NUMERICAL SIMULATION IN FINITE ELEMENT METHOD AND MANUFACTURING OF LUG MATERIAL COMPOSITE BY RTM PROCESS

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Abstract

This work focuses on developing the numerical simulation methodology on finite elements to manufacture a composite material lug through the Resin Transfer Molding (RTM) method. The main goal of this project is to apply this methodology into the manufacturing of thick composite laminated components for aeronautical applications. The following points were established: lug conception, mold design, and component manufacturing. The conception of the lug was determined by numerical analysis used to calculate its ideal thickness and geometry under the load condition for a specific structural application. The mold design and the component manufacturing were part of the experimental phase, developed by RTM process.

1 Introduction

The aeronautical industry has always been in a constant search for structural design improvement by developing components that would result in a greater reliability. Studies have shown that when one is able to correlate the material properties with the manufacturing process, it´s possible to gain more productivity, increase quality, and reduce costs considerably.

The application of composite materials, such as fiberglass and carbon fiber, is being largely used in the aeronautic industry, and replacing metallic materials. Many commercial, military, and executive aircraft projects have already adopted this component manufacturing process. According to Rezende [1], the replacement of the metallic materials by composite materials has been growing on aircraft projects over the years.

Nowadays, composite materials application is restricted to thickness structures normally that are applied to manufacture skins, fairings and widely applied on finishing parts. There are few applications with highest thickness and high structure responsibility. Then there is a focus of study that focus to change metallic parts for composite components manufacture by high thickness, with the objective to manufacture simplify, lose weight and reduce cost of final product.

Regarding this demand increase, the manufacture processes are also change to develop increasing with regard to costs and production time.

The application of components manufactured of composite materials also goes in this direction, especially by the fact that these components are not usually associated with a low cost. Structural components that before manufactured separated parts, now has been manufacture on one assembly, simplified the manufacture process and increasing structural reliability, based on Kassapoglou *et al*. [2] described.

Among the parts of manufacturing processes of composite materials there are some that are widely used. Due to its versatility and simplicity, the vacuum bag molding has been consolidated over the years as a method to presents these main features. By the way there are processes in increasing development that present in addition to these advantages, others represent a great differential.

The RTM process has already been used in the manufacture of composite material structural components, which offers advantages in relation to other processes established in the aircraft industry.

The main applications for the RTM process, highlights are pieces that are manufactured in large batches, with complex geometries, precise dimensions and high thicknesses, as is illustrated in Fig. 1.

Figure 1. Aeronautical components manufacture by RTM process (Hart-Smith [3] and Bickley [4]).

The study of thick laminates can contribute significantly to the structural component, for replacing parts that are currently made of metallic materials for composite materials.

This replacement is also aligned to improve the manufacturing process, for industrially intended to reduce cost and manufacture time, results of structural weight reduction in a better performance of the aircraft. According to the proposed method will require only one mold for manufacturing many parts, guaranteeing the reproducibility, and avoiding the finishing process.

Currently, there are already assemblies that are made of composite material, among them we can mention horizontal and vertical stabilizers, but the connection components are still manufactured in metallic materials. With this work aims is also integration between these structural assemblies, that is, all components can be manufactured in composite material.

2 Methodology

The work can be divided into two parts:

1st part) Definition of lug geometry: at this first phase is necessary to study the basic characteristics of the component to be produced by ligning the manufacturing method proposed to mold manufacture aiming at simplifying the geometry.

2nd part) Mold and lug manufacturing: the second phase, it is proposed to design and manufacturing the mold and subsequently, the component manufacturing through the RTM. Variables of process manufacturing can be modified at this stage, if there is any discrepancy in the manufacturing component.

3 Results

3.1 Lug Geometry

The lug geometry was studied by observing various applications in structural assemblies to which associated a similarity with the objectives of this project. This structural element may be used in the connection between the horizontal stabilizer and the fuselage and it´s responsible for load transfer between these parts of the aircraft.

