MECAHNICAL BEHAVIOR OF STITCHED 3D COMPOSITE

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Abstract

This article aims to assess the effect of stitches in laminated composite materials. A complete mechanical characterization of stitched and non-stitched composites showed that out of plane mechanical properties were considerably increased while the in-plane properties reduced about 20%. This drop in in-plan properties is due to the sewing process. SEM observations showed the damages that may cause by the introduction of a needle into a laminate. Short beam bending tests were conducted in order to compare these two materials in terms of interlaminar shear behavior.

1 Introduction

The traditional laminates composite exhibit high in-plane performances, good stability and conformability, but the out-of-plan stiffness and strengths are determined by the matrix and exhibit very low properties when compared to the in-plan properties which are greatly influenced by the fiber properties. These materials are also susceptible to delamination especially for thick structures. A few methods have been developed in order to reinforce the through-thickness properties of laminated composites, such as weaving and stitching. Tufting is a peculiar stitching method, which is considered to be one of the key technologies to improve interlaminar fracture of composite with technical and economic rationality. This technology is developed at the DLR Institute of Structural Mechanics of German Aerospace Centre of Brunswick.

Many studies about polymer matrix composites reported that the reinforcement in the through-thickness-direction improve the interlaminar mechanical properties. This insertion of local through-thickness reinforcements into dry preforms by stitching provides a possibility to enhance the out-of-plan properties of polymer-matrix-composite[1, 2]. Dexter and Funk [3] reported that in comparison with the unstitched laminated, the compressive strength after impact can increase, by stitching, by more than 80%.

In this study, to quantify the effect of through-thickness reinforcement on a glass/polyester composite laminate, an experimental study has been carried out. A comparative assessment of the influence of tufting yarn on the out-of-plane mechanical performances is presented. The microstructure of the stitched composite before and after the tests was observed by a scanning electron microscope (SEM) to evaluate the microstructure changes. The mechanical response, damage development were evaluated.

2 Experimental study

2.1Materials

The composite material used in this study is a Glass / Polyester laminate, impregnated in our laboratory by the infusion process. The architecture of the reinforcing fabric is a taffeta having a surface density of 300 g / m². For the purposes of the study, plates of different thicknesses were performed (2, 6, 8 and 20 mm).
The 3D reinforcement was achieved with a sewing head (KSL) fixed on a KUKA robot. The sewing thread consists of three fiberglass twisted strands. The values of 5mm for the tufting space and tufting length has been adopted, the schematization of the tufted composite is shown in Figure 1. The stitching process is characterized by the insertion of a through-thickness tufting yarn into the traditional two-dimensional (2D) perform, as a secondary processing step following lay-up. The needle enters the laminate with the tufting yarn inside. Once the needle arrived at the desired depth, the needle is removed and a retention mechanism allows the tufting to remain in the laminate and leave a ringlet on the recto face of the laminate, as shown in Figure 1and Figure 2. The presence of these loops generates an extra thickness which has the effect of reducing the volume fibers fraction during the infusion process. Thus, the tufted composites exhibit volume fractions below the unstitched. The RTM process, using closed molds, would be, more appropriate to use for the future because it will ensure the same thickness. The measurement of volume fractions by resin incineration shows that the unstitched composites have V_f = 55%, while the stitched exhibit V_f of 50%.

