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# Structural properties of stitched T-stiffeners: web tear-off and column buckling

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**Key words:** one-sided-stitching, T-stiffener, web tear-off, compression test, textile preform

**Summary:**
*The process quality and the structural behaviour of carbon-epoxy T-stiffeners, produced from stitched textile preforms, were studied. Constituent content tests showed that stitching increases the local void content. Five different stitching patterns, using the one-sided-stitching (OSS®) technique, were compared using symmetrical and asymmetrical tear-off tests. Using an unstitched reference specimen, symmetrical test results showed a decrease in both failure initiation load and failure load for all patterns. For asymmetrical tests, when the stitching was not located near the noodle, specimens showed an increase in failure initiation load (10%) and failure load (7%-9%). Column compression tests were carried out for a favorable stitching configuration and a reference unstitched column. The damage tolerance of an unstitched column and of a stitched column was also evaluated using the column compression tests. Stitching showed limited influence on the global buckling behaviour.*

## 1 INTRODUCTION

Composite materials are progressively more common in primary aircraft structures applications such as wings, fuselages and pressure bulkheads. However, the prohibitive cost, due in part to the labour intensive operations required, limits the use of these advanced materials. Therefore, a more general usage of composite materials can only be achieved by a reduction in processing costs. This can be addressed by automated fiber placement (AFP) techniques and different dry fiber preform techniques. Stitching has shown to be an effective method to mechanically assemble dry fiber preforms and has been studied extensively [1]. Stitching can also potentially eliminate subsequent expensive assembly and fastening steps when complex parts are produced from single-piece preforms [2]. However, stitches have shown to reduce in-plane properties by creating distortions in the textile. These are produced by the stitching needle and by the line tension in the yarn [3,4]. These local disturbances can create local resin rich pockets and can be failure initiation points [4]. In-plane properties can also be reduced by local porosity around the stitches [3]. For large parts, when access to both sides of the preform can be challenging, conventional stitching is not practical. The one-side-stitching (OSS®) technique has been developed to assemble preforms where access is limited.

This study focuses on the effect of stitching location and orientation on the performance of “T” shaped stiffener. The process quality was evaluated with constituent content tests. The structural behaviour was studied by subjecting the stiffeners to web tear-off and column compression tests. A favorable stitching pattern was then determined to guide the design of a large stiffened demonstrator panel (610 mm x 1220 mm) to be built in a later phase of the project.

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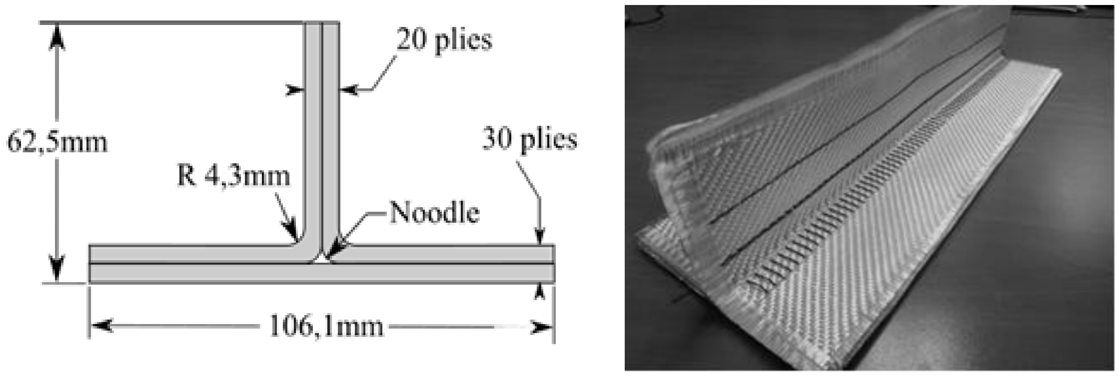
## 2 METHODOLOGY

### 2.1 T-stiffener geometry

The T-stiffener (see Figure 1a) is composed of a flat skin and a perpendicular web, both made of a 20-ply quasi-isotropic laminate with the following ply sequence $[(\pm45°, 0°/90°)_5]_S$. The web is folded onto the skin to create a flange and ensure the structural integrity of the joint. A filler material (noodle) is added in the fold of the web, at the skin interface, to promote proper compaction in the filet region and to create a smooth transition between the web and the flange.




a) b)

*Figure 1: T-stiffener geometry: a) Cross-section b) Stitched glass preform example*

### 2.2 Materials

The T-stiffener elements are made of a carbon-epoxy composite. The plies are a 3k carbon 2-2 twill weave (TC-06-T) supplied by Texonic and the matrix is a one-part liquid resin system. The preforms are assembled using 67 x 2 Tex (linear mass of 0,14g/m) TENAX® carbon fibre yarns produced by Tenax. The noodle is made with a bundle of 22 12K un-twisted carbon unidirectional yarns, also supplied by Texonic, in order to achieve a fiber volume content (*Vf*) of 65%.

