Analysis of the Manufacturing Process of Aeronautical Composite Parts and Assemblies

Case study of the ovalization of the hole for a Hi-Lok fastener

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Abstract

The manufacturing process of composite parts and assemblies is complex and constant review to improve the process is crucial in the optimization of profits in a company in the aerospace business.

The paper includes case studies of actual improvements in processes carried out in the company OGMA, in a partnership with mutual benefits. Lean tools were applied in the process improvements as well as a wide range of theoretical knowledge on the understanding of the processes and the origin of certain anomalies inherent to the process.

Academic interest was sparked in the analysis of a process defect and, in Ansys environment, was created, a finite element model of the bolted joint between two laminates with a Hi-Lok type fastener with countersunk head and its modification was made to include ovalization of the hole in various orientations. Was modeled orthotropy of the material with the respective stacking sequence of the layers of the laminate, with some simplifications in the geometry of the fastener.

The results allowed the identification of the difference in the stress distribution in each case of ovalization and a comparison was made with the case of a regular hole. The ovalization of the hole generally causes an increase in the radial and hoop stresses in zones of stress concentration and very high gradients in specific angular positions of the hole.

Symbols

E	–	Young's Modulus
G	–	Shear Modulus
R	–	Hole radius
t	–	Laminate thickness
t_{cyl}	–	Cylindrical thickness
U_x	–	Displacement in the x direction
U_y	–	Displacement in the y direction
U_z	–	Displacement in the z direction
w	–	Laminate width
α	–	Fiber orientation angle
Δ	–	Difference between maximum stresses
σ_R	–	Radial stress
σ_z	–	Axial stress
σ_θ	–	Hoop stress
θ	–	Angular position
ν	–	Poisson's Ratio

Introduction

This project arose from a proposal made by "OGMA Industria Aeronáutica de Portugal SA" to Instituto Superior Técnico in order to analyze the process of composites manufacturing and assembly of sets of Aeronautical manufacturing and production of the respective instructions with the objective of optimization, using Lean tools.

The company has more than nine decades of history and today holds a leading role worldwide in the aviation maintenance and manufacturing business. OGMA has a number of certifications including PRI / Nadcap Composites and Non - Destructive Testing and presents itself today as a provider of integrated solutions for the following clients: Boeing, Embraer, Dassault, Airbus Military, Lockheed Martin, Pilatus Aircraft, AgustaWestland and Eurocopter.

The composites manufacturing section has many clients, thus resulting in the need for such a project.

This paper is the objective analysis of the manufacturing and assembly of composite components, with a view to their optimization process. With the collaboration of OGMA and the needs of the company for the production of composites and assembly of sets made by the company , set up the following main objectives of the project:

- Monitoring of all production processes;
- Analysis of existing technical instructions and their suitability for production;

- Improving and developing appropriate technical instructions;

- Application of Lean tools in the manufacture and assembly.

From the presence on the field, interest from the academic point of view emerged in the analysis of a recurrent anomaly, including the analysis of the effects caused by ovalization of countersunk holes in composites. Therefore, were settled more goals for this project:

- Construction of a finite element model;

- Modification of the model to take account of the defects;

- Identify the effects of induced defects.

As such, the thesis was developed according to the objectives, with a view to improving knowledge in various areas and application of knowledge in practical cases.

Manufacturing Processes

Lay-up

The construction of the parts corresponds to the stacking of successive layers of prepreg required for the part [1]. The molding must be performed within the clean room, following the stacking sequence of the drawings. Use of gloves is mandatory to handle all materials.

It's not allowed the stacking the polymerization of different materials (resins) if these are not approved as compatible.

All parts are checked, ensuring the registration of all steps of the raw material and process.

Before starting stacking, it is checked if the preparation of the tool was made and whether it is in perfect condition for the onset of labor.

Each kit will correspond to one part. The opening of the kit must be made mandatory within the area of molding parts. The kit is identified with tissue - specific sequence information layer and this sequence is inspected during molding by the team leader.

The stacking sequence is described in the records to support the construction, describing the position and orientation of layers in relation to the tool locators.

The removal of the protective film performed, without affecting the orientation of the fibers or producing any type of damage in the prepreg.

The orientation of the various materials is a critical step and therefore the operator must take extra care on the location and orientation of various materials.

The orientation of the layers should always be indicated and can be identified by the direction of the longitudinal and transverse fibers orientation and identified by the bond of sheets that were form the honeycomb

During lay-up one should avoid the introduction of any foreign material into the piece, creating wrinkles or air bubbles between layers.

To avoid wrinkles or air bubbles, use the compression roll parallel to the direction of the fibers in order to eliminate them. Note that at this stage any material introduced into the layers becomes impossible to remove and a non-compliance will be created.

If it is necessary to improve the molding of the pre-preg during its stacking, hot air tools may be used as long as the temperature in stacked layers does not exceed 65 ° C.

The compression of layers is accomplished to within 0.5 mm thick, or as indicated in the FACP, the part must be covered with a temporary vacuum bag, applying a vacuum least 0.33 bar at room temperature for about 15 minutes. Then turning off the vacuum and removing the bag for further stacking sequence.

The overlap of the layers during stacking are made as indications of the designs or specifications of the customer. Unless otherwise, layer overlays should have a width of 20 ± 3 mm, is not allowed more than two overlays in the same location and a minimum distance between two overlays of 100 ± 10 mm must be guaranteed.