Wallin et al. [5] established the lug geometry as a laminated divided into three parts, formed by two symmetrical parts and a flat plate in the center of the piece. Symmetrical parts have flanges for attachment to assembly in the structure where it will be installed. These flanges are responsible for transferring the load between the lug and the structure according to Fig. 2:

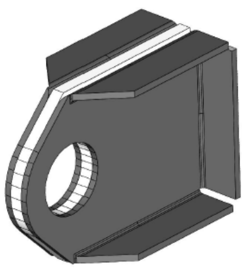

Figure 2. Isometric view of lug, Wallin *et al.* [5].

Based on this model was the first proposal to defined the lug geometry being studied as shown in Fig. 3:

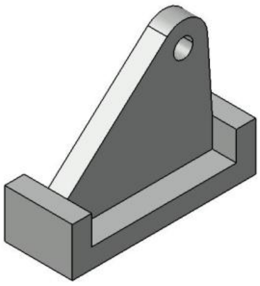

Figure 3. Isometric view of first lug proposal.

Thus, it was possible to define a first proposal of mold manufacturing geometry and also a proposal for the design of test instruments. This was the basis to develop the numerical analysis of piece, mold, and both of manufacturing processes.

From preliminary analysis, was defined a new geometry of piece, taking into consideration some parameters that could cause problems in manufacturing, but Small changes in relation to first geometry, as can be seen in Fig. 4:

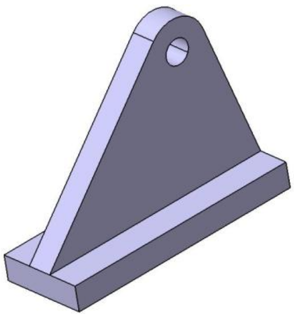

Figure 4. Isometric view of second lug proposal.

It´s concluded from these analysis that the lug geometry presented wouldn´t be the most feasible from the view of productive. Parameters were identified which make it difficult to manufacture the part, mold and test instruments. Furthermore, the lamination process of piece would be more difficult because the resin injection into the mold can´t be very efficient causing "dry spots" in the final product. Therefore, the first two geometrical lug proposals were modified in order to improve the points mentioned above.

With manufacture parameters analyzed and the proposed changes, the lug geometry it has been modified, as can be seen in Fig. 5:

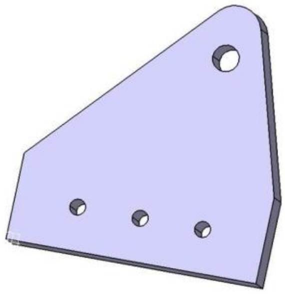

Figure 5. Isometric view of third lug proposal.

Has developed a finite element model with linear analysis to determine the thickness. This model serves as the basis for defining the basic geometry and number of layers laminated to the predefined load. The only input data for development of the model is the load value at which the element is subject in its application. It was found in literatures the typical value of 80 kN load for this type of structural element, applied in executive aircraft configuration of stabilizers named as with "T". This value will be used as the basis of all development of this work. The crimping and loading conditions were assumed ideal and applied to the finite element model.

According to Fig. 6, three holes on the bottom of specimen is clamped, that is been restricted to three translations and three rotations according to the reference coordinate system, simulating the condition for three mounting screws. In the hole of upper specimen where the pin is installed and applied prescribed load (F) in the y direction, the rotation is restricted in all axes and the displacement on the axis perpendicular to the applied load (z axis). It created a reference point on the top pin for application of load. It characterized the contact condition between the pin and lug and that were modeled as 3D rigid analytical.

The 3D model has been established deformable shell-like elements, but with characteristics and mechanical properties through the thickness, defining the amount of specimen layers. The element used is named S4R, classic element for modeling laminated surfaces of composite materials in ABAQUS/*Explicit*. The element has four nodes and reduced integration. The Fig. 6 illustrates the geometry of the developed model and boundary conditions.

