Experimental Methodology for Testing Metal-Composite Bolted Joints

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Abstract: This work consists of a new experimental methodology for testing metal-composite bolted joints. Single-lap titanium-composite structure joints attached by monel fasteners were investigated. Finite element analyses were carried out in order to predict the mechanical behavior of the joints up to the first failure, as well as to aid test setup. The experimental tests were carried out by using geometry specifications for composite-composite joints, and procedures established by the Secondary-Modulus Method for metal-metal joints. Based on the experimental tests, using the proposed methodology, it was possible to observe the mechanical behavior of the metal-composite joints, mainly the determination of the stiffness and strength of the structures. Therefore, the proposed methodology can contribute for designing metal-composite bolted joints, estimating not only the compliance, but also allowable stress values for those structures.

Keywords: Metal-composite joints, Bolted joints, Composite materials, Experimental method.

1. INTRODUCTION

In the literature, there are standard methods for testing composite [1-3] and metal materials [4]. However, based on the knowledge of the authors, there is not any specific standard method for testing metal-composite joints, mainly bolted ones. It is very important to highlight that joint design is one of the most challenging problems in aerospace structures, when involves metallic and/or composite structures [5]. In fact, the number of metallic structures replaced by composite materials has been increased not only in military applications, but also in civil aircraft [6]. Thus, composite material application is a current reality, mainly in the aeronautical and space industries, where some structures have been manufactured by joining two or more different kinds of materials, such as hybrid structure joints, which are a combination of two different materials (e.g. metal-composite joined by fasteners) [7]. One of these applications consists of joining metallic and composite parts in order to obtain the aircraft fuselage or other structure. Other example is the repair process of metallic structures by using composite patches. Hence, it is possible to find many positive aspects, which motivates the usage of metal-composite joints. However, these joints can fail due to many reasons, such as secondary moment caused by the loading eccentricity, stress concentrations, excessive deflections and difficult to design the joint with dissimilar materials. These negative aspects not only affect static mechanical behavior, but also have strong influence on the fatigue life of the joint and adjacent structures.

Considering the aspects pointed above, there are several researches about structural joints. Hart-Smith [8] conducted an analytical investigation on bonded-bolted stepped lap joints for titanium alloy and Carbon Fiber Reinforced Plastic (CFRP) as adherents. The strength of those joints was calculated to be the same as well-designed bonded joints. Chan and Vedhgiri [9] investigated the stress field in laminated composite joints with multiple pin loads, using finite element analysis. The structural responses of different configurations of single lap joints (bonded, bolted and bonded-bolted joints) were predicted via 3D finite element models. Xiao and Ishikawa [10] developed an analytical model for simulating the bearing failure of bolted composite joints. The model was implemented into the finite element code ABAQUS™. The proposed model considered the contact conditions between pin and hole, as well as progressive damage on composite material, finite deformation and nonlinear material behavior. An experimental study was carried out by Kabche [11-12] in order to quantify the performance of joints with different geometries under flexural loads. Experimental results showed that double-lap joints can be stronger and stiffer than standard bolted joints. Kolesnikov et al. [6] showed experimental results, demonstrating the positive influence of titanium on composite-metal joints. In fact, the authors proved that CFRP-titanium joints have good mechanical performance when used for highly loaded conditions. Matsuzaki et al. [13-14] proposed a new method for manufacturing metal-compo-
site joints by using inter-adhered fibers, bolted and cocured process. Experimental investigations were carried out by the authors in order to measure the increase of the joint strength. Barut and Madenci [15] developed a semi-analytical solution method to calculate the stress field in a single-lap (bolted-bonded) joint of composite laminates under in-plane loading. Sen and Sayman [16] performed experimental failure analyses to determine the failure behavior of two serial-bolted glass-fiber-reinforced epoxy composite plates. Tests were carried out by using two different strategies, one with different preload moments, and another without. Yu et al. [17] showed experimental results about the size effect in bonded-bolted joints, and an analytical formulation to evaluate this phenomenon based on Fracture Mechanics. Ucsnik et al. [18] presented a new joining technology between steel and carbon fiber reinforced plastics for developing lightweight design applications in aviation industries. Tsouvalis and Karatzas [19] studied a simple concept composite-metal joint, which can be easily obtained by conventional manufacturing methods of composite materials, via numerical and experimental approaches. Baker [20] presented a paper focused on the difficult issue for aeronautic certification of adhesively bonded repairs, approaching the patch for restoring residual strength of critical structures. The scope of the paper included both adhesively bonded composite repairs to composite structures, and composite repairs to metallic ones. Bak et al. [21] presented a model and static analyses of three types of joints (bonded, riveted and bonded-bolted). A parametric study was performed to compare the performance of the bonded-bolted joint, considering different adherents, adhesive thicknesses and overlap lengths. The study was focused on the analysis of stress field in the three types of joints (bonded, riveted and bonded-bolted joints).

