STUDY OF AERONAUTIC FASTENED HYBRID JOINTS METAL-COMPOSITE

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Abstract. *Design of aircraft structures must consider aspects related to the durability and damage tolerance requirements provided by the airworthiness authorities. Besides, manufacturing aspects and operational/maintenance costs are important to be evaluated. However, the composite materials application is a current reality, mainly in the aeronautical and space industries, where some parts are manufactured by joining two or more materials, i.e. hybrid joints (e.g. metal-composite joined by fasteners). These joint parts can fail for many reasons, such as secondary moment due to eccentricity of loading, stress concentrations, excessive deflections and other conditions (difficult to assess the joint).This work consists on an experimental investigation of hybrid joints (metal-composite) joined by fasteners, using a new procedure proposal. Thus, hybrid joints of titanium joined to composite (carbon fiber with epoxy resin) by monel fasteners were manufactured. It is important to mention that only single lap joints were investigated. However, before manufacturing specimens of joints, composite specimens were tested following the ASTM D3039 and ASTM D3518. The tensile and shear tests provided the mechanical properties and strength values of the composite part. Finite element analyses of the hybrid joints were carried out, using average mechanical properties and strength values. These simulations followed the specifications of ASTM D5961 in order to predict the mechanical behavior of the joints during the experimental tests, as well as, to provide a good strategy for the test setup. The experimental tests were performed following some orientations of ASTM D5961, but there are some modifications, because the specimens are joints between metal-composite. During the experimental tests, the mechanical behavior was observed, mainly the stiffness and the strength of the hybrid joints, using the new procedure proposal. Hybrids joints with the composite layers oriented $0^o/90^o$ fail by net-tension, while the composite layers oriented $\pm 45^o$ fail by tear-out. In addition, joints with laminates oriented at $\pm 45^o$ failed at a load much lower when compared to joints with laminates oriented $0^o/90^o$, demonstrating the influence of stacking in the response of the hybrid joint. Finally, experimental method proposal provided an effective approach to obtain the mechanical properties of a hybrid metal-composite joint.*

Keywords*: Hybrid joints metal-composite, Fastened joints, Composite aeronautical structures, Experimental method.*

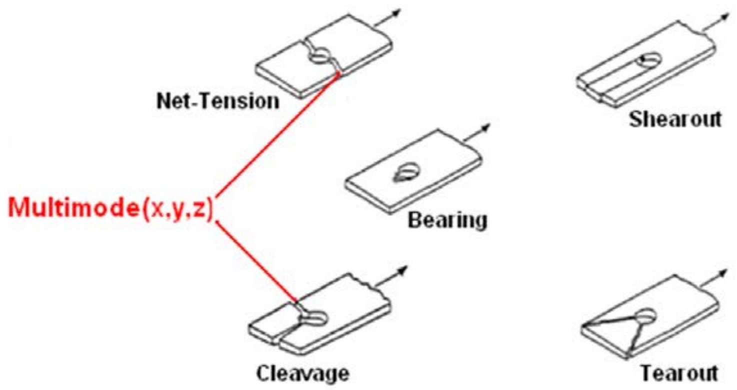
1. INTRODUCTION

Composite are being extensively used in aircraft industries, thus the increasing use of composite materials and its popularity has prompted significant research effort to develop reliable designs methods. In fact, the composite materials application is a current reality, mainly in the aeronautical and space industries, where some parts are manufactured by joining two or more materials, i.e. hybrid joints (e.g. metal-composite joined by fasteners). These joint parts can fail for many reasons, such as secondary moment due to eccentricity of loading, stress concentrations, excessive deflections and other conditions (difficult to assess the joint). These factors not only affect the static behavior, but also have a strong influence on the fatigue life of the joint and the adjacent structure. Therefore, there are many works at literature that investigate the failure mechanisms only in the composite part. Rowlands (1985) presented and discussed 21 different failure criteria and according to the report of Paris (2001), there are 53 references under the application of criteria for damage/failure for composite materials. It can be seen more works, like Turon *et al.* (2006), Renard and Thionnet (2006), Paepegen *et al.* (2006a), Paepegen *et al.* (2006b), Stephen and Wisnom (2006), Coutellier *et al.* (2006), Tita *et al.* (2008) and others. However, it is difficult to find works that investigate specially the mechanical behavior of hybrid joints (metal-composite) joined by fasteners. Less and Makarov (2004) investigated the feasibility of a new type of connection technique where mechanical and bonded systems are combined in order to obtain a hybrid joint with better mechanical properties. Grassi (2006) presented a simple and efficient computational approach for analyzing the benefits of through-thickness pins for restricting of debond failure in joints. Experimental analyses confirmed that debond and ultimate strength depend on the material, dimension, density, location and angle of deployment of the pins, as well as the mechanisms of pin deformation. Kabche (2007) presented an investigation of the structural performance of hybrid composite-metal bolted joints loaded under flexure. Matsuzaki *et al.* (2008a and 2008b) proposed a novel reinforcing method for metal-composite co-cured joints, using inter-adhered fibers, bolted and co-cured process. Experimental investigations were carried out in order to measure the increase of the joint strength. Kolesnikov *et al.* (2008) presented experimental results, demonstrating the advantageous of joints manufactured by titanium and carbon fiber reinforced plastic due to high strength values. Barut and Madenci (2009) developed a semi-analytical solution method to calculate the stress distribution on a single-lap hybrid (bolted/bonded) joint of composite laminates under in-plane loading, as well as lateral loading. Yo *et al.* (2010) and Le *et al.* (2010) presented experimental results about the size effect in hybrid joints and an analytical formulation to evaluate this phenomenon, based on Fracture Mechanics. Ucsnik *et al.* (2010) presented a new joining technology between steel and carbon fiber reinforced plastics for developing lightweight design applications in aviation industries.

