DESIGN OF HYBRID (BONDED/FASTENER) COMPOSITE JOINTS: FROM LOAD TRANSFER TOWARD STRENGTH PREDICTION

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Abstract

Most of aeronautic mechanical joints made of metallic fasteners or inserts include adhesive or interface mastic. These joints constitute hybrid joints in which loads are transmitted both by the metallic part and the adhesive joint. The dimensioning of hybrid joints involves the evaluation of load transfer distribution before dealing with joint strength prediction. In this paper we propose a general strategy for the mechanical analysis and the strength prediction of hybrid composite joints. The influence of non-linear behaviors of materials on load transfer is evaluated using FEM. The strategy is illustrated on tow joints configurations. These mechanical analyses allow identifying relevant degradation mechanisms that influence the loads transfers and thereby an analytical model can be proposed for a design purpose.

1 Introduction

Most of aeronautic mechanical joints made of fasteners (bolts, rivets, thread insert or bushings) include adhesive or interface mastic in order to ensure sealing and avoid fretting corrosion phenomena. The structural function of this interface material is rarely studied and almost never taken into account in the estimation of joint strength. In some applications, aircraft manufacturers wish use the interface material as a structural part in the way to reduce the number of fasteners or increase the joint efficiency.

The dimensioning of hybrid joints needs two main stages. The first one consists in evaluating the load transfer rate between fasteners and the adhesive part. The second one deals with the strength behavior associated to each failure mode. For example, dealing with a bonded/bolted joint, we have to study the strength behavior of the bolt (shear failure), of the composite part (bearing, net section failure) and of the adhesive (cohesive or adhesive failure). Unfortunately, in most of studied cases the load transfer rate depends on the degradation mechanisms of constituents. In previous example, the adhesive plasticity leads to reduce the effective stiffness of the adhesive joint and consequently increasing the bolt load transfer [1,2].

In this paper we propose a general strategy for the mechanical analysis and the strength prediction of hybrid composite joints. In this way the strategy proposed here consist in using a complex model that includes adhesive plasticity, composite damage and others potential non-linear effect. These simulations make it possible to identify relevant degradation mechanisms that influence the load transfers. Since non-linear approach is time-consuming, a simpler model is then developed where only relevant degradation mechanisms are taken into account.

According to joint configuration (complex geometric), failure mode (progressive failure or brittle failure) and design objective (high numbers of design parameters), this simpler model can be analytical or numerical, linear or non-linear.

This strategy is illustrated on two types of CFRP (T700GC/M21) assemblies. The first one is a bonded/bolted double lap composite joint and the second one is a bonded bushing composite hole reinforcement (Figure 1 and 2). The results validity is discussed using tests performed on non-hybrid and hybrid joints.

