STUDY AND ANALYSIS OF THE MECHANICAL BEHAVIOR OF REINFORCED STITCHING STIFFENERS

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Abstract

Carbon/epoxy stiffeners to skin T joints by one side stitching (OSS), injected by Resin Transfer Molding (RTM) process have been performed. The macroscopic performances of the resulting stitched structure have been then compared with unstitched one, using pull-off tests. To complete this study, stitching effects have been analyzed thanks to a multi-instrumented approach based on the use of Digital Image Correlation (DIC) and Acoustic Emission analysis (EA). The crosscheck of the results has clearly demonstrated that stitching modify local strain distribution on stiffeners and therefore delays the advent of the first damage.

1. Introduction

The aeronautical industry is always looking for lighter structures for evident reasons. Thus engine nacelles are built using a network of composite stiffeners. Nevertheless, the delamination reminds the weak point of 2D composites [1], [2], [3] and [4]. In order to counteract this deficiency, it is possible to reinforce these composites in the third direction by introducing a mechanical link between the different plies of the composite laminate, this link being a stiff carbon fiber rod in the case of Z-pinning [5], [6], [7] and [8], or a thread (glass, carbon or aramid) in the case of stitching [8] and [9]. Currently only few composite components containing 3D reinforcement are in service in the aeronautical industry [10]. This may be explained by the lack of knowledge concerning mechanical behavior and modeling tool of this new generation of materials. This study fits into this framework by conducting pull-off tests on stiffeners assembled by OSS. In order to identify accurately damage mechanisms involved, a multi-instrumentation including EA, DIC and in-situ observations have been used.

These works are focused on two aspects: the first one concerns the stiffener manufacturing process, the second one deals with the analysis of the stiffeners mechanical behavior.

2. Manufacturing techniques and materials

2.1. One side stitching reinforcement

The assembly and the reinforcement of composites can be made with different types of stitching such as for example tufting, lock stitching or one side stitching (OSS). In this study one side stitching is used to manufacture the stiffeners.

The OSS technique is stitching kind using one needle and one hook (**Erreur ! Source du renvoi introuvable.**). The needle crosses dry preform to 45° with thread, hook crosses plies to 90° to pick up needle thread and goes back it by the same way. Thus a loop is forming for the next step. The head of OSS is installed on KUKA robot and permits to stitch complex shapes accurately.

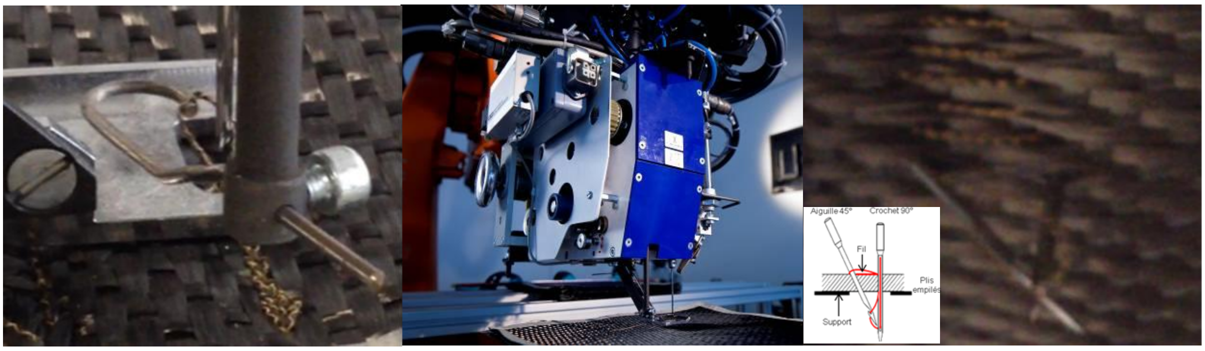


Figure 1- One side stitching illustration

2.2. Stiffener manufacturing

A stiffener consists of four major parts (**Erreur ! Source du renvoi introuvable.**a):

- Vertical part
- Stiffener base
- Curve area
- Critical area

These different parts are constituted by carbon piles fabrics and assembled by a carbon / zylon thread. The dry preform resulting is injected by RTM process with epoxy resin.

