NUMERICAL MODELLING OF COMPOSITE PIN-JOINTS AND EXPERIMENTAL VALIDATION

Fabrice PIERRON*, François CERISIER*, and Michel GRÉDIAC**

* SMS/ Département Mécanique et Matériaux, École Nationale Supérieure des Mines de Saint-Étienne, 158, cours Fauriel, 42023 Saint-Étienne Cedex 2, France
** LERMES, Université Blaise Pascal, 24, avenue des Landais, 63174 Aubière Cedex, France

SUMMARY: A numerical and experimental study was carried out to determine the stiffness and the bearing strength of bolted woven composite joints. The main objective was to investigate the possibility of predicting the properties of the joint from the properties of the material measured with standard tests. A refined finite element model was developed in which the nonlinearities due to both the material and the contact angle between the pin and the hole were taken into account. Particular attention was paid to account for the influence of the clearance which has been shown to be very significant. In conclusion, good agreement between experimental results and numerical predictions has been obtained.

KEYWORDS: pin-joints, woven composites, finite element modelling, non-linear modelling, experimental validation, design of composite joints.

INTRODUCTION

Many papers deal with the failure analysis of bolted composite joints. This is mainly due to the fact that joining composite structural components often requires mechanical fasteners which ultimate mechanical response is difficult to predict. Contrary to many metallic structural parts, for which the strength of the joints is mainly governed by the shear and the tensile strengths of the pins, composite joints present specific failure modes due to their heterogeneity and anisotropy. Three main basic failure modes are often described in the literature: bearing, net-tension and shear-out ([1,2] for instance). In the present work, the specimen geometry is adjusted so that the bearing mode is enhanced. The main reason is that net-tension and shear-out can be avoided by increasing the width and the end-distance of the structural part for a given thickness. On the contrary, the bearing strength involves local effects which are mainly influenced by the material properties and the contact area between the pin and the hole. As a result, this type of failure cannot be avoided by any modification of the geometry of the structural part for a given thickness and pin diameter and can be considered an intrinsic property of the joint for given constitutive material, stacking sequence, diameter and clearance. The final objective of the present study is to develop a model for failure prediction of the joints. However, many such models already exist in the literature [1,3,4,5] for instance, though generally the materials under study are carbon/epoxy laminated composites. Nevertheless, it has appeared to the present authors that a common weakness of the above papers is the lack of

thorough experimental validation of the numerical finite element models used to calculate the stress and strain fields around the hole. Indeed, Hamada et al. [3] use a linear elastic finite element model with a rather crude contact model for the pin/composite interface and by using a Yamada-Sun failure criterion together with a characteristic length approach [6], the strengths of the pin-joints are predicted. Nevertheless, no experimental validation of the model is given and their good agreement between predicted and measured failure loads does seem rather fortuitious. A more rigorous approach is presented by Hung et al. [5] who use a cumulative damage model to predict the response of the pinned and clamped joints. An experimental validation of the finite element model is given in the form of comparisons between strain gauge measurements and numerical results. These seem rather satisfactory. However, the difference between measured and calculated strains increase when the gauges get closer to the hole though the closest gauge remains one hole radius away from the hole edge, which is too far away since failure occurs much closer to the hole edge. Moreover, the clearance between the pin and the composite is not considered and the behaviour of the joint seems linear up to failure because of the particular quasi-isotropic lay-up. Therefore, the validation presented in this paper does not seem to be particularly conclusive. The objective of the present paper is to study the behaviour of woven glass fibre epoxy pin-joints both numerically and experimentally, with particular attention paid to the sensitivity of the model to different parameters (clearance, friction, non-linear material behaviour). This work is aimed at a thorough experimental validation of the numerical results so that the model can subsequently be used for the development of a relevant predictive failure model.

TESTING

Joint testing configuration

The material chosen for this study is a woven glass fiber cloth embedded in an epoxy resin and the fibres lie at 45° (see Fig. 1). The reason for this is that the present study is part of a design study for which ±45° reinforcement was required [7]. The material is an Hexcel Composites prepreg (7781/XE85AI). It has been mechanically characterized to provide data for the modelling. The values can be found in Ref. [8].