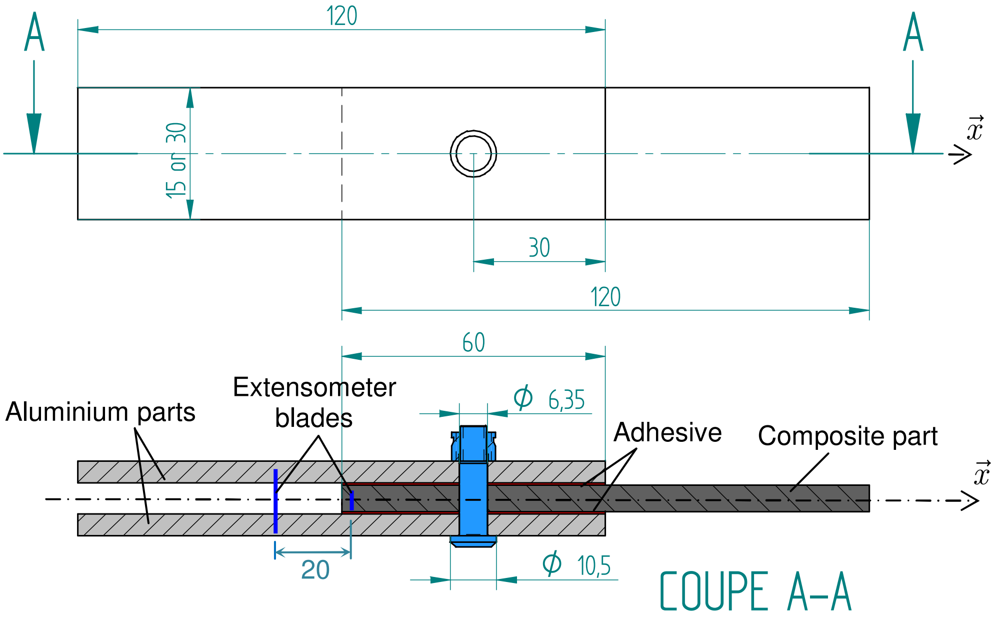

Figure 1. Hybrid (bonded/bolted) double lap composite joint.

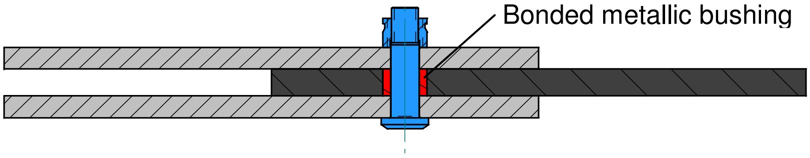

Figure 2. Composite hole reinforcement with a bonded metallic bushing (dimension in mm).

2 Composite model dedicated to composite assemblies

Composite parts joining generally use fasteners or bushing hole reinforcement. In joining area, composite parts include hole that are highly loaded. It is well known that the stress field obtained around the hole with a linear composite model cannot be used such as it is to predict the structure strength. Some authors propose modified failure criteria based on non-local approach [3] or corrected stress intensity factor [4].

These methods make it possible to take into account the material scale effect and to suppress mesh dependencies. However, they are not able to estimate the progressive degradation and associated loss of stiffness that occurs in the compressive zone of a pin loaded hole (bearing degradation). As said before, this degradation potentially influences the load transfer and consequently the assembly strength.

So, we develop a composite 3D damage model that includes:

- Elastoplastic behavior due to matrix cracking (shear and transverse directions)
- Non-linear elastic behavior in fiber direction (compression and tension)
- Progressive damage for compression loading in fiber direction (including post failure)
- Progressive delamination using cohesive interface elements

This model is written at the ply scale and is based on a thermodynamical formalism. All model parameters were identified for T700GC/M21 CFRP composite.

Damage and plastic evolution laws in shear and transverse directions were identified on tensile test on $[+45/-45]_{ns}$ and $[90]_n$ laminates. The extension to out-of-plane direction needed for the 3D model is based on an isotropic transverse behavior hypothesis.

The non-linear elastic behavior in fiber direction was found in [5]. Progressive damage model for compression loading in fiber direction is qualitatively built in order to be coherent with experimental and numerical work presented in literature [5,6]. Classical tests used to evaluate the ultimate stress or strain in fiber compression lead to a mixed failure mode including micro-buckling (kink band) and delamination. In this way, these tests underestimate the strength when the material is confined (no delamination). Thus, as shown on Figure 3, in order to be coherent with the ultimate load obtain in bolted joint test, the maximal stress should be increased. A numerical study on a pure bearing configuration show that results (load versus displacement curve, damaged area …) are not very sensitive to damage model parameters provided that maximal stress does not change.

We chose a bilinear behavior for cohesive interface to predict delamination. The mains parameters needed for this model are the energy release rates in mode I and mode II.

In order to avoid numerical localization due to softening behavior and reduce mesh dependency, a late shift effect is introduced in damage evolution law.

This model was implemented in Abaqus code using an U-MAT subroutine.