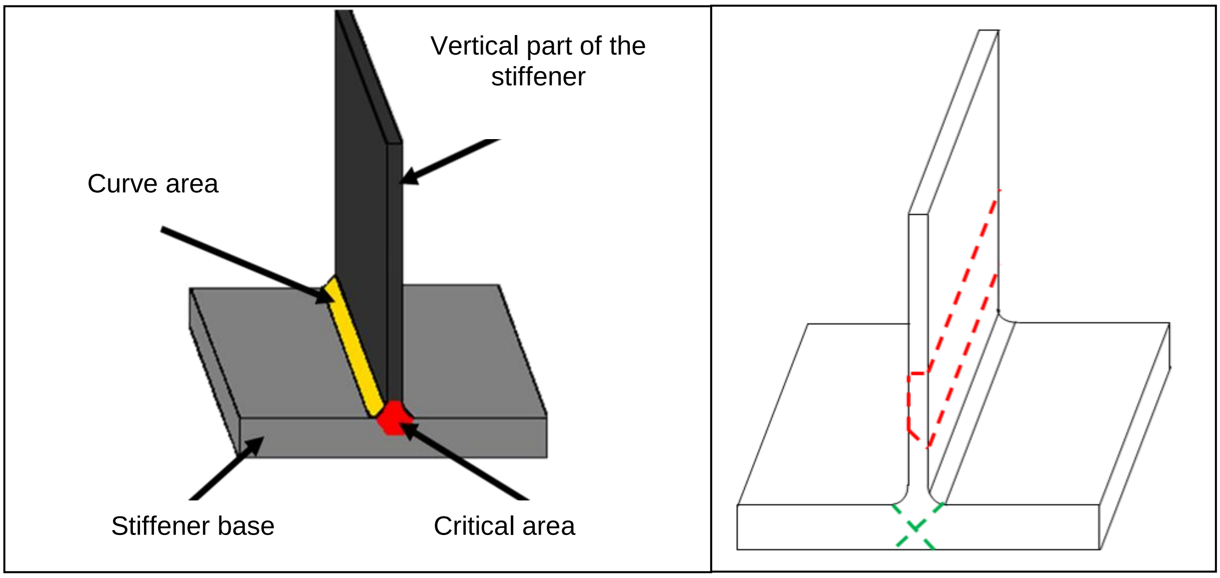


Figure 2- a: Stiffener vocabulary; b: Stiffener reinforced by OSS

Two stiffeners have been made. The first one, without stitching constitutes the reference and the second one, is reinforced by stitching in its vertical part and in its base (**Erreur ! Source**

du renvoi introuvable.b). Stiffeners are assembled in three steps: firstly the plies used to make the two "L" are assembled independently. Secondly the two "L" are assembled in vertical part with OSS. The last step concerns the assembly of the base with the "L" using the OSS head. Thus, stiffener reinforced by stitching (**Erreur ! Source du renvoi introuvable.**b) has cross stitching in critical area (red), well as a stitching in vertical part (blue).

2.3 Pull-off tests

The specimen geometry and the test configuration are schematized in **Erreur ! Source du renvoi introuvable.**. The quasi-static tests were carried out at constant cross-head displacement speed of 1 mm/min, on an Instron test machine equipped with a 200 kN load cell.

The principle of a pull off test is to apply a vertical load thanks to the rollers (to avoid the punching effect) placed on the stiffener base while holding the vertical part of the specimen in self-tightening grips.