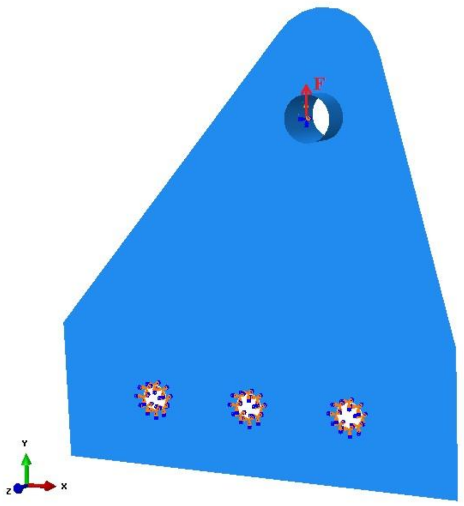

Figure 6. Geometrical model developed and boundary conditions.

With this model the linear analysis results were obtained concerning the number of layers sufficient to support the predetermined load as measured by the failure criteria Tsai-Wu and Tsai-Hill. This analysis doesn´t characterize the catastrophic failure of the element, but the failure of the first layer according to the failure criteria mentioned. These define only if the number of layers used to obtain the results is sufficient to support the load proposed.

After testing some quantities of model layers with the same boundary conditions, several results were obtained and it was concluded that for the proposed load withstand would be required #56 layers of material used in the modeling. Thus defined number of layers and the thickness specimen. These layers are arranged in the specimen modeling according to eq. (1):

$$[+45, -45, 0, 90, 90, 0, -45, +45]_{7T} \qquad (1)$$

Where: *T* – is total of layers

The results obtained are describe in Tab.1.

Tabel 1. Results of first analysis.

Displacement (mm)	Von Misses (MPa)	Tsai-Hill	Tsai-Wu
0,48	854	1,33	1,05

For this same model was developed nonlinear analysis to compare the results of the previous analysis, but with some modifications necessary to establish the area where you want to occur catastrophic component failure.

On the upper hole of the specimen was inserted a pin and apply a prescribed offset (δ) in the direction y of 2 mm. Restricted rotation about all axes and the displacement in the perpendicular axis to the applied load (z axis). It was characterized the contact condition between the pin and lug. This pin was modeled as a deformable 3D using C3D8R element with the mechanical properties of the material. This element has eight nodes with reduced integration and curl control.

The specimen was prepared with 3D shell elements deformable, but with characteristics and mechanical properties along the thickness, defining the number of specimen layers. The element used for modeling the specimen is called S4R, classic element for modeling laminated surfaces of composite materials in ABAQUS/Explicit. The element has four nodes and reduced integration.

In this model simulated the nonlinear condition using the fail model, implemented in Fortran software based on paper developed by Yokoyama *et al* [6] and Donadon *et al* [7].

With this analysis it was possible to evaluate the catastrophic failure and determine the optimal diameter of the upper pin, and drive for failure to occur in this predetermined region. Fig. 7 illustrates the geometry, boundary conditions and the mesh used in the modeling.

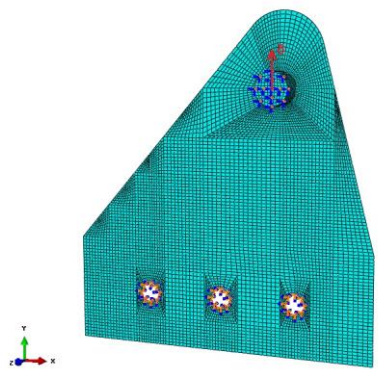

Figure 7. Geometry, boundary conditions, and mesh using in modeling.

With the non-linear analysis of this model results were obtained regarding the specimen failure load, changed the diameter of the upper hole for failure to occur in that region.

After testing some values of diameter of upper hole and using the same boundary conditions, it is concluded that the ideal diameter for failure occurs at the desired region should be equal to 32 mm.

Thus defined the number of layers, the basic geometry, failure load and the location where you want to occur catastrophic failure of the specimen. The arrangement of the layers has not changed and is the same as previously described sequence.

