PROGRESSIVE DAMAGE AND STRENGTH OF BOLTED JOINTS IN COMPOSITE STRUCTURES

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ABSTRACT

This paper aims at improving the industrial multilevel calculation strategy by introducing expert multiscale analysis to overcome the limitations of the current approach, and to increase the reliability of its predictions. The industrial strategy is presented and shown to be mostly empirical at local level. Therefore, the proposed developments focus on the introduction of numerical simulation for the analysis of the critical fasteners. The challenge is to pass from an entirely empirical situation to a reasoned compromise between numerical analysis and experiments. First, a detailed model of the single-fastener joint is proposed. This model is based on a progressive damage material model and gives promising results for bearing strength prediction. Nevertheless, its computational cost is prohibitive. Thus, a simplified model is proposed, based on the critical damage area criterion applied in post processing of a FE element calculation with linear material behaviour. Analysis of the impact of uncertainties on the identification of the parameters of the criterion emphasizes its problematic sensitivity to uncertain data.

1. INTRODUCTION

Due to their high specific strength and stiffness, Carbon Fibre-Reinforced Plastics (CFRP) are increasingly used in aeronautical applications. These applications usually require the use of mechanical joints in order to transfer loads between composite laminates and other composite or metallic parts. Therefore, ability to joint elements efficiently is necessary for a full exploitation of high performance fibre-reinforced plastics. Nevertheless, ensuring the load transfers between composite and other composite or metallic parts remains problematic. Since the use of bonded joints is often prohibited by the industrial imperatives of reproducibility and maintenance, mechanically fastened joints - such as bolted or riveted joints - are preferentially used. However, composite components are considerably weakened by the drilling of holes, mostly because of the resulting high stress concentrations. The mechanical joint is often a limiting factor for the overall performance of the structure that severely handicaps the replacement of the existing light alloy structures by composite solutions.

The present paper aims at improving the industrial calculation strategy by introducing expert multiscale analysis to overcome the limitations of the current approach, and to increase the reliability of its predictions.

The first part of this paper presents the industrial multilevel calculation strategy used for the sizing of complex junctions involving numerous fasteners. The main drawback of this strategy is to be based on empirical methods for the strength analysis of the critical fasteners. These methods are unable to capture the influence of the stacking sequence on the strength of the joint. In this context, the second part deals with the proposed developments. The purpose is here to introduce numerical methods to improve the capacity of prediction for strength analysis. First, a detailed model of a single-pin joint is developed for virtual testing. Second, a simplified model is proposed in order to reduce the calculation cost. The influence of uncertain data on the identification of the parameter of the method is evaluated.

2. INDUSTRIAL CALCULATION STRATEGY

The industrial strategy enables the sizing of large-scale structures involving several hundred fixations. Because of the geometrical complexity of industrial structures, multilevel design strategy is necessary. On the one hand, the global behaviour of the joint in its environment is computed. On the other hand, the strength of the fasteners is evaluated at local level in order to identify the critical areas, and to predict the failure of the joint.

2.1. Global level

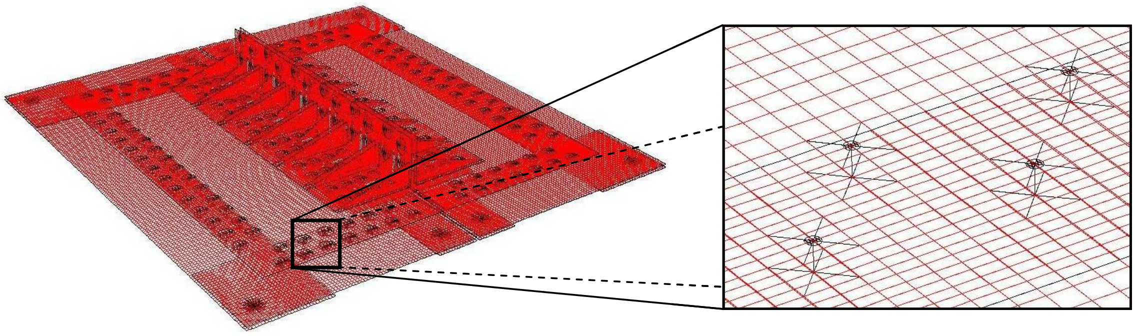

Figure 1: Mesh of a large-scale joint. Fasteners are represented by springs.