The precise determination of the stress field in joints with dissimilar materials is the first step to have a good prediction of the failure mechanisms. Regarding the failure mechanisms of composite part in bolted joints, it is possible to consider four in-plane and two additional out-of-plane failure modes, as well as failure of the fasteners. The in-plane failure modes consist on net section, shear-out, transverse and bearing failure. The two out-of-plane failure modes are surface damage (due to pre-tension and out-of-plane bending) and delamination (due to loading on edge of the hole). For thick joints, fasteners can be subjected to different failure modes such as head and net section failure, and yielding. In fact, there are many scientific contributions in the literature, which are mainly dedicated to the failure mechanisms in the composite part of the joint. Rowlands [22] presented and discussed 21 different failure criteria for composite materials. According to report of Paris and Hampton [23], there were 53 references about the application of damage/failure criteria for composite materials. Moreover, other works can be highlighted, such as Roy et al. [24], Turon et al. [25], Tita et al. [26], Ribeiro et al. [27-28] and others. However, it is more difficult to find scientific works, which investigate specially the mechanical behavior of metal-composite bolted joints. Camanho and Matthews [29-31] developed a 3D finite element model to predict damage progression and strength of composite-composite fastened joints, which failed in bearing, tension and shear-out modes. Experimental results concerning damage progression, joint stiffness and strength were obtained and compared to the computational predictions. Less and Makarov [32] investigated the feasibility of a new connection technique type, where bolted and bonded joints were combined in order to obtain a structure with better mechanical properties. Grassi et al. [33] showed a simple and efficient computational approach for analyzing the benefits of through-thickness pins for restricting debonding failure in joints. Experimental analyses confirmed that debonding mechanism and ultimate strength depend on the material, dimension, density, location and angle of the pins, as well as the mechanisms of pin deformation.

As shown by the researchers cited previously, in general, the preferred joint for composite structures is adhesive ones, because these joints are less intrusive. It is not necessary to punch holes for fasteners and ductile adhesives decrease stress concentrations, but bonded structures are very difficult to disassemble and can add complexity to maintenance, repair, and access to other structures. Besides, additional care needs to be taken in the quality control of bonding (process and environmental control) to ensure that a satisfactory load transfer capability is maintained. This can be very hard to guarantee for certification and to be maintained over long time, mainly for highly loaded joints in critical aeronautic structures. These are the reasons that fastened joints are still used for specific applications, for example in highly loaded critical composite-composite or composite-metal joints. However, as commented earlier, there is not a standard method to investigate the mechanical behavior of metal-composite joints. ASTM D5961 [3] provides a methodology for composite-composite joints, while the Military Handbook [4] presents a test procedure for metal-metal joints, which is
defined as Secondary-Modulus Method. Therefore, the present work consists on proposing an experimental methodology for fastened metal-composite joints. Thus, joints of titanium and composite (carbon fiber and epoxy resin) joined by monel fasteners were investigated by using the proposed methodology. Single lap joints were studied, because they are the most common type of joints applied on the aeronautic industry. First of all, composite coupons were tested by using ASTM D3039 [1] and ASTM D3518 [2]. Tensile and shear tests provided mechanical properties, strength values and strain limits of the composite part. After that, computational analyses of metal-composite fastened joint were carried out via Finite Element Method (FEM). Based on the results of numerical stress analysis and employing a failure criterion developed by Ribeiro et al. [27], the tensile load, which produces initial failure in the metal-composite single lap joint, was predicted. The computational model simulated the test specified by ASTM D5961 [3], aiming to predict the mechanical behavior of the joints up to the first failure, as well as to aid test setup. The experimental analyses were performed based on ASTM D5961 [3] (composite-composite joints) by employing a procedure analogous to Secondary-Modulus Method established by Military Handbook [4] (metal-metal joints). However, some modifications were applied in the Secondary-Modulus Method, because the coupons are not metal-metal joints, but metal-composite. Based on the experimental tests, using the proposed methodology, it was possible to observe the mechanical behavior of the metal-composite joints, mainly the determination of the stiffness and strength of the structures. Therefore, the proposed methodology can contribute for designing metal-composite bolted joints, estimating not only the compliance, but also allowable stress values for those structures.

