SIZING OF BOLTED JUNCTIONS FOR 3D-WOVEN CERAMIC MATRIX COMPOSITES STRUCTURES USING ONERA DAMAGE MODEL AND COMPARISONS WITH MULTI-INSTRUMENTED TESTS

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ABSTRACT

The introduction of Ceramic Matrix Composites (CMC) in the hot parts of turbojet engines seems to be an attractive solution in order to reduce their ecological footprint and their fuel consumption. To succeed in this introduction, it is essential to master the assembly of these materials with other structures.

Bolted junctions are interesting options due to their robustness and their capabilities to be assembled and disassembled several times during the life of the aircraft. However, it shall keep its functionality facing all flight conditions and during the whole part lifecycle.

It is worth mentioning that the use of CMC imposes to take into account the several thermal environments and the specific behavior of this kind of materials. Therefore, the goal of this study is to present the modelling strategy used to analyze the bolted junctions introduced during the Arcoce program. This strategy is based on the dialog between experimental tests and numerical results in order to study the influence of thermal conditions on the bolt preloading conditions and to analyze the damage mechanisms of this kind of junctions.

1 INTRODUCTION

ACARE (Advisory Council for Aviation Research and Innovation in Europe) has set ambitious goals to the next generation of turbojet engines in order to reduce their ecological footprint and their fuel consumption. One way to achieve this is to introduce Ceramic Matrix Composites in the hot parts of these engines. Therefore it is compulsory to master the assembly of these materials with other structures. Bolted junctions are interesting options due to their robustness and their capabilities to be assembled and disassembled several times during the life of the aircraft.

If many studies about the behavior of bolted junctions exist [1-3], the specific case of Ceramic Matrix Composite (CMC) assemblies is less known in literature. Particularly, it is worth mentioning that the use of CMC imposes to take into account the several thermal environments and the specific behavior of this material. Thus the efficient sizing of such composite technologies can only be achieved through a dialog between test campaigns and powerful Finite Element Models.

This paper presents the approach proposed for the analysis of the behavior of bolted junctions introduced during the Arcoce program for the fly certification of ceramic matrix composite after-body [4].

2 PRESENTATION OF CMC BOLTED JUNCTION TECHNOLOGY AND THE ASSOCIATED MODEL

2.1 The CMC bolted junction technology

The studied technology allows the assembly of several structures manufacturing in CMC, based on silicon carbide (SiC), using a metallic fixing. The CMC used, developed by SAFRAN-Herakles and named A40C, is based on a silicon carbide matrix, manufactured by a mixed process (liquid and chemical vapor infiltrations), reinforced by a SiC fiber 3D woven. In order to avoid brittle behavior, a pyrocarbon (PyC) interphase is used. The CMC behavior is illustrated in Fig. 1.

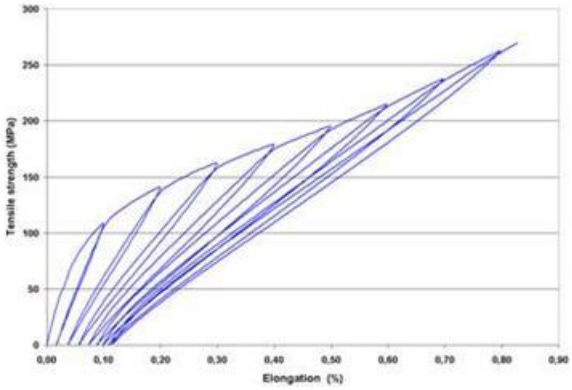

Figure 1: Typical curve of A40C CMC behavior.

The difference between the thermal expansions of both materials present in the assembly (metal and CMC) imposes the use of a thermal compensation technology.

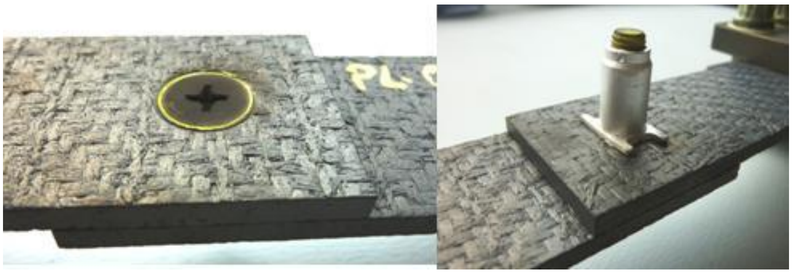

Figure 2: CMC bolted junction.