In order to enhance the bearing failure mode, the dimensions given in Fig. 1 have been chosen as a result of a preliminary study. The experimental setup is composed of a classical hydraulic grip at the bottom and of a double lap rig at the top. All details can be found in Ref. [8].

Different clearance values have been used between the bolt and the composite hole in order to assess the influence of this parameter which is seldom studied in the literature, mainly because the much studied aeronautical riveted joints have a nearly zero clearance.

The joints have been tested quasi-statically at a cross-head speed of 1 $mm.min^{-1}$. Fig. 2 represents a set of typical results for different clearance values.

As can be seen, the clearance has a limited effect on the initial stiffness but a very significant one on the failure load and displacement. This is easily explained by the fact that the initial stiffness, which is a global response, is not much affected by the local load distribution around the hole. On the other hand, the failure load is directly related to these local stress distributions.

The objective of the rest of the paper is to derive a model to predict the failure load of these joints.

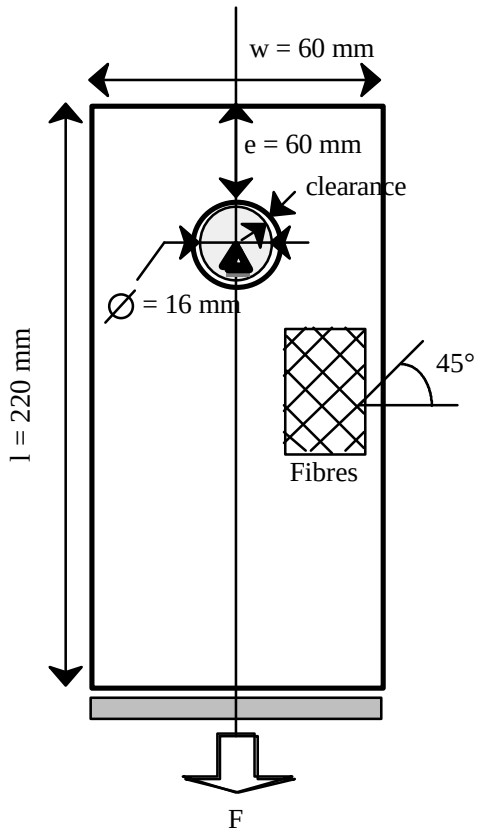


Fig. 1: Pin-joint configuration

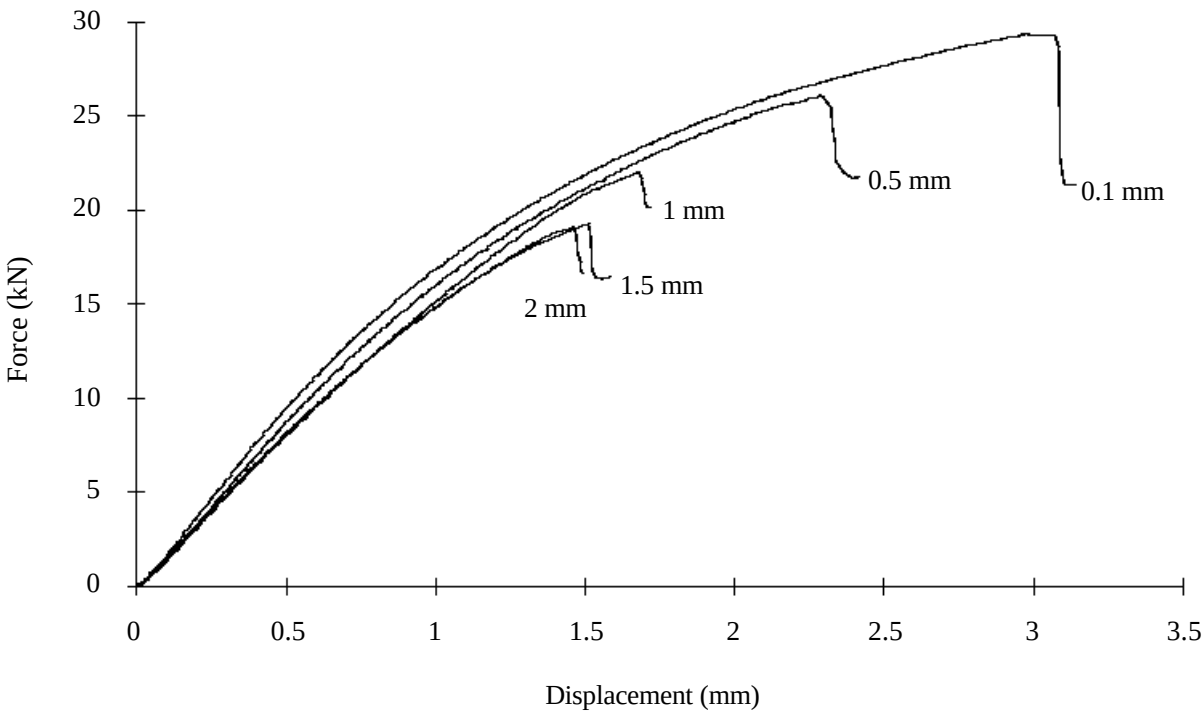
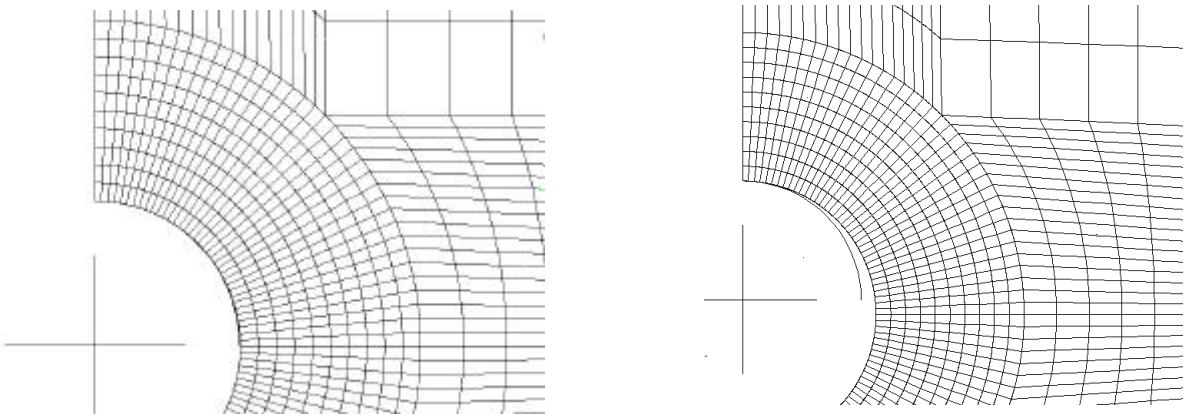


Fig. 2: Influence of the clearance on the global response of the joint

FINITE ELEMENT MODELLING

In order to compute the local stress distribution around the hole, a finite element model has been developed using the ABAQUS 5.5 package. The model is a plane stress one, using Abaqus CSP8 elements. For symmetry reasons, only half of the joint has been modelled.
After different trials, it was found that it was necessary to model the non-linear in-plane shear behaviour of the material. This was performed through a UMAT procedure. The stress-strain curve has been modelled by a fifth order polynomial [8]. Also, it was found that contact elements were necessary to describe the local effects around the hole correctly. Friction has also been taken into account. It was verified that the deformation of the bolt had an unsignificant effect on the stress fields. Therefore, the bolt has been modelled by a rigid surface. Details of the mesh are given in Fig. 3. For the rest of the study, only the extreme values of the clearance have been considered.
The boundary conditions were as follow:
- clamping of the center of the bolt (u and v set to zero) and rigid body for the bolt ;
- constant longitudinal displacement of the end of the plate (u=constant, v=0).

These boundary conditions are supposed to simulate as closely as possible the experimental conditions. The next step is now to validate the model in terms of local strain distributions. This is the objective of the next section.



0.1 mm clearance 2 mm clearance

Fig. 3: Local meshes around the hole for the two values of the clearance.

