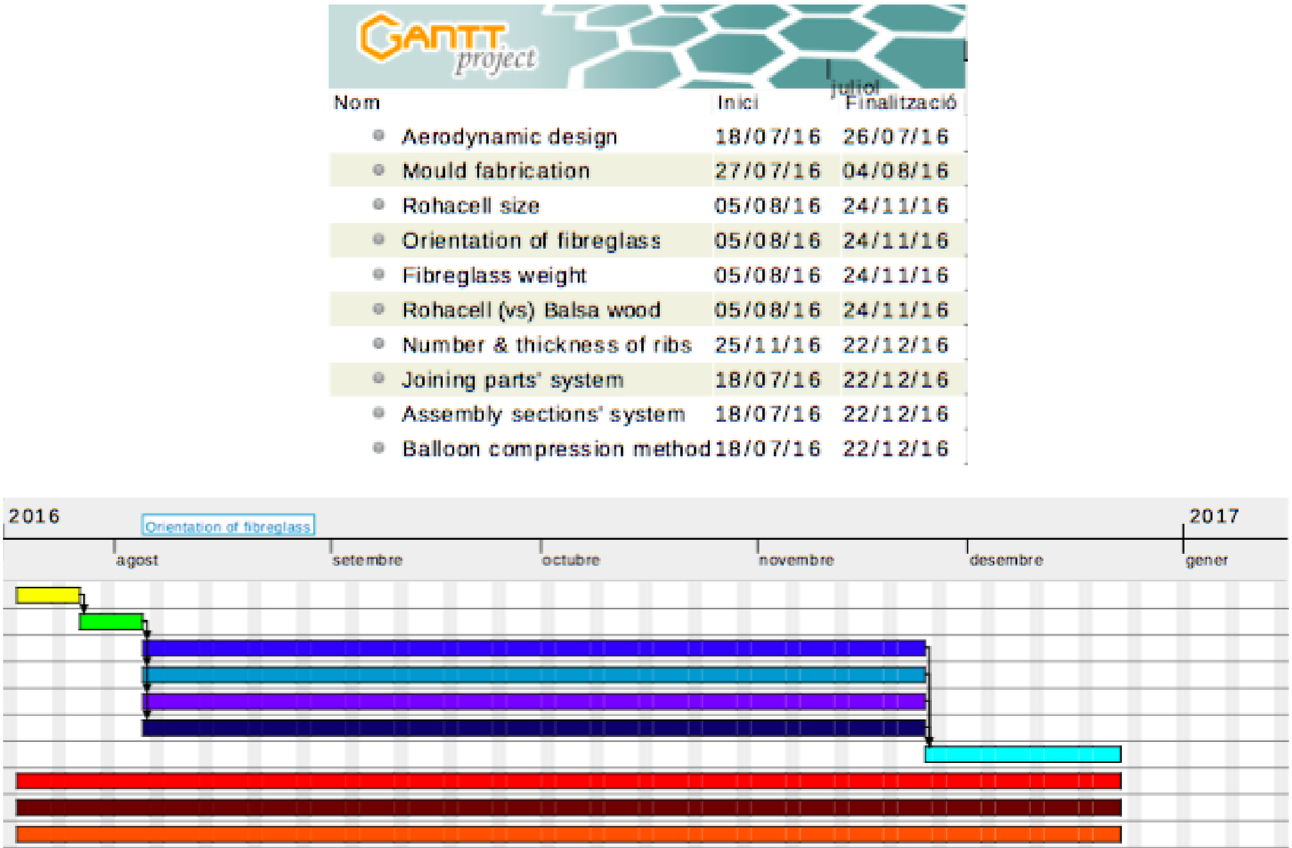
To accomplish the objective of this study, several tasks must be fulfilled. These tasks are presented in the table 8.1.

CODE OF THE TASK	TASK IDENTIFICATION	PRECEDING TASK(S)
	Mould construction	
MC1	Aerodynamic design	None
MC2	Mould fabrication	MC1
	Vacuum bagging iteration	
VBI1	*Rohacell* size (and tests)	MC2
VBI2	Orientation of fibreglass (ans tests	MC2
VB32	Fibreglass weight (and tests)	MC2
VBI4	*Rohacell* (vs) balsa wood (and tests)	MC2
	Wing assembly	
WA1	Number and thickness of ribs (and tests)	VBI1, VBI2, VBI3, VBI4
WA2	Joining parts' system (and tests)	None
WA3	Assembly sections' system (and tests)	None
	Alternatives	
A1	Balloon compression method	None

Table 8.1: Interdependency of tasks

[10] To blow a bag and to cure the lamination sheet with compression pressure.

