EFFECT OF PROCESS PARAMETERS ON DAMAGE TOLERANCE OF CARBON EPOXY LAMINATE PREFORMED USING ONE-SIDED STITCHING

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Abstract

The damage tolerance of 4.5 mm thick vacuum-infused quasi-isotropic carbon-epoxy laminates made from one-sided stitched (OSS®) preforms using different process parameters were benchmarked using open-hole compression (OHC) and compression after impact (CAI) standard tests. The three process parameters considered in the study are the stitching pitch, the molding strategy and the stitching orientation (relative to the loading direction). A conventional (non-stitched) laminate was manufactured and used as a reference for comparison purposes. Mechanical testing showed that stitching the preform preserved, and slightly enhanced in certain cases, OHC and CAI strength for specific combinations of process parameters. However, the use of OSS® caused a resin rich local laminate thickening (up to 0.5 mm) in the vicinity of the stitches that resulted in an increase of the laminate surface weight (between 3 % to 9 %).

1. Introduction

Developments in computer-assisted textile manufacturing techniques now enable the production of complex preforms for out-of-autoclave composite fabrication processes like vacuum assisted resin transfer molding (VARTM). Among the variety of preforming techniques, the method of assembling multiple layers of fabric using stitching has been widely studied and has shown a significant potential to simplify dry reinforcement handling and improve interlaminar performance of the laminate [1, 2]. When a co-cure of multiple elements is possible, stitching may also reinforce joints and reduce subsequent bonding operations [3]. However, stitching may alter intralaminar properties depending on laminate properties, stitching process and stitching parameters. Therefore, several studies focused on measuring and explaining effects of stitching parameters like density, pattern and orientation, tension in the yarn and yarn characteristics (i.e. material, stiffness, interface, diameter, number of threads and twist) [4, 5].

Unlike conventional stitching techniques that require access to both sides of the preform, OSS® allows stitching from a single side. Robotic assisted OSS® heads consist of a highly flexible cost-effective method to assemble multiple elements of complex preforms [6, 7]. However, in terms of geometry, OSS® stitches (see Figure 1(a)) are hardly comparable to conventional stitches and are, therefore, unlikely to behave in the same way.

Based on the premise that process parameters affect the laminate's mechanical performances, this paper presents an experimental study of the effects of three process parameters on a carbon-epoxy laminate preformed using OSS® subjected to open-hole compression (OHC) and compression after impact (CAI) standard tests. Physical effects of OSS® on the laminate were evaluated through thickness measurements and laminate surface weight and constituent content measurements. The present study is part of the project *3D Textile Carbon Fiber Preforms* involving, among others, Bombardier Aerospace (BA) and Bell Helicopter Textron Canada (BHTC) and is funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ). The results presented in this paper are meant to guide the selection of optimal process parameters for the forthcoming preforming of a demonstrator panel containing a skin-stringer configuration as it is commonly found in the aerospace industry.

2. Methodology

2.1. Materials

All preforms were made using 3K carbon fiber 2/2 twill weave (TC-06-T) supplied by project partner JB Martin (Saint-Jean-sur-Richelieu, Quebec, Canada). For stitched preforms, stitching was made using 67 x 2 Tex (linear mass of 0.14 g/m) TENAX® carbon fiber yarn produced through a partnership between Schappe Techniques (Blyes, France) and Toho Tenax (Tokyo, Japan). Adapted for stitching with dry and impregnated reinforcements, the yarn was selected for its compatibility with most matrices and its good flexibility and resistance to friction. The composite was consolidated with the mono-component liquid resin system CYCOM® 890 RTM made by Cytec Engineered Materials (Wrexham, United Kingdom).

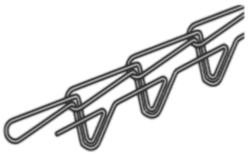
2.2. Preform manufacturing

Plies of 450 mm (width) by 500 mm (length) were cut and stacked up with the sequence $[(\pm 45°)/(0°, 90°)]_{5\,sym}$ to obtain a 4.5 mm thick quasi-isotropic laminate. For stitched preforms, the assembly was executed by the CTT Group (Saint-Hyacinthe, Qc, Canada) using a two-needle stitching head (see Figure 1(b)).