At the global level, the geometry of the whole junction is generally provided by the computer assisted design of the structure. It often contains a lot of geometrical details (see Figure 1). The corresponding mesh can have several million degrees of freedom. Therefore, its calculation cost is extremely high. At that level of model, the mesh consists in shell elements. Material behaviours are linear elastic.

Because of the complexity and cost of the global model, it is unrealistic to take into account, at that level, the contacts at each fastener of the junction (contact between the fastener and the composite plates, but also contact between the plates). Therefore, bolts are represented by mere anisotropic springs whose stiffnesses are obtained by empirical formulae. The normal stiffness r_n is given by:

$$r_n = \pi R^2 E_3 / l_0 \tag{1}$$

The in-plane stiffnesses r_l and r_t are calculated by the following formula [1]:

$$\frac{1}{r_{t,l}} = \frac{\xi}{n}\left(\frac{t_1 + t_2}{2D}\right)^{2/3}\left(\frac{1}{E_1 t_1} + \frac{1}{nE_2 t_2} + \frac{1}{2E_3 t_1} + \frac{1}{2nE_3 t_2}\right) \tag{2}$$

Where: ξ = 4.2 for CFRP joints,

n = 1 for single-shear joint and n = 2 for double-shear,

D is the diameter of the fastener (adjusted to the hole),

E and t are respectively the stiffness in the loading direction and the thickness of the plate. The index 3 stands for the fastener. In case of a double-lap joint, 1 is central plate and 2 represents the exterior plates.

2.2. Local reanalysis

Bypass (N_x, N_y and N_{xy}) and bearing (F) loads are extracted from the global calculation for each fastener. Critical fasteners are identified.

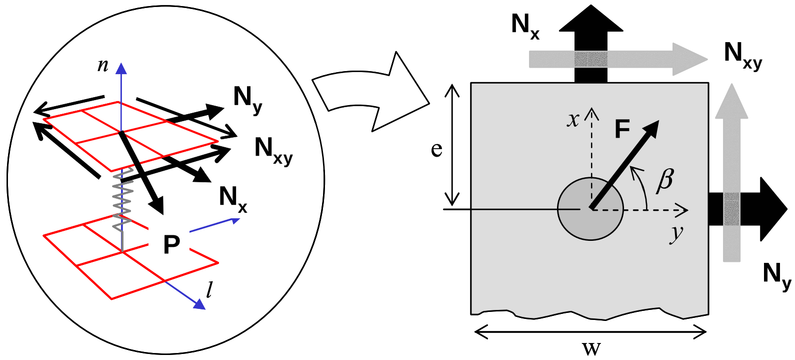

Figure 2: Single fastener local analysis with boundary conditions extracted from the global calculation.

The loads issued from the global calculation are injected as input data for the local reanalysis of the critical fasteners; using semi-empirical models (see Figure 2). It is supposed that there is no bolt-hole clearance. By respecting some classical design guidelines for the geometry of the joint and the choice of the stacking sequence, shear-out failure mode can be easily avoided. Therefore the critical failure mode taken into account in the model is a combination of tensile and bearing failure modes. Failure occurs when the following criterion is reached:

$$K_t.\left(\sigma_t^n + K_m.\sigma_m\right) \geq \sigma_r \qquad (3)$$

Where: σ_t^n is the average tensile stress in the net cross-section,
σ_m is the average bearing stress,
σ_r is the admissible stress,
K_t and K_m are respectively the hole coefficient and the bearing coefficient.

K_t and K_m are empirical coefficients whose identification requires many experiments. These coefficients depend on the material, the stacking sequence, the nature of the bypass loads (tension or compression) and the diameter D of the fasteners. Moreover, the hole coefficient also depends on the pitch w, and whether it is large enough for the holes to be considered independent or not ($w < 5D$).