VALIDATION AND FAILURE PREDICTION

Experimental validation of the model

This is the key issue of the present paper. It was found by the present authors that the papers dealing with joint failure modelling were rather poor on this point, as already stated in the introduction.
A first validation has been attempted on the global load-displacement response of the joint [8]. However, it was found that this parameter was not sensitive enough to the contact modelling (pressure surface, friction coefficient). Moreover, deformation of the fixture and some sliding of the specimen in the grips did not allow a precise modelling of the experimental response. Finally, it is rather pointless to focus on the global response of the joint to predict its failure

load since this is basically related to the local stress distribution around the hole. Therefore, the efforts have been concentrated on a local validation around the pin.

To do so, three directional rosettes have been glued on each side of the specimens to measure the longitudinal and ±45° strains below the pin-hole contact (see Fig.4).

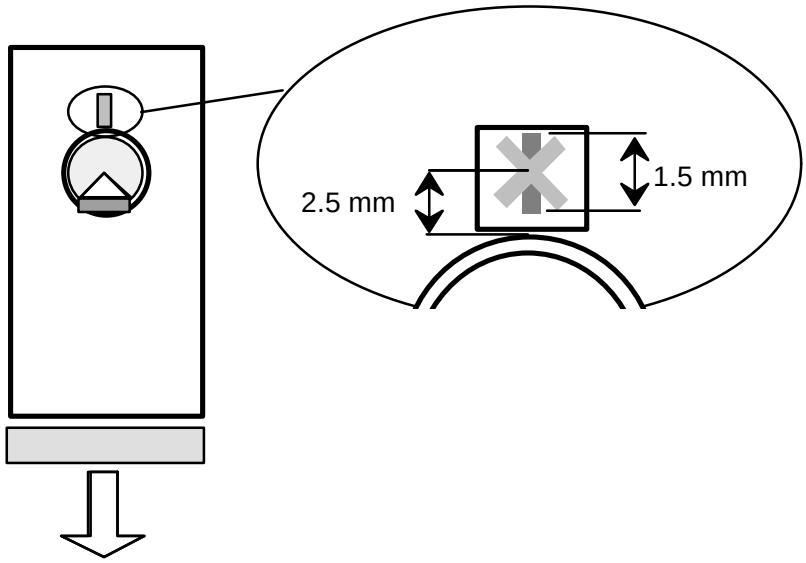


Fig. 4: Detail of the position of the rosette

It was found that the response of the two back-to-back rosettes were quite different. After some complementary test, it was found that these differences were due to local Saint-Venant effects due to imperfect cylinder to cylinder contact [8]. Such an effect had already been observed for the Iosipescu specimens where the loading points are very close to the strain gauges [9]. It was shown that for both cases, the effect could be eliminated by averaging the back-to-back strain values (see [8,9]). This procedure was adopted here.
In order to compare the experimental and numerical stress-strain responses, the numerical strains were averaged over the gauge grid to overcome the presence of a strong strain gradient.
The experimental/numerical comparisons are given in Fig. 5 and Fig. 6, for different friction coefficients.
It can be seen from the above figures that the friction coefficient has a very important effect on the local strain distribution, particularly for the 0.1 mm clearance specimen. It is important to note that good experimental/numerical correlation is obtained for a 0.3 friction coefficient, which has been experimentally determined by sliding a metallic coupon on a composite plate and measuring the sliding angle. This confirms that the model developed here is relevant to describe the local strain distribution around the hole. This has been confirmed by further whole-field measurements [8].
The next step is now to analyze the failure of the joints and to predict the failure load.