The column integrated to the bolt makes an added high of metal expansion possible using metallic material with a differential thermal expansion coefficient compared with the screw one (Fig. 2). Using the sizing of the relative highs of the materials, it becomes possible to compensate for obtain a low evolution of the bolt preload for the targeted temperatures. Safran patents have been proposed concerning these technologies [5,6].

2.2 Presentation of the model of the bolted assembly

The finite element (FE) model has been developed in 3D with an implicit commercial FE code (Fig. 3). Contacts between the different parts of the assembly are represented from the nominal dimensions between components. The friction between all parts is also taken into account.

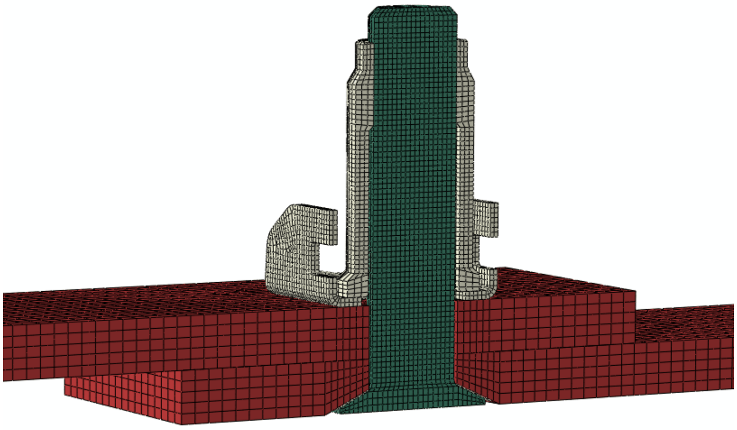

Figure 3: 3D mesh describing the junction.

An isotropic elastic behavior, taking into account the temperature influence on the Young modulus, is used for the metallic components.

Concerning the quasi-static behavior of CMC materials, the macroscopic damage model ODM-CMC (ONERA Damage Model for Ceramic Matrix Composite) is used. This model has recently been adapted for matrix ceramic materials having 3D-woven interlock armor [7-9]. This model defined at the macroscopic scale is thermodynamically admissible. Moreover it is “pseudo-tensor” and it is strictly identical to a tensor model through 0°, 90° and ±45° directions. This damage approach using scalar variables, already validated on CMC material specimens under in-plan solicitations, presents an interesting compromise between model complexities, difficulties about its identification and its predictive capabilities. Therefore, this model seems to be very efficient and relevant for industrial structures sizing.

As shown in Fig. 4, three parts are distinguished in the model: an elastic part, a nonlinear part corresponding to matrix damage and a softening part associated with the progressive yarns failure.

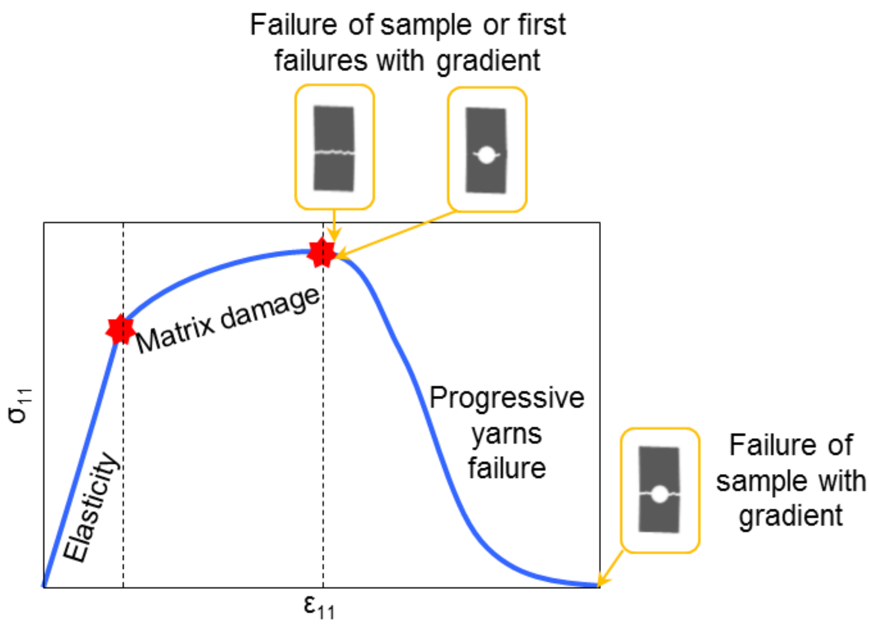

Figure 4: CMC material behavior under tensile solicitation.