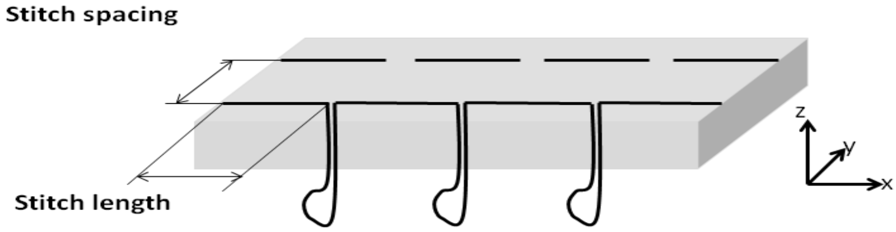
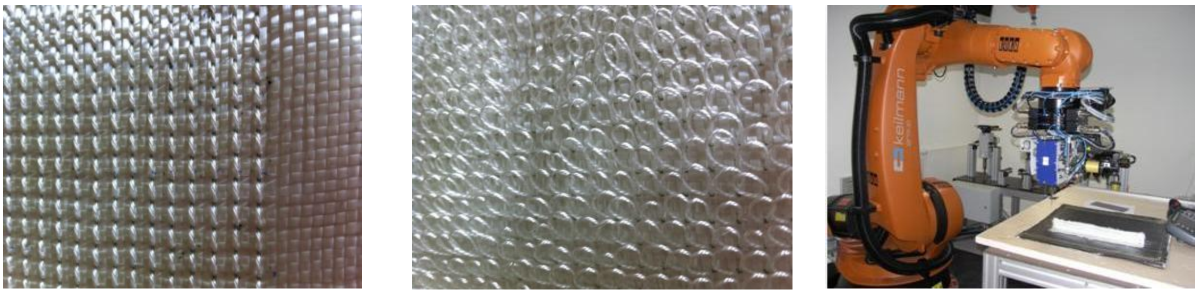


Figure 1 : Schematization of the tufted composite



(a) (b) (c)

Figure 2 : The tufting on the surface (a), the ringlet on the back (b), Stitching Robot(c).

2.2 *Mechanical tests*

In order to assess the contribution of the stitches, a complete characterization campaign was undertaken on both stitched and non-stitched materials. Through various tests such as uniaxial tension, torsion on rectangular bars and compression on cubes, carried out in different directions, we obtained the 3D elastic constants of these materials and the majority of ultimate stress. The results for the in plan mechanical properties are summarized in Table 1. In this table, each value is an average score of at least five samples. Concerning the tufted composite, the direction 1 corresponds to the direction of sewing; the direction 2 corresponds to that of the sewing rows.

	E_1(GPa)	E_2(GPa)	G_{12}(GPa)	ν_{12}	X^+(MPa)	Y^+(MPa)
Non-tufted composite	24±10%	25±4%	3.6±5%	0.164±5%	335±16%	352±7%
Tufted composite	18±2%	19±5%	3.2±7%	0.17±3%	298±4%	245±3%
Comparison	-25.7%	-23.5%	1.1%±%	5.7%±%	-11%±%	-30%±%

Tableau 1: 2D mechanical properties of both materials.

The out of plane mechanical properties of both materials are presented in Table 2.

	E_3(GPa)	υ_{31}	υ_{32}	G_{13}(GPa)	G_{23}(GPa)	Z^-(GPa)
Non-tufted composite	12±2%	0.173±1%	0.178±4%	4.6±2%	4.6±3%	48±6%
Tufted composite	35±5%	0.22±2%	0.23±3%	5.2±4%	5.4±4%	467±2%
Comparison	191%	27%	29%	13%	17%	834%

Tableau 2: Out of plane mechanical properties of both materials.

The above results show that the normal out of plane properties are multiplied drastically while those of in plane (2D) are slowed down by about 20%. This drop is due to the combined effect of lower fiber volume fraction and the damage introduced by the sewing needle. Indeed, the insertion of the needle (with the yarns) in the through-the-thickness direction causes some detrimental effects, e.g.: the induced undulations of the reinforcement fibers, broken in-plane fiber, increased porosity and resin-rich regions. All these findings were confirmed by SEM observations on the stitched materials. The obvious change brought by the tufting is the waviness near the tufting, as shown in Figure 3a.
Figure 3bshows a typical longitudinal cross-section of the composites in the 1-3 plan, all the plies are interlinked by the tufting yarns, and no delamination was found (before the tests). But a slight off-set (about 5°) of the stitching is observed, this could be attributed to the fabrication of the composite.
It emerges from this first series of tests that the strengthening in the third direction finds are whole interest in the mechanical improvement of the properties out-of-plan. So, in spite of the weakness of the volume fraction, the earnings in performance are considerable.
Following this work focuses on the analysis of the effect of stitching on short beam 3 points bending test (interlaminar shear strength ILSS).