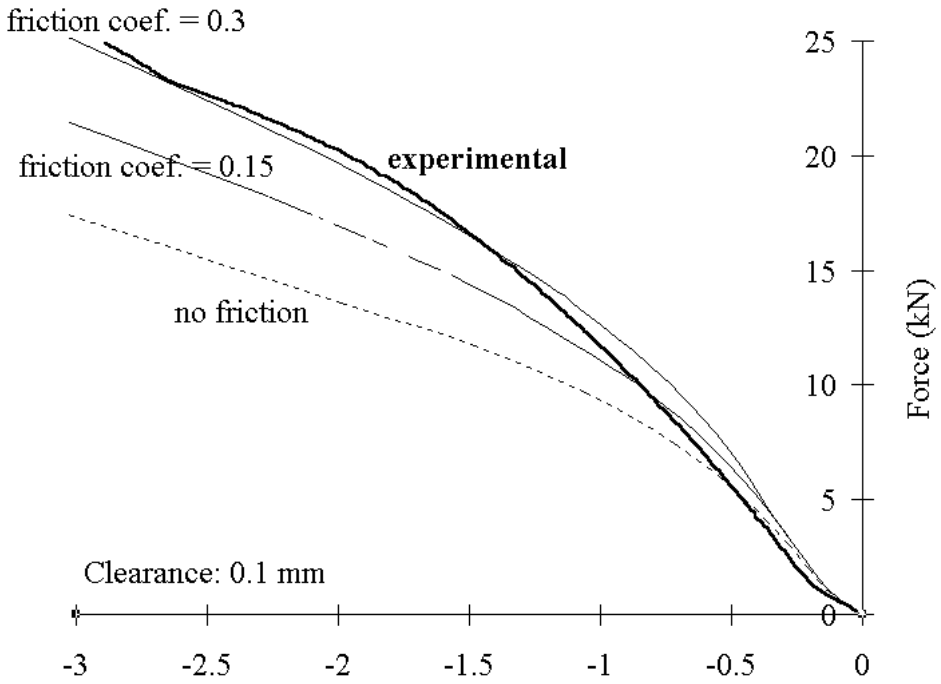


Fig. 5: Comparison of experimental and numerical local strain response (0.1 mm clearance)

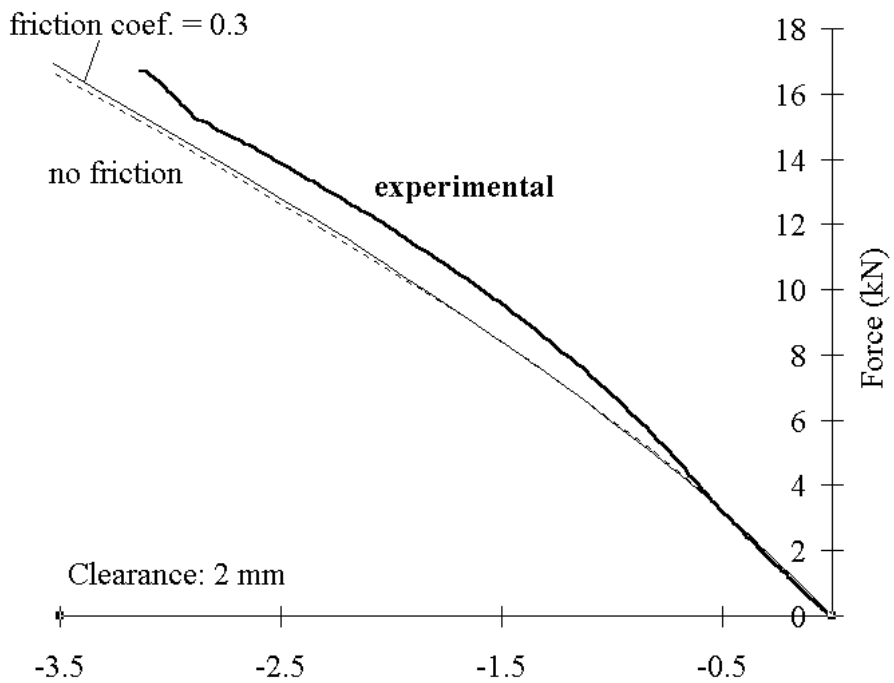


Fig. 6: Comparison of experimental and numerical local strain responses (2 mm clearance)

Failure prediction

When loaded to failure, the specimen behaves as represented in Fig. 7. The first load drop is accompanied with a local v-shaped buckling. After this point, the joint takes up additional load until local shear-out ruins the joint.