It is important to mention that there is not a typical or standard method to investigate the mechanical behavior of hybrid joints. Therefore, this work consists on an experimental investigation of hybrid joints (metal-composite) joined by fasteners, using a new procedure proposal. Thus, hybrid joints of titanium joined to composite (carbon fiber with epoxy resin) by monel fasteners were manufactured. Only single lap joints were investigated. However, before manufacturing specimens of joints, composite specimens were tested following the ASTM D3039 and ASTM D3518. The tensile and shear tests provided the mechanical properties and strength values of the composite part. Finite element analyses of the hybrid joints were carried out, using average mechanical properties and strength values. These simulations followed the specifications of ASTM D5961 in order to predict the mechanical behavior of the joints during the experimental tests, as well as, to provide a good strategy for the test setup. The experimental tests were performed following some orientations of ASTM D5961, but there are some modifications, because the specimens are joints between metal-composite. During the experimental tests, it was observed the mechanical behavior, mainly the stiffness and the strength of the hybrid joints, using the new procedure proposal.

2. FAILURE MODES IN FASTENED JOINTS

According to ASTM D5961, failure mechanisms occur in a fastened joint due to the effect of bearing or bearing-bypass. First, it is important to note that the failure mode depends on the type of failure mechanism activated and there is a code related to this mode. For example, if there are failures in different directions that cause the separation of the material, then there is a Multimode and the letter "M" is used as showed in Fig. 1. Second, it is important to observe that the failures in tension/compression and combined tension/shear are characterized as being of bearing-bypass, which produces the separation of the material. On the other hand, the effect of bearing produces a localized failure and does not cause the separation of the material.



Type of Failure	Code
Bearing	B
Cleavage	C
Fastener	F
Net-Tension	L
Multimode	M(x,y,z)
Shearout	S
Tearout	T
Other	O

Area of Failure	Code
First Hole	1
Second Hole	2
Both Hole	B
Fastener	F
Unknown	U

Location of the Failure	Code
Bolt Read Side	B
Nut Site	N
Inapplicable	I
Unknown	U

Figure 1. Failure mechanisms by bearing and bearing-bypass (ASTM D5961/D5961M, 2007)

3. MATERIALS AND METHODS

Hybrid single lap joints studied in this work are manufactured by combining the following materials: a composite material, a metal part and fasteners.

The composite material is an epoxy resin reinforced by carbon fiber fabric, specifying G0904 D 1070 TCT from Hexcel™. This bidirectional textile is used in composite structures that require high performance, for example, aircraft structures. The epoxy resin is produced by Hexcel™ too, and one is named as HexPly M20. This resin is applied on designs that require high temperatures combined to a fast cure cycle. According to its flexibility of processing (vacuum bag with or without autoclave), HexPly M20 is suitable for primary and secondary aircraft structures and also for repair in composite structures. The supplier has indicated the following cure cycles: 1) In Autoclave: 130 ° C for 2 hours under 4 bars of pressure; 2) With Bag Vacuum: 130 ° C for 2 hours under 1 bar of pressure. In this work, it was used the second option for cure cycle.

The fasteners used this work consist on rivets of nickel-copper alloy (Monel) and all specifications are given by the "Military Specification - MS 20615" (1995). This type of fastener was selected, because one has high shear strength and galvanic compatibility with the other elements of the joint (titanium and composite reinforced by carbon fiber).