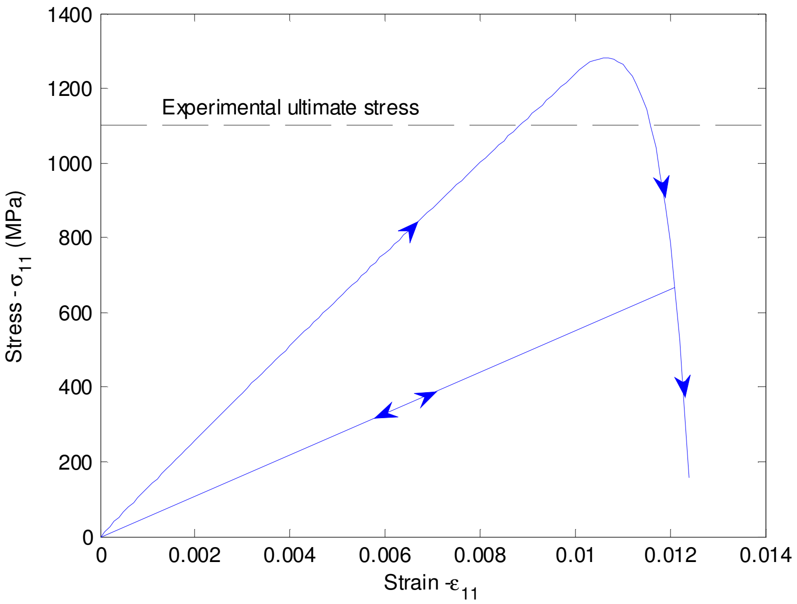

Figure 3. Stress versus strain curve for compression loading in fiber direction.

3 Adhesive behavior and failure criteria

The adhesive used in this study is the structural epoxy 3M 2216. This adhesive has a non-linear behaviour with a high ultimate strain. The behaviour is modelled with a linear elastoplastic law. A tensile test was used to identify the elastoplastic law. The model and the experimental curve are compared on Figure 4.

Concerning adhesive failure criteria, as proposed in literature for ductile adhesive, we used a maximal strain criteria [7-10].

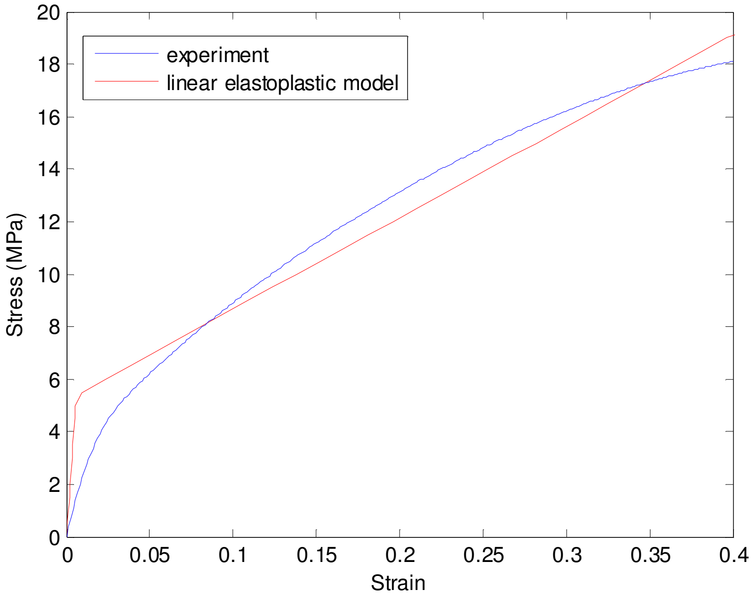

Figure 4. Comparison between model and experimental curve of 3M 2216 adhesive.

4 Study of hybrid double lap composite joint

The geometry of the assembly is described on Figure 1. The composite adherent is made of a quasi-isotropic laminate with the following stacking sequence: $[90/45/0/-45]_{2s}$. The evolution of the bolt load transfer rate defined as the ratio between the load transmitted by the bolt and the total load transmitted by the hybrid assembly is plotted on Figure 5. In order to highlight the effect of non-linear behavior of materials, 3 configurations are plotted:

- Linear (elastic) behavior for all the materials
- Non-linear behavior: elastoplastic for adhesive only
- Non-linear behavior: elastoplastic for adhesive and damageable for composite

The case of non-linear (damageable) behavior for composite only is not studied because damage in composite material occurs after plasticity in adhesive. Note that the ultimate load obtained experimentally is between 48 kN and 52 kN whereas it is close to 44 kN with the simulation. As expected, results show that only the elastoplastic model for adhesive allows predicting a realistic bolt load transfer rate. The damageable behavior of composite leads to slightly decrease the bolt load transfer rate from 35 kN. More precisely, damage in matrix occurs at 20 kN while damage in fiber direction occurs at 30 kN. To conclude, we can say that adhesive plasticity have to be taken into account to predict the strength of the hybrid joint while composite degradation effect is not necessary, at least in a continuous manner.