### 2.3 Preform manufacturing

Preforms were fabricated using an OSS® head mounted on a multiaxis robot at CTT group (Centre d’excellence des technologies textiles, géosynthétiques et matériaux souples, St-Hyacinthe, Qc, Canada). T-stiffeners were stitched lengthwise in the web and in the skin on both sides of the web (see Figure 1b). In this study, the stitch (see Figure 2) is composed of three sections named the ladder, the loop and the simple yarn. The ladder is the thread perpendicular to the stitching direction and is located beneath the preform while being assembled. The loop is located on the top of the preform and it binds each stitch. The simple yarn is located on the top of the preform, opposite of the loop.

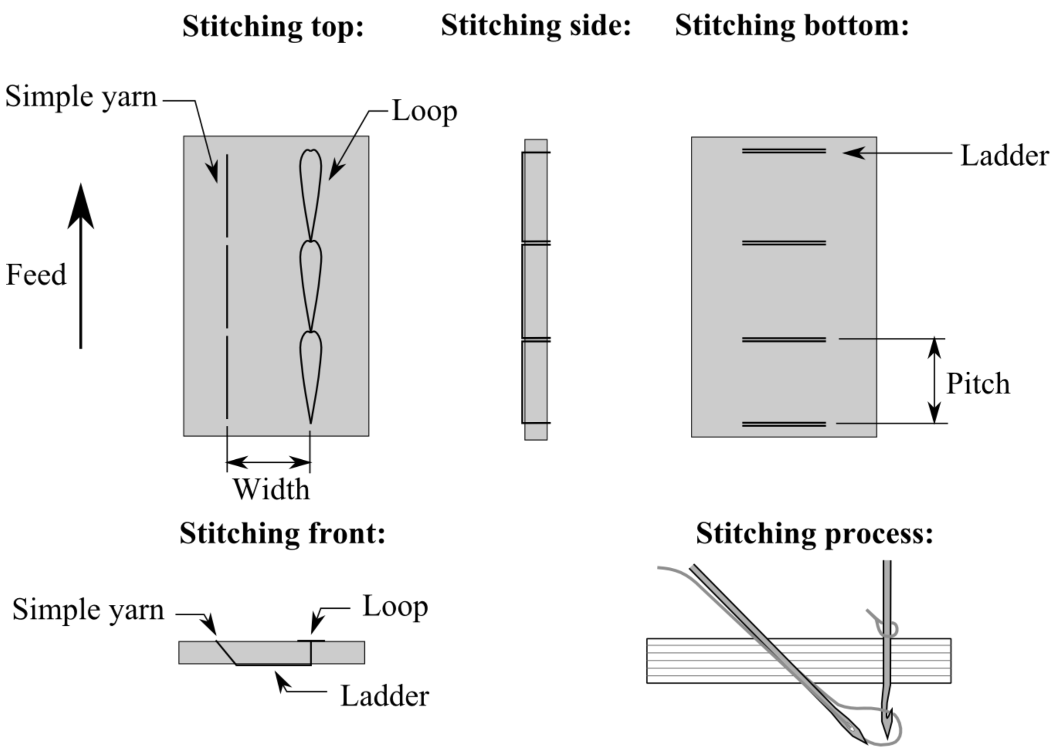



*Figure 2: Illustration and nomenclature used for One-Sided-Stitching®*

2.4 Stitching parameters

The flexibility of the stitching setup allows versatility in the assembly strategy of the parts. A test plan was therefore elaborated to study the influence of the distance and the orientation of the stitch in a T-stiffener. Table 1 and Figure 3 show the different stitching parameters studied. The stitch distance (d) is measured from the center of the loop to the center of the noodle while the orientation refers to the position of the loop relative to the noodle. The orientation is considered adjacent when the loop is near the noodle and is considered opposite when it is away from the noodle. All other stitching parameters were kept constant throughout the test program including the stitching pitch (4 mm), the width of the stitch (25 mm) and the tension on the yarn. The effect of different stitching pitches was previously studied on flat panels [5]. Five stitching patterns were chosen for tear-off tests with the objective of strengthening the T-joint by adding carbon thread through the noodle or near its periphery.

| | Web | | Skin | |
|---|---|---|---|---|
| Specimen | Stitch Distance (d) | Stitch Orientation | Stitch Distance (d) | Stitch Orientation |
| 00.0 | -- | -- | -- | -- |
| ST.1 | 5 mm | Adjacent | 20 mm | Adjacent |
| ST.2 | 20 mm | Adjacent | 20 mm | Adjacent |
| ST.3 | 32 mm | Opposite | 20 mm | Adjacent |
| ST.4 | 42 mm | Opposite | 27 mm | Opposite |
| ST.5 | 42 mm | Opposite | 34 mm | Opposite |