For the metal part of the joint, titanium alloy (Ti6Al4V) was chosen, as specified by the "Aerospace Material Specification - AMS 4907H" (2005). This material has excellent mechanical properties as well as impact resistance and maintains the properties at temperatures up to -253 °C. Its application is recommended for in-service structures that operate under such conditions. Besides, titanium alloy does not have galvanic incompatibility in contact with the composite reinforced by carbon fibers.

Tensile and shear tests of composite material followed the orientations of ASTM D3039 and ASTM D3518, respectively. The tensile and shear tests provided the mechanical properties and strength values of the composite part. Finite element analyses, using Nastran code, were carried out with average mechanical properties and strength values. These simulations followed the specifications of ASTM D5961 in order to predict the mechanical behavior of the joints during the experimental tests, as well as, to provide a good strategy for the test setup. In fact, single lap joints tests followed some orientations given by ASTM D5961, but there are some adjustments, because the specimens are not joints of metal-metal. Thus, a new experimental procedure is established to evaluate fastened hybrid joints (metal-composite) and its limitation and potential are discussed in the next section. Finally, all experimental tests were carried out in a Universal Testing Machine EMIC DL 10000 with a 100kN load cell and strain-gauges were used to measure the strains in composite specimens.

4. RESULTS AND DISCUSSIONS

4.1. Results of Finite Element Analyses (FEA)

FEA (using Nastran code) were performed to predict the mechanical behavior of hybrid joints to be tested. The modeling of the hybrid joints followed some specifications of ASTM 5961, as showed in Fig. 2 and Tab. 1. Using the failure criterion of Tsai-Wu, it was possible to calculate the load that produces the damage in the composite part of the joint. The fasteners and the shims were modeled as rigid elements, such as all strain is transferred to the metal and composite portion.

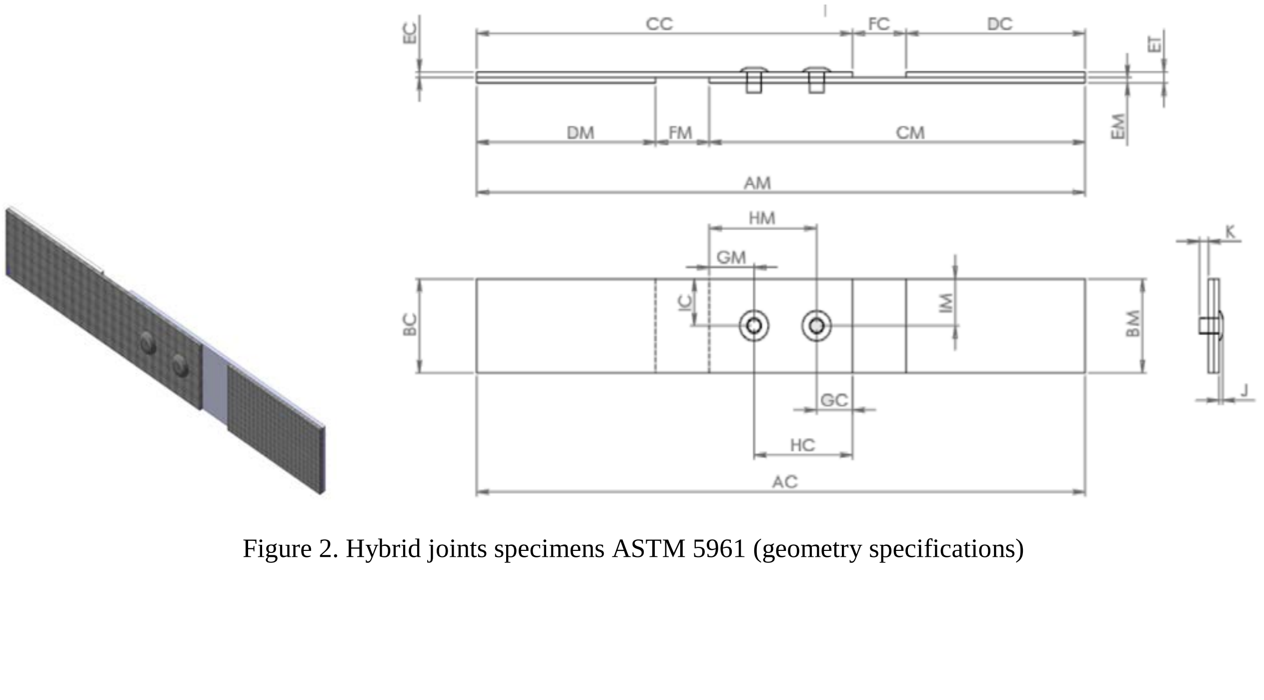


Figure 2. Hybrid joints specimens ASTM 5961 (geometry specifications)