However, the application of this lug was modified before it could be used to make the connection between the vertical stabilizer and fuselage. With these changes, this structural element can be used to make the connection between the horizontal stabilizer and the vertical stabilizer assembly.

When doing new analysis of mold manufacturing process, the manufacturing of the part and the specimen of the test procedure, there were some changes that could cooperate to achieve the desired results. The geometry given above viewpoint testing is not feasible, because the risk of failure occurs on the part of the bottom line of fasteners would be great, since there is an asymmetry in the load.

It was necessary to modify the geometry of the part again, looking for associate the mold manufacturing processes and parts and perform the test, as shown in Fig. 8.

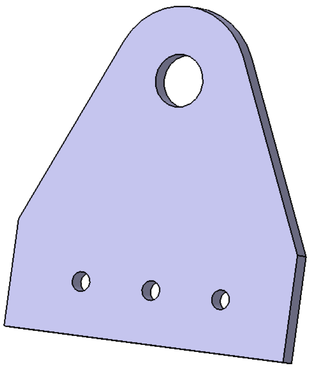

Figure 8. Isometric view of final lug design.

Thus, it became necessary to develop a new finite element model for analysis of the results with the new geometry.

The conditions of fastening and loading were assumed ideal and applied in the model.

The boundary conditions, load characteristics and model were regarded as identical to the previous one, only changed the geometry.

Geometry is represented by Fig. 9, boundary conditions and the mesh used in the new model.

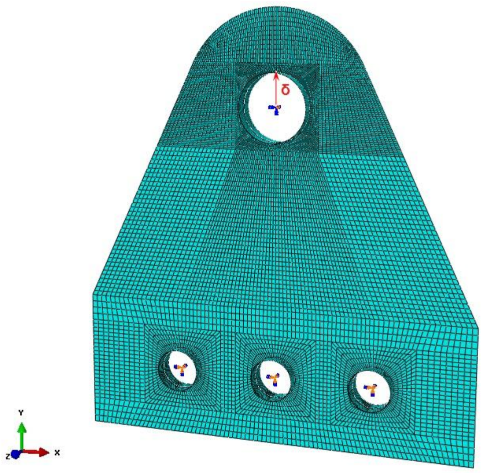

Figure 9. New geometry, boundary conditions and mesh using in problem modeling.

The number of layers should be reduced. As required forty-eight layers are required to meet the proposed requirements for loading and failure specimen according to results of the numerical analysis.

These layers are arranged in the specimen modeling in the following order in eq. 2:

$$[+45, -45, 0, 90, 90, 0, -45, +45]_{6T} \qquad (2)$$

The other characteristics of the model remain unchanged.

The result obtained in the finite element model shown in Fig. 10.

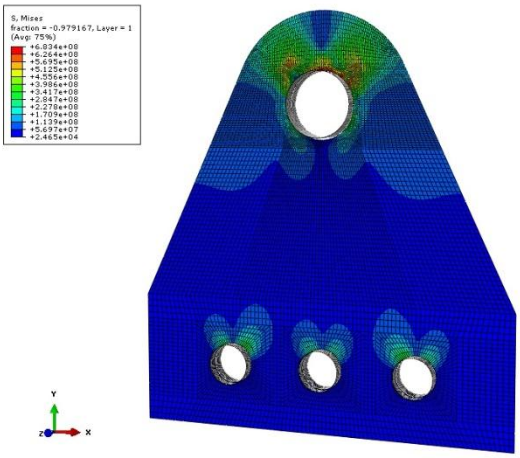

Figure 10. Finite elements results for new geometry.

3.2 Lug Topology

With the lug topology defined according to criteria of manufacture and failure region described in section 3.1 "Lug Geometry", determines the values of geometric element measured.