*Table 1: Description of stitching patterns*

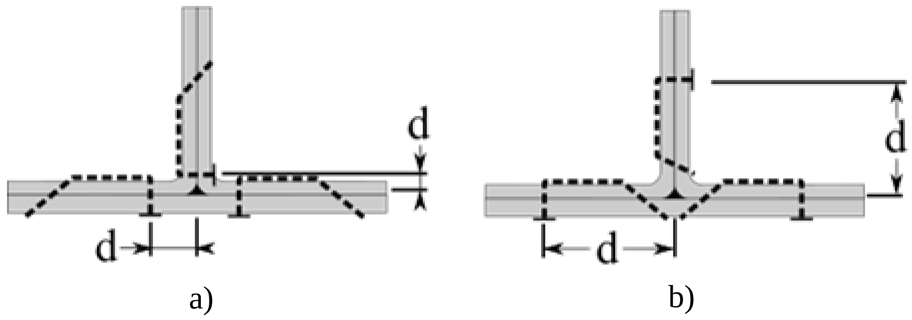



*Figure 3 Stitching orientation: a) Adjacent stitching b) Opposite stitching*

2.5 Composite manufacturing process

A high-temperature liquid moulding technique (VARTM) was used to produce the composite parts. The epoxy was heated to 80°C with an electric heating collar while the tooling was pre-heated to 90°C. The resin was infused at full vacuum and the pressure was maintained until the part was completely wetted out. Once the inlet was clamped, a partial vacuum was maintained (-22 inHg) for curing. Tear-off specimens were manufactured at Hutchinson Aerospace on a heating plate and were cured at 180°C for 2 hours. Compression test specimens were manufactured at École de technologie supérieure in a convection oven at 150°C for 4 hours. Rigid tooling (see Figure 4) was used to support and compress the web, ensuring the proper compaction of the laminate and to reduce any thickness variability around the stitch.

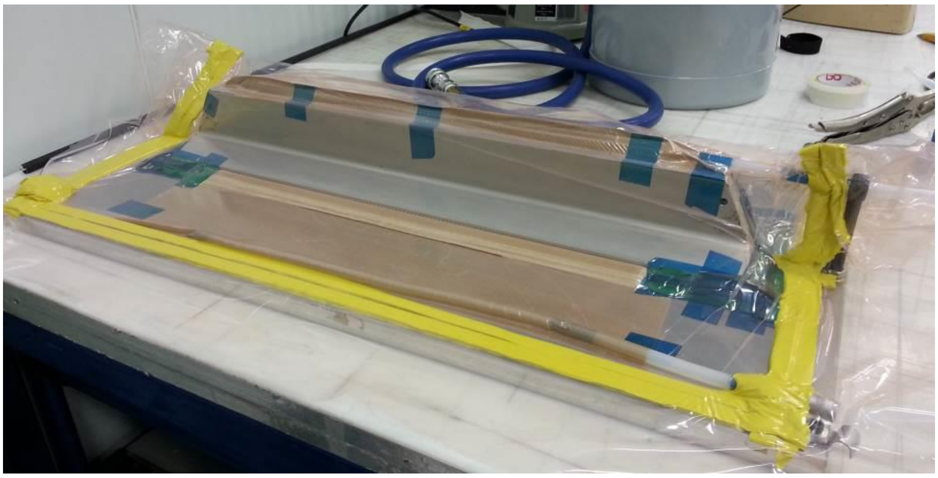


*Figure 4: VARTM setup with rigid tooling*

2.6 Mechanical tests

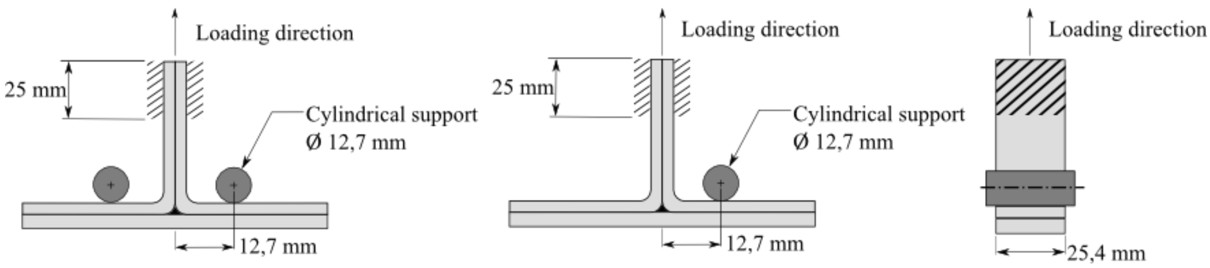
The performance of the stitched T-stiffeners was evaluated with two types of mechanical test, web tear-off and column compression. These specific tests were chosen with the help of industrial partners and with regards to the building block approach which is generally favored in the aerospace industry [6]. These tests are commonly used for the design of element such as stiffeners and beams. In order to limit the size of the test program, the results from the tear-off test series were used as a basis for choosing the optimal stitching configuration for the compression tests.