2.3. Limitations

Generally speaking, the models used at local level require strong corrections to fit the predictions to experimental data. Because of the high cost of the necessary experimental campaigns, engineers are limited to a few stacking configurations. Moreover, the models turn out to be increasingly ineffective as they are forced away their conditions of identification. The models are unable to capture the influence of the stacking sequence on the strength of the joint. The possible clearance between the bolt and the hole, which has a strong influence on the strength of a bolted joint, is not taken into account. Finally, in case of interfering fasteners, the validity of the single-bolt local reanalysis is questionable. This presents serious obstacles to the emergence of innovative and optimized composite solutions.

3. PROPOSED IMPROVEMENTS AT LOCAL LEVEL

The two-level strategy presented being efficient for the sizing of complex junctions, our purpose is not to modify it, but to overcome its limitations at local level. Therefore, the proposed developments focus on the introduction of numerical simulation for the analysis of the critical fasteners. The challenge is to pass from an entirely empirical situation to a reasoned compromise between numerical analysis and experiments.

In this context, it is necessary to develop a powerful Finite Element model of the elementary joint in order to conduct virtual testing, allowing extrapolation beyond the experimental configurations, and then, to feed the empirical models. Our aim is to develop a predictive model of the behaviour, progressive damage and failure of the composite plate in the single-fastener joint. Thus, the model has to describe: tensile failure mode, shear-out failure mode, bearing failure mode, and whatever combination of two of these modes. Tensile and shear-out failures are catastrophic. Bearing is different, in the sense that the plate continues to sustain loads even after having lost its functionality. It is therefore necessary to define a precise bearing failure criterion, for experiments as well as for simulations. Most of the existing criteria employed for the sizing of junctions are based on the definition of a maximum deformation of the hole (varying from 4% to 8% deformation for neat-fit joints). Another criterion is based on a maximum loss of stiffness in shear for the joint (2%). Nevertheless, in this study, we prefer to use a criterion more conform to physics, by considering that bearing failure is reached at the first peak in the load displacement curve of the bearing test. Therefore, the following work is focused on the prediction of the onset of the bearing failure in order to capture the first peak in the bearing curve.

3.1. Bearing tests

To gain better insight of the bearing failure mode, several bearing tests were conducted in ONERA. The specimen were fabricated from T300/914 carbon/epoxy composite, with a $[(90_2/0_2)_2]_s$ lay-up. Four geometrical configurations were tested with 6 mm, 8 mm, 10 mm, and 12 mm hole diameters. The experimental set-up is shown in Figure 3. The plates were cut by half at their net cross-section. The load was applied through the hardened steel pin on the boundary of the half hole on the edge of the plate, and the specimen was clamped on its opposite portion. This set-up was inspired by [2], but applying the load on a half hole is thought here to be more representative of a joint than applying it on the straight edge of the plate. That test is simple and enables easier observation of the development of bearing failure, without interactions with other failure modes, than the conventional bolted joint test. A total of ten specimens were tested beyond their peak bearing load Figure 4. Different measurement techniques were used to follow the onset of bearing failure. Acoustic emissions reveals that first single fibre failures (acoustic events superior to 90dB) may sporadically occur for weak loads, but the first important series of energetic events occurs at the bearing peak load. Digital image correlation was used to measure the displacement fields. Unfortunately, important three-dimensional displacement soon appeared near the hole boundary, so that the displacement obtained in that zone were only accurate at the beginning of the tests. Therefore image correlation did not provide useful information on the bearing failure itself. Nevertheless the measured displacement fields far from the hole were used to validate the boundary conditions used in FE simulations and to correct the experimental data provided by the displacement captor.