The model state law is defined by the effective stiffness tensor ($\underline{\underline{C}}^{eff}$) and the effective compliance tensor ($\underline{\underline{S}}^{eff}$):

$$\underline{\sigma} = \underline{\underline{C}}^{eff} : \left(\underline{\varepsilon} - \underline{\varepsilon}^{th} - \underline{\varepsilon}^{0}\right) - \underline{\underline{C}}^{0} : \left(\underline{\varepsilon}^{r} - \underline{\varepsilon}^{s} - \underline{\varepsilon}^{0}\right) \tag{1}$$

with:

$$\underline{\underline{C}}^{eff} = \left(\underline{\underline{S}}^{eff}\right)^{-1} \quad \text{and} \quad \underline{\underline{S}}^{eff} = \underline{\underline{S}}^{0} + \Delta\underline{\underline{S}}_{m}^{eff} + \Delta\underline{\underline{S}}_{tow}^{eff} \tag{2}$$

where $\underline{\underline{C}}^{0}$ (resp. $\underline{\underline{S}}^{0}$) represents the initial elastic stiffness (resp. compliance) tensor. $\Delta\underline{\underline{S}}_{m}^{eff}$ (resp. $\Delta\underline{\underline{S}}_{tow}^{eff}$) represents the part of the compliance tensor influenced by matrix damages (resp. yarn failures). Five matrix damages (Fig. 5), each one associated with a damage threshold, and two progressive yarns failure damages are used in the model. ε is the total strain whereas ε^{th} is the thermal strain, ε^{0} the elastic strain, ε^{r} the residual strain and ε^{s} the stored strain. The residual strain and the stored one are induced during cycle loadings as shown in Fig. 6.

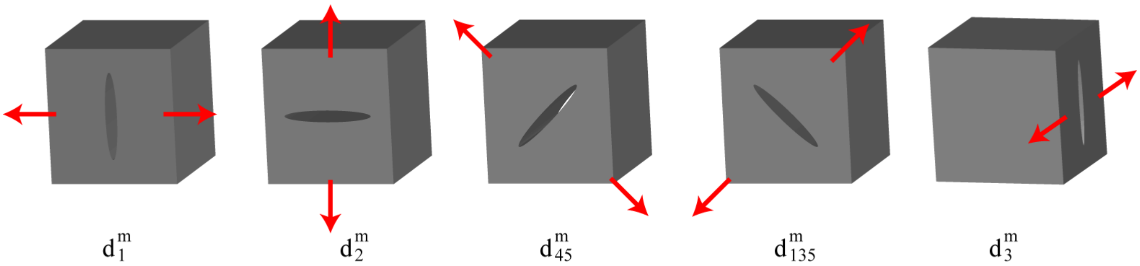

Figure 5: matrix damage variables.

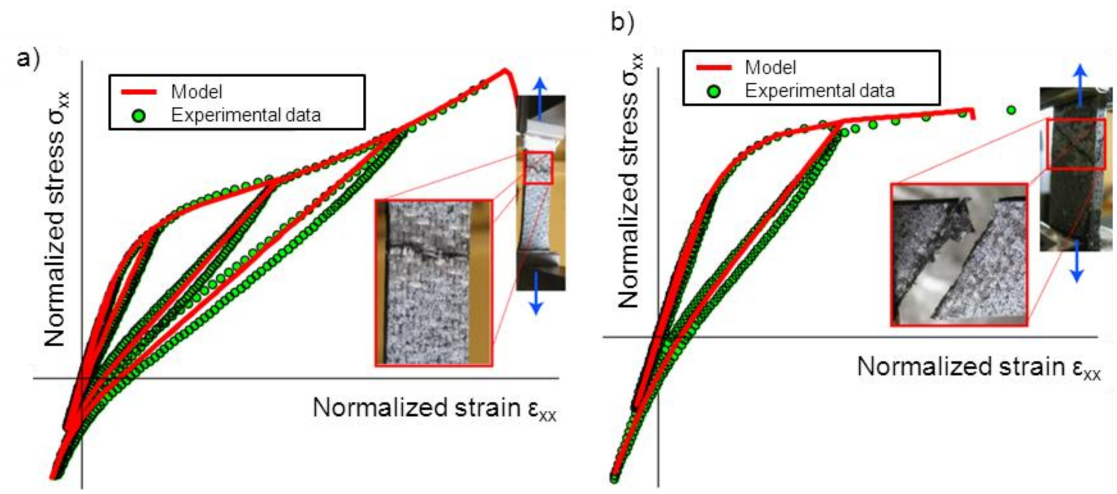

Figure 6: Modeling of the CMC material behavior using ODM-CMC for tensile solicitations applied on (a) 0° specimen and (b) 45° specimen.