Table 1. Hybrid joints specimens ASTM 5961 (geometry specifications in [10^{-3} m])

Composite 1																					
Specimens	**AC**	**AM**	**BC**	**BM**	**CC**	**CM**	**DC**	**DM**	**EC**	**EM**	**ET**	**FC**	**FM**	**GC**	**GM**	**HC**	**HM**	**IC**	**IM**	**J**	**K**
0.1	169.0	168.0	26.0	26.0	105.0	105.5	50.0	49.0	1.5	1.3	2.8	14.0	13.5	15.0	9.0	33.0	27.5	13.0	13.5	1.0	2.5
0.2	167.5	168.0	26.5	26.0	105.0	106.5	48.0	49.0	1.5	1.3	2.8	14.5	12.5	16.0	10.0	34.0	27.0	14.0	13.5	1.0	2.5
0.3	169.0	168.5	25.5	26.0	105.5	106.0	48.5	49.0	1.5	1.3	2.8	15.0	13.5	15.0	10.0	33.0	28.5	12.0	12.5	1.0	2.5
0.4	169.0	169.0	27.0	26.0	106.0	106.0	48.5	49.5	1.5	1.3	2.8	14.5	13.5	15.5	10.0	33.5	28.0	13.5	13.0	1.0	2.5
0.5	167.0	167.0	25.0	26.0	105.0	105.5	49.0	48.5	1.5	1.3	2.8	13.0	13.0	15.0	10.5	33.0	28.0	13.0	13.5	1.0	2.5

Composite 2																					
Specimens	**AC**	**AM**	**BC**	**BM**	**CC**	**CM**	**DC**	**DM**	**EC**	**EM**	**ET**	**FC**	**FM**	**GC**	**GM**	**HC**	**HM**	**IC**	**IM**	**J**	**K**
45.1	167.5	167.5	26.0	26.0	105.0	106.0	47.5	49.0	1.5	1.3	2.8	15.0	12.5	16.0	10.0	34.0	28.0	13.0	13.0	1.0	2.5
45.2	169.0	168.5	26.0	26.0	107.0	106.5	49.0	49.0	1.5	1.3	2.8	13.0	13.0	17.0	10.0	35.0	28.0	14.5	12.5	1.0	2.5
45.3	169.0	169.0	25.0	26.0	105.0	105.0	49.0	48.5	1.5	1.3	2.8	15.0	15.5	14.0	10.0	32.5	28.0	13.0	14.0	1.0	2.5
45.4	169.0	168.5	25.0	26.0	104.0	106.0	48.0	48.5	1.5	1.3	2.8	17.0	14.0	13.0	10.0	31.0	28.0	12.0	13.0	1.0	2.5
45.5	168.0	168.0	25.0	26.0	106.0	105.0	48.5	50.0	1.5	1.3	2.8	13.5	13.0	15.5	10.0	34.0	27.5	12.0	12.5	1.0	2.5

The geometry was reproduced by coplanar surfaces in the finite element model; so there is no influence of secondary moment. The boundary conditions were also applied as follows: fixed the left side; total load applied on the right side; free displacement only in the X direction (Fig. 3). The element CQUAD4 was used in order to simulate a plane stress state. This quadrilateral element has four nodes and each node has six degrees of freedom. Data for metallic materials, e.g. fasteners and metal part, were obtained from MIL-HDBK-5J (Tab. 2). Data for composite materials were obtained from experimental tensile and shear tests (Tab. 3).

Table 2. Material properties for metals (MIL-HDBK-5J)

Material	**Elasticity Modulus [MPa]**	**Poison**	**Shear modulus [MPa]**
Monel	170000	0.32	66000
Ti6Al4V	110300	0.31	42750

Table 3. Material properties for composite

Properties	**Unit**	**Value**
Young's modulus in fiber direction - E_{11}	MPa	41413 ± 2563
Young's modulus in matrix direction - E_{22}	MPa	39854 ± 1749
Poisson's ratio - ν_{12}	-	0.107 ± 0.012
Shear modulus in plane - G_{12}	MPa	2812 ± 276
Tensile strength value in fiber direction - X_T	MPa	494 ± 21
Shear strength value in plane - S_{12}	MPa	81 ± 3
Tensile strain limit in fiber direction - X'_T	mm/mm	0.0116 ± 0.0013