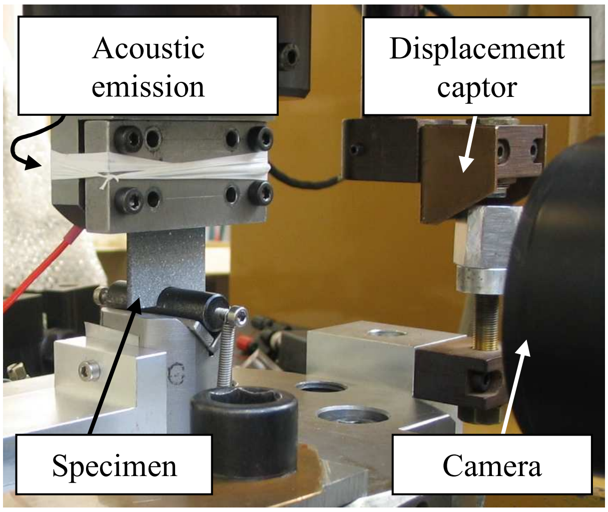

Figure 3: Bearing test of a T300/914 $[(90_2/0_2)_2]_s$-specimen. Experimental set-up.

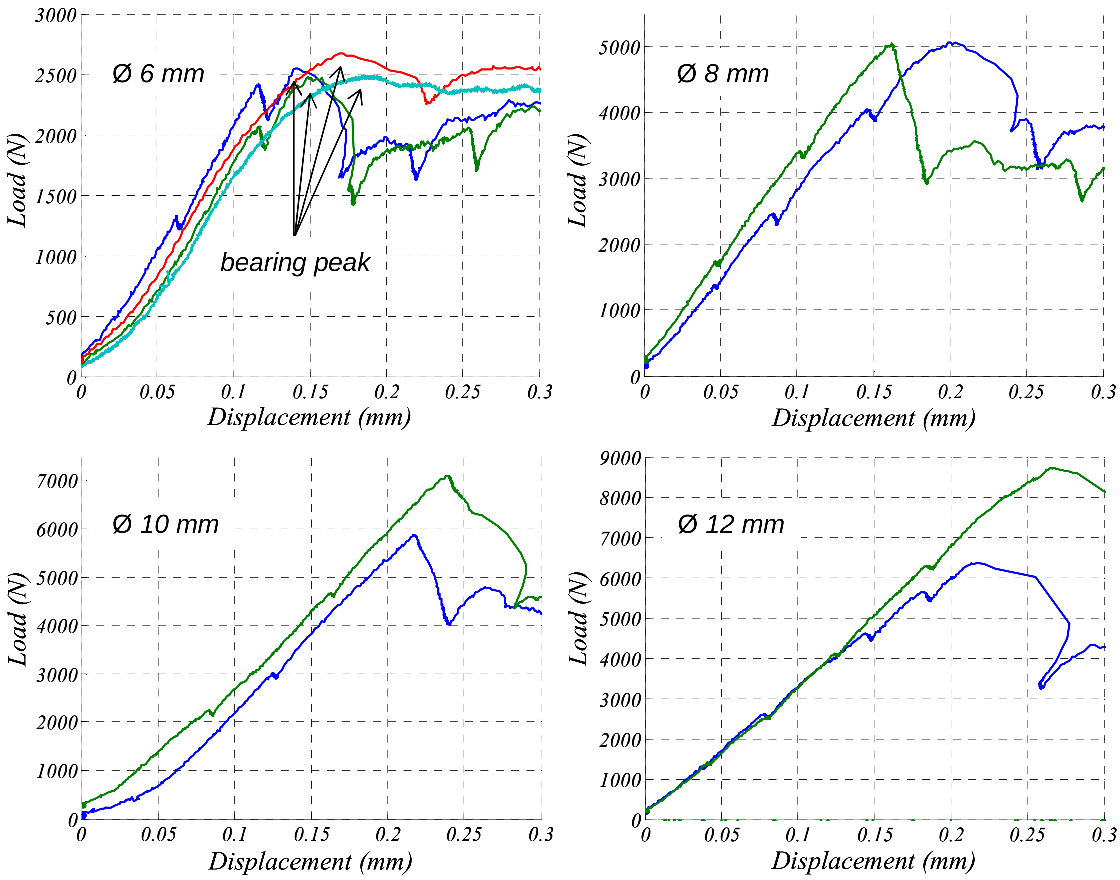

Figure 4: Bearing test of a T300/914 $[(90_2/0_2)_2]_s$-specimen. Load / displacement curves.