The lug is manufactured according to measurements shown in Fig. 11

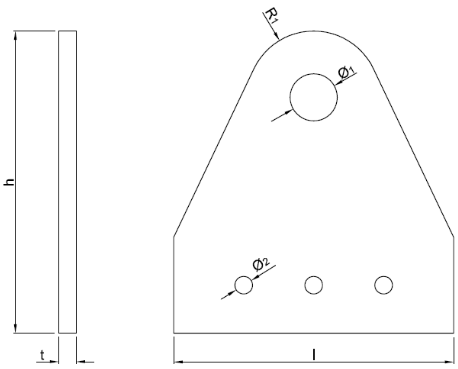

Figure 11. Lug Topology.

Where: t – thickness

l – width

h – height

R_1 – radius of lug

ϕ_1 – pin diameter

ϕ_2 – bolts diameter (typical – 3x)

The dimensions listed above are shown in Tab. 2.

Table 2. Basic dimensions of lug

Parameter	Dimension (mm)
t	11,76
h	200
l	190
ϕ_1	32
ϕ_2	12
R_1	45

The geometry described above is used to define the geometric characteristics of the mold.

3.3 Lug characteristics

The mold geometry is based on the geometry of the lug, as described in Fig. 8. The mold is composed of three main parts: Spacer, upper and lower plates. They are also part of the set other secondary parts: support for injectors, alignment pins, cylinder of the hole, O-ring, and fixing bolts. The Tab. 3 presents each party and the materials that were manufactured.

Table 3. Mold components and materials that were manufactured.

Upper plate	Lower plate	Spacer	Suport	Pin	Cylinder
Al 7075-T651	Al 7075-T651	Al 7075-T651	Al 6351-T6	Al 6351-T6	Al 7075-T651

The upper and lower plates were manufactured in the thickness of 12.7 mm (1/2 in.), machined on the outer and inner faces with ± 0.1 mm tolerance to ensure parallelism and design tolerances. To ensure proper alignment of the plates and the spacer there are two side holes for installation of alignment pins. The external holes channel will be used to install bolts to attached plates and spacer. In the upper and lower plates there are channels, where the O-rings are installed to ensure the sealing between the parts.

In the lower plate there is an external hole to inject resin, which is installed the support for the nozzle. This hole is connected to an inner channel, responsible for ensuring a homogeneous distribution of resin during the injection process.

In the upper plate there are three outer holes to extract excess resin, where the holders are installed nozzles. These three holes were opened if needed any correction in resin removal process during mold filling. The lower and upper plates are shown in Fig. 12.

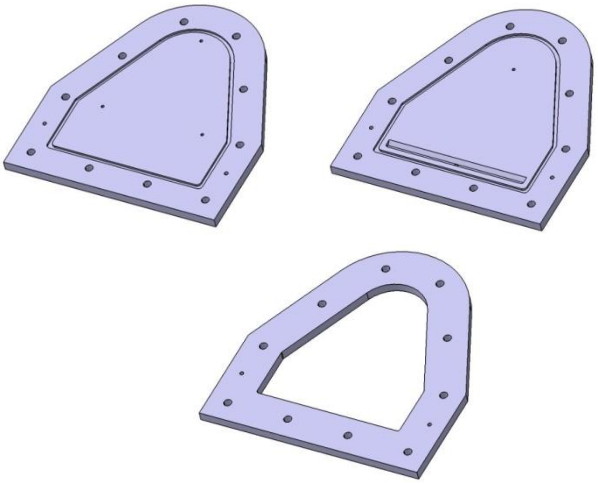

Figure 12. Upper and lower plates and spacer.

The spacer corresponding to the lug negative geometry, that is, the geometric characteristics of the lug are identical to the spacer. Thus, the tolerance of lug manufactered are guaranteed by the spacer tolerances. The thickness of the lug is controlled by the thickness of the spacer, and if necessary any subsequent adjustment on the part of the manufacturing due to a change in thickness of the lug, is only necessary to add a spacer with a larger or smaller thickness.

The Fig. 13 shows the mold assembly manufactured and ready for use.