Two types of single lap joints metal-composite were evaluated: 1) Composite 1 with stacking sequence equal $[0°/90°]_6$; 2) Composite 2 with stacking sequence equal $[\pm 45°]_6$. For example, in Fig. 3, the maximum principal stresses on the composite part of Composite 2 can be seen. After stress analysis, it was carried out a failure analysis at the highest stress region (more critical element), using the failure criterion of Tsai-Wu (Tsai and Wu, 1971). Considering Composite 1 ($[0°/90°]_6$), the load applied must be equal 3351N to produce an initial failure in the composite part of the joint. However, for the Composite 2 ($[\pm 45°]_6$), the load applied must be equal 2473N to produce an initial failure in the composite part of the joint. These numerical results are coherent, because the fibers at 0^o aligned to the load in the Composite 1 can offer more resistance than fibers at ± 45° in the Composite 2.

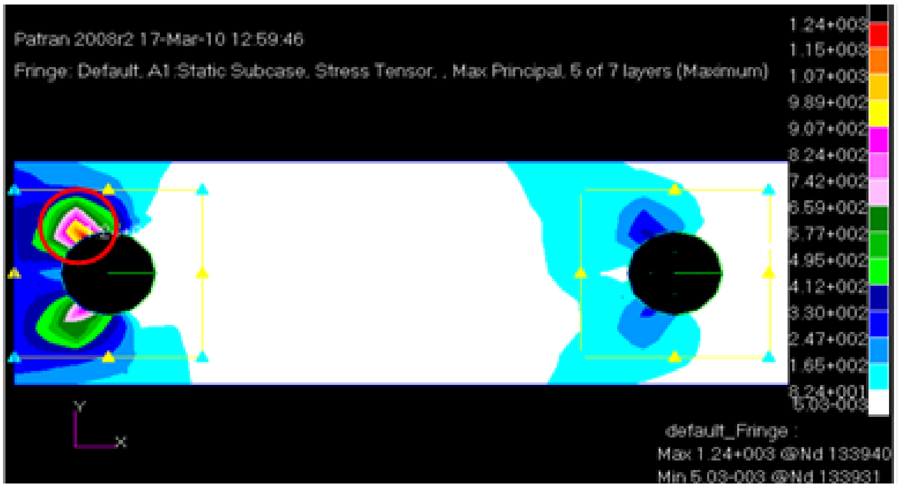


Figure 3. Maximum principal stresses on composite part for Composite 2 (highest stress region in detail)

It is important to notice for this work, non-linearity effects were not considered, because the paper purpose does not consist on simulating the mechanical behavior of the joints during the whole experimental test. In fact, the numerical results can provide a preliminary prediction in order to aid the test setup. Therefore, simulations were carried out only for linear elastic behavior. However, further analyses have been performed, considering non-linearity effects, which will be published in the future works.

4.2. Results of Experimental Procedure Proposal

Analyzing the failure mechanisms for the Composite 1, it was observed that occurs Multimode Failure due to the separation of the material (Fig. 4). As commented earlier, these failures are created by the interaction of bearing-bypass, producing inelastic strain of the hole ("bearing") (Fig. 4a) and the rupture by tension in the critical area (net-tension) (Fig. 4b). It is important to mention that there are factors that influence the resistance to "bearing". One of these factors is a function of the ratio between the diameter of hole and the thickness of the composite part (MIL-HDBK-17-1F, 2002). It is recommended that the ratio should be higher than 2.2 and, in this work, the specimens tested have around 2.44.

(a) (b)

Figure 4. Composite 1: (a) Inelastic strain of the hole -"bearing"; (b) Separation of composite material due to effect of bearing-bypass (net-tension)

Experimental analyses were performed only for laminates [0°/90°] and [±45°]. Regarding to literature, the authors know that these stacking sequence are not adequate for composite joints due to bearing phenomenon does not occur as main mode failure. However, the main goal of this work consists on showing an experimental method to provide the mechanical behavior of hybrid metal-composite joints joined by fasteners.

Using modified Secondary Modulus Method, it was possible to evaluate the mechanical behavior of the hybrid joint. Therefore, in this work, the following experimental procedure was adopted:

- First, a monotonic loading up to the initial of a non-linear response is applied (Fig. 5);
- After that point, an unloading and a reloading is applied;
- After that cycle, a monotonic loading is applied (again) until the total failure of the joint;
- In Fig.5, there is a secant line (in red) crossing the cycle created by unloading and reloading;
- A line parallel to that secant line is translated until cross the x-axis (displacement) corresponding to a value of 0.04d (d is the diameter of the hole);
- The slope of the straight line parallel can determine the "elasticity modulus" of the hybrid joint;
- When this line crossed the curve of the test, the limit loading is calculated. This loading corresponds to the allowable value for design of the hybrid joint;
- The maximum value of the force is the ultimate loading of the hybrid joint.