3.2. Detailed simulation of the behaviour, progressive damage and failure of a single-bolt joint

The choice has been made to take into account a maximum of physical phenomena in the model. The mesh is three-dimensional with one layer of prismatic linear elements per ply. A mesh convergence study was realized on the in-plane stress fields, that resulted in a satisfying mesh with one element each 2° on the hole circumference. Interface elements are introduced between each ply to capture the initiation of delamination. Contact is enforced between the pin and the plate with a Coulomb-type friction law. The coefficient of friction is supposed to be as low as 0.05 [3]. It is also supposed constant on the boundary of the hole and during the evolution of the loading, which is a strong hypothesis, but commonly used in studies relating to joint simulation. The material of the pin has linear elastic behaviour. The interface elements have damage elastic behaviour in normal tension, and damage elastic behaviour with friction in shear.

A Mesoscopic Progressive Failure (MPF) approach [4] was used for the modelling of the behaviour of the unidirectional ply. In this approach, the mesoscopic behaviour is described by a thermo-viscoelastic law. The failure criterion is based on Hashin's assumptions. Two local failure modes are considered: fibre failure mode and interfibre failure mode. Failure in tension and compression are distinguished for each ones. When the first failure of a ply is reached in the laminate (failure criterion value is higher than 1), the effective elastic compliance of the failed ply is increased. Both the failure criterion and the degradation law are written in two dimensions. In order to avoid numerical problems such as mesh dependency, the degradation law is non-softening, which means that stresses cannot increase anymore in a failed ply. Therefore, after failure, the stress in the corresponding direction reaches a saturation point and keeps constant. The MPF model has proved efficient for the behaviour and strength prediction of moderate gradient structures for which the ultimate failure is often due to the first ply failure in fibre mode. In case of high gradient structures such as perforated plates loaded in tension, the first ply failure in fibre mode occurs, near the hole, long before the ultimate load. Nevertheless good results were obtained in combination with a non-local failure criterion to predict the final failure [5]. Since bolted joints are high gradient structures, we already know the limitations of the model for the tensile failure mode prediction. However, in case of bearing failure, crushed material on the hole boundary still transfers loads to the adjacent material. Therefore, a non-softening degradation rule was thought to be an interesting way to approximate this phenomenon. The corresponding results are presented in Figure 5 for the 6 mm diameter bearing experiment.

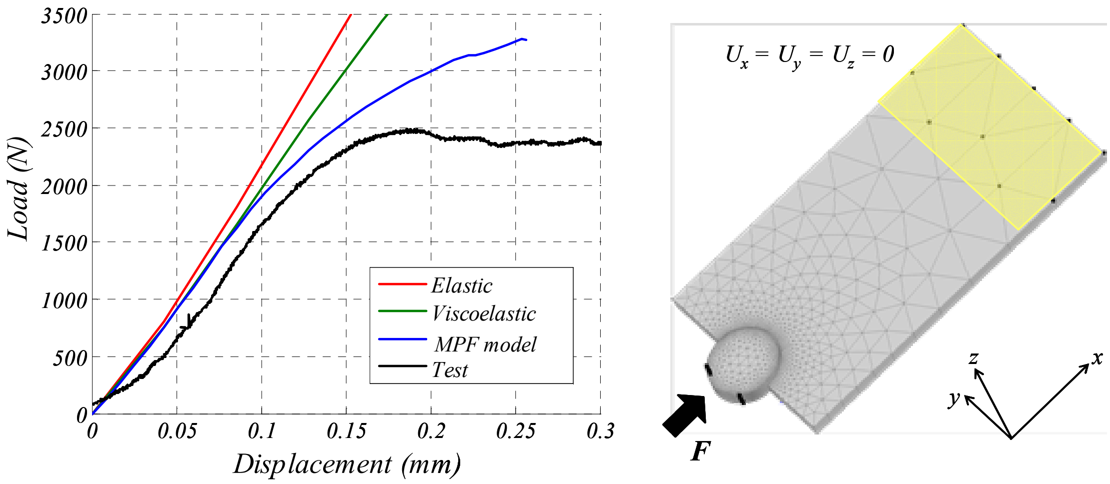

Figure 5: Mesh and comparison between numerical and experimental results.