2. PROPOSED METHODOLOGY: MATERIALS AND METHODS

2.1. Materials

Three different materials were employed to manufacture the single lap metal-composite fastened joints. These materials are: Composite (epoxy resin reinforced by carbon fiber), titanium alloy and monel.

The specifications of composite material are provided by Hexcel™ as G0904 D 1070 TCT. This bidirectional carbon textile is used in aircraft structures, which requires high performance. The HexPly M20 epoxy resin can be cured either under high temperatures (using a fast process cycle) in autoclaves or in vacuum bag. Due to this flexibility in manufacturing process, HexPly M20 is suitable for critical aircraft structures, as well as for repairing composite structures. The supplier has recommended two strategies for HexPly M20 cure cycles: 1) In autoclave: 130°C for 2 hours under 4 bars of pressure; 2) in vacuum bag: 130°C for 2 hours under 1 bar of pressure. In this work, the second option for cure cycle was used.

The fasteners consist on rivets made of nickel-copper alloy (monel), and all specifications are provided by Military Handbook - MIL-HDBK-5J [4]. This type of fastener was selected due to high shear strength and galvanic compatibility with the other elements of the joint (titanium alloy and composite made of carbon fiber). Regarding the geometry, fastener diameter is equal to 1/8” (around 3.175 mm) before the assembling process.

Titanium alloy (Ti6Al4V) has all specifications in the MIL-HDBK-5J [4], as well. This material has excellent mechanical properties, high impact resistance and galvanic compatibility to the composite part of the joint. Moreover, Ti6Al4V maintains the properties at temperatures up to -253 °C. Its application is recommended for structures, which work under extreme conditions.

2.2. Methods

Tensile and shear tests for composite material coupons were carried out based on ASTM D3039 [1] and ASTM D3518 [2] in order to obtain the mechanical properties and the failure behavior. Five coupons for each type of test were investigated by using a Universal Testing Machine EMIC DL 10000 with a 100kN load cell, and strain-gauges were used to measure the strain in the coupons. Based on experimental stress-strain curves, it was possible to determine the mechanical properties, the strength values and strain limit for the composite material (Table 1).

The computational analyses were carried out using average data from mechanical properties and strength values obtained by experimental tests for composite material. Moreover, mechanical properties and yield stress for metallic materials, e.g. fasteners (monel) and the metal part of the joint (titanium alloy - Ti6Al4V), were obtained from MIL-HDBK-5J [4] (Table 2).

The computational analyses simulated the ASTM D5961 [3] tests (Figure 1). Therefore, Finite Element models (Figure 2a) were developed in order to predict the mechanical behavior of the composite-metal joints.
Furthermore, the end tabs were also modeled to avoid secondary bending moment during the tests. For the boundary conditions, the left side of the joint was fixed as in the machine test, and symmetry conditions were applied in the y-direction (Figure 2a). Moreover, the tensile load was applied on the right side of the joint model, which has free displacements only in the x-direction (Figure 2a).