Figures 5 and 6 show the mechanical behavior for Composite 1 and Composite 2, as well as how the limit loading (Fa), the ultimate loading (P_{max}) and elasticity modulus (E_{jh}) are calculated.

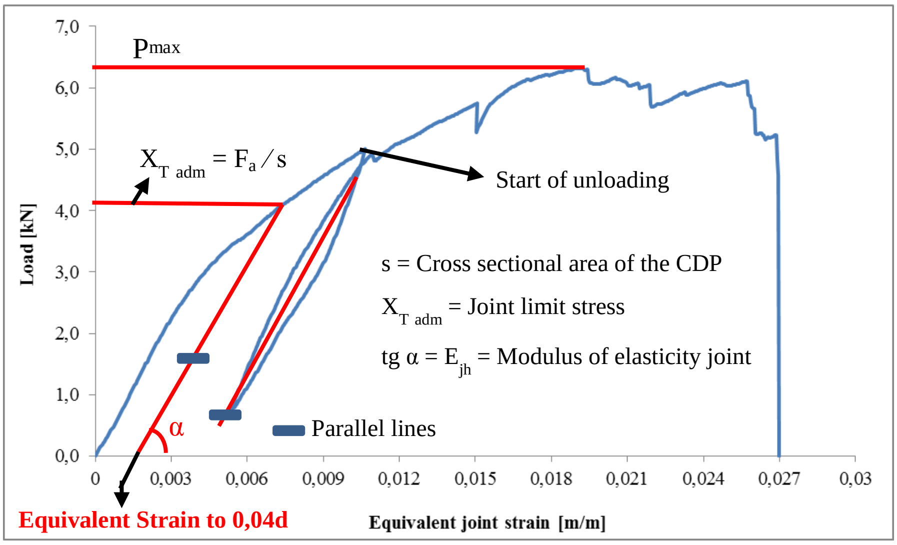


Figure 5. Mechanical behavior Composite 1 - $[0°/90°]_6$

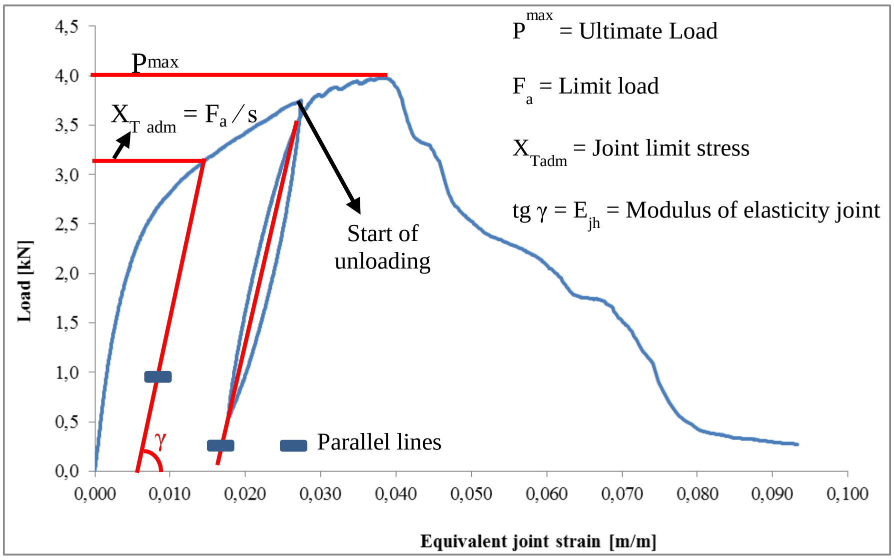
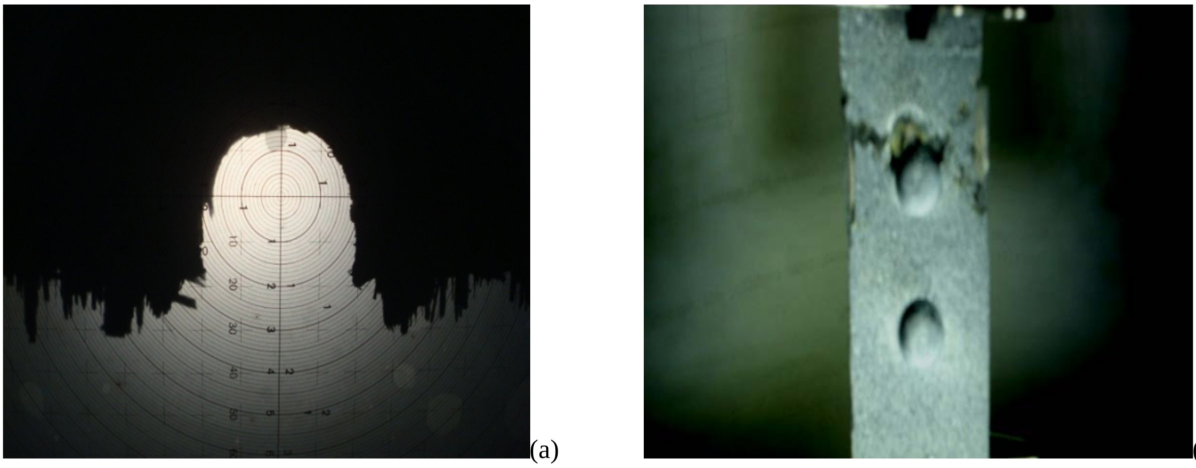