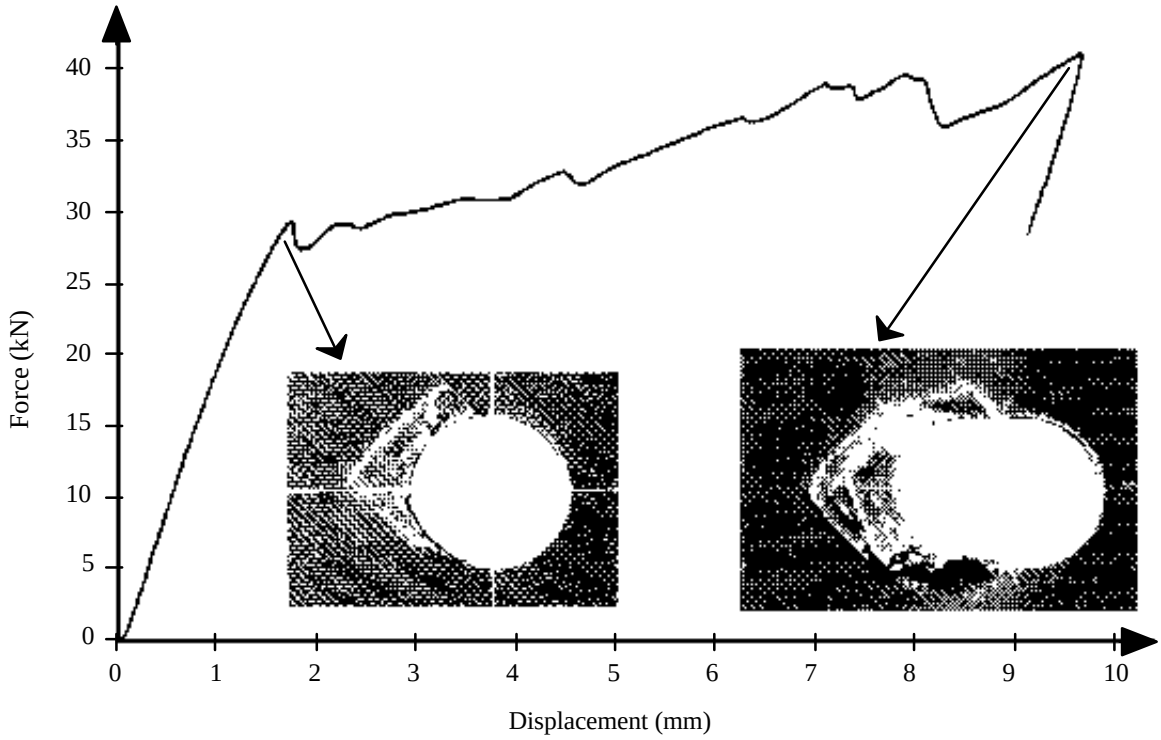
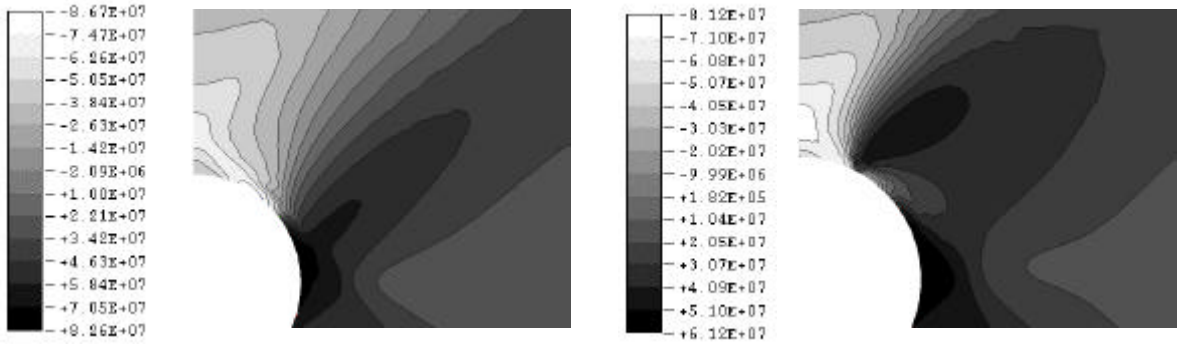