### Table 1: Composite Material: Mechanical Properties, Strength Values and Strain Limit

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<th>Mechanical Properties / Strength Values / Strain Limit</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>Young’s modulus in fiber direction - E_{11} MPa</td>
<td>MPa</td>
<td>41413 ± 2563</td>
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<td>Young’s modulus in matrix direction - E_{22} MPa</td>
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<td>Poisson’s coefficient - ν_{12}</td>
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<td>Shear modulus in ply plane - G_{12} MPa</td>
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<tr>
<td>Fiber direction tensile strength - X_T MPa</td>
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<tr>
<td>Fiber direction compressive strength – X_C MPa</td>
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<td>Shear strength value out of plane – S_{23} MPa</td>
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<td>Tensile strain limit in fiber direction - X'_T mm/mm</td>
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### Table 2: Joint Metal Part and Fasteners: Mechanical Properties and Yield Stress (MIL-HDBK-5J [4])

<table>
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<tr>
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<th>Poisson’s Coefficient</th>
<th>Shear Modulus [MPa]</th>
<th>Yield Stress [MPa]</th>
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<td>Joint - Ti6Al4V</td>
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**Figure 1:** Metal-composite joint coupon geometry (specifications from ASTM 5961).
A damage model proposed by Ribeiro et al. [27] was used to predict on-set and type of damage in the composite part. This damage model requires parameters, which can be easily determined via experimental tests. In fact, a User Material subroutine (UMAT) was implemented based on the damage model, and after that, it was linked to Abaqus/Standard [34]. Detailed information about the formulation of the damage model, computational implementation and the parameters identification can be found in Ribeiro et al. [27-28].

Regarding the finite elements used in the joint model, for the composite part, it was used continuum shell elements (SC8R) with reduced integration. Solid elements (C3D8 – eight nodes hexahedron element) were used for the titanium part and fasteners. Abaqus general contact algorithm was used to model the interaction between fastener and composite or metallic part. Besides damage for the composite, the finite element model regards yielding phenomenon for the fasteners and titanium. In addition, geometric non-linearity was considered in the numerical simulations.

Based on the computational results, the test setup for single lap structure joints was designed. In fact, as commented earlier, coupons were based on the geometry specifications presented by ASTM D5961 [3], which was developed for composite-composite joints (c.f. Figure 1 and Table 3). Combined to this standard, a test procedure analogous to Secondary-Modulus Method, which was established by Military Handbook [4] for analyzing metal-metal joints, was employed. Thus, a new experimental procedure to evaluate metal-composite single lap fastened joints (metal-composite) was proposed based not only on the ASTM D5961 [3], but also on the Secondary-Modulus Method [4]. Two different types of metal-composite joints have been investigated using the proposed methodology: 1) Composite 1 – titanium and composite parts with stacking sequence equal to \([0^\circ/90^\circ]_6\); 2) Composite 2 – titanium and composite parts with stacking sequence equal to \([\pm 45^\circ]_6\). To evaluate those metal-composite joints, whose geometry is specified in Figure 1 and Table 3, five coupons were analyzed for each type of metal-composite structure joint (Composite 1 and Composite 2). The experimental tests were carried out by using a Universal Testing Machine EMIC DL 10000 with a 100kN load cell. It is also important to mention that clip-gauges were used to measure the strains in the composite-metal joint coupons.
Therefore, in this work, the experimental tests for the joints were performed following 11 steps:

1. It was applied a monotonic loading on the metal-composite joint in order to obtain the load vs. strain curve under tensile loading (Figure 3). In fact, the strain axis is named "equivalent joint strain", which is measured by clip-gauges.

2. The point-shift equivalent to 0.04d (d is the hole diameter – around 3.3 mm) was identified in the abscissas axis as specified by MIL-HDBK-5J [4] (Figure 3).

3. Through that point, it was drawn a parallel line (dashed line – Figure 3) to the preliminary estimation of the joint "stiffness".