The surface modification materials as " Peel - ply", " Tedlar ", " PVF -film" or "Copper Mesh" usually are the first in stacking sequence and should not be in contact with the material of vacuum bagging, with the exception of resin separator materials "Release film" or mold release films, where it is guaranteed that the drainage of volatile materials are not glued on the surface of the part.

Assembly

The assembly is performed in appropriate jigs that allow the correct fastening of the parts to bond/ drilling/rivet and the pressurization of interfaces to join.

One must have particular regard to the references in the jig for parts [1]. After the location and positioning of the pieces, proceed according to the instructions in the Workbook.

Rivets

The requirements for rivets for the connection of composite structures are different from those for connecting metal structures [1]. The selection of fasteners includes corrosion compatibility, fastener material, strength, stiffness, head configuration, importance of grip, hole clearance, and lightning protection. Steel alloys are not compatible, galvanization is rapidly eroded and solid rivets can crush the composite or expand the hole and cause delamination.

The assembly of most composite structures for the aerospace industry is done with Hi-Loks (Hi-Shear Corp.) or Lockbolts (Huck International, Inc.), for permanent installations. The Hi-Lok is a threaded fastener which incorporates an hex-key into the threaded end to apply torque to the threaded collar during installation. The collar includes a fragile portion that separates at a certain value of preset torque. Figure 1 shows a typical installation sequence.

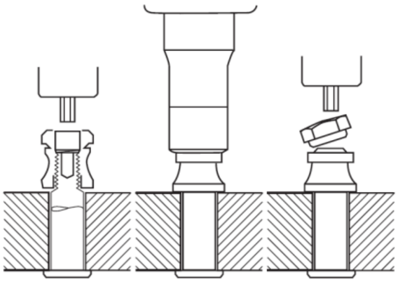

Figure 1 – Instalation sequence of a Hi-Lok.

Fiberglass or Kevlar cause no corrosion problems when used with most materials. Composites with carbon fibers, however, are quite cathodic when used with materials such as aluminum or cadmium, the latter metal is used regularly in electroplating of fasteners. Titanium and its alloys seem to be the most compatible materials with carbon fiber, and, luckily, titanium alloys have a more desirable strength/weight rati. The Ti- 6Al -4V alloy is titanium alloy most often used in composite structures of carbon fibers.

Manufacturing Processes Definition

FAI

The FAI - First Article Inspection is a complete, physical and functional, independent and documented process that verifies that the tools and production methods used ensure product compliance with applicable specifications and requirements of the contract with the customer [2]. A process resulting FAI report (FAIR) consist of documents and records required and necessary to show compliance of the first article produced.

In order to ensure the appropriateness of the production process, ensuring that the methods, means and materials used are the most suitable to obtain a product conforming to the requirements, an inspection process, in which generally are analyzed, among others, the following parameters :

• Production sequence;

• Appropriateness of methods and means of production and control used;

• Raw material used and their traceability;

• Special processes used and respective qualifications;

• Records of quality (dimensional tests, etc.).

• Records of weighing.

The FAI inspection ensures compliance of the product with regard to the technical definition, the first series of plays performed in accordance with the manufacturing processes series.

Engineering is responsible for drawing up the FAI ranges and classifications, taking into account the reason for running the FAI, proceeding to amend it whenever inspection results FAI so determine. Engineering also puts ranges in the state FAI, to allow the release of FAI work orders, if there are changes in the designs of the products, for example. The monitoring of the FAI inspection process is also performed by Engineering which consequently proposes solutions to detected problems and deviations.

The FAI inspection is performed every time before starting series production, which is only released after its approval and, where applicable, the FAIR report resulting from this inspection. These reports are prepared only when contractually required by the Client.

Support Phase or Post Industrialization

After the industrialization, culminating in the success of the FAI, the manufacturing or assembly process is proceeded.

At this stage, are carried out a set of activities:

• Adjustments to the process in terms of sequence of operations, methods and times;

• Incorporation of modifications from the client, after the analysis and definition of the new structure of product engineering;

• Implementation of actions to support production.

All processes leading to repairs and/or inspections are supported where necessary by ranges of repair and / or inspection.

In the context of product realization, the implementation of specific programs for process improvement, such as reducing time and cost, reducing variation of process parameters, quality improvement, waste reduction, elimination of stock values are not necessarily accompanied with consequent cost/benefit analysis.

Are considered as the object of process improvement:

• Proposals for the amendment and correction processes of manufacture and / or assembly;

• Manufacturing and / or modification of tools;

• Deviations from production in order to optimize processes and reduce costs.

LEAN

Any work or activity is made of processes [8]. When you have an ineffective and inefficient process, it ceases to be profitable because the goods or services produced failed to offer an advantage to its customers.

In the context of organizations, the word Lean is associated with process flexibility, the lack of excess production or inventory, the absence of timeouts, and the fast response to orders. Lean has its origins in the Toyota Production System (TPS - Toyota Production System). The Japanese word for “changes” commonly used in Lean organizations, means waste, a concept that began to be understood as any activity that does not add value in the eyes of the customer. This means that either the activity increases the value or doesn’t increase value, there is no third option. This means that you must make a very clear distinction of what is and is not waste, and who defines it is the end customer. All the hand-labor time spent, raw material, energy needed to accomplish something are seen as resources, it is important that these resources remain allocated to value-added activities , eliminating the other .