ODM-CMC has been implemented in implicit commercial finite element code by ONERA in order to be integrated in the sizing approach of SAFRAN group [7].

3 ANALYSIS OF THE BOLT PRELOADING

Bolted joints properties are significantly managed by the bolt preload [1]. During its life, the assembly is submitted to important variation of temperature (from 20°C to 600°C). Thus, it is important to analyze the influence of this variation on the bolt preload. As shown in Fig. 7, the bolt preload increases until 400°C, then the load decreases due to the metallic Young modulus reduction. As expected, thanks to the technology proposed, the bolt preload evolution stays low (<10%) whatever the temperature variation.

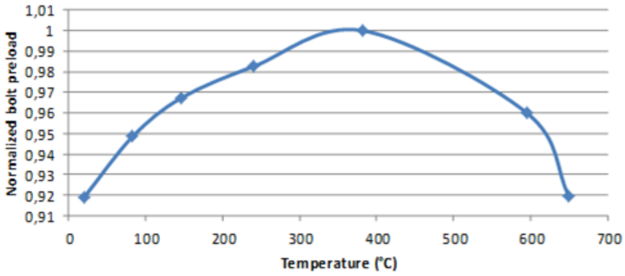

Figure 7: Evolution of the normalized bolt preload versus temperature.

However, the equilibrium state of the junction is influenced by the temperature level. Indeed, as shown in Fig. 8, the position of the head screw depends on the temperature. This variation has a potential impact on the assembly behavior. Moreover, the first step of preload involves an overstress into the countersunk head screw (Fig. 9). This observation is consistent with the experience about the failure under the head screw when the bolting torque increases.

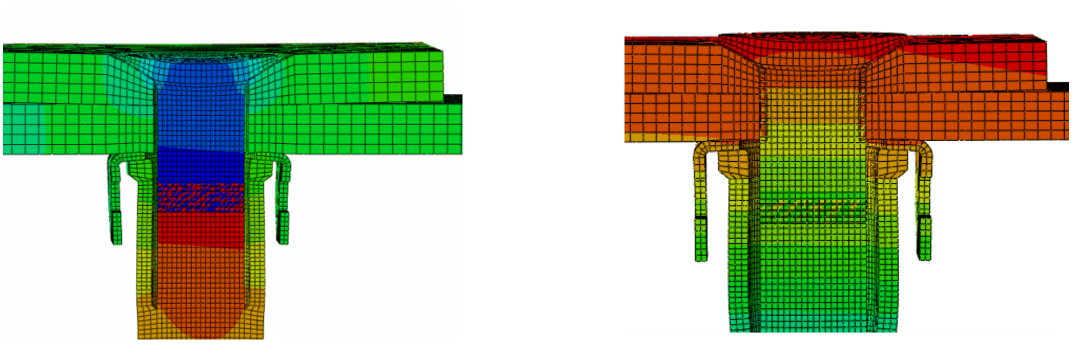

Figure 8: Strain of the junction for two temperature levels (20°C and 650°C).

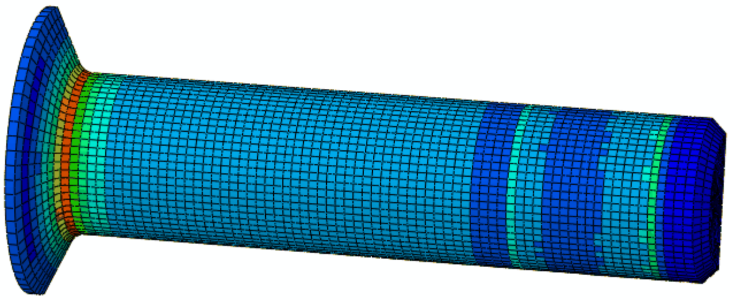

Figure 9: Illustration of the stress concentration under the countersunk head screw.