4. The threshold load value for the unloading process is determined by the intersection between the dashed straight line and the continuous experimental curve (Figure 3).

5. The unloading and loading cycle was imposed to be performed slightly above the threshold load point in order to ensure a test condition in which all machine gaps were eliminated (Figure 4).

6. After that cycle, the joint was monotonically loaded again up to the complete failure.

7. A secant straight line was traced inside the load cycle as shown in Figure 4.

8. A parallel line to the secant straight line, obtained in the previous step, was moved until crossing the abscissas axis (equivalent joint strain – Figure 4) at the "equivalent strain value", which corresponds to 0.04d.

9. A similar curve stress vs. strain can be obtained by dividing the load by the cross section area (s) of the joint. Thus, the slope of the parallel line (of this curve) allows determining the "elasticity modulus" of the metal-composite joint. Based on

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(*) where: C = Composite; M = Metal; T = Total.
10. When the line parallel to the secant line intersects the experimental curve, the limit load \( F_a \) is determined (Figure 4). This load divided by the cross section area \( s \) of the coupon provides the “joint limit stress” \( X_{Tadm} \), which can be used as an allowable stress value for the structure joint design.

11. The maximum or ultimate load \( P_{max} \) supported by the metal-composite joint is displayed in the experimental curve (Figure 4). This load divided by the cross section area \( s \) of the coupon provides the “joint strength” \( X_{Tmax} \), which can be used as an allowable stress value for the metal-composite joint design, as well.

3. RESULTS AND DISCUSSION

Before performing experimental tests in metal-composite joints, Finite Element Analyses were carried out to predict the joints mechanical behavior up to the initial failure in order to aid the test setup. Figure 2b showed the maximum principal stress on the composite part observed around the fasteners. After the stress analysis, and using the damage model for the composite part, it was possible to calculate the tensile load, which produces the first damage in the composite. For
Composite 1 joint, titanium and composite parts with stacking sequence equal to \([0^\circ/90^\circ]_6\), the applied load should be around 3,369 N to produce an initial failure in the composite part of the joint. However, for Composite 2, titanium and composite parts with stacking sequence equal to \([\pm 45^\circ]_6\), the applied load should be around 2,910 N to produce an initial failure in the composite part of the joint.

Those numerical results were coherent, because the fibers in \(0^\circ\) aligned to the load for the Composite 1 may offer more resistance than fibers in \(\pm 45^\circ\) for the Composite 2. Thus, the numerical results just aim to provide a preliminary prediction of the failure loading, aiding the experimental setup. After the finite element analyses, the experimental procedure proposal was applied for analyzing the mechanical behavior of metal-composite joints, considering the loading numerical predictions.

Figure 5 shows the load vs. displacement curves by using the proposed methodology for Composite 1 joint, numerical and experimental results. Composite 1 failure mechanisms may be classified as “Multimode Failure”, following the specifications described by ASTM 5961 [3]. This failure mode consists on the complete separation of the material as shown in Figure 6. In fact, this failure mode occurs due to the interaction of bearing-bypass effects, creating inelastic strain around the hole (bearing effects – Figure 6a). Also, there is a material rupture by tension in the critical area (net-tension phenomenon – Figure 6b).

Figure 5: Mechanical behavior of Composite 1 - titanium and composite part with stacking sequence equal \([0^\circ/90^\circ]_6\).

Figure 6: Composite 1 metal-composite joint: (a) Inelastic strain around the hole – bearing effects; (b) Separation of composite material due to effect of bearing-bypass (net-tension phenomenon).
It is important to mention that there are some factors, which influence the resistance to bearing effects. One of these factors is function of the ratio between the diameter of the fastener and thickness of the composite part (EC – Table 3). In fact, ASTM 5961 [3] recommends 1.2 to 2.0 for diameter to thickness ratio, and, in this work, the evaluated coupons had 2.0.