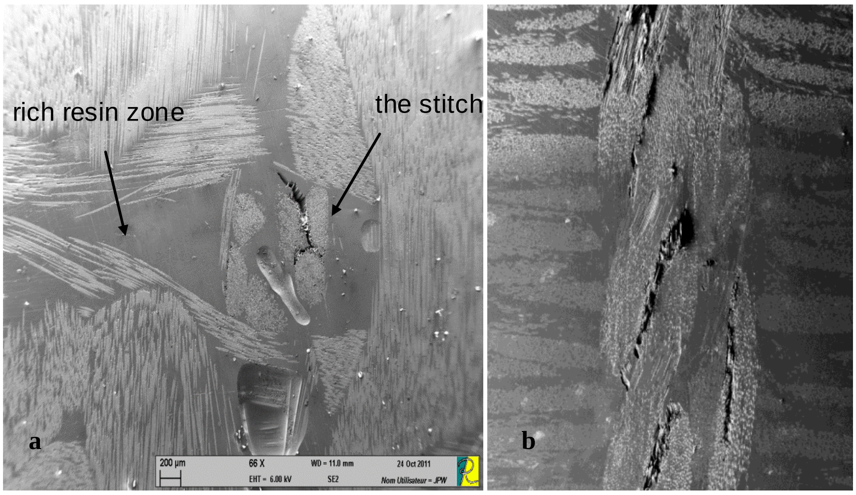


Figure 3 Microstructure of tufted composite (a) top view; (b) cross section

3 Interlaminar shear strength (ILSS)

Given that the strengthening in the thickness (by sewing) aims, first of all, to improve the resistance to delamination, we perform short beam bending tests (ISO 14130) to compare the interlaminar shear behavior of the two types of composites.
The stitched composites were tested in two directions (row direction and column direction of the tufting yarn), 7 specimens for each direction. The specimen shape and dimensions for the three-point bending are presented in Figure 4. The digital image correlation was used to measure the strain field of the 3D composites. Each specimen was also instrumented by acoustic emission sensor.

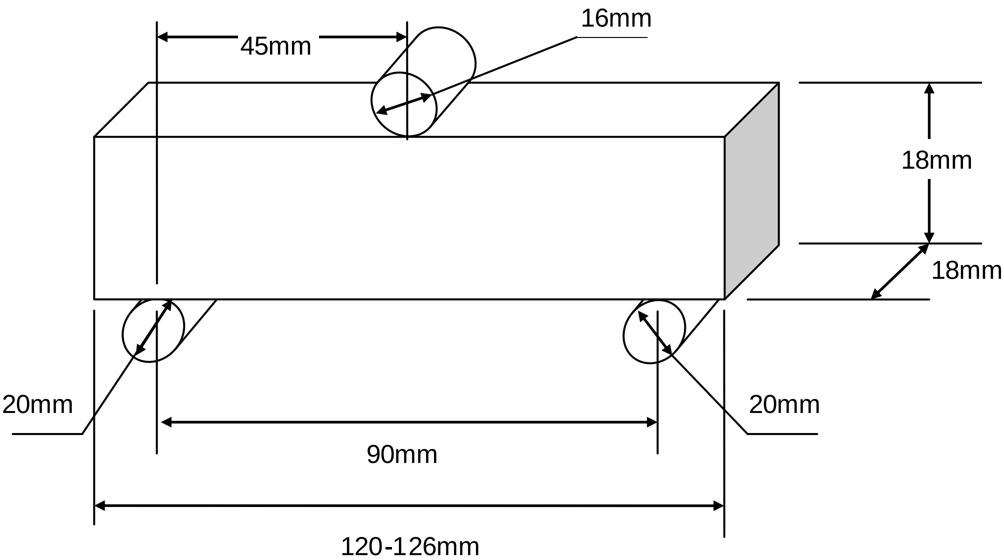


Figure 4: Geometry of three-point flexion test.

Figure 5 shows the comparison between the mechanical behavior of non-stitched and stitched composite (shear stress versus displacement). In both cases the failure is sharp and is located on the median fiber of the specimen. Compared with the non-stitched composite, the tufting yarn plays a positive effect on the flexural properties. A steady improvement of 13% (in the row direction) and around 17% (in the column direction) in the flexural strength can be found.

