ANALYSIS OF OUT-OF-PLANE BEHAVIOUR OF BOLTED JOINTS ASSEMBLIES FOR THERMOPLASTIC LAMINATES

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Abstract

To achieve weight reduction of structures, composite carbone fabric materials are used extensively in various industrial applications such as aerospace and automotive. Their high mechanical performances and good fatigue durability offer advantages compared to more traditional metallic materials. To be able to design composite structures, it is necessary to characterize their behaviour. It often leads up to hybrid solutions combining composite materials and metal components. The assemblies can be mechanical junctions based on rivets, screws or bolts. Most studies in this field are focused around the hole drilled composite mechanical behavior. Therefore, there are currently no design rules for predicting fracture of bolted bonds on thermoplastic based composite substrates. The bolted assemblie principle is to introduce and maintain axial load in a fastener, so we are investigating the out-of-plane behavior of thermoplastic composites. An experimental study of the compliance of thermoplastic laminates using inductive displacement transducers is presented. Meanwhile, numerical simulations based on a 3D finite elements analysis have been realized to understand the assembly out-of-plane behaviour and have then been compared with experimental results. Results are promising but not enough to draw a general conclusion therefore further studies need to be done to find the ideal design rules answering conception specifications.

1. Introduction

Bolted joints are widely used in many industrial sectors like the automotive industry or aeronautical structures. These mechanical junctions have a lot of advantages, they are easy to disassemble for maintenance or inspection purposes, and benefit from a long return on experience with metallic assemblies and are fast to clamp. Another advantage of bolted joints is the robustness to environmental conditions.

Composite materials appear to be a promising alternative to metallic materials and have taken more and more importance in many industrial sectors (aerospace, energy and automotive industry). Consequently, new design challenges appear with the increasing use of composite materials. We need to define new design rules for composite materials to safeguard a good functioning of this new generation of mechanical junctions. Composite materials are anisotropic so their behaviour lead to complex failure mode [1, 2]. The design and behavior of metallic bolted joints have been completely investigated in the past decades, for exemple, in the German bolting guideline VDI 2230 [3]. These studies are primarily based on empirical approaches and analytical formulas. However, it was the development of finite elements which led up to more accurate models. For example, we can quote the

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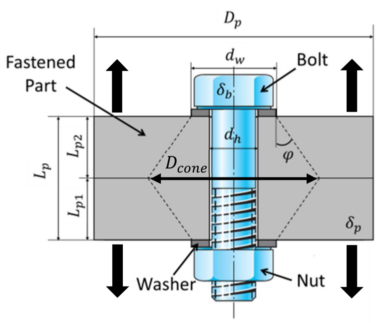
studies of Wileman [4], Guillot [5] or Massol [6]. The design rules established in these recommendations are valid for metallic assemblies but not directly applicable to composite materials. Bolted joints induce stress concentrations and discontinuities localized around the hole and under the washers. To design correctly these mechanical junctions, we have to know the behaviour under several loading configurations, both in-plane and out-of-plane. The in-plane behaviour of composite bolted joints has already been extensively studied. The majority of authors have limited their work to shear tests (single or double lap specimens). These studies focus on the experimental identification and the modelling of bolted joints damage or pinned holes [7,8]. The influence of design: tightening effect, clearance and washer effects have been also studied [9,10].

In this paper, a new approach for compliance calculation is presented for thermoplastic laminates: this approach takes into account the various geometrical parameters and the material properties in the case of axial loading. Three-dimensional finite elements (FEM) computations are conducted to compute the apparent compliance of the subassemblies using an energy criterion. Then, results are compared to previous studies and validated by an experimental approach.

2. Compliance of fastened plates

2.1. Methodology

In this section, extensive numerical and experimental studies are conducted to investigate the out-of-plane behavior of bolted joints. More generally, we aimed to evaluate and to measure the compliance δ_p of clamped parts for the out-of-plane axial loading for thermoplastic laminates. Indeed, in the VDI guideline [3], the principal parameters used to design a bolted joint with an axial loading and to calculate δ_p are : D_p, d_w, d_h, d_w, L_p, E_p and φ, see Fig. 1.