The first conclusion that can be extracted from Figure 5, is that it is necessary to take into account the viscoelastic behaviour of the matrix to obtain the good experimental global stiffness. This is due to the fact that the load is applied through the pin, which results in very specific load paths. Therefore, in a $[(90_2/0_2)_2]_s$ laminate the matrix accounts for a great deal of the global stiffness of the joint, contrary to the plane plate compression test, for instance.

The second conclusion is that non-softening degradation rules are not sufficient to capture the bearing load peak. The impact of fibre compressive failure on the load redistribution in the laminate is underestimated. Therefore, in this study, a modified version of the mesoscopic progressive failure model was used, with softening degradation rules. The problems of numerical damage localization inherent to that kind of models were avoided using a non-local calculation method based on a delay effect [6,7]. Nevertheless the use of viscoelastic behaviour together with that kind of non-local method is still problematic for static simulations. The corresponding results are presented on Figure 6.

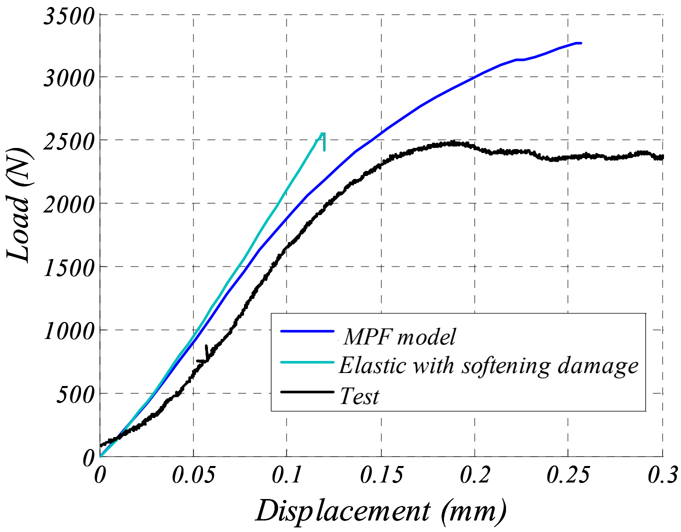

Figure 6: Comparison between experimental results and results obtained with viscoelastic non-softening damage model and elastic softening damage model.

Those results are promising since the bearing load peak was predicted in an acceptable way. Nevertheless the main current limitation of that model is that both the failure criterion and the damage model only involve the in-plane components of the stress tensor, whereas experiments clearly show the importance of three dimensional effects. To obtain a predictive model, the influence of out-of-plane stresses on matrix damage must be taken into account, as well as the influence of matrix damage on fibre micro-kinking and delamination. Finally it is worth pointing the prohibitive calculation cost of such simulations. It is therefore necessary to develop simplified models to be used for sizing.

3.3. Simplified model for strength prediction

The aim of this part is to propose different tools for strength prediction of bolted junctions. These tools have different complexities and computational times; the corresponding predictions are a function of the required accuracy and the accepted computation cost. In fact, the detailed simulation presented in section 3.2 is promising, but very time consuming. In this section a simplified approach to achieve fast calculations is presented. This method is called critical damage area method and was proposed by [8] for woven composites, and extend in [9] for laminate composites. It consists in considering that the final failure of a structure occurs when all Gauss points in a given critical volume (a cylinder defined by its radius l_0 and the thickness of the ply) has failed in fibre mode. It means that the final failure of the structure occurs when a critical area failed in fibre failure mode and thus the whole structure can no more carry out the applied load. The method is applied in post-treatment of a FE computation, for each ply of the structure.