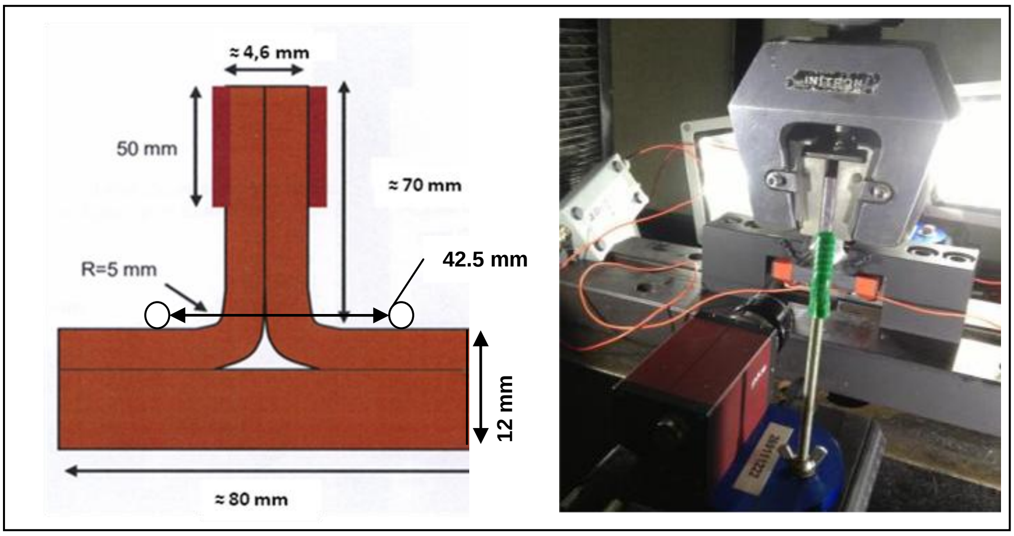


Figure 3- A: Geometry specimen; B: pull off test illustration

The tests have been multi-instrumented, using DIC, SEM, and AE analysis.

DIC has been applied on the side of the tested samples, to acquire strain fields. The samples' macroscopic response has been measured, thanks to virtual strain gauges applied on the strain fields.

Acoustic emission signals, resulting from tensile solicitation, have been acquired and then analyzed. Thanks to non-supervised clustering three clusters have been defined, using the similarity of the signals **[11]**.

Scanning electron microscope observations are performed before and after the test to better understand the mechanisms of damage. A second camera is positioned to view the second stiffener side to follow in real time the cracks appearance during the test.

3. Results and discussion

3.1. Global mechanical response

The mechanical behavior characterized by the load/displacement curve is almost linear up to failure (**Erreur ! Source du renvoi introuvable.**A). This behavior differs from T joint assembled by tufting (**Erreur ! Source du renvoi introuvable.**B). In fact Cartie and al [12] show that an early damage occurs characterized by initial load drop. Then an increase load is observed due to tufting presence. It appears that in the case of OSS this early drop effect was avoided.

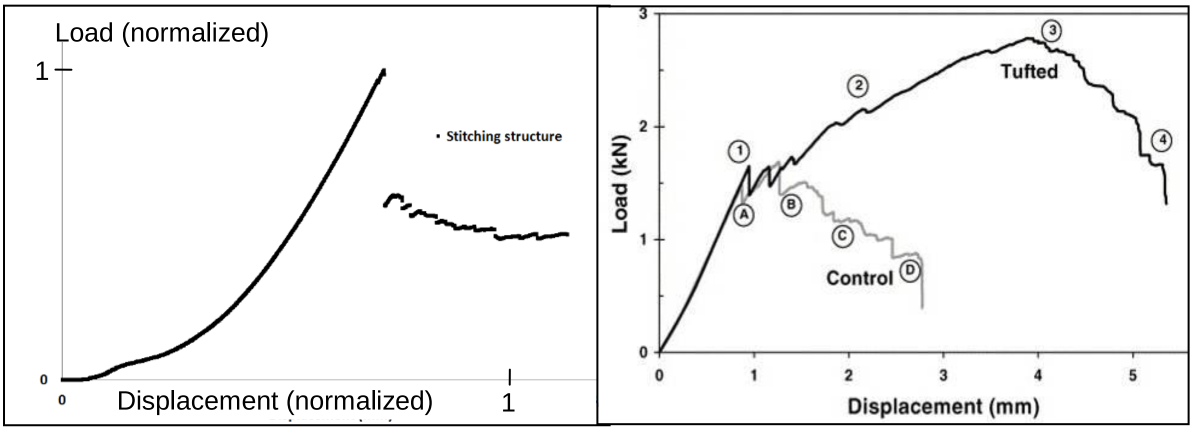


Figure 4- Pull-off test of stitched stiffener: a: OSS reinforcement; b: Tufting reinforcement [12]

From mechanical response rigidity, maximum load and failure drop load for both configurations are measured. Tableau 1 summarized these results.