Nomenclature

- $\boldsymbol{D_p}$ Diameter of the fastened part
- $\boldsymbol{d_w}$ Washer diameter
- $\boldsymbol{d_h}$ Bolt hole diameter
- $\boldsymbol{\delta_p}$ Part compliance
- $\boldsymbol{\delta_b}$ Bolt compliance
- $\boldsymbol{L_p}$ Length of the assembly
- $\boldsymbol{\varphi}$ Deformation cone angle
- $\boldsymbol{E_p}$ Young's modulus

The compliance $\boldsymbol{\delta_p}$ of concentrically clamped parts for the case $\boldsymbol{D_p > D_{cone}}$

(1)

$$\delta_p = \frac{2\ln\left[\frac{(d_w + d_h)(d_w + L_p \tan\varphi - d_h)}{(d_w - d_h)(d_w + L_p \tan\varphi + d_h)}\right]}{E_p \pi d_h \tan\varphi}$$

with

$$\tan\varphi = 0.362 + 0.032\ln\left(\frac{L_p}{2d_w}\right) + 0.153\ln\left(\frac{D_p}{d_w}\right)$$

Figure 1. Schematic representation of a bolted joint loaded in tension and principal parameters used in the empirical model [3] for the axial loading.

The calculation of the compliance δ_p of the parts preloaded by the bolt are governed by the clamping region and more exactly by the deformation cone angle φ. This cone angle φ of the deformation solid is not constant. The parabolic deformation solid depends on the material structure (isotropic or anisotropic), and so of the compliance of concentrically clamped parts. Another point concerns the main dimensions of the plates. To adjust VDI formulas to thermoplastic composites, we need to re-evaluate the cone's shape. From finite element analysis, we propose a new approach to calculate the axial compliance of clamped parts based on homogenization procedure and an energy equivalence.

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2.2. Materials' properties and RVE FE modelling

First of all, to calibrate the FEM, we use a flexible isotropic material, the Aluminium 7075T6. The aim is to create several reference points between the FE modeling and the current VDI formulas. Secondly, after this validation, two woven thermoplastic laminates were tested, a T700/PA66 and a GF/PA6. All the material properties are summed up in the following table 1 and table 2.

	ρ (g.cm^{-3})	E11 (GPa)	E22 (GPa)	E33 (GPa)	ν_{12}	ν_{13}	ν_{23}	G12 (MPa)	G13 (MPa)	σ11m (MPa)	σ22m (MPa)	σ12m (MPa)
GF/PA6	1.8	22.4	21.5	5.7	0.17	0.17	0.12	1840	1840	404	390	116
T700/PA66	1.43	53	51	6.5	0.07	0.07	0.02	1960	1960	785	725	150

Table 1. Undamaged material properties : GF/PA6 and T700/PA66 - Thermoplastic composites Dynalite®.

ρ (g.cm^{-3})	ν	E (GPa)	Re (MPa)	Etan (GPa)
2.81	0.33	70	331	26.9

Table 2. Material properties : Aluminium 7075T6.

The out-of-plane Young's modulus E_{33} indicated in table 1 are obtained through an experimental campaign. To confirm these first experimental results, we propose to investigate another option with a FE modelling of the RVE. Analysis of this problem is broached but not fully explained in this paper.

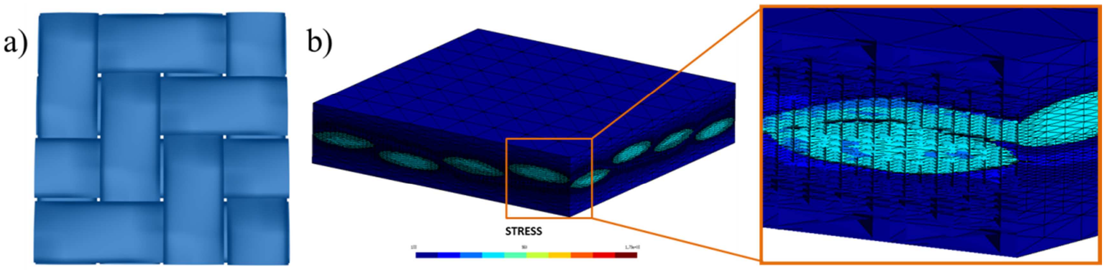

Figure 2. RVE 3D FE modelling : a) generation of textile geometric model using TexGen and b) mechanical analysis performed with X-FEM.