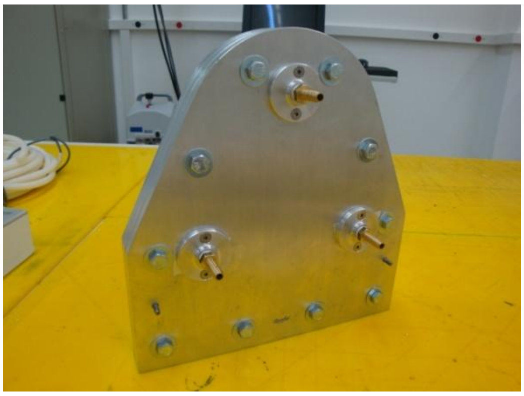

Figure 13. Mold assembly used for lug manufacturing.

3.3 Lug manufacturing

The lug manufacturing process is composed of four parts, and can be divided as described below:

a) Cutting fabric and manufacture of the preform;
b) Injection molding with preform;
c) Demolding;
d) Finishing and drill the holes;

Each part of the process will be detailed sequentially.

a) Cutting fabric and manufacture of the preform

The raw material used for the layers is a carbon fiber plain weave style fabric with epoxy 2F HS fastener (Binder), supplied in rolls 1070 mm wide, weighing 206 g/m^2 by Hexcel manufacturer.

Following completion of the analysis of the geometric parameters of the cut, the data is sent to the machine Lectra Vector 2500, which performs cutting of the material, reducing the loss of raw materials.

After cutting the layers, one can then manufacture the preform of dry fabric. The layers before being assembled in the mold are deburred with scissors and electric stylet, removing excess on the sides and inside the hole, avoiding compromise the assembly of layers in the mold and demolding the part.

The material used in its composition a binding agent component called binder which, when heated, causes the fabric layers join, giving the ensemble a reasonable stiffness.

Fig. 16 shows the assembled set with the fiber layers within the mold before being taken to curing in oven.

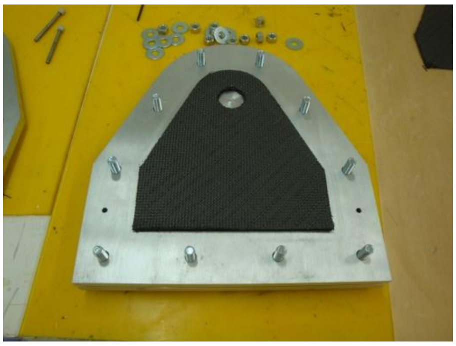

Figure 16. Mold assembly and positioned layers.

The number of layers used in each lug is described below:

- 12 layers oriented +45°
- 12 layers oriented -45°
- 12 layers oriented 0°
- 12 layers oriented 90°

Totalizing 48 layers, in the following stacking sequence:

$$[+45, -45, 0, 90, 90, 0, -45, +45]_{6T} \qquad (2)$$

After the positioning of the layers, the mold was closed and placed in a stove. The cycle for pre-forming is, heating to 100 °C and 1 hour at this temperature level. After cooling the mold is opening on obtains the manufactured preform as shown in Fig. 17:

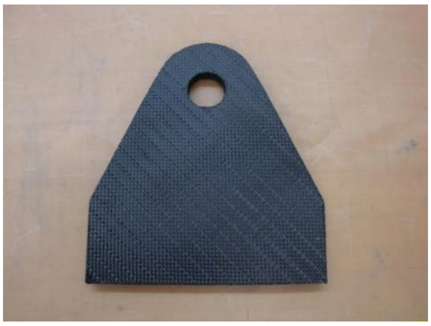

Figure 17. Preform manufactured on dry layers.

b) Injection molding with preform

After the preform manufactured in a dry layers the mold was clean and was applied demolding agent. Used nylon adhesive (Toltek®) on the side of the spacer and the hole of the cylinder to facilitate demoulding of the piece.

The preform was position on the mold. Thereafter, mounts all injection system with the controller, the injector, the closed mold, the trap and the vacuum pump. The assembled system can be illustrated by Fig. 18.