Figure 6. Mechanical behavior: Composite 2 - $[\pm 45°]_6$

Analyzing the failure mechanisms for the Composite 2, it was observed that did not occur the complete separation of the material (Fig. 7). As commented earlier, these failures are created mainly due to the effect of "bearing", producing more strongly the inelastic strain of the hole (Fig. 7a) and a crack propagation aligned to the fiber orientation at 45°. In fact, the maximum stress is normal to crack propagation direction as showed by numerical analysis (Fig. 3).



(a) (b)

Figure 7. Composite 2: (a) Inelastic strain of the hole -"bearing"; (b) Not complete separation of composite material due to predominant effect of bearing

Table 4 shows the comparison between the two configurations, where the Composite 2 has mechanical properties lower than Composite 1. For instance, the stiffness of the hybrid joints with fiber orientations equal ±45º is less than 50% of hybrid joints with fiber orientations equal 0°/90°. Besides, the tensile strength of Composite 1 is around 1.6 times higher than strength of Composite 2.

Table 4. Properties of hybrid joints

Properties of hybrid joints	**Composite 1** $[0°/90°]_6$	**Composite 2** $[\pm 45°]_6$
Tensile Strength (MPa)	192	121
Fa/S (MPa) (*)	144	93.5
Modulus of Elasticity (MPa)	266	104

(*) S = cross section area of specimen

Table 5 shows a comparison between different methods for determining Limit Loading (Fa), considering the Composite 1. It can be seen that the numerical result obtained by FEA is very close to the result found at literature (MIL-HDBK-17) for a similar hybrid joint. The experimental result obtained by modified Secondary Modulus Method is about 1.2 times higher than numerical result. This difference can be better explained by the Fig. 8 and Fig. 9.

Table 5. Comparison between different methods for determining Limit Loading (Composite 1)

Method	**Theoretical Limit Loading [N]**	**Experimental Limit Loading [N]**
MIL-HDBK-17	3275 (*)	NA
FEA	3351	NA
Secondary Modulus Method (modified)	NA	4070

(*) by-pass; (NA) Not Applicable

Figure 8 shows the numerical value of 3351 N and the experimental value of 4070 N for limit loading, considering hybrid joint of Composite 1 ($[0°/90°]_6$). It is important to note that the theoretical limit loading obtained via FEA and criterion of Tsai-Wu coincides to the experimental value, where the curve is no more linear. After this value, the composite can have micro damages, which reduce the strength of the hybrid joint. Thus, the numerical approach has underestimated the resistance of the hybrid joints that can support more loading. The same situation can be seen at Fig. 9, where the theoretical value obtained via FEA is lower than experimental value for hybrid joint of Composite 2 ($[\pm 45°]_6$).