The procedure is composed of two main parts. The first one concerns the geometrical modelling of the woven composites RVE, and it was developped within the TexGen software. The second part concerns the finite element model and analysis of the RVE, and was performed using the extended finite element method (X-FEM) homogenization process [11]. X-FEM is suited to treat problems with material discontinuities and complex interfaces like this RVE. The levelset approach is used to track the positions of the material interfaces on the mesh. The levelset values are interpolated on the finite element mesh, and the location of the interfaces between the matrix layers and the yarns is obtained by looking for the iso-zero of the levelset. The geometry of the RVE is represented with a levelset that is interpolated on a level 6 octree mesh. We can't see the frictional sliding at the fiber-matrix interfaces with this method but we can observe the stress discountinuities shown in Fig. 2. (b). The X-FEM results are compared with experimental results and are shown in table 3.

E33 (MPa)	T700/PA66		GF/PA6	
	X-FEM	Experiment	X-FEM	Experiment
	7300	6500	6400	5800

Table 3. Comparaison between X-FEM and experimental results.

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2.3. Finite element model development to determine the compliance δ_p

In this section we show that we can find the compliance δ_p from a finite elements analysis and an energy criterion defining the elastic resilience of the assembly, and especially, for the clamped parts. In this case, to define a volume of interest V_r, we propose to use the iso-zero value of the volumetric elastic deformation energy reduced to the out-of-plane component $E_{D33} = \sigma_{33}\varepsilon_{33}$. Then, with this elastic deformation energy E_{D33}, the equivalent compliance δ_p can be deduced by an energy balance formula. This compliance can be calculated using the following relations :

$$E_{D33} = \int_{Vr} \sigma_{33}\varepsilon_{33}\, dv \tag{2}$$

and

$$E_{D33} = FU \tag{3}$$

With F the axial load, and U the axial displacement due to clamping. From Eq. (2) and (3), one can deduce :

$$\delta_p = \frac{U}{F} = \frac{\int_{Vr} \sigma_{33}\varepsilon_{33} dv}{F^2} \tag{4}$$

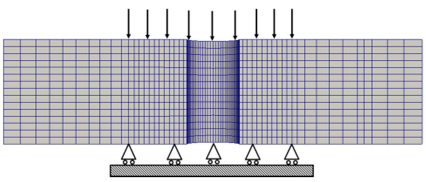

Figure 3. Finite element mesh and boundary conditions.

Consequently, the equivalent compliance δ_p is calculated by extracting E_{D33}. This approach is advantageous since it does not require the displacement along the axis. Besides, it is simple and accurate since the elastic deformation energy is precisely estimated with the finite element software. The finite element modelling was developped under the finite element software Cast3M. Radial translations along the part are restrained. The bottom of the assembly part is restrained in displacement along z axis and the load is applied by a pressure at the top of the part. The mesh, the geometry of the model and the boundary conditions are shown in Figure 3.

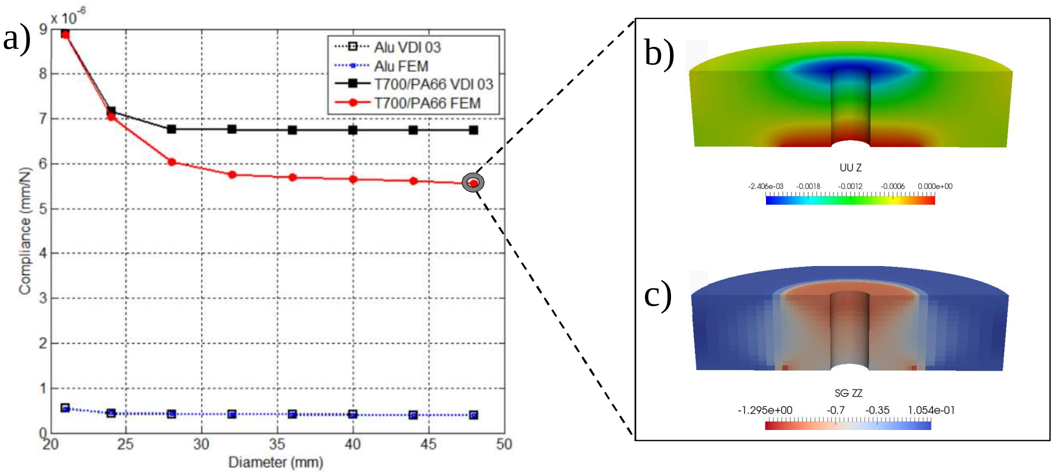

Figure 4. a) Validation of 3D FEM model, b) and c) displacement and stress distributions respectively.