2.6.1 Laminate quality assessment

The influence of stitching on the quality of the parts was assessed with a constituent content test following test standard ASTM D3171-11 (Standard Test Methods for Constituent Content of Composite Materials). The fiber volume fraction (*Vf*) and the void volume fraction (*Vv*) was found by acid digestion following procedure C. Samples were taken from the web and the skin of an unstitched reference specimen and also of a stitched specimen. For the stitched specimens, samples were taken from both the ladder and the loop area. An unstitched noodle section was also tested to assess the *Vf* and the *Vv* in the noodle area. Three samples were tested for each configuration and location with the exception of the noodle section for which four samples were tested.

2.6.2 Web tear-off

To assess the strength of the T-joint and to evaluate the effects caused by the addition of stitching, the web of the specimens was pulled until failure while the skin was supported by rollers. A custom testing rig was used to simulate two loading conditions: symmetric and asymmetric. The symmetric test (see Figure 5a) is representative of a situation where the load is perpendicular to the skin. The asymmetric test (see Figure 5b) configuration is representative of a situation where out-of-plane loads are generated such as those created in a buckled stiffened panel. ASTM standard C297M-04 (Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions) was used as a starting point to guide these tests but was adapted. The nominal width of the specimens (see Figure 5c) was 25,4 mm and each test series included 6 specimens. The crosshead displacement rate was chosen to produce failure in 3 minutes to 6 minutes. A displacement rate of 0,5mm/min was chosen for the symmetric tests while a rate of 1,5mm/min was chosen for the asymmetric tests. A faster displacement rate was chosen for asymmetric tests to compensate for the larger deformation of the specimens.




a) b) c)

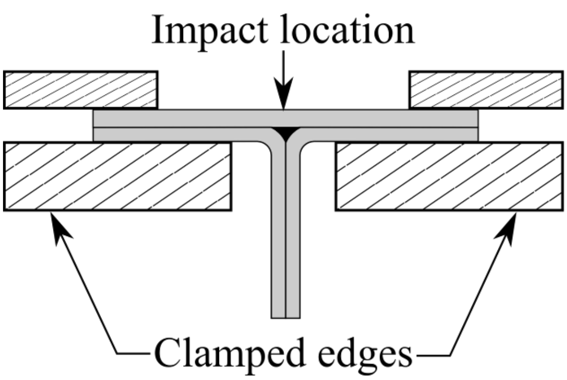
*Figure 5 Tear off test: a) Symmetric test b) Asymmetric test c) Side view*

2.6.3 Column compression

T-shaped columns were axially loaded in compression to investigate their strength and their buckling behaviour (see Figure 6a). The column had a free length of 350mm and both extremities of the column were encapsulated with epoxy in an aluminium support to create built-in boundary conditions, preventing the rotation, and insuring a uniform load transfer aligned with the column's centroid. To determine the buckling onset load, the columns were equipped with a set of back-to-back strain gauges. An image correlation system (ARAMIS®) was also used to get the full field displacement of the bottom of the skin and to study the post-buckling behaviour of the columns. A crosshead displacement rate of 0,5mm/min was chosen to keep the test duration under 5 minutes.

Damage tolerance is a critical parameter for structural design of aircraft components. Therefore, a stitched column and an unstitched column were impacted in accordance with ASTM standard D7136M12 (Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Even). Using a custom setup, both columns were impacted using a 20mm impactor with an energy of 50J (see Figure 6b). An Instron CEAST 9350 drop tower impact system was used. The T-stiffeners were impacted on the skin directly under the web. In total, four columns were tested to failure: a pristine unstitched column, a pristine stitched column, a damaged unstitched column and a damaged stitched column.

a)




b)