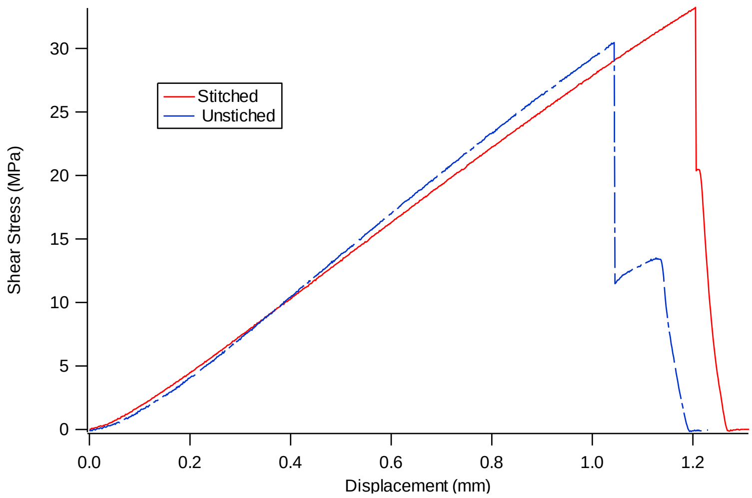


Figure 5: Comparison of typical "Shear Stress/displacement" curves of the non-stitched and stitched composite.

The acoustic activity recorded indicates that initiation of damage is earlier in the case of stitched composites. Indeed, as shown in Figure 6 (evolution of accumulated energy versus the load), the presence of seams produces a stress concentration which initiates the first damage. The in-plane fiber broken, the rich resin zone, etc.(as shown in **Erreur ! Source du renvoi introuvable.**), all these changes in the microstructure caused stress concentration of the stitched composite, that why lower force could arose macrocracking in the stitched composite. A large amount of energy is needed to overcome the frictional resistance of the stitch during the test. That is why the energy of stitched composite is much more than that of non-stitched composite.[4]

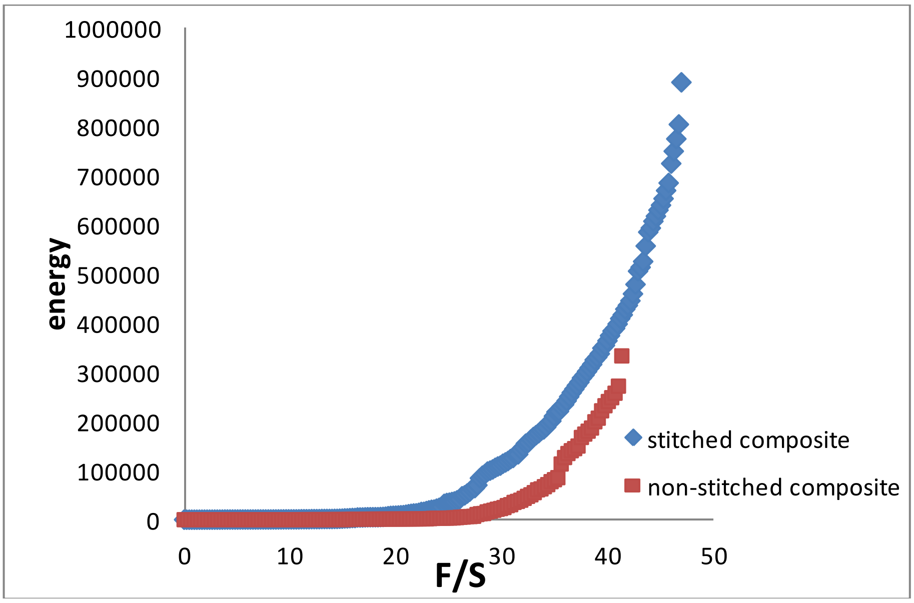


Figure 6 : Acoustic emission energy versus load for unstitched and stitched composites