For the aluminium parts, the curves presented in Fig.4. show an excellent match between the results from VDI 2230 guideline and our finite elements model using the proposed energy criterion. Decreasing flexibility values are observed with the increase of the outer diameter of the parts until a

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threshold value initiating a plateau. This behaviour change is explained with the truncation of the deformation cone. The calculation error between these two appoaches is around 1 %. On the other hand, for the thermoplastic composite T700/PA66, this error between VDI 2230 recommandation and the FEM is around 17 % for D_p = 48 mm. This error comes from an overestimation of the clamped part, and so, the angle φ in the VDI guideline.

2.3. Experimental validation

To complete the FE model, numerical results have been compared to experimental ones from an experimental campaign. The analytical results (according to VDI2230 under COBRA V6 software), FEM calculations (under Cast3M) and experimental results are presented in Fig. 5. This summary Fig. 5. a) shows a good agreement between these three approaches.

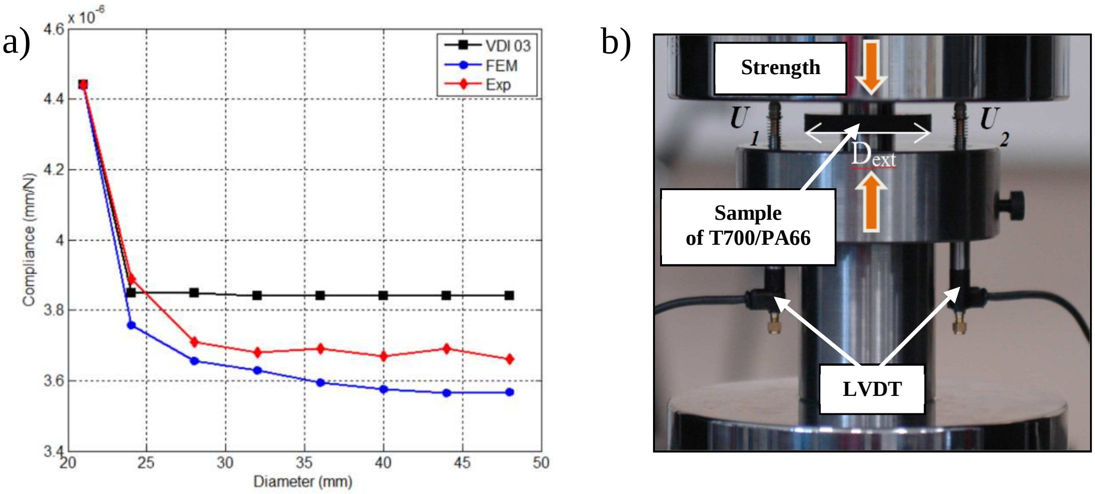

Figure 5. a) Comparaison of results between VDI formulas, FEM and experimental results. b) experimental setup.

3. Preload efficiency factor λ and load introduction factor β for thermoplastic laminates

3.1. Introduction

We have now completed our study of bolted joints and the out-of-plane behaviour with the verification of the initial tension in the bolt. To adapt the bolted joints design for thermoplastic laminates, we need to ascertain, in addition to the compliance δ_p, the preload factor λ which depends on β, the load introduction factor. Not only a correct preload is important but we need to know and control the service loads on the bolted joint. The behaviour of these mechanical junctions can change quickly for thermoplastic laminates with moisture, creep, temperature, under vibrations, cyclic loads, etc. In the case of an axial loading and a concentrically clamped joint, λ is obtained from the formula indicated in Fig. 6. The aim of this section is to reappraise these parameters λ and β for the thermoplastic laminates.