*Figure 6 Test setups: a) Compression setup b) Impact rig setup*

## 3 FINITE ELEMENT MODEL

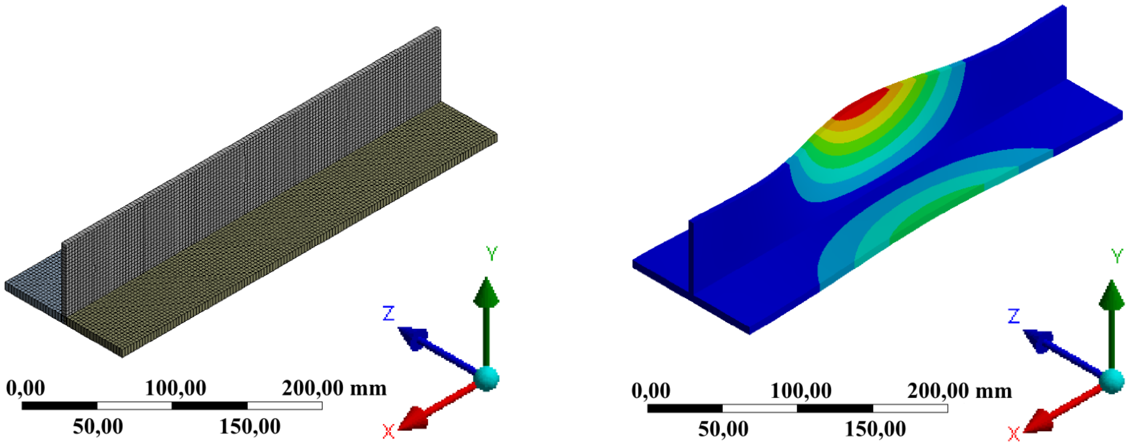
A finite element analysis, using the Ansys Workbench® linear buckling module, was conducted for the unstitched specimen to predict the behaviour of the column under load and to properly setup the test equipment. The geometry was created using DesignModeler® and was simplified by eliminating the filets located at the junction of the web and the skin. The noodle was also not included in the model. These conservative simplifications underestimate the actual buckling load.

Lamina properties were derived, using the classical laminate theory [7], from flat panel coupon tests, found in an early study [5]. The longitudinal and transverse stiffness modules are considered identical. Properties are presented in Table 2.

| Longitudinal stiffness | Transverse stiffness | Shear stiffness | Major Poisson's ratio |
|---|---|---|---|
| 54127 MPa | 54127 MPa | 3995 MPa | 0,033 |

*Table 2: Lamina properties*

The column was modelled (See Figure 7) using shell element 181 (four-node element with 6 degrees of freedom at each node) with a total of 8448 elements and 15645 nodes. At one of the extremities of the column, all degrees of freedom were restrained. At the other end of the column, all degrees, with the exception of axial motion, were restrained. Neither the potting material nor the aluminium supports were modelled. A uniform displacement of 1 mm was imposed for the loaded edges. The buckling load was found by applying a load multiplying factor to the reaction force of the imposed displacement of 1 mm.




a) b)

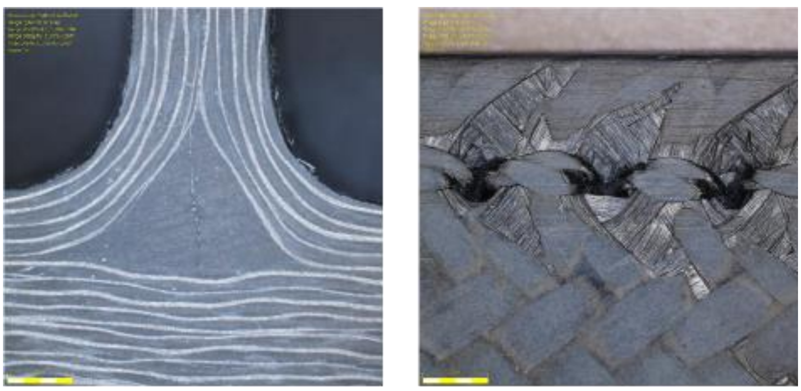
*Figure 7 Finite element model of column: a) Meshing b) predicted buckling mode*

## 4 RESULTS AND DISCUSSION

### 4.1 Quality assessment

Constituent tests presented in Table 3 reveal a similar fiber volume content in the skin than in the web for both the reference and the stitched specimens. The *Vf* achieved for the parts (62% to 64%) is typical for the VARTM manufacturing process. The void volume content is slighty higher for stitched specimen than for reference specimens. The stitches create local porosity in the distorted areas of the fabric. The fiber volume content in the noodle area is close to the desired content of 65%. This demonstrates that the filler material in the noodle is successfully compacting the nearby laminates (see Figure 8a).