The five principles that constitute the essence of Lean are:

• Specification of value;

• The value stream as the path described by the service or product being sold;

• Flow or cadence of the product or service;

• The orientation of the production system based on actual orders. ;

• Pursuit of perfection.

Pursuit of perfection

Some of the tools used in this search are:

• Poka-Yoke: proofing error. The design or restructuring of products, processes and/or tools so that the error does not occur. These systems may have different natures, either to focus on control as opposition - does not allow the error to occur - either to focus on warning - visual warnings error.

• Visual Management: promoting control of operations through signs, directions, colors, etc... Results in a greater understanding of reality and response times to unexpected situations decrease.

• 5S +1: Sort, Set in Order, Shine, Standardize, Sustain and Safety .

a. Only the important and necessary things are in the workplace;

b. Everything should be in place, with a place for everything;

c. Keep the work area clean and tidy;

d. Create procedures, rules and instructions related to the previous point;

e. Support these actions, i.e., continuous updating;

f. Safety is never called into question.

• SMED - Single Minute Exchange Die: Tool change in one digit. In a case where there are multiple tool changes is important that these setup times are optimized.

• TPM - Total Productive Maintenance: the goal is to achieve the lowest possible number of accidents, malfunctions and unplanned stops of equipment. Focuses on good operation thereof to the availability of hours to produce.

Case Study - Pilatus Fairings

This case study concerns the manufacture of an assembly of components with a value stream mapping of relatively simple. The different components of this set are relatively similar, with only minor differences in geometry between them.

The technical instructions built for these components focus on the placement method of reinforcements, with more precise information possible. These are components with complex geometries, large curvatures and tools have a difficult access for lay-up. To facilitate and ensure the existence of material in the rims of the component, if the turn-marking templates to make the mold for the tissues covering the contours transferred. Figure 2 illustrates the marking of the contours.

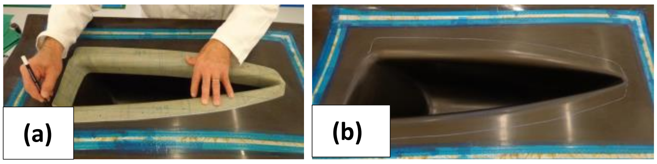

Figure 2 – Using the template (a) to mark the contours (b)

With respect to the reinforcements, the focal point of improvement of these components, the position thereof is also marked with templates, as shown in Figure 3.

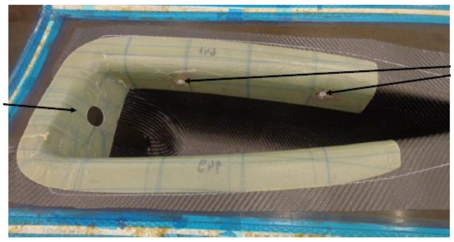

Figure 3 – Using the template to mark the reinforcements.

Directions on how to use the template for correct positioning in the tool, ensuring the correct marking the center of the reinforcements are given. For placement of reinforcement areas are specifically indicated which are often poorly placed and a suitable method to correctly center the circular reinforcements. Different materials are used as reinforcements, with different geometries. In case of being square is indicated to the operator to trace the diagonal and use the intersection of the lines to center the reinforcements.

However, due to having been created from the lay-up tool and not from a final piece, the template's width does not allow its correct positioning during the lay-up. When leaning against the bottom of the mold, the template is deformed due to stress and the position of the holes of the template relative to the correct location changes. This effect is evident in Figure 4, where it can be also observed that the reinforcement incorrectly placed has suffered rework to level the area as it is an area for assembly.

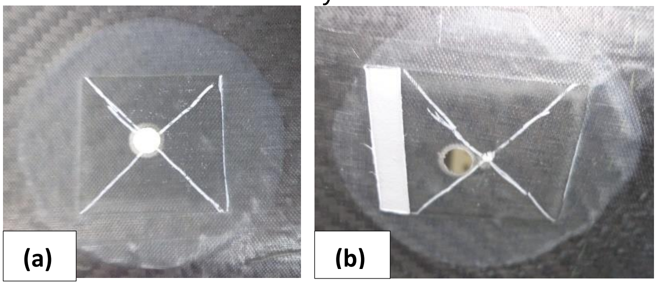

Figure 4 – (a) Incorrectly placed reinforcements VS (b) correctly placed reinforcements.

Since the error was systematic and only on one side of the components, the holes made by CNC machine were correct and the reinforcements were diverted.

Since the templates had fractures due to their excessive wear and width, these were repaired. Besides repaired and to allow their use have been cut in half, so there is no interference in width and continue its purpose. This process is illustrated in Figure 5.

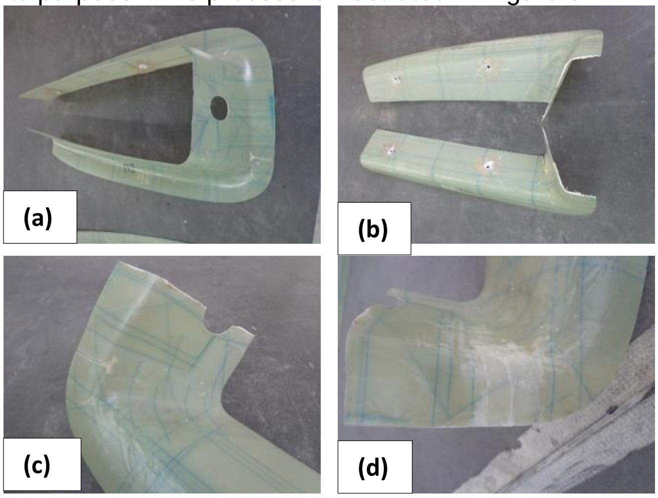

Figure 5 – Repair sequence.