Furthermore, the progressive creation of the “Rotscher” pressure-cone-envelope can be observed with the modeling (Fig. 10). This cone is present when the CMC is under out-of-plan compression due to the bolt preload. The compression effect, known to strongly influence the bearing strength for organic matrix composites, must be studied for CMC.

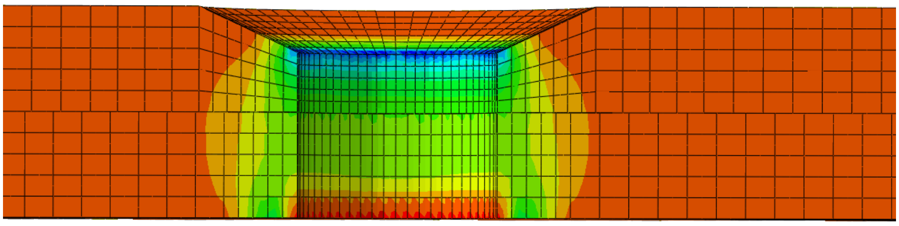

Figure 10: Representation of the “Rotscher” pressure-cone-envelope.

4 EXPERIMENTAL ANALYSIS OF THE FAILURE MODES OF SINGLE LAP JOINT CONFIGURATIONS

In this study, several quasi-static tests have been performed [10, 11]. Two different set-ups were investigated for this experimental study. For the first set-up, the sample was fastened by two fixed clamping jaws preventing any rotation, whereas in the other case, one of the clamping jaws was ball joint connection, thus allowing some degree of freedom in rotation. In order to distinguish the two types of configurations in the following of this article, the set-up with two clamping jaws is referred as “no swiveled clamp”, and the other set-up with one swiveled and one fixed clamping jaws is referred as “with swiveled clamp”. In both cases, the tests were performed until failure based on a prescribed displacement control.

Each test has been multi-instrumented using acoustic emission (AE) and digital image correlation (DIC). The specimens have been realized following the classical rules of bolted joints conception. The failures are obtained systematically into CMC components. The failure modes are similar to the ones obtained with organic matrix composite materials and metallic materials (Fig. 11) [1].

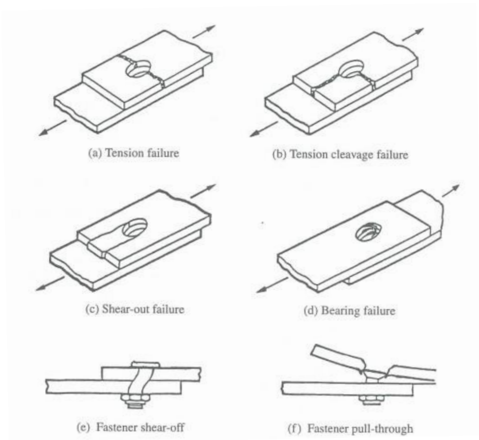

Figure 11: Failure modes of bolted joints [1].

Using results obtained by DIC, it is possible to describe the junction behavior. Four phases can be distinguished (Fig. 12): *(i)* the first loading with a linear behavior, *(ii)* a nonlinear behavior followed by a plateau, corresponding to the sliding of both CMC plates between each other, *(iii)* the establishment of the bearing failure mode between the CMC and the screw, and *(iv)* the loss of strength corresponding to the net cross-section failure. The four phases are present for both configurations of bolted joints studied (“no swiveled clamp” and “with swiveled clamp”).