Fig. 7: Typical load-displacement curve for a composite joint

The idea of the present work is to predict the first failure load, after which there is no integrity of the joint anymore. The failure of this kind of joint had already been hinted to be caused by the accumulation of in-plane shear damage [5]. This has been experimentally verified by the present authors by the following procedure. Specimens were loaded up to a fraction of their local buckling load and then, micrographs of the contact zone between bolt and composite were performed. These micrographs revealed local whitening of a v-zone which is characteristic of in-plane shear. Therefore, it is the accumulation of local in-plane shear damage that causes the local buckling. These experimental observations were confirmed by the finite element calculations. In Fig. 8, the shear stress distributions are represented for the experimental load values. It can be seen that the shear stresses concentrate in a v-zone where the damage was observed and that the values of the maximum shear stresses are close to the experimental strength measured with the 45° tensile test (S=90 MPa).

In-plane shear stress in Pa



Clearance 0.1 mm

Clearance 2 mm

Fig. 8: In-plane shear stress maps for the two clearance values
(load is the experimental failure load)

In order to perform the failure load prediction, a failure criterion has to be chosen. This is at present a very controversial issue [10]. However, the fact that the reinforcement is a woven cloth has enabled to consider here that the normal stresses did not play any role in the failure process. Therefore, the maximum stress criterion was applied with the in-plane shear stress. Also, the important stress gradient in the damage zone is difficult to take into account. Nevertheless, since the alternative approaches remain to be validated [6], the maximum stress from the finite element calculation was taken as the input value.
From the above, it is possible to compare the predicted and experimental failure loads. The failure loads have been determined on four specimens for each clearance value. The results are reported in Table 1.

Table 1: Experimental failure loads for the two clearance values

	Average failure load (GPa)	Extreme values (GPa)
0.1 mm clearance	29.0	[28.2 - 29.4]
2 mm clearance	18.8	[18.0 - 19.7]

To compare with the predicted values, two experimental load have been selected. The first one is called "first visible damage". It is the load at which the micrographs have revealed visible shear damage. The second is the "local buckling" load which corresponds to the first load drop on the force-displacement curve.
The results are reported in Table 2.
It can be seen that the predicted values fall within the 'fvd' and 'lb' loads, with a maximum difference of about 10%. As expected, the fvd load is slightly below the predicted load and the lb one, slightly above. To describe the failure load more accurately, there is a need for a failure model taking the gradient into account. However, considering the fact that the present approach is aimed at a simplified design procedure, the achieved accuracy is found to be fully satisfactory.

Table 2: Comparison of experimental and predicted failure loads

	0.1 mm clearance	2 mm clearance
Experimental failure load (kN) First visible damage (fvd)	25	17
Experimental failure load (kN) Local buckling (lb)	29	19
Predicted failure load (kN)	**26**	**19**
Relative difference (%)		
- fvd	-4	-12
- lb	+11	0

CONCLUSION

In conclusion, the following points can be expressed:

- the clearance between the pin and the hole has an important influence on the failure load of pin-joints. Minimum clearance should be ensured according to the assembly requirements ;
- local Saint-Venant effects due to pin-hole contact defects cause significant strain differences between the two specimen faces ;
- strain gauges should be fixed on the two specimen faces and the strains averaged to correctly validate the finite element local strain calculations ;
- the minimum level of finite element modelling required to describe the behaviour of the pin-joint considered here requires the use of friction contact and shear nonlinearity ;
- thorough experimental validation of the finite element model is required to see the influence of certain parameters of the model (friction, in particular) ;
- the failure of the present ±45° joints is caused by in-plane shear ;
- using the maximum stress criterion applied to the maximum stress value from the finite element computations, the failure loads of the two types of joints (clearances of 0.1 and 2 mm) has been predicted within 10% of the experimental values ;
- the present approach has been limited to a certain type of material and layup and should be extended to other configurations for additional validation. Also, the influence of the tightening of the bolt has been discarded. However, the procedure is compatible with design department requirements where more complex failure models cannot be implemented because of the very costly identification procedures, particularly in industrial sectors where the added value is much lower than that of the aerospace industry. The present study is a step towards simplified design procedures for composite bolted joints.

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