Visual inspection of the parts after the cure revealed the presence of resin poor zones around some of the stitches when they were located near the transition from the rigid tooling to the vacuum bagging (see Figure 8b). Stitching is known to affect locally the permeability of the laminate [8]. The variability in the compaction of the laminate and the reduced local permeability caused by the stitching could be preventing a proper wet-out in that region.



a) b)

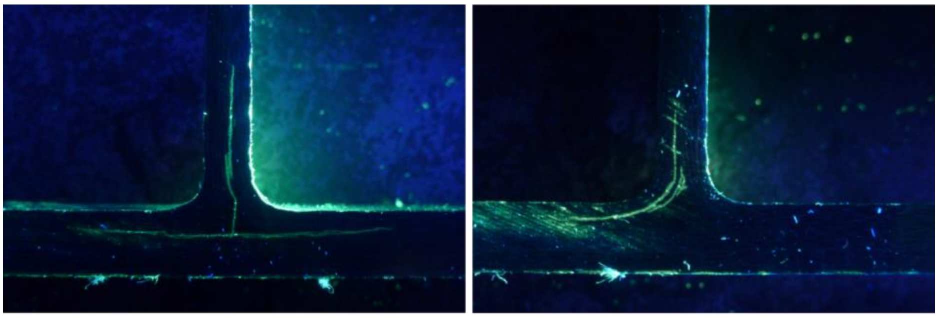
*Figure 8 Optical inspection: a) Noodle area b) Resin poor zones near stitching*

| ID | | *Vf* (%) | St. Dev. | *Vv* (%) | St. Dev. |
|---|---|---|---|---|---|
| Reference | Web | 62,1 | 1,88 | 0,92 | 0,12 |
| | Skin | 63,5 | 1,35 | 1,17 | 0,15 |
| Stitched | Web | 62,2 | 2,69 | 1,80 | 0,44 |
| | Skin | 64,0 | 0,62 | 1,46 | 0,26 |
| Noodle | -- | 64,6 | 0,36 | 1,24 | 0,32 |

*Table 3: Constituent contents*

4.2 Web tear off tests

Results presented in Table 4 are normalized for a specimen width of 25,4 mm to compensate for specimen preparation variability and the loads are normalized to the reference unstitched specimen average strength for comparison. For both tear-off loading modes, the failure initiation point was in the noodle periphery, specifically at its interface with the web or skin laminate (see Figure 9). This observation is coherent with similar studies [9,10].



a) b)

*Figure 9 General crack propagation path: a) Symmetric loading b) Asymmetric loading*

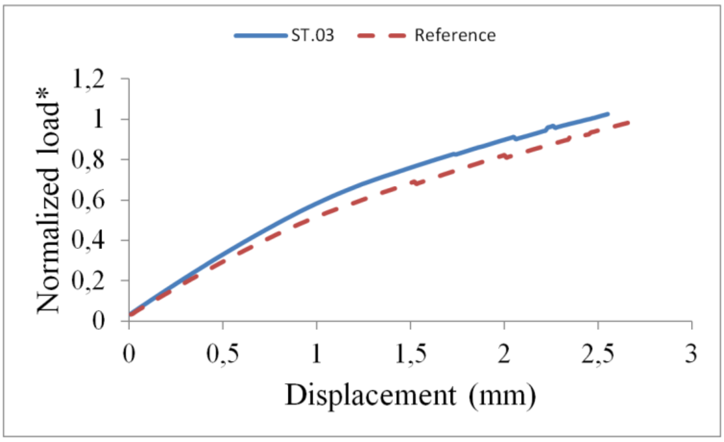
| ID | Symmetric | | | | Asymmetric | | | |
|---|---|---|---|---|---|---|---|---|
| | Failure initiation | | Final failure | | Failure initiation | | Final failure | |
| | Load* | CV [%] | Load* | CV [%] | Load* | CV [%] | Load* | CV [%] |
| Ref. | 1,000 | 14,0 | 1,000 | 14,0 | 1,000 | 19,6 | 1,063 | 9,0 |
| ST.01 | 0,449 | 21,7 | 0,537 | 2,3 | 0,862 | 9,6 | 0,981 | 10,6 |
| ST.02 | 0,858 | 10,6 | 0,858 | 10,6 | 0,790 | 21,2 | 1,153 | 7,5 |
| ST.03 | 0,579 | 58,4 | 0,943 | 10,0 | 1,108 | 6,6 | 1,138 | 6,6 |
| ST.04 | 0,405 | 18,6 | 0,475 | 7,5 | 0,432 | 35,4 | 0,670 | 8,8 |
| ST.05 | 0,777 | 17,1 | 0,777 | 17,1 | 0,489 | 47,6 | 0,855 | 15,8 |

* Results normalized to the reference unstitched specimen

*Table 4: Symmetric and asymmetric tear-off results*

For symmetric tear-off tests, all stitching patterns showed a decrease in both failure initiation load and final failure load. The perturbations, caused by the stitching, can create defects in or near the filet of the T-stiffener which create stress concentration points. For this reason, the expected increase tear-off performance due to the transverse reinforcement provide by the stitch seems to be alienated by the damage done to the fabrics. This hypothesis is coherent if we consider that configurations ST.01 and ST.04, which are stitched the closest to the noodle, show the greatest decrease in strength.