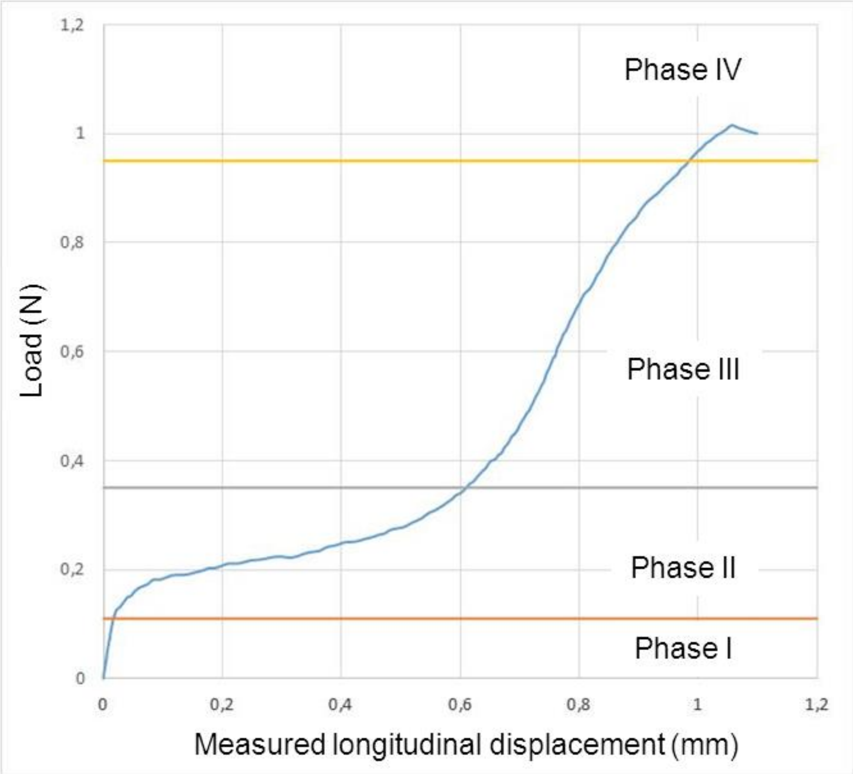

Figure 12: Load versus displacement obtained experimentally with “no swiveled clamp” configuration [11].

Using acoustic emission instrumentation, three specific classes of signal can be distinguished (Fig. 13). They are related to the damage mechanisms of the junction (friction (green class), matrix damages (red class) and fiber damages (pink class)). These classes are similar whatever the boundary conditions of the experimental test.

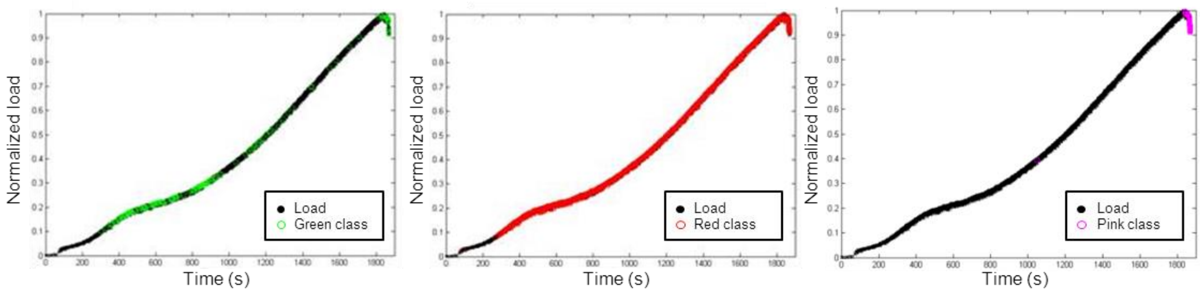

Figure 13: Classification of acoustic signals during the “no swiveled clamp” test: friction (green class), matrix damages (red class) and fiber damages (pink class) [11].

5 MODELLING OF THE SINGLE LAP-SHEAR TEST

The modelling of the tensile shearing test has been performed with two different assumptions concerning the CMC behavior. On one hand, the material is considered as orthotropic linear elastic and on the other hand, the damage model ODM-CMC is used.

The comparison with the experimental macroscopic curve shows that phase I and phase II are qualitatively obtained whatever the CMC behavior used (Fig. 14). From the phase III, the numerical curves depend on the law used. Indeed, compared with the elastic model, the slope of the macroscopic response obtained with the ODM-CMC model is reduced due to the matrix damage level. In fact, as indicated by the classification of the acoustic signals, matrix damages (red class in Fig. 13) are observed when the assembly behavior becomes nonlinear (at the beginning of phase II in Fig. 12). But, the matrix damages effect is only clearly visible after the end of the sliding.

Finally, it appears that the simulation with ODM-CMC model permits to describe qualitatively the assembly behavior. An additional work about the identification of the model seems necessary in order to represent quantitatively the experimental response. However, this first result is very satisfying for understanding the damage mechanisms of bolted junctions during a single lap shear test. Furthermore, it confirms the interest of the integration of damage model in sizing approach for 3D woven CMC structures.