Additionally, each pair of templates was identified with a color and the number, not to be used incorrectly in another component. By dividing the two template also removes the difficulty of placing it in the mold due to the tack of pre-pregs. In a cured part is easy to drag the template across the surface, but during the lay-up was impossible.

Finite element analysis

Resulting from monitoring the manufacture of composite materials and assembly of composite components process, the interest of the analysis of a recurring anomaly arises. The anomaly of interest is then the faulty drilling. In Figure 6 it can be seen that the holes are anything but perfect, presenting ovalizations in multiple directions, in a star effect. These holes were generated by an operator in the finishing area in which the pre-drilling of the component is extended to the end dimension. Using a sword drill and poor support, the vibration of the component and/or drill generated this defect.

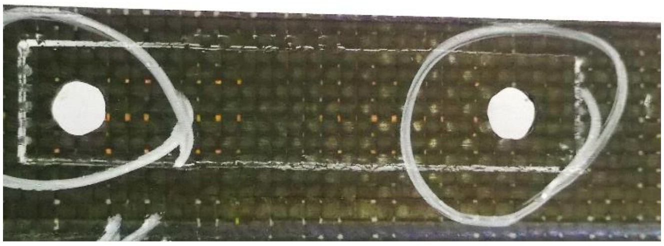

Figure 6 – Abnormal hole.

Combining this type of defect modeling to the complexity of the materials involved, assembly of the two laminated with a countersunk rivet and contact existing between all surfaces geometry, the problem becomes rather complex.

This analysis is based on the work done by B. Egan et al [3], stress analysis of single-bolt, single-lap, countersunk composite joints with variable bolt-hole clearance and the model created by McCarthy et al [4] [5].

In this case, it is assumed minimum clearance between the rivet and the hole in the first analysis and then the hole is modified to introduce ovalizations in certain directions, considered the most important and most interesting.

First, the model under consideration consists of two laminates - a countersunk and non-countersunk laminate - with the same sequence of layers: 5 layers of glass and polyamide fabric with fibers oriented according to the illustration in the x direction is the direction of loading. The countersunk laminate is also called top laminate top and laminated non-reamed by lower laminate.

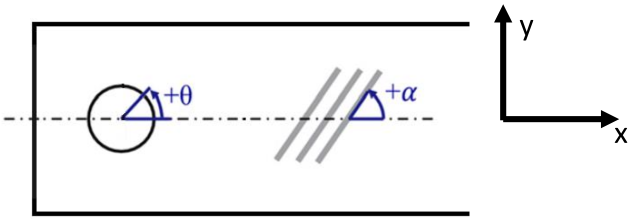

Figure 7 – Angular position θ, fiber orientation α and cartesian coordinate system xy.

In Figure 8 a detail of countersunk laminate geometry of volumes created for modeling the layers of the material is presented. Each layer has a thickness of 0.35 mm which results in a total thickness of 1.75 mm. The laminate numbering used for the layers in the figure is the numbering used in the description of the results.

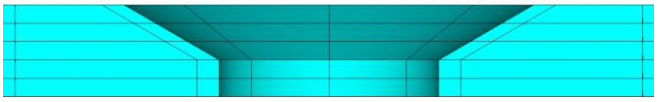

Figure 8 – Countersink volumes.

The dimensions used are based on measurements performed on manufactured components and an assembly in particular. The hole radius was 2.1 mm and the laminate has a width w of 24 mm and a total length equal to twice the width of 48 mm.

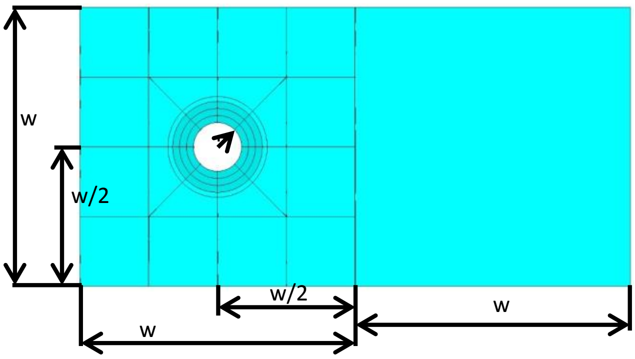

Figure 9 – Countersink volumes.

Regarding the geometry of the countersink, the cylindrical hole in the thickness of laminate is equal to the thickness of two layers, so as to facilitate the creation of the model. As the laminate has five layers, the depth of the countersink corresponds to 60% of the thickness of the laminate and are thus within the permitted maximum of 70% of depth MIL-HDBK-17 [6] specification.

The maximum radius of the countersink is obtained by calculating the angle from the reaming integrated in the geometry generation code.

Regarding the rivet, it has a 2.07 mm radius ensuring 30 µm clearance with the bore so as to prevent interference of initial contact that generates unnecessary stresses and complicates the analysis of the final results. The grip of the rivet is simulated by creating interference between the head/pinch collar and bottom laminate. The grip was considered ¼ turn, which translates into a 50 micron interference.