Asymmetric tear-off tests also show a decrease in both failure initiation and final failure loads when the stitching pattern is located near the noodle. However, configuration ST.03 showed an increase in both failure initiation and final failure loads, while configuration ST.02 showed a slight increase in final failure load. The increase in asymmetric tear-off resistance for some samples is believed to be caused by an increase in the flexural stiffness of the stitched laminates. This can be observed with the load-displacement curves of the asymmetric tear-off tests illustrated in Figure 10. This is also backed up by experimental results on flat coupons that showed a slight increase in the flexural modulus for stitched specimens [11]. With the web and the skin being stiffer, the load is redistributed away from the fragile noodle region. Overall, the stitching configurations tested in this study failed to strengthen the noodle area and only produced stronger parts when the stitching was located away from the noodle area.



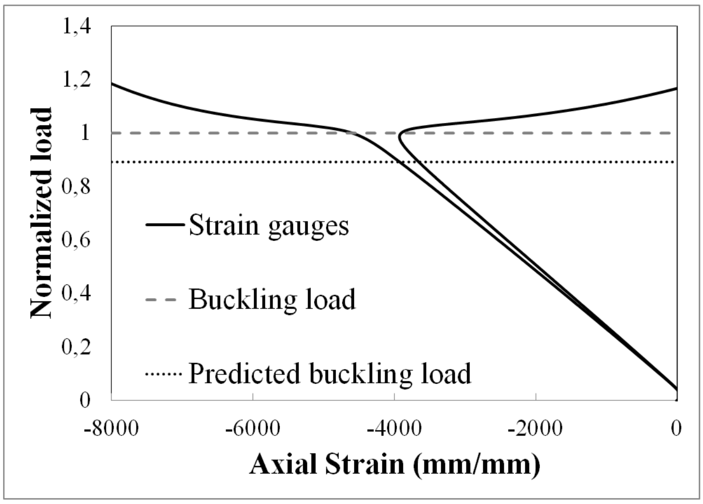

*Load normalized to average failure load of the reference specimen

*Figure 10: Average load-displacement curves for asymmetric tear-off test*

## 4.3 Column compression

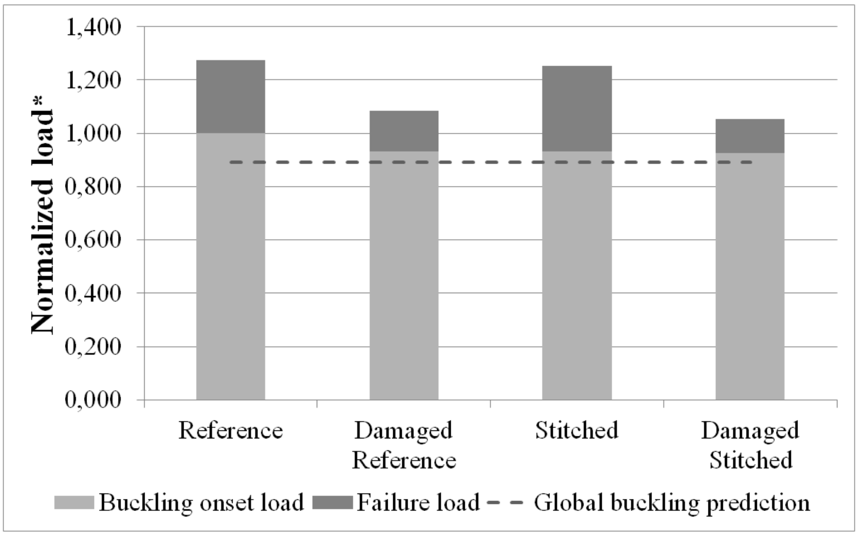
Based on the observations made during the quality assessment tests and the tear-off tests, a new pattern was developed for the rest of the study and the demonstrator panel. The pattern has an adjacent stitch in the web located at 20 mm from the noodle and an opposite stitch in the skin located at 40 mm from the noodle. This new pattern maximizes the distance of the stitch from the noodle while choosing an orientation that facilitates the manufacturing of the preform and the part.

The failure mode for all columns was global torsional buckling which was confirmed with visual observation and with the deformation analysis from ARAMIS®. The buckling onset load was determined with the set of back-to-back strain gauges (see Figure 11). To ease comparison, the results presented in Figure 12 are normalized to the undamaged reference specimen's buckling load. The finite element model properly predicted failure mode of the undamaged unstitched column but underestimated the global buckling load by 10,8%. This could be explained by the simplified model (removal of filets and noodle) which adds considerable rigidity to the structure. The use of a non-linear solver could also help reduce the gap between the model and experimental data. The undamaged stitched column buckled at a slightly lower load (-6,8%) when compared to the reference column. However, both failed at approximately the same load.