Configuration	**Failure load Normalized (N)**	**Rigidity Normalized (N/mm)**	**Failure drop load Normalized (%)**
Unstitched	**$\bar{X}$: 0.93** ± 10.6 %	**$\bar{X}$: 0.89** ± 7 %	**$\bar{X}$: 1.34** ± 11.2 %
Stitched	**$\bar{X}$: 1** ± 8.7 %	**$\bar{X}$: 1** ± 3.15 %	**$\bar{X}$: 1** ± 9.3 %

Tableau 1- Results of pull off tests

Regarding unstitched structure the failure load average is 0.93 (normalized value) with standard deviation of 10.6%. For stitched configuration average is 1 with standard deviation of 8.7%N. It seems that failure load is the same for both configurations taking into account the standard deviation. Further tests will confirm or refute this trend. Concerning the rigidity the same remark can be made. It is important to note that the stitching contribution does not generate decrease in stiffness as might be expected. The structure effect seems to outweigh the impact of material properties.

3.2. Local mechanical response

Digital image correlation permits to obtain information to understand phenomena in stiffener structure. Virtual gauge has been defined on several positions of the stiffener structure (**Erreur ! Source du renvoi introuvable.**a).

Three virtual gauges are positioned on vertical part of stiffener, two virtual gauges on stiffener base and one gauge is located on critical area at center of stiffener. For each gauges the average strain ε_{xx}, ε_{yy} and ε_{xy} are calculated (**Erreur ! Source du renvoi introuvable.**b).

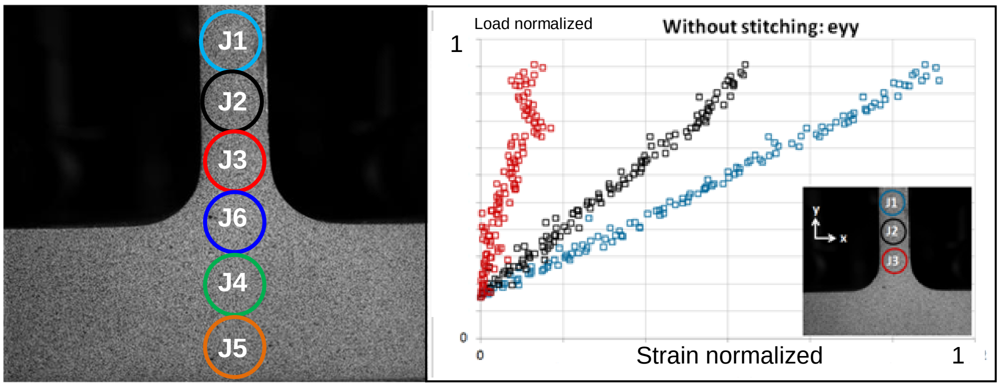


Figure 5- a:Virtual gauges positions; b: curves example of strain εyy

Erreur ! Source du renvoi introuvable. represents local strain for stitched and unstitched structures. We remark that the strain ε_{xx} and ε_{yy} are the same for both configurations. Stitching does not modified local strain field following “x” and “y” directions.

On vertical part of stiffener compressive effect on following “x” direction and tensile effect on following “y” direction are observed while a stiffener base we observe a compressive strain on both “x” and “y” directions.

On the other hand on the middle of structure i.e on critical area positive strain on “x” direction and negative strain along “y” direction are observed. Digital image correlation permits then to observe that the upper part is deformed less than the lower part of the structure and therefore it pushes against on the upper part creating compressive effect on the critical area.