Regarding defects in drilling, was modeled ovalization of the hole in four different ways, by moving points in the geometry. In all cases, the maximum radius increased by 0.2 mm, approximately 10% of the radius of the rivet. For the purpose of identifying defects are identified as ovalization at 0°, 45°, 90° and double 90°. This is angular orientation relative to the direction of loading but on the side of the headrest countersunk laminate, where applicable. This defect is arranged in the following figure.

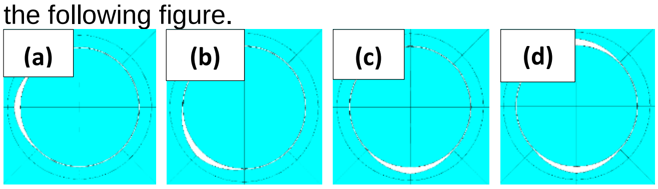

Figure 10 – Ovalization at (a) 0°, (b) 45°, (c) 90° and (d) double 90°.

Mesh and boundary conditions

The mesh model is parameterized so as to be facilitated handling. Initially volumes are created from a plate which is longitudinally sectioned hence in order to simulate different each layer oriented material. Each of these layers is automatically associated with the appropriate reference material to the orientation Cartesian coordinates. Thereafter each of these layers may be subdivided while maintaining the orientation of the material throughout the layer.

The boundary condition applied to the laminate is countersunk to draw only in the longitudinal direction, as shown in Figure 11.

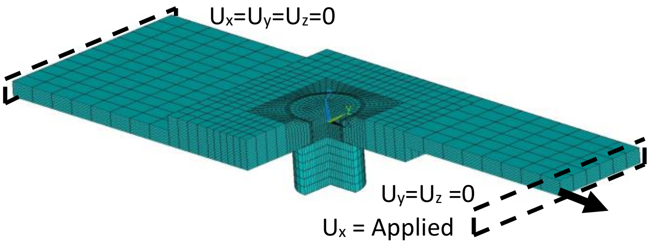

Figure 11 – Finite element model with the boundary conditions.

The loads are applied in two stages. In the first stage is applied only to interference of the rivet head countersunk non-laminated to simulate axial clamping. In the second phase the displacement is applied in the longitudinal direction with a value equal to a quarter of the radius of the rivet. Symmetries in the model were not used because the interest is to observe the stress field in the layers of the laminate deformations generated by the drilling. The analysis was applied to nonlinear static geometry for loading deformation generates not compatible with linear geometry, not converging. Although a very small deformation loading, requires the inclusion of non-linear geometry.

Material modeling

To model the composite material, the approach taken was to assign each layer of elements local coordinate system with the desired rotation. So just setting an orthotropic material, it is automatically transformed by ANSYS in each layer. The properties used were obtained by Tabiei and Yi [7] with the four-cell method for a plain weave fabric of glass fiber and polyamide, since all the physical properties of the materials are not easily obtained.

Laminate	E_{11} (GPa) 45.08	E_{22} (GPa) 45.08	E_{33} (GPa) 10.12
	G_{12} (GPa) 3.815	G_{13} (GPa) 2.763	G_{23} (GPa) 2.763
	ν_{12} 0.056	ν_{13} 0.4643	ν_{23} 0.4643
Titanium	E (GPa) 110	ν 0.29	

Table 1 - Material properties.

The objective of the analysis is to investigate the tensions layer to layer in elastic around countersunk holes and are therefore not included laws degradation of materials.

Contact description

The contact conditions were imposed by defining pairs of contact between the interacting surfaces. The discretization method the surface area was used because it prevents penetration of surfaces in a common sense [3]. The contact pairs are created and represented in Figure 12 are the following: inner surface of the hole and countersink / surface of the rivet contact pair, interlaminate pair and non-countersunk laminate and rivet head.

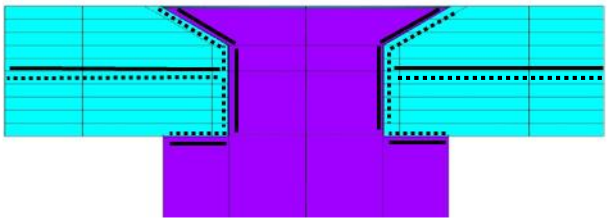

Figure 12 – Finite element model with the boundary conditions.

Results and Discussion

Pre-load

This first result is on the first phase of loading, solving the initial contact and interference between the three components of the assembly: the rivet and the two laminates. Figure 13 depicts the distribution of axial stresses σ_Z in laminates. The maximum compression of 96.9 MPa is located in the transition zone of the cylindrical bore countersunk. It can be seen a good continuity of stresses in the transition between the two laminates.

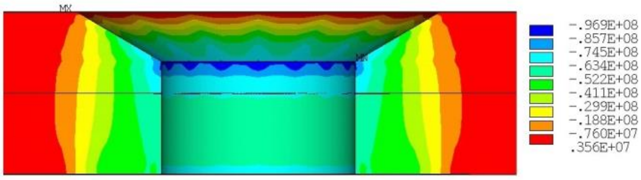

Figure 13 – Axial stresses across the laminates (Pa).

On the face of the threaded collar, the stress distribution is illustrated in Figure 14, having a circular distribution. This result demonstrates a good modeling of contact between the components with regard to the transmission of axial stress.

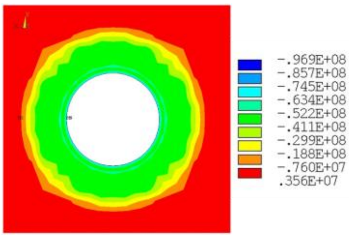

Figure 14 – Axial stresses across the laminates (Pa).