8.3 Scheduling



Nom	Inici	Finalització
Aerodynamic design	18/07/16	26/07/16
Mould fabrication	27/07/16	04/08/16
Rohacell size	05/08/16	24/11/16
Orientation of fibreglass	05/08/16	24/11/16
Fibreglass weight	05/08/16	24/11/16
Rohacell (vs) Balsa wood	05/08/16	24/11/16
Number & thickness of ribs	25/11/16	22/12/16
Joining parts' system	18/07/16	22/12/16
Assembly sections' system	18/07/16	22/12/16
Balloon compression method	18/07/16	22/12/16

Figure 8.1: GANTT chart used for the plannig of time

In the figure 8.1, a planning of the time can be seen.
This planning, see figure 8.1, is though in two stages. The first, the variables of skin sandwich design should be determined. But a parallel work should be done by thinking of the other concepts: the joining system of parts, the assembly system of sections and the possibility of performing a balloon compression method.

9 Conclusions

Trencalòs had confidence that this TFG should be the first iteration of a large way to a perfect monocoque structure. According to this starting purpose, it is clear that it has been done. In the following paragraphs, some of the solution though for all the processes are presented as conclusions of the TFG. Furthermore, it has been confirmed that structural skin is viable in terms of production of Trencalòs Team (which would be three or four gathered in six or seven months).

Talking about plug and mould construction issues, it has been concluded that the same plug for the lower and upper surface is not the optimal solution because the quality of one will be reduced when the worker is claying and hand-sanding the other. For this problem, it has been thought two alternatives:

- To fabricate an wooden wing formed by two parts (separated using the chord line). This way, one could work both work-station with a high-quality result. Working in two different plugs, the quality can be higher in both surfaces and, also, manufacturing the moulds is more comfortable and efficient. Both moulds can be produced at the same time and, also, realising both mould would be independent, avoiding one of the problems of this TFG. It seems to be the most optimal option (for its economic price and workability).

- To mechanise the female mould directly, saving hours working in the plug. If this path is taken, a superficial treatment to achieve a good finish might be done.

Regarding TFG's planning, the modelling of the plug and the mould construction have been taken a longer amount of time that what was initially planned. Otherwise, spending this amount of time reaching a proper quality in the plug and mould have let to produce better specimens.

Talking about the construction methodology, epoxy is not as determinant, to the quality of the plug, as are moulds and vacuum bagging process. It is important to perform the best surface quality possible in the mould because the final part is always a little worse. For improving the vacuum bagging method, the maintenance of the pump is really important, the mould should have the less thickness that the airfoil permits.
In addition, it has been corroborated that the soldering iron is a solution, but it might not be the best solution for big vacuum bagging processes.
The alienation of the LE is critical and it is really difficult to ensure the complete continuity on it. So that, a balloon method applied to the entire wing should be better. But, to implant

this methodology, it must be found a way of introducing the internal structure inside without breaking the skin sandwich.
Using concrete from the beginning, the behaviour of the mould would be improved and longer life's cycles of moulds might be achieved. From this TFG, it is possible to claim that the life's cycle of moulds are 2.
Continuing with construction issues, the variance in room temperature –which is not pretty ranged– is not important in the curing process of epoxy.
Then, the core of the sandwich should be also improved. Firstly, more narrow sheets should be cut in order to define better the curvature of the airfoil selected. Secondly, it may be used from a nearer position to the LE because, as it has been seen in the test, the wrinkle starts at LE but it is stopped by the *Rohacell*. So that, if the *Rohacell* starts before, the wrinkle should be less critical.

Talking about the final results, the shear condition tested is more demanding than in real flights because, in real flights, pressure is distributed along the wingspan, not only in a central region and gathered in the 20-40% of the chord.
Furthermore, it has been seen that the number of ribs affects the ultimate load but it seems to increased less than expected the value of K. The most reasonable meaning of these results is the fact that the foam located in the edges have deformed more in one test than in the other. Therefore, as the results are not clear, more tests must be performed to achieving the best solution.

Besides, in order to reduce weight –which is primordial–, lighter fibreglass should be used. For example, it should be test fibreglass of $40g/m^2$.

To sum-up, as it has been explained in the planning section, more tests and practice should be performed in order to mature this technology, that seems to be reliable and interesting. From a good mould, it may be constructed three or four wings without dependence of anybody.

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