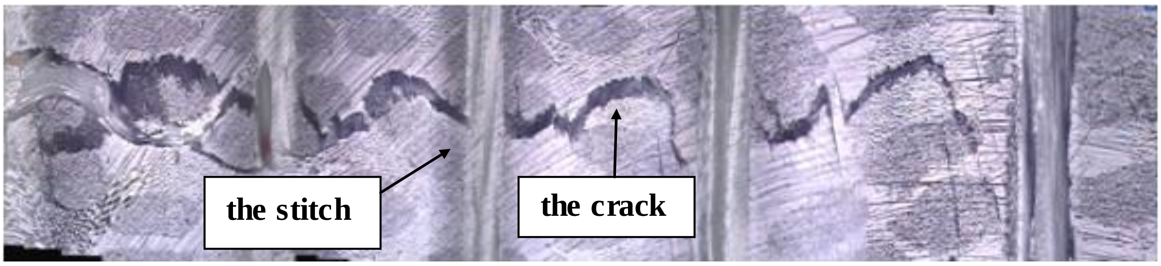
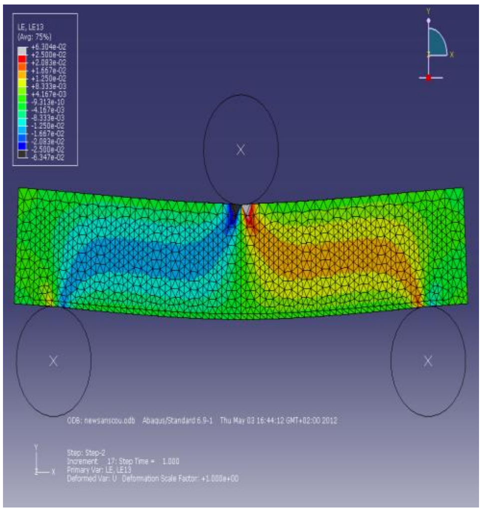


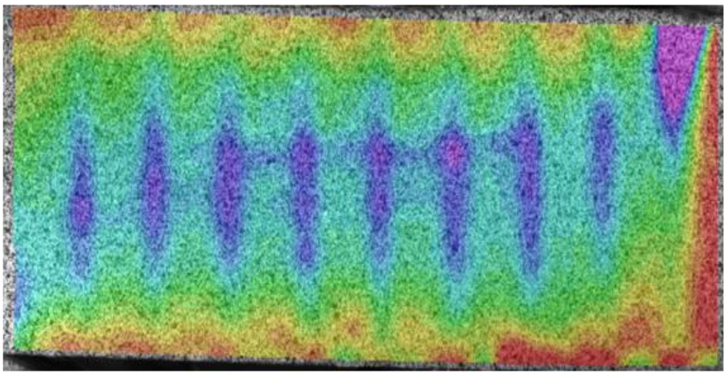
Figure 7 Crack propagation in the stitched composite in three-point flexion test

In situ observations by video microscopy show the process of ruin in the case of materials sewn. Thus the initial damages are introduced between the seams. We can observe the wavy delamination (figure 7). The propagation of this delamination is stopped by the presence of stitches. With the increase of the load, and thus the mechanical energy, a stress concentration is located within seams to reach their threshold. Failure occurs suddenly, breaking all the out-of plane reinforcement.

These observations are corroborated by the measurement of strain fields. Figure 8b shows the shear strain on one half of the specimen. It is found that the seams are changing the traditional distribution of strain fields, such as we would have obtained in the case of 2D reinforced composites (figure 8a :Finite element analysis on 2D composite).



(a)



(b)

Figure 8 : a)Finite elements Shear strain field on unstitched composite b) experimental shear strain field on stitched composite

The presence of seams produces a local discontinuity of the strain fields due to difference of rigidity between the seam and 2D composite. A local measure of deformations, along the median plane of the specimen is shown in Figure 9. Thus, the relative difference between the area reinforced by sewing and unreinforced exceeds 35%. This clearly disturbs the local stress state and therefore the scenarios of ruin.