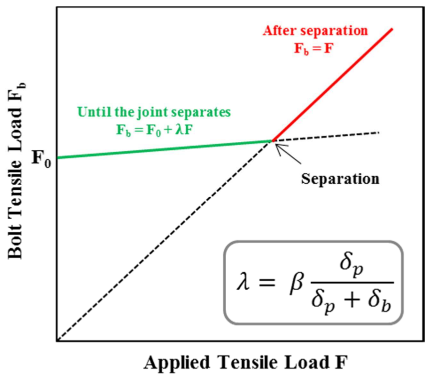

Figure 6. Schematic representation of the preload effect.

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3.2. Procedure

The joint tested in the experimental investigation is shown in Fig. 7. Two bolt testing fixtures made of high strength steel are clamped with a bolt and a nut. One fixture is fixed at one end and an axial loading is applied at the end of the other fixture. The bolts used in the experiments are made of class 8.8. The washers are made of 42CrMo4 steel. The axial loading, the stroke (the displacement of the bolt testing fixture) and the clamping force are measured continuously throughout an experiment with two inductive displacement transducers (WI 5 mm) and a piezoelectric force washer (CFW/50 kN) respectively. In these experiments, one level of tightening torque is used and the bolt's preload applied was F_b = 8 kN. The tensile tests were carried out on a quasi-static testing machine INSTRON 5584. A 3D FE model of the setup is also proposed in order to verify the experimental results.

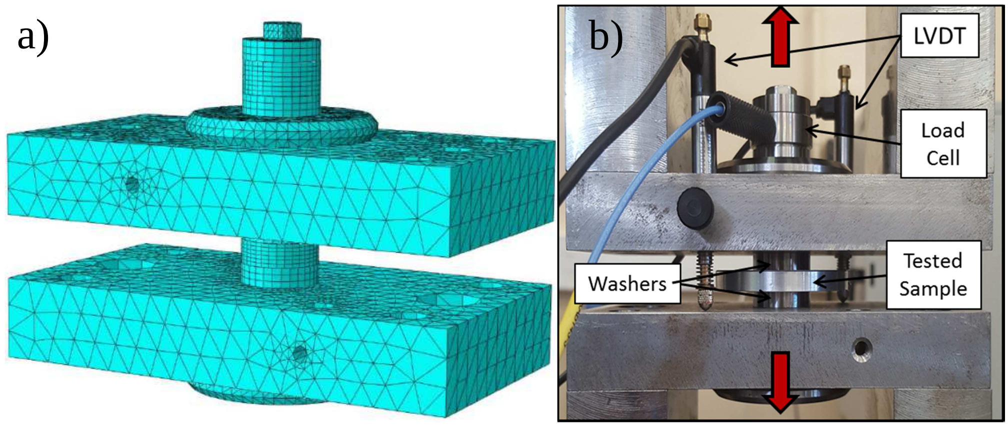

Figure 7. a) 3D FE model and b) experimental setup to determine the preload factor λ for β ≈ 1.

3.3. Results

The test conducted for each experimented configuration is repeated three times for repeatability verification and contact surfaces accomodation. The preload factor λ is obtained with a linear regression applied on the last measure, test 3, and until 6 kN for the applied tensile load, see Fig. 8.