In this way, we can propose a judicious analytical model. The model is based on 1-D model developed by Paroissien et al. [11]. Adherents assume a pure tensile load while adhesive joint assumes a pure shear load [12]. The bolt is modelled by a linear spring which the stiffness is adjusted according to experimental and simulation results. This model gives out the shear stress and strain along the adhesive joint that make it possible to apply a maximal shear strain criteria to predict the adhesive failure. More, the model gives out the total load crossing the net section and the load applied by the bolt on the composite hole. Thus, dealing with composite joint need to predict two failure modes: bearing degradation due to compressive load around the hole and net section failure due to tensile load. Physical mechanisms are significantly different for this two failure modes, thus two different failure criteria should be used.

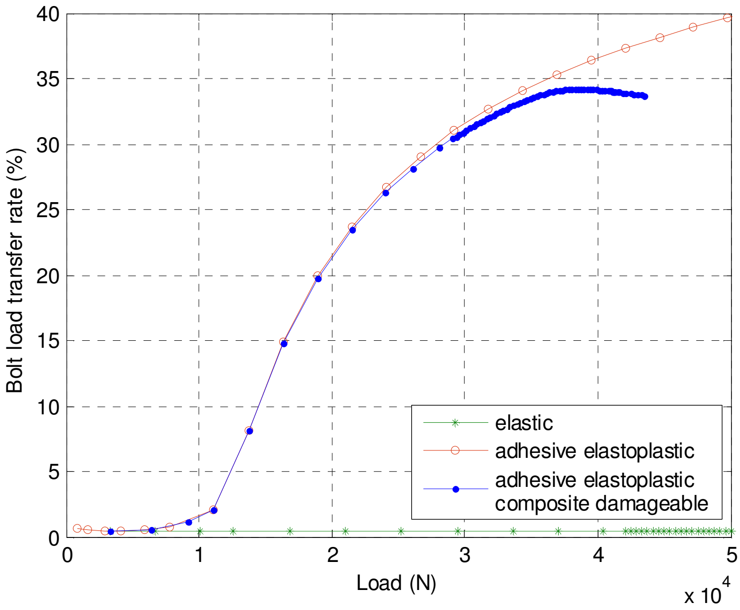

Figure 5. Evolution of the bolt load transfer rate according to the total load.

The maximum load F_b that leads to bearing initiation is calculated by a mean pressure criterion:

$$F_b = p_b t d \tag{1}$$

where p_b is the allowable pressure, d the hole diameter and t the composite thickness. For the composite material use in this study (T700GC / M21), the allowable pressure estimated with a test on a bolted joint is 475 MPa at the first stiffness loss (damage of 0° plies) and 600 MPa at the second stiffness loss (damage of ±45° plies).

The maximum load $F_{ns}^{\max}$ that leads to net section failure is calculated by a maximal stress criterion at the laminate scale associated to a corrected stress intensity factor [Hart-Smith, 2004].

$$F_{ns}^{\max} = \frac{t\left(w-d\right)}{K_{tcs}}\sigma^{\max} \tag{2}$$

where $\sigma^{\max}$ is the ultimate stress of the laminate in the considered direction, w the sample width and K_{tcs} is the corrected stress intensity factor. K_{tcs} is expressed analytically according to the d/w ratio and it is corrected empirically in order to takes into account the stress redistribution due to damage. Details on the calculation of K_{tcs} can be found in [4].

The analytic model can be used to study the influence of some design parameters as the adhesive behavior (modulus and non-elastic strain), adhesive's and adherent's thickness, overlap length or d/w ratio. Figure 6 shows the results obtained in terms of joint efficiency versus d/w ratio. The joint efficiency is defined as the ratio between the joint strength and the strength of the composite laminate (section w x t). Tests were performed for two different configurations (d/w = 0.21 and d/w = 0.42) in order to validate the model and associated criteria.