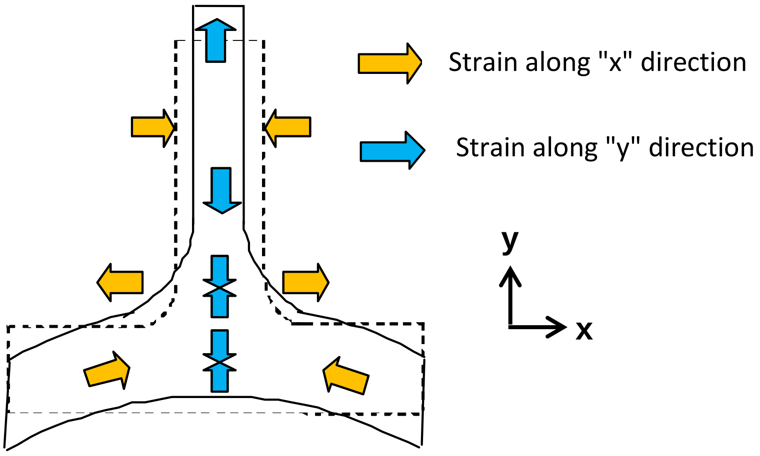


Figure 6- Local strain εxx and εyy for stitched and unstitched structures

The **Erreur ! Source du renvoi introuvable.** illustrates shear strain for both configurations. As expected, there is no shear effect on vertical part for unstitched stiffener. However the stitching modifies the strain field by introducing shear component in vertical part of stitched stiffener.

This shear effect can be explain by dissymmetry of the stitching because the OSS generates one thread at 90° and the other one at 45°. Moreover there is a positive shear and a negative shear in critical area for both configurations.

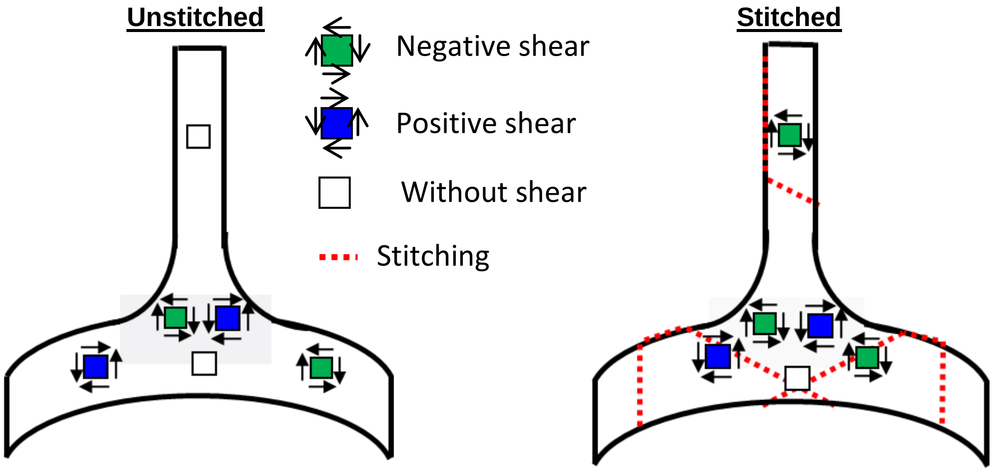
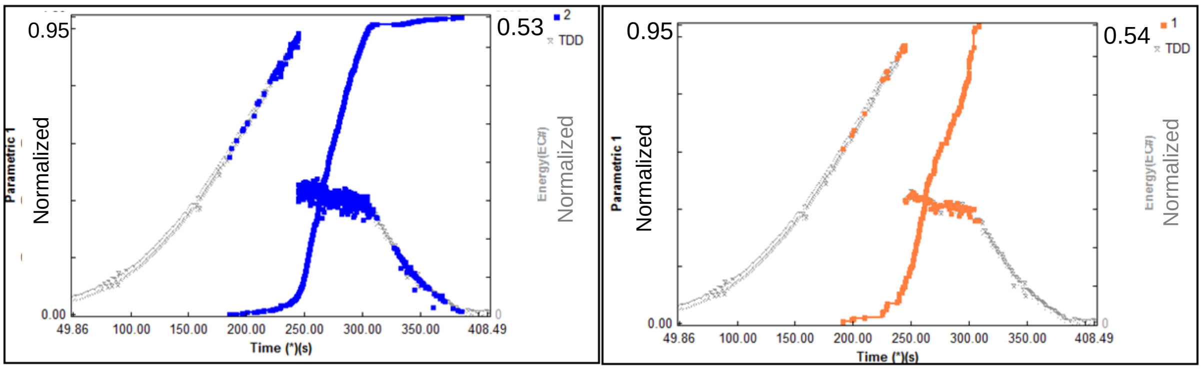