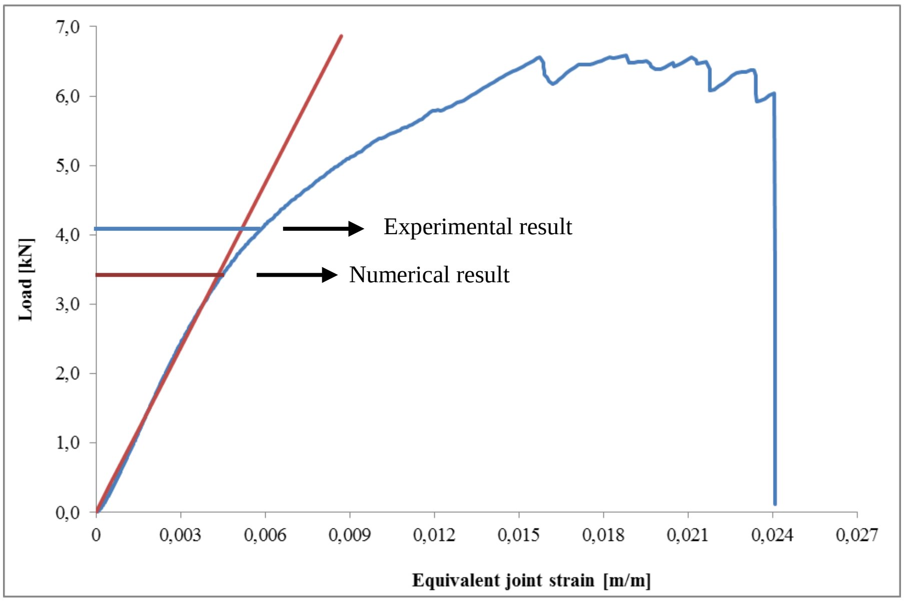


Figure 8. FEA × Experimental Results: Composite 1 - $[0°/90°]_6$

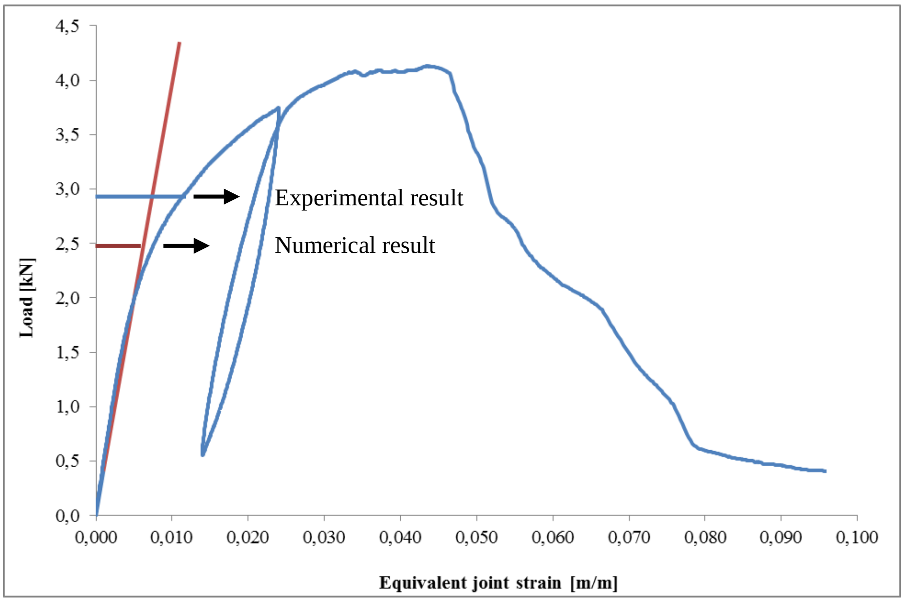


Figure 9. FEA × Experimental Results: Composite 2 - $[\pm 45°]_6$

5. CONCLUSIONS

Using the experimental approach proposal based on the Secondary Modulus Method (modified), limit loading (Fa), the ultimate loading (P_{max}) and elasticity modulus (E_{jh}) were determined for hybrid joints. The mechanical behavior of the hybrid joint was observed, using a very simple experimental method, also. For the other side, the failure mode can be evaluated, investigating the failure mechanisms, like “bearing”, “by-pass” or multimode failure (“bearing” effect with “by-pass”). Therefore, the experimental method proposal can help engineers during development of composite structures, mainly for investigating the best stacking sequence to be used. For example, this study showed that hybrid joints with the composite layers oriented $0^o/90^o$ fail by net-tension, while the composite layers oriented $\pm 45^o$ fail a tear-out. In addition, joints with laminates oriented at $\pm 45^o$ failed at a load lower when compared to joints with laminates oriented $0^o/90^o$.

Linear numerical analysis via finite element model is a good strategy to predict the mechanical behavior of hybrid joints in order to aid the experimental setup. Using the failure criterion of Tsai-Wu, the load that produces the damage in the composite part of the joint was calculated. However, it is important to note that this approach underestimated the strength of the hybrid joints, which can support more loading. Therefore, further works to improve the numerical results, the effects of contact nonlinearity (between the fastener and the hole) and material nonlinearities (inelastic strains and/or damage mechanisms in composite) are necessary to consider.

6. ACKNOWLEDGEMENTS

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