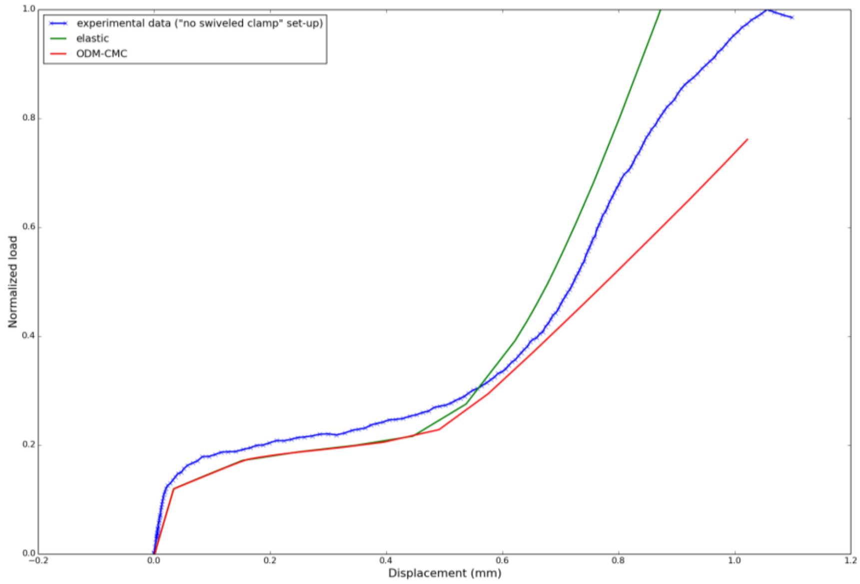

Figure 14: Normalized load versus displacement: comparison between numerical simulations (with elastic and ODM-CMC models) and experimental result for the "no swiveled clamp" set up [11].

6 CONCLUSIONS

A sizing method of bolted junctions for 3D woven ceramic matrix composite structures using ONERA Damage Model ODM-CMC and comparisons with multi-instrumented tests have been proposed in order to describe and to understand the CMC bolted joints behavior. The first results are qualitatively satisfying and have permitted to understand the different damage mechanisms occurring during a single lap-shear test.

In the future, works about a more efficient identification of ODM-CMC parameters will be realized, particularly concerning the damage kinetics and the out-of-plan damage mechanisms. After, in order to complete the sizing method with the damage model, fatigue and oxidation behaviors will be studied. Moreover, the damage tolerance will be also important for improving the sizing method of bolted junctions.

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REFERENCES

[1] M. C.Y Niu, *AIRFRAME stress analysis and sizing*, 2nd edition of Honk Kong conmilt press, 1999.

[2] F. Lachaud, R. Piquet, G. Aldebert, J. Huet and L. Michel, Analyse du comportement mécanique des assemblages boulonnés composites à renforts tissés, *Revue des composites et matériaux avancés*, **24**, 2014, pp. 449-464

[3] T. Ireman, T. Nyman and K. Helibom, On design methods for bolted joints in composite aircraft structures, *Composite Structures*, **25**, 1993, pp. 567-578

[4] F. Bouillon, A. Candeau, F. Dupé, G. Mecuson, P. Metge and R. Etchart-Salas, Développement et certification d'un échappement de turboréacteur en CMC pour l'aviation civil, *Proceedings of Matériaux 2014, Montpellier, France, November 24-28, 2014*

[5] Safran patent : n°1355705, June 18, 2013

[6] Safran patent : n°0856009, September 8, 2008

[7] F. Laurin, M. Kaminski, N. Tableau, Z. Aboura and F. Bouillon, Validation du modèle ODM-CMC au travers de comparaisons avec des essais multi-instrumentés sur structures tissées interlocks à matrice céramique, *Proceedings of JNC 19, Lyon, France, June 29- July 1, 2015*

[8] E. Hémon, *Modèles multi-niveaux de prévision des durées de vie en fatigue des structures composites à matrice céramique pour un usage en turbomachines aéronautiques*, PHD Thesis of Université Bordeaux I, France, 2013

[9] L. Marcin, J.-F. Maire, N. Carrère and E. Martin, Development of a Macroscopic Damage Model for Woven Ceramic Matrix Composites, *International Journal of Damage Mechanics*, **20**, 2011, pp. 939-957

[10] B. Legin, Z. Aboura and F. Bouillon, Etude du comportement mécanique d'un assemblage boulonnée par multi-instrumentation, Technical Report, *2014*

[11] B. Legin, Z. Aboura, P. Feissel and F. Bouillon, Experimental investigation of the mechanical behavior of bolted ceramic-matrix composite joints using multi-instrumentation, *Proceedings of ICCM20,Copenhagen, Danemark, July 19-24, 2015*