* Results normalized to the buckling load of the reference unstitched specimen

*Figure 11: Measured force and strain for reference column*



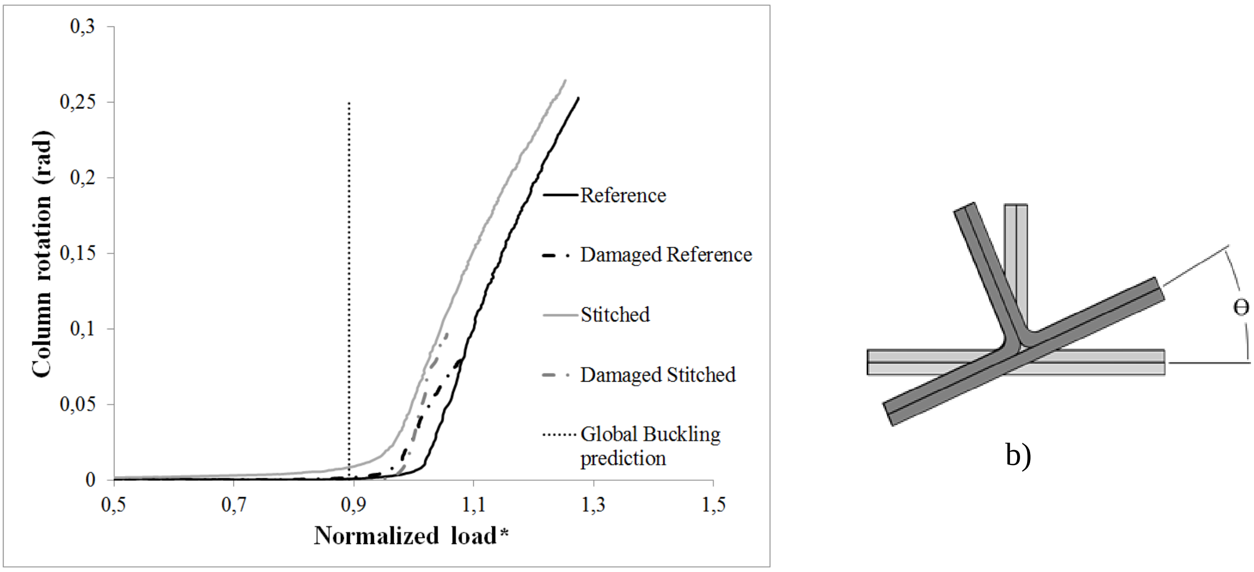

* Results normalized to the buckling load of the reference unstitched specimen

*Figure 12: Column compression results*

For the damaged specimens, both the reference and the stitched columns showed a similar degradation for buckling load when compared with the undamaged reference column (-6,8% and -7,4% respectively). While both damaged columns failed considerably earlier than the undamaged columns, the stitched column failed at a lower load. Stitching failed to improve the damage tolerance of the t-stiffeners for the tested stitching patterns used in this study.

The post-buckling behaviour of all columns was studied with the ARAMIS® system. Torsional buckling is characterized with the rotation of the cross-section while the skin stays perpendicular to the web, see Figure 13b.  Figure 13a plots the rotation of the skin against the normalized load for all columns. The post-buckling response for both undamaged columns is similar. A significant rotation before buckling can be observed for the stitched column. It is possible that the early buckling onset was created by a misalignment of the T-stiffener. If this is the case, stitching does seem to not influence either the buckling load or the post-buckling behaviour of the T-stiffener.

For damaged columns, the stitched column shows a similar response when compared to the undamaged columns while the unstitched damaged column shows a significant degradation in post-buckling response. It is possible that the stitching limits damage propagation and helps maintain better the structural integrity of the structure.




* Results normalized to the buckling load of the reference unstitched specimen

a) b)

*Figure 13 Post-buckling analysis: a) Column rotation plotted against normalized load b) Example of column rotation*

## 5 CONCLUSIONS

Stitching was studied as a method to effectively assemble textile preforms and possibly strengthen components. Multiple stitching patterns were tested to observe the influence of stitch position and orientation on the tear-off strength of a T-Stiffener. A favorable stitching pattern was chosen with regards to the tear-off tests results and was used for the manufacturing of column buckling test specimens.

T-stiffener tear-off results show that the studied stitching patterns failed to reinforce the T-stiffener when it is located in or near the noodle. However, under certain loading conditions, stitching strengthen the joint by limiting the load applied to the noodle area by stiffening the adjoining laminates. For compression tests, stitching showed little influence, for both pristine and damaged columns when compared with their unstitched counterpart.

Although mechanical performance was not directly positively affected by the stitches, the use of dry fiber preforms, using OSS®, considerably simplified the dry fiber handling steps and significantly reduced the time spent producing the parts. This has proved that OSS® is an effective preform assembling technique but processing methods must be better understood in order to control the quality of the final product.

## 5 ACKNOWLEDGEMENTS

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