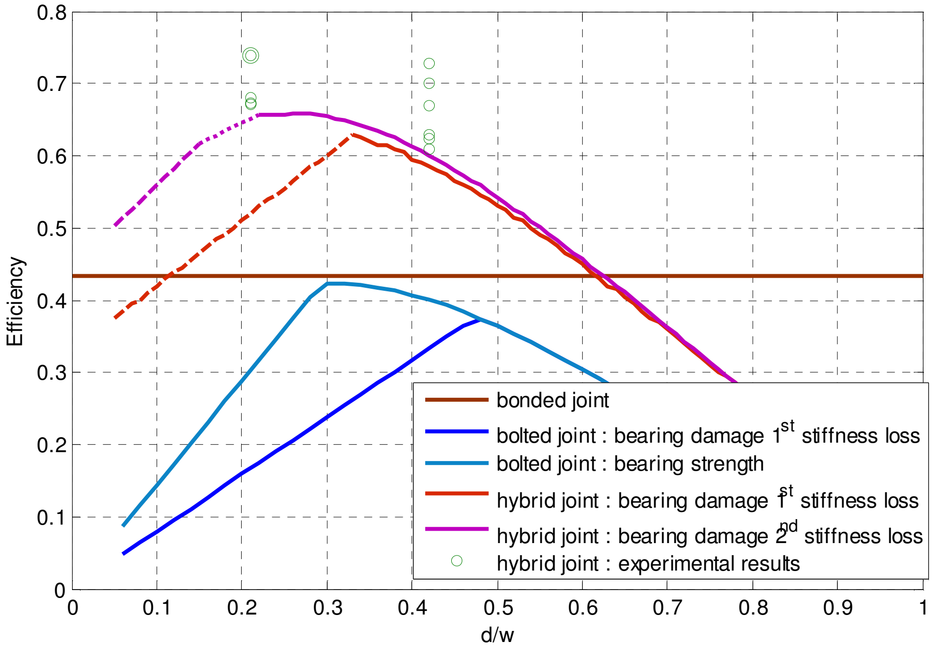

Figure 6. Joint efficiency of several joint types.

5 Study of a composite hole reinforcement with a bonded metallic bushing

The second application presented in this paper deals with a bushing hole reinforcement as described on Figure 2. Like for the previous application, the composite part is made of a quasi-isotropic laminate with the following stacking sequence: $[90/45/0/-45]_{2S}$. The composite hole diameter is 9 mm. The bushing is made of A286 alloy steel and its internal diameter is 6.35 mm. The yield stress of this alloy steel is 576 MPa. The adhesive joint is 0.05 mm thick.

The bushing reinforcement by adhesive joining offers one main advantage. In fact, thanks to the adhesive, a part of the pin loading is transmitted before the pin [13]. In this way, the bearing zone and the net section are theoretically less loaded. In practice, the load transfer rate between the pulled side and the compressed side of the hole highly depends on geometric parameters (bushing thickness …) and material behavior. In order to highlight the effect of non-linear behavior of materials, 4 configurations have been simulated:

- Linear (elastic) behavior for all the materials
- Non-linear behavior: elastoplastic) for bushing only
- Non-linear behavior: elastoplastic for bushing and adhesive
- Non-linear behavior: elastoplastic for bushing and adhesive, and damageable for composite

Results are presented on Figure 7 and Figure 8. The first non-linear phenomenon that is visible on force versus displacement curves is the bushing plasticity and hardening (load 6 kN). Nevertheless, adhesive plasticity occurs from the start of loading. But the thickness of the adhesive joint being small, in spite of plasticity, the adhesive joint stiffness remains high compared to others parts.

Figure 8 shows that bushing plasticity significantly reduces the load transfer rate. Adhesive plasticity also reduces the load transfer rate from the start of loading, but in a lesser extent than bushing plasticity. Dealing with composite behavior, composite damage also reduces the assembly stiffness but only at a load level close to assembly ultimate load. On the other hand, composite damage does not alter the load transfer rate.