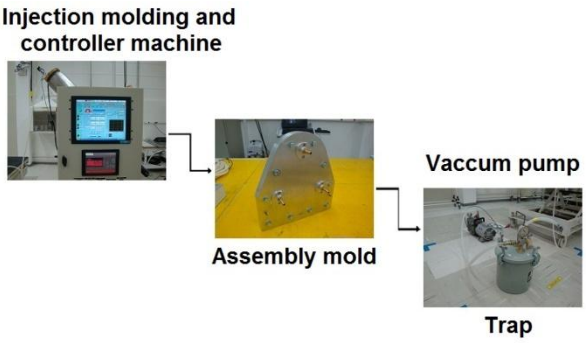

Figure 18. Preform and injection system.

The epoxy resin used in the manufacture of the specimen is the SC-79 manufacturer of bi-component Applied Polleramic, Inc. The amount used in the manufacture of each specimen is described below:

- 600 g of the resin - Part A;
- 240 g of curing agent - Part B.

It will be mixing the two components until a homogeneous compound is obtained. The mixture is placed of container internal injector. Begins the process of degassing the vacuum kept constant for 15 minutes.

After degassed resin, moves the piston of the injection. It stops with a locking plier, the resin inlet hose into the mold. The piston of the injector is displaced with a flow of 100 cm^3/min until it is realized that all resin inlet hose into the mold is filled.

Selecting the resin inflow to 50 cm^3/min limiting pressure at 8 Bar and after removed from the locking pliers of the resin inlet hose. The resin injection process the mold is started. All the resin application process was monitored and is illustrated in Fig. 19.

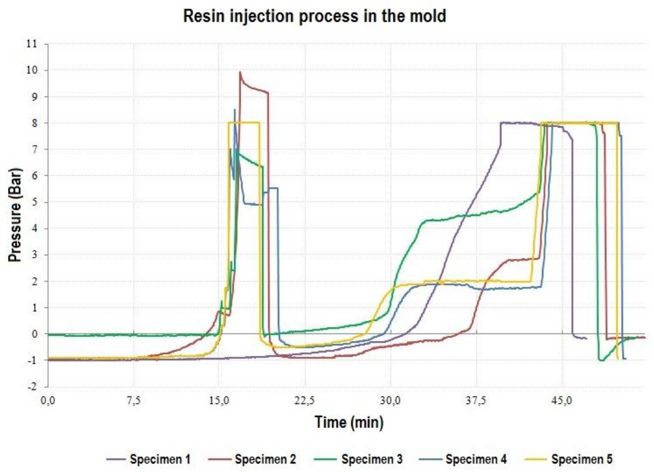

Figure 19. Resin injection process monitoring.

All parts of injection system are connected by hoses and the assembly is represented according to Fig. 20, connecting the injection into the assembly mold, the trap, and vacuum. All hoses are connected and secured with cable ties to ensure that there is any leakage in the system.

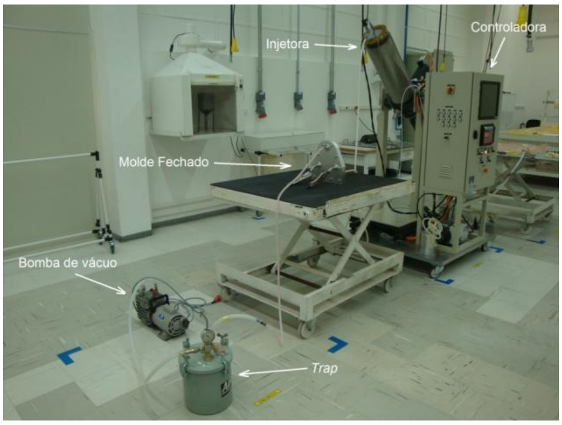

Figure 20. Injection system assembly of specimens.

To monitoring throughout curing process of assembly, thermocouples are installed on the outside of the mold. The system will have the configuration as shown in Fig. 21.