Figure 7 shows the load vs. displacement curves by using the proposed methodology for Composite 2 joint, numerical and experimental results. Analyzing the failure mechanisms for Composite 2 coupons, it was observed that there was not a complete separation of the material (Figure 8). For this case, the failure mode is mainly due to the bearing effects on the hole wall, causing cracks spreads until the ends of the coupons (tear-out phenomenon) and creating higher inelastic strains around the hole (Figure 8a). A crack propagation aligned to the fiber orientation in 45° can also be seen. In fact, the maximum principal stress is normal to crack propagation direction as shown by the numerical analysis (detail in Figure 2b).

Table 4 shows the comparison between important variables for metal-composite joint designs, considering both types of evaluated joints. It can be observed that Composite 2 joint showed allowable stresses values and elasticity modulus lower than Composite 1. Thus, the stiffness of the metal-composite joints with fiber orientations equal to ±45° (in composite part) is lower.

![Figure 7: Mechanical behavior of Composite 2 - titanium and composite part with stacking sequence equal [±45°].](image)

![Figure 8: Composite 2 metal-composite joint: (a) Inelastic strain around the hole – bearing effects; (b) Not complete separation of composite material due to predominant effect of bearing.](image)
than joints with fiber orientations equal to 0°/90°. Besides, the tensile strength of Composite 1 joint is around 1.6 times higher than strength of Composite 2.

Table 5 shows a comparison between different methods for determining the Limit Loading (F_a). It can be seen that the numerical result obtained by FEA is very close to the result found in literature [35] for a similar metal-composite joint. The experimental result obtained by proposed methodology is about 1.2 times higher than the numerical one. The Limit Loading for the Composite 1 structure joint is around 3,369 N obtained by the computational model (initial failure), and around 4,070 N obtained by the experimental analysis (limit load – F_a). A similar analysis can be made for Composite 2 joint. The numerical value obtained by FEA (2,910 N) is slightly smaller than the experimental one (2,976 N) obtained by the proposed methodology.

The difference between the experimental and numerical results can be explained by the fact that the value of allowable stress determined experimentally by the methodology may be overestimated by the FEA. Moreover, considering that the proposed methodology is based on the Secondary-Modulus Method for metal-metal joints, so the reference value of equivalent strain equal to 0.04d (d is the hole diameter) may not be the most suitable for the design of metal-composite joints.

4. CONCLUSIONS

The Limit Load (F_a), the Maximum Load (P_{max}) and the Modulus of Elasticity (E_jh) have been determined for metal-composite joints by using a proposed experimental methodology based on the ASTM D5961 [3] method and the Secondary-Modulus Method [4]. Furthermore, it can be observed that the coupons can show different failure modes caused by bearing, bypass or multimode (bearing with by-pass) effects. Therefore, the experimental methodology proposal can aid engineers during development of metal-composite joints, mainly for investigating the joint stiffness to be used. For example, this study showed that composite-metal joints with layers oriented 0°/90° fail by net-tension, while composite-metal joints with layers oriented at ±45° by tear-out. In addition, metal-composite joints with plies oriented at ±45° failed for lower load than plies oriented at 0°/90° for the same composite (width and thickness). Consequently, it is possible to evaluate the mechanical behavior of a metal-composite joint, applying the proposed experimental methodology. It is also very important to mention that this methodology is relatively simple. However, it can still be improved, mainly related to the reference value of equivalent strain equal to 0.04d (d is the hole diameter), which is more suitable for metal-metal joints.

Regarding the computational analyses, it was shown that non-linear numerical analysis via finite element model is a good strategy to predict the mechanical behavior of metal-composite joints up to the preliminary failures in order to aid the experimental setup.

Finally, although the proposed experimental methodology has been applied for two specific metal-composite joints, this methodology can aid engineers to design other metal-composite joints, which involve other
types of composite and/or metallic materials. Therefore, it is possible to investigate different parameters, such as the elasticity modulus (or the compliance) of the metal-composite joints, the joint limit stress (\(X_{\text{adm}}\)) and strength (\(X_{\text{Max}}\)), which can be used as allowable stress values for the metal-composite joint design.

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