These results demonstrate that non-linear behaviors of bushing and adhesive have to be taken into account into load transfer distribution and consequently in assembly strength prediction.

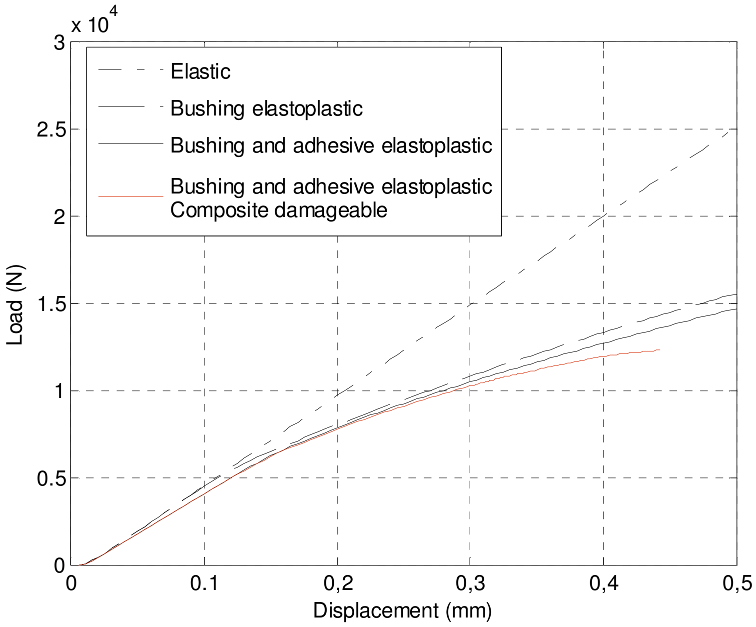

Figure 7. Force versus displacement curves.

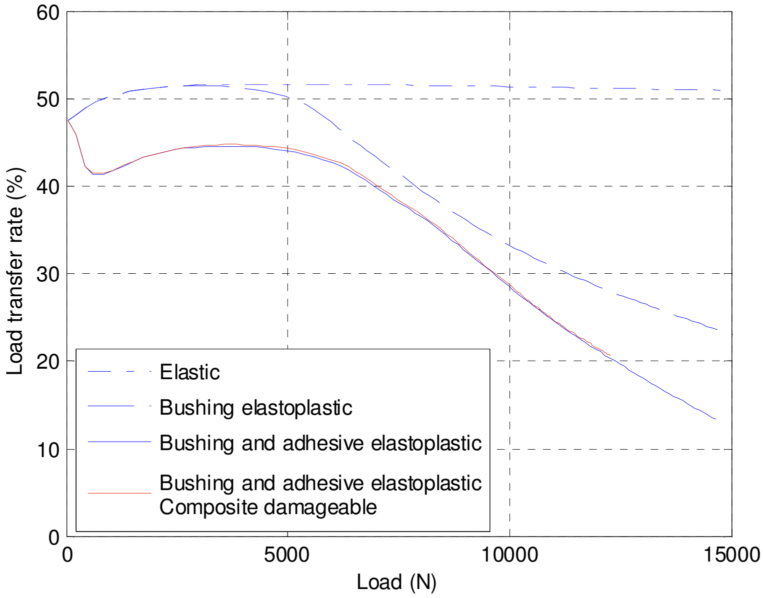

Figure 8. Evolution of the load transfer rate of the pulled side according to the total load.

6 Conclusions

This paper aims to propose a general strategy for the mechanical analysis and the strength prediction of hybrid composite joints. Through two examples, we highlight the influence of non-linear behaviors on loads transfers. According to joint configuration (geometry, materials), influence of each non-linear phenomenon can be more or less important.

As illustrated on a hybrid double lap composite joint, the numerical study allowed us to make judicious hypothesis and thus propose a suitable analytical model. As shown on composite hole reinforcement with a bonded metallic bushing, the coupling between non-linear behaviors can be complex. The analysis of force versus displacement curves is not representative of load transfers in the assembly.

Even if simulations help us to understand load transfer distribution from linear to non-linear behavior, experimental investigations with multi instrumentation are in progress in order to improve model and consequently reach strength prediction in complex configurations.

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