Figure 7- Shear local strain εxy for stitched and unstitched structures

3.3. Analysis of acoustic emission signal

In order to get additional information on the stiffener behavior during pull-off test, two acoustic emission sensors were placed on structure. The study of the acoustic emission signal allows obtaining information in real time during the loading of the material.

Unstitched



Stitched

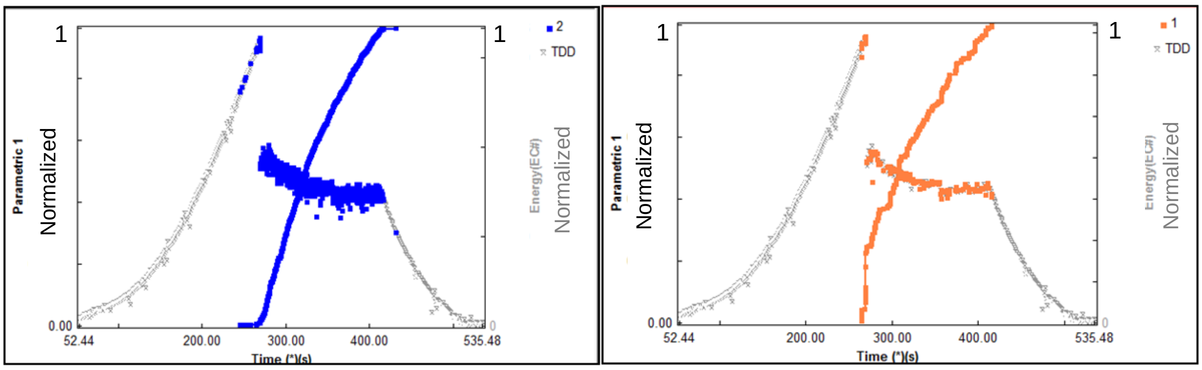


Figure 8- Acoustic emission signals families

The aim of the acoustic emission analysis signals is to determine when the first significant damage appears. The second aim is the classification of signals into several families to better distinguish damage.

First class is composed by low energetic signals. These signals are present all through of solicitation. As this class includes low energetic signals, we can assume that these signals are not linked to important damage mechanisms. Consequently this class has been neglected. The second one includes moderate energetic signals (represented by blue dot on Figure 8). These signals can be associated with early damage. The last one which includes the most energetic signals (represented by orange dot on Figure 8), can be attributed to critical damage mechanisms (leading failure). graphic for unstitched structure shows that both signals families occurred in same time. However on graphic associated at stitched structure orange signals arrive after blue signals. The first signals of bleu family appear at 56% of failure load for unstitched stiffener. The first signals of orange family arrive at 63% of failure load. For stitched stiffener the first signals of blue family arrive at 82% of failure load and the first signals of orange family appear at 93% of load failure. Considering these results we can say that the stitching delay the advent of ruin.

4. Conclusion

3D reinforcement of stiffener to skin T joint by OSS stitching and unstitched stiffeners have been manufactured by RTM process. Damage mechanisms have been established thanks to multi instrumented tests. It appeared that the OSS delay the onset damage without decreasing elastic rigidity.

Adding stitching on stiffeners will necessarily have an impact on the fatigue strength of these structures.

Work in progress will turn to the understanding and analysis of the fatigue behavior.

Acknowledgements

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