Originally developed for open-hole tensile-test calculations, the progressive aspect of ply failure in fibre mode in the structure was taken into account by using The MPF non softening model. However, in this paper, the combination of contact calculation and progressive damage behaviour turned out to be too much time consuming for our purpose. Therefore linear elastic material behaviour was considered only.
Our purpose is here to extend that failure approach to the strength prediction of composite bolted joints. Unlike perforated plates, two critical failure modes must be taken into account: tensile and bearing failure modes. The idea is to identify one internal length l_0 for each of these modes. The internal length for tensile failure being identified on the tensile test of perforated plates (see [9]), and the internal length for bearing failure identified on bearing tests such as the ones presented in this paper. The following deals with the identification of the bearing internal length l_0.

The bearing tests presented in section 3.1 were simulated taking into account contact and linear elastic composite material. The pin was rigid. One layered element was used in the thickness direction to model half of the lay-up, and a condition of symmetry in the thickness direction was enforced on the lower face of the mesh. The identification method consisted in evaluating the necessary internal length leading to the observed experimental failure loading. The identified internal length was found to be a function of the pin diameter (see Figure 7).

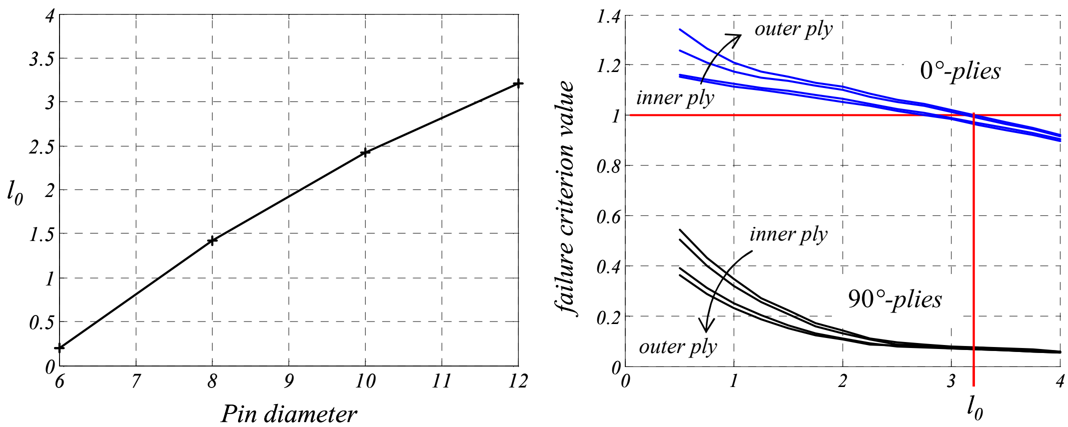

Figure 7: Identified internal distance l_0 for bearing failure, for several pin diameters.

The problem of the dispersion of the experimental results raises the question of the influence of uncertain data on l_0. In this paper, this influence was evaluated by using a method proposed by [10]. The method is based on the approximation of the response, here l_0, as a function of the uncertain data. It is simple to use and consists in a pre and post processing of the calculation. Response Surface Methods are used for the approximation of l_0. The identification point necessary to the identification are defined

in pre processing. Then, the results of the calculations are used to identify the parameters of the approximation and evaluate its stability and accuracy.
Twelve uncertain data were considered in this study. The clearance between the pin and the hole λ ranges from 0.01 mm to 0.1 mm, the total thickness t of the plate ranges from 1.8 mm to 2.04 mm, those being the observed variations in the bearing tests. The five in-plane elastic material properties (E_1, E_2, G_{12}, ν_{12}, ν_{23}) were supposed to vary from ±10% from their average value (±5% for E_1). The five in-plane failure strengths (X_t, X_c, Y_t, Y_c, S_c) vary from ±5% for the tensile properties and ±10% for the compressive and shear strengths. Forty calculations were necessary for each test of different pin diameter.
Polynomial response surface were used to approximate the distance $\boldsymbol{l_0}$. A Gram-Schmidt orthogonalization algorithm was used in order to select the 12 influent monomials between all the monomials of a polynomial of order 3 with 12 variables. The obtained approximations were then used to evaluate the minimal and maximal possible values of l_0. In order to account for the dispersion on experimental bearing failure loads, the whole process was repeated for the minimal and the maximal experimental failure loads. The greatest interval of variation for l_0 was kept. Results are summarized in Figure 8.