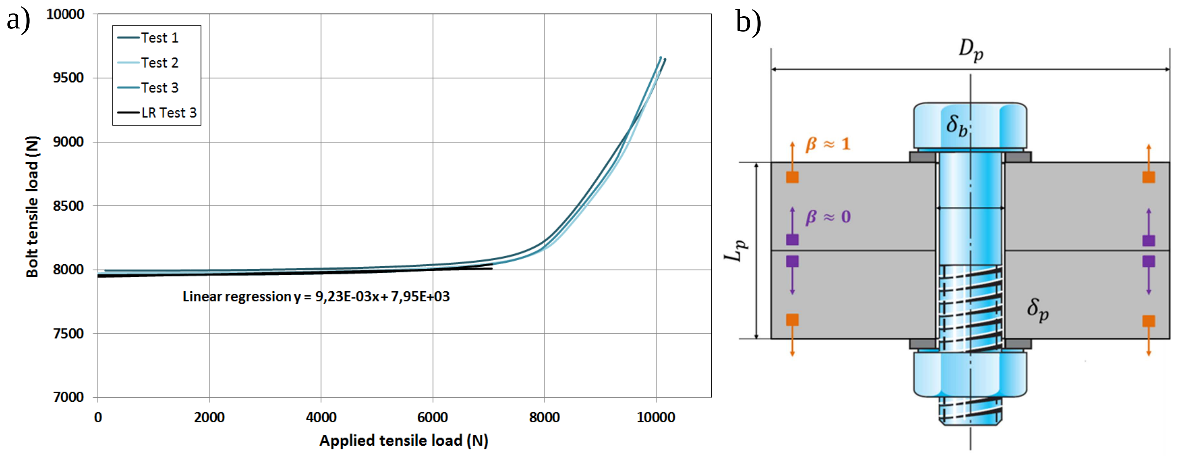

Figure 8. a) Experimental results of the identification of preload factor λ. b) Schematic representation of load introduction factor β for the axial loading.

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The numerical and experimental results are shown in histogram plots in Fig. 9. Several noteworthy observations can be made :

- First, for β ≈ 0 and β ≈ 1, a good concordance is noticed between the experimental and simulation results for the aluminium and the thermoplastic laminates.

- Secondly, the difference of the λ values between the aluminium and composite parts are larger for β ≈ 1 than β ≈ 0. This result was expected from λ definition, see Fig. 6.

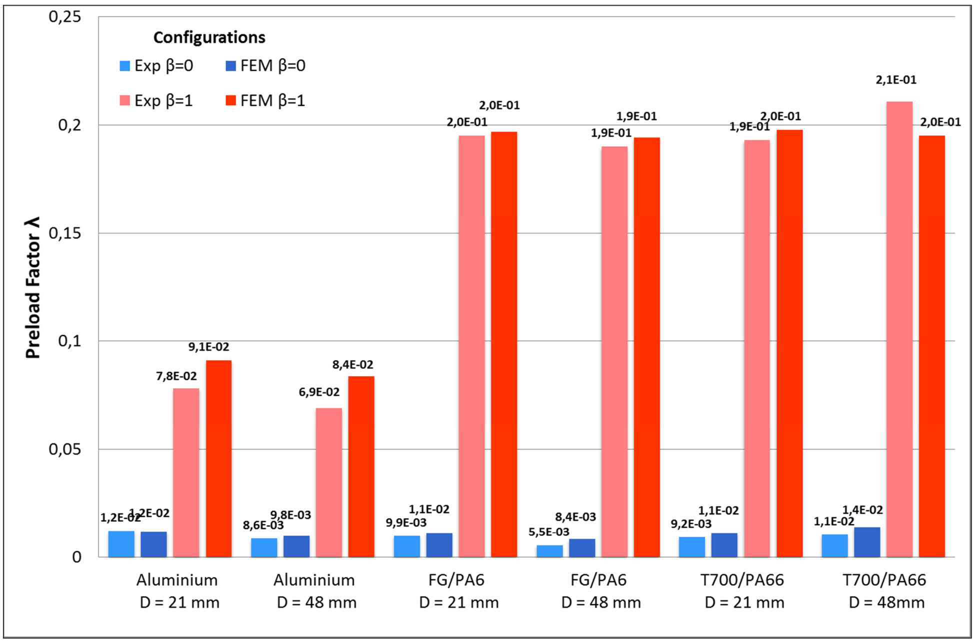

Figure 9. Identification and comparative analysis of preload factor λ for aluminium and thermoplastic laminates : experimental and numerical results.

4. Conclusion

Axial compliance of the various elements in a bolted joint is an important criterion for problems related to such assemblies such as the tightening angle, thermal stress and fatigue calculations. This paper presents a strategy to adapt the design bolted joints guidelines to thermoplastic laminates. 3D FE analysis based on an energy criterion is proposed to calculate the compliance of fastened parts. The experimental and numerical results confirm the importance of the cone angle φ to define the compliance δ_p of clamped parts for a concentrically axial loading. Then, the study is oriented around two main parameters, the preload factor λ and the load introduction factor β. The experimental and finite elements results change markedly with the load introduction position and then with the material properties. These first results between an isotropic (Aluminium 7075T6) and orthotropic materials (GF/PA6 and T700/PA66) enable us to improve the classical formulas in the bolted joint recommandations.

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