Joint Deformation

The qualitative result of deformation is important in confirming the modeling of contact. In Figure 15 the deformation of the joint with the mapping of nodal deformations in the direction of loading U_x is presented. It can be observed the saddle effect caused by the rolling and inclination of the axis of the rivet.

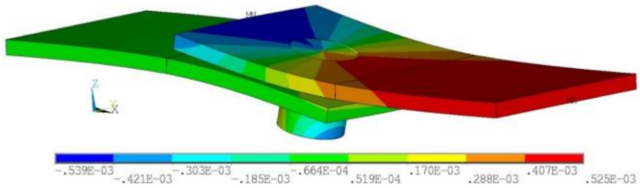

Figure 15 – Axial stresses across the laminates (Pa).

In the longitudinal section perspective in the figure, it is observed in Figure 16 that the rivet contacts to the laminates in the correct locations, with the appearance of larger voids due to the deformation of the laminate. This deformation confirms the correct modeling of contact between the rivet and laminates.

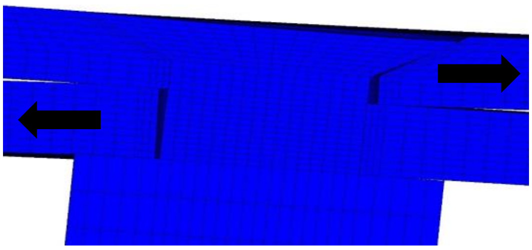
Figure 16 – Longitudinal section of the deformation.

Loading Result

The results presented for the stresses were obtained directly from ANSYS applying a coordinate transformation to a cylindrical coordinate system centered in the shear-plane and hole center, and Z direction also concentric with the hole, as shown in Figure 66, where θ = 0 ° is for the loading.

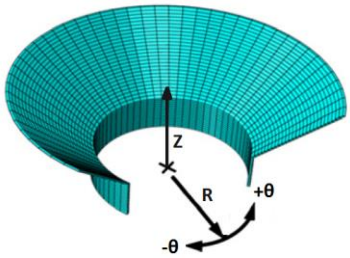

Figure 17 – Cylindrical coordinate system.

Being the object of study the contact rivet countersunk laminate in the following charts is organized by distance to the shear-plane and by the angle to the direction of loading the radial stresses and hoop stresses.

The maximum radial stress in oriented at 0°/90° to 180° zone and the layers oriented at ±45° in the zone ±135° layers. In the layers 4 and 5, or observing the graphic layers with the distance from the cutting plane of 1.05 mm, there is a severe decrease the magnitude of the radial stress due to the countersink.

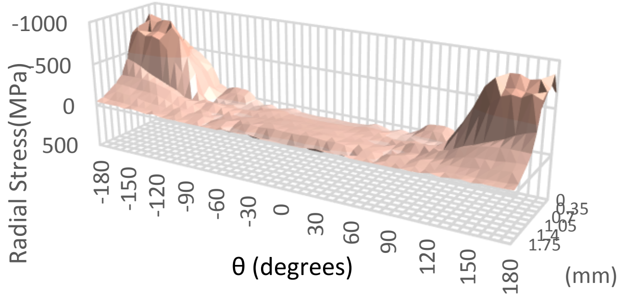

Figure 18 – Radial stress distribution.

Regarding hoop stress, the following chart is analogous to the previous one. As described, are evident from the maximum hoop stress oriented according to the direction of the fibers, existing surge in layers 0°/90° to 90° and ±45° layers to ±135 °. As in the case of radial stress, shear stress also decreases in magnitude with increasing distance from the cutting plane.

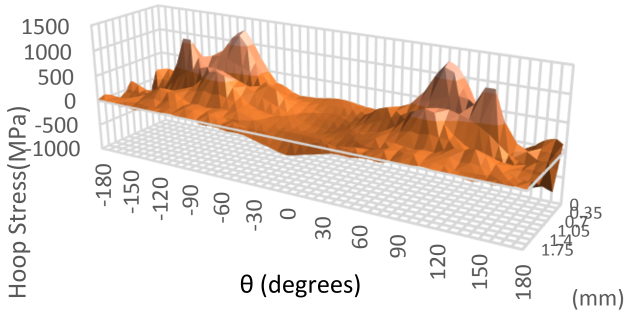

Figure 19 – Radial stress distribution.

Ovalization at 0º Results

The final contact for the case of deformation of the hole is different from the undeformed rivet hole is not in full contact zone of the cylindrical countersink laminate, as illustrated in Figure 20.

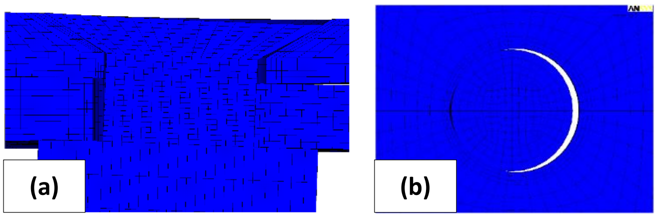

Figure 20 – Final deformation.

Regarding radial stress, in Figure 21, the maximum compression is located within ±135° in the cylindrical region of the hole with their magnitude decreasing with the distance to the shear-plane due to the countersink.