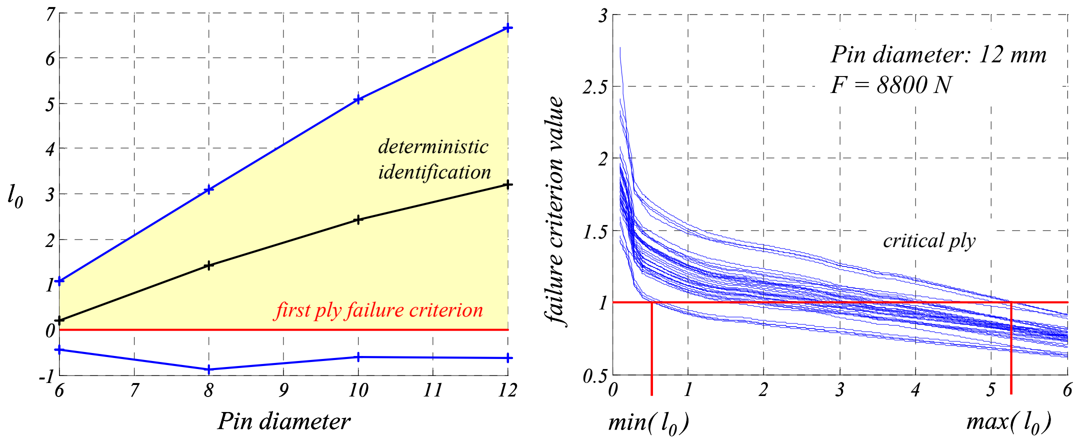

Figure 8: Left: impact of uncertain data on the identification of the bearing distance l_0. Right: example of dispersion on l_0 for the maximal failure load observed with a pin diameter of 12 mm.

It is evidenced from Figure 8 that the identification of the bearing distance l_0 is very sensitive to the impact of uncertain data. The post processing of the approximation of l_0 resulted in a negative minimal value for every pin diameters. Therefore the minimal bearing distance was taken to 0, which corresponds to the classical first ply failure criterion which is extremely conservative for high gradient structures. The uncertain data with the greatest contributions on l_0 are λ, t, E_1, X_c.
These results highlight the limitations of the proposed simplified model. The simplification of the composite material behaviour is too coarse to obtain stable identification of the bearing distance l_0. Making predictions is all the more hazardous. Even with the critical damage area method, it is necessary to include more non-linear mechanisms in the material behaviour to obtain a reliable strength prediction method.

4. CONCLUSIONS

This study has been designed in order to propose tools of increasing complexity and calculation cost for strength prediction of bolted junctions. The detailed simulation presented in section 3.2, physically based but very time consuming, could be used to identify, through virtual testing, the parameters required for simplified simulations. Such a strategy should permit to reduce the cost of the test campaigns used to identify the simplified simulations that are employed for the sizing of bolted joints in composite structures in aeronautical industries.

However much work is still to be done to achieve that purpose. The proposed detailed model gives promising results, but three-dimensional failure criterion and degradation models have to be taken into account to obtain reliable predictions. Moreover the use of softening degradation rules raises numerical issues that are difficult to solve. Finally progressive damage approach together with contact calculations are very time consuming.

In order to propose a simplified failure approach with reduced calculation cost, the critical damage area was applied to bearing failure in post processing of FE calculations with linear elastic behaviour for the composite material. The method is based on a non-local failure criterion quite similar to the average stress method. The identification revealed itself extremely sensitive to the influence of uncertain data.

ACKNOWLEDGEMENTS

This work was carried out under the AMERICO project (Multiscale Analyses: Innovating Research for Composites) directed by ONERA and funded by the DGA/STTC (French Ministry of Defence) which is gratefully acknowledged.

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