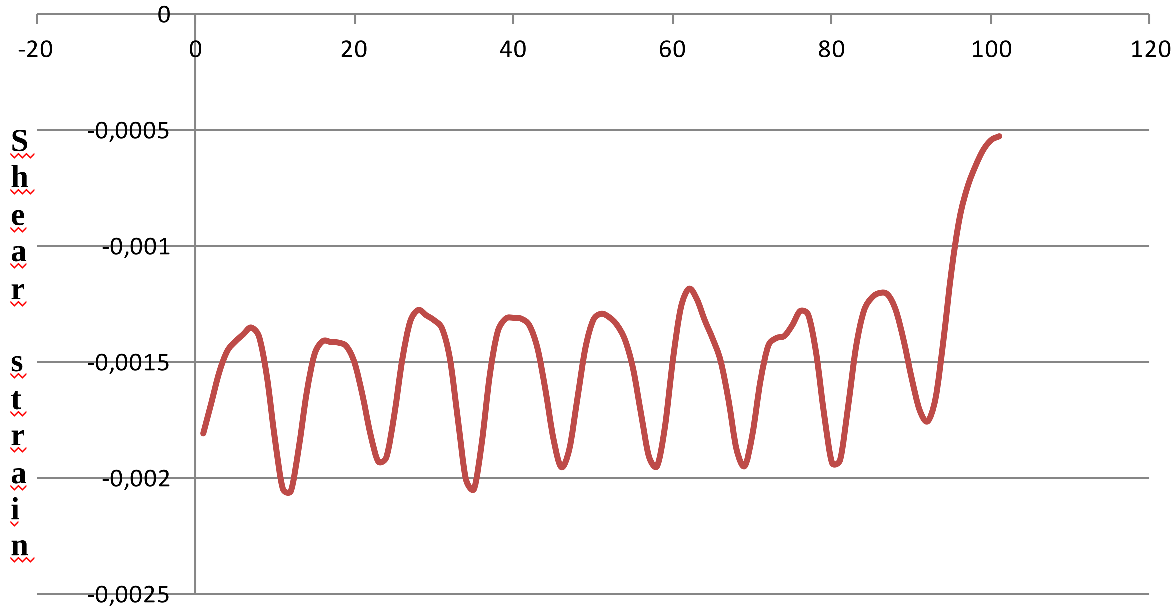


Figure 9 : Shear strain measurement along median plane of the sample

Microscopic observations before the destruction of the specimen and postmortem were performed by SEM. We can see from the picture in Figure 10, how the main crack is stopped by the presence of the seam. A secondary crack, growing perpendicular to the main fissure, arises along the seam. We note at the same time twisting of sewing that weakens local reinforcement.

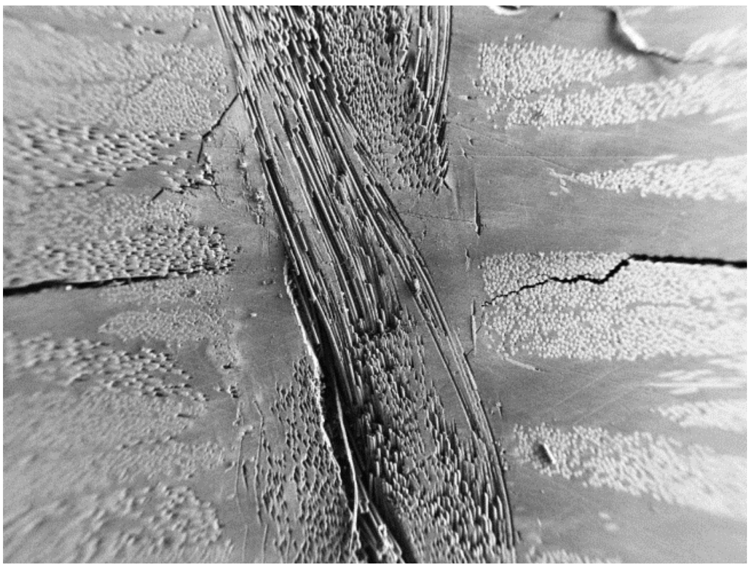


Figure 10: SEM observation of crack propagation around a stitch.

4. Conclusion

The results match those of the literature indicating a moderate fall in terms of in plane properties and a large increase in performance out of plane. This study has also demonstrated the effect of the introduction of seams in the case of a shear test. It shows that the presence of seams completely alters the local field deformations and therefore the failure mechanisms of the material. The data from this work will, in future, to feed and validate numerical approaches whose goal is to predict the mechanical behavior of this new generation of composite materials.

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