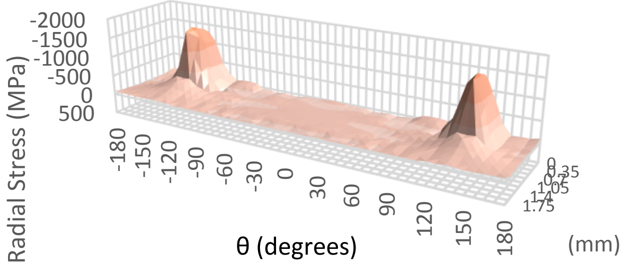

Figure 21 – Radial stress distribution.

The hoop stress in Figure 22, shows the maximum stress at ±90 ° and 180° and compression at ±135° in the 0°/ 90° layers. ±45° layers in the compression peaks are located at the same site of the 0°/90° layers, however, the stress peaks are displaced to ± 120 °.

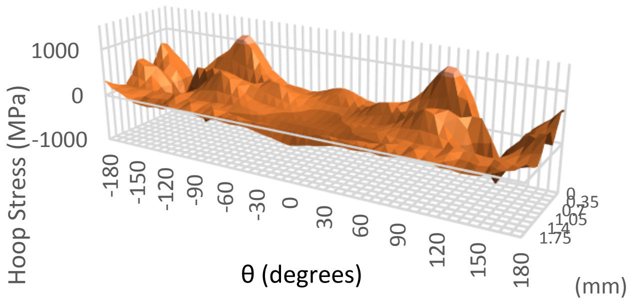

Figure 22 – Hoop stress distribution.

Ovalization at 45º Results

The graphs of radial stress (Figure 23) and hoop stress (Figure 24) on the distance to the shear plane and the angle to the direction of loading are shown below. The radial tension has an offset, starting to rise from 120° to 180°.

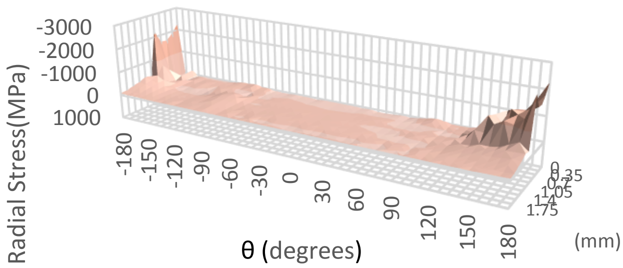

Figure 23 – Radial stress distribution.

It can be seen in the graph of hoop stress that higher peaks are located at 90° to 135° area.

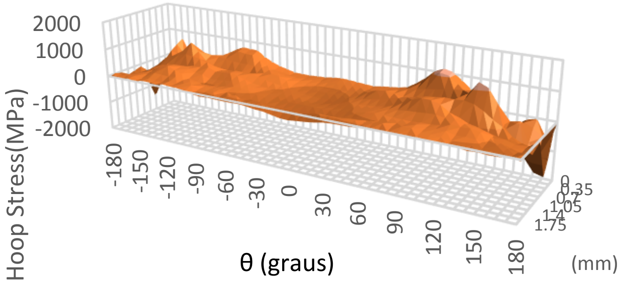

Figure 24 – Hoop stress distribution.

Ovalization at 90º Results

The asymmetries in the distribution of stresses are most evident in the graphs of Figures 25 and 26. In the graph of radial stress can be seen that the side of the defect (-135°) there is a stress gradient much steeper than on the other side, 135°. Compared to the non-deformed case, tensions are also higher.

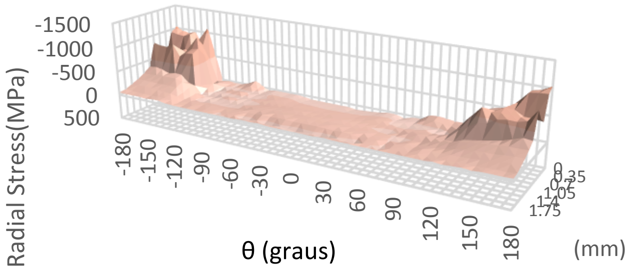

Figure 25 – Radial stress distribution.

Also in the distribution of hoop stress is observed that in the 0° to 180° area distribution is qualitatively quite similar to the non-deformed case and that in the 0° to -180° zone stresses and gradients are higher.

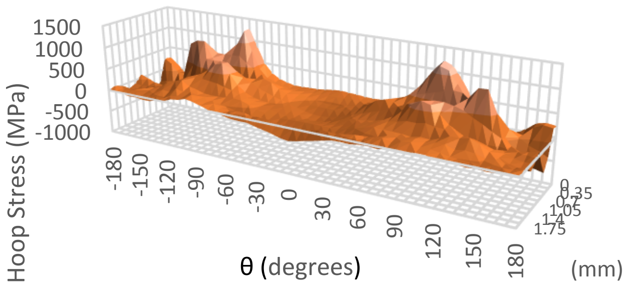

Figure 26 – Hoop stress distribution.

Double Ovalization at 90º Results

The radial stress presents itself symmetric and with high gradients at ± 120 °, in Figure 27.

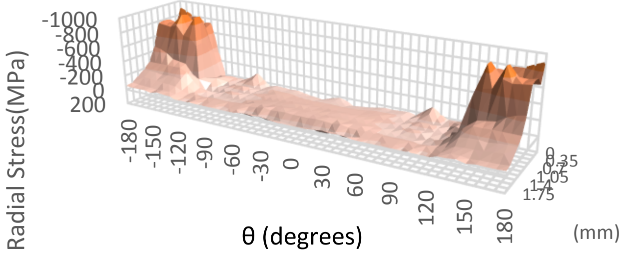

Figure 27 – Radial stress distribution.