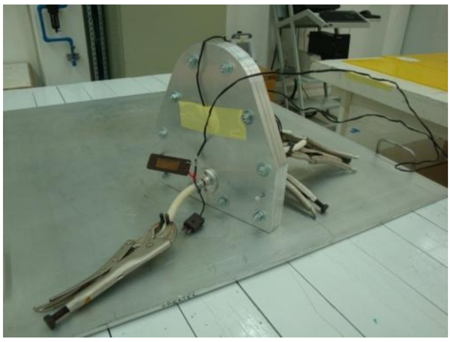

Figure 21. Mold assembly injeted with resin prepared to curing process with thermocouples.

c) Demolding

After the curing process and subsequent cooling, the mold is opened by separating the side plates and the separator obtained with specimen still no demold and demolded, as can be seen in Fig. 22.

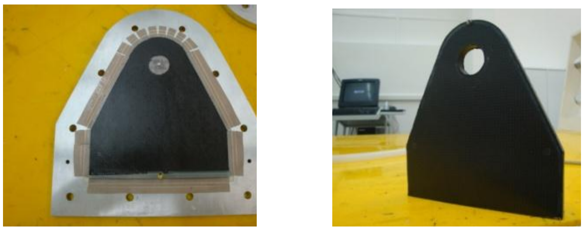

Figure 22. Specimen manufactured within the mold and demolded.

d) Finishing and drilling

The final manufacturing process consists in finishing of the specimens, which is done in a rotary sanding machine using a sandpaper number 320, removing the manufacturing burrs and sharp edges. Excess resin which corresponds to the channel of the mold must be carefully removed, leaving the CDP with a completely smooth surface.

These drill points have been previously defined in the finite element model therefore be an important factor in the test results, as may specimen fail at these points if the geometric characteristics of these holes aren´t appropriate for the specimen loads.

It should also be taken into account their relevance to the drilling process as a process performed incorrectly can cause damage specimen, as a result, failure may occur at these points during the test. Drilling process and final specimens shown on Fig. 23 and Fig. 24.

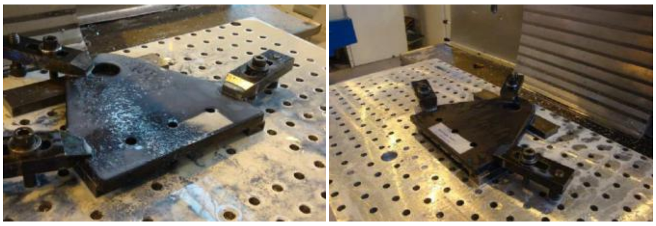

Figure 23. Drilling process of specimens.

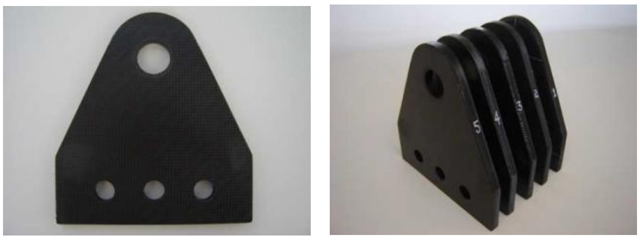

Figure 24. Final specimens ready to test.

4 Conclusions

The design and manufacture of the mold meet fully the proposed objectives, it was not necessary any changes during use in the manufacture of specimens. As the mold release process may be improved because the lug manufactured offered certain resistance when removed from the spacer.

In the manufacturing of the specimen, the process has been improved from the first production since the first manufactured specimen, such wasn't used because it wasn't possible to remove the spacer.

On second specimen, the preform was manufactured and demoulded before the injection part. With this, the specimen removal problem spacer was avoided, given the purpose of manufacturing. As regards the finishing of specimen, the objective is fully met, it isn't identify any problem in manufacturing them. The finish of the upper hole, which is manufactured together with the lamination, produces satisfactory results, the parts aligned with the finish requirements.

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