The hoop stress also has high gradients in layer 1, i.e. distance to the shear plane between 0 and 0.35 mm. It can be observed, in Figure 28, the maximum stresses alternating between layers of different orientations.

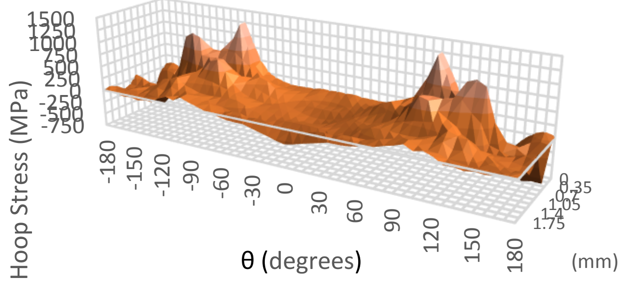

Figure 28 – Hoop stress distribution.

Comparison between maximum tensions

The stresses obtained are high when compared with the high tensions in cases where materials are metallic, but taking into account that they are contact stresses and the values obtained by Egan B. et al [3] are of the same order of magnitude and that the model material is elastic, at least the analysis reveals areas of stress concentrations in each case.

It is important, however, comparing the maximum stresses obtained. The defects numbered 1 through 4 in the table correspond to the order of ovalizations at 0°, 45°, 90° and double 90°.

Mostly the differences between the stresses obtained in the case without defects and defects are increased stresses in compression. Regarding radial stress, in Table 2, the compression reaches a 111.21% increase in the case of defective laminated at 45°.

	Layer	**σ_R** (C) MPa	
No defect	1	1070	
	2	967	**Δ%**
Defect 1	1	1440	34.58%
	2	1960	102.69%
Defect 2	1	2260	111.21%
	2	1740	79.94%
Defect 3	1	1110	3.74%
	2	1170	20.99%
Defect 4	1	946	-11.59%
	2	1070	10.65%

Table 2 – Maximum compressive radial stresses comparison.

Defects 1 and 2 are causing major differences in hoop compression with maximum differences of 429.41% in defect 1 and 241.67% in defect 2 in relation to the case with the perfect hole. Hoop compression differences shown in Table 3.

	Layer	**σ_θ** (C) MPa	
No defect	1	204	
	2	628	**Δ%**
Defect 1	1	1080	429.41%
	2	557	-11.31%
Defect 2	1	697	241.67%
	2	1470	134.08%
Defect 3	1	481	135.78%
	2	541	-13.85%
Defect 4	1	332	62.75%
	2	673	7.17%

Table 3 – Maximum compressive hoop stresses comparison.

Hoop stress is the one that has smallest differences, often in reducing stress, but the general increases in compression in all cases are much larger. Results for the comparison of hoop stress in tension is shown in table 4.

	Layer	**σ_θ** (T) MPa	
Sem defeito	1	1260	
	2	1080	**Δ%**
Defeito 1	1	1140	-9.52%
	2	665	-38.43%
Defeito 2	1	1140	-9.52%
	2	1230	13.89%
Defeito 3	1	1270	0.79%
	2	1020	-5.56%
Defeito 4	1	1270	0.79%
	2	1050	-2.78%

Table 4 – Maximum compressive hoop stresses comparison.

These increases in compression may lead to the emergence of micro-fractures or delamination, thereby reducing the resistance of the laminate earlier than expected. Delaminations and micro-fractures can lead to the inclusion of moisture in the joint that degrades it severely. Experimental tests would be of interest in the analysis of possible failure modes.

Conclusion

The analysis of the manufacturing and assembly process generated sets of composite process improvements analyzed and monitored as described in the case study presented in which there was the systematic application of all the knowledge acquired and the Lean ideology.

Some recurrent anomalies were corrected by creating the necessary tools and documentation. However, these processes have a strong human intervention, defects are always likely to occur and documentation created can only improve the process up to the quality of hand labor. A culture of continuous improvement is rooted in the company and the search of perfection directs ideas and decisions.

The analysis and process improvement is a job that cannot stop, because it is one of the important and fundamental in increasing the company's profit ways of reducing costs.

Regarding the finite element analysis, the tensions resulting from the existence of ovalizations when drilling in a riveted joint, with results indicators of serious increases tensions in the layers of the cylindrical zone of the countersunk laminate, and these same areas that mostly support the radial and tangential stresses.

The need for a 3D finite element analysis was confirmed by the presence of asymmetry in the distribution of stresses and strains in the significant thickness of the laminate around the hole and countersink. The results were quite satisfactory as possible to confirm the adverse effect caused by the roundness of the hole, why is monitored for quality control.

The material was not modeled most often used in this type of rivet joints, however, the code created accommodates any other physical properties.

For future work, the model can be analyzed for fatigue test or a bond laminates with multiple fasteners [9][10] and the introduction of defects in the holes. It would also be interesting the experimental analysis of samples with the type of defect caused in this paper for comparison of results using another type of material, such as carbon fiber composites.

Using laws of material degradation and a more realistic geometry of ovalization, could also be performed finite element analysis to simulate the testing of experimental traction and comparison of results.

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