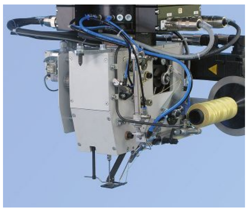
2.3. Studied process parameters

For each of the three studied process parameters — the *stitching pitch*, the *molding strategy* and the *stitching orientation* — two variants were tested. A *stitching pitch* of 8 mm and 4 mm (see Figure 2) were considered in the study, namely, the longest and the shortest *pitch* achievable with the selected stitching head. Considering the asymmetry of the preforms (see Figure 2), the preform was either non-flipped (i.e. bottom of the preform against the rigid mold) or flipped (i.e. top of the preform against the rigid mold) in the VARTM process. *Stitching orientation* was either longitudinal or transversal relative to the resin flow during infusion and the loading direction during mechanical testing.

The *width* of the stitches (see Figure 2) was fixed at a value of 25 mm due to technical limitations of the stitching head. *Spacing* between stitching lines (see Figure 2) was set at 42 mm to obtain a *stitching density* in the range of 1 to 25 Z-yarns/cm^2 as recommended by Tong *et al.* [8]. Due to the absence of a tension-measuring device on the current stitching machine, the *yarn tension* was initially adjusted to minimize fiber misalignment and then kept fixed for all preforms. Tested combinations of process parameters are summarized in Table 1.



(a) OSS® geometry



(b) Two-needle OSS® stitching head

Figure 1. One-sided stitching

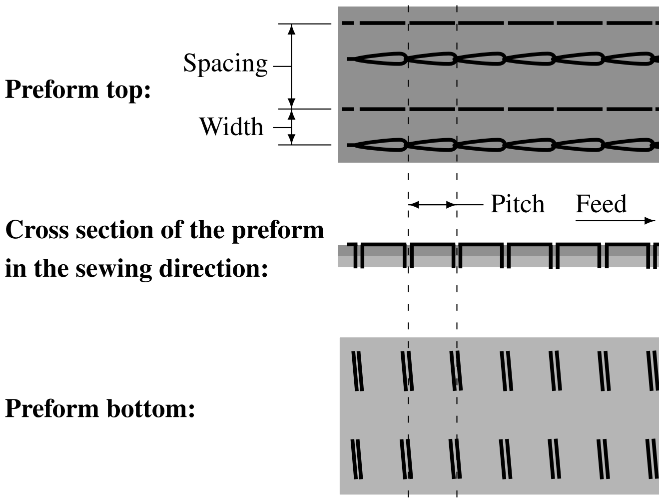


Figure 2. Definition of stitching parameters

ID	Studied parameters			Constant parameters		Stitching
	Stitching pitch [mm]	**Molding strategy**	**Stitching orientation**[1]	**Spacing** [mm]	**Width** [mm]	**density**[2] [Z-yarn/cm^2]
REF.	-	-	-	-	-	0
8-NF-L	8	Non-flipped	Longitudinal	42	25	11.5
8-NF-T	8	Non-flipped	Transversal	42	25	11.5
8-FL-L	8	Flipped	Longitudinal	42	25	11.5
8-FL-T	8	Flipped	Transversal	42	25	11.5
4-NF-L	4	Non-flipped	Longitudinal	42	25	23.0
4-NF-T	4	Non-flipped	Transversal	42	25	23.0
4-FL-L	4	Flipped	Longitudinal	42	25	23.0
4-FL-T	4	Flipped	Transversal	42	25	23.0

[1] Relative to the loading direction.
[2] *Stitching density* is a parameter based on the *stitching pitch*, the *spacing* and the *number of Z-yarns* contained in each stitches (4 Z-yarns are contained in each OSS® stitch).

Table 1. Tested combination of process parameters

2.4. Laminate manufacturing

Preforms were infused widthwise under full vacuum on an aluminum mold using media flow, peel ply on both surfaces and flexible bagging. During infusion, the resin was maintained at 80 °C using an electrical collar regulated by an on-off controller and a thermocouple placed in the resin pot. Similarly, the tooling was maintained at 90 °C using an electrical hot plate and a thermocouple placed on the molding surface. To minimize heat loss, while allowing visual control during infusion, the tooling was placed in an insulated case with a double-glazing glass top. This set-up helped to visually verify that preform stitches did not disturb the resin flow. Immediately after infusion, the laminate was cured for 2 hours at 180 °C. A ramp of 1 °C/min was used for heating and cooling.

2.5. Laminate quality assessment

A laser scan mounted on a coordinate measuring machine (CMM) was used to measure the laminate exact thickness at each point. Global laminate surface weight (LSW) was calculated by dividing weight of the panel by its surface area (after trimming). Fiber volume fraction (V_f) and void volume fraction (Vv) were measured according to the ASTM D3171-11 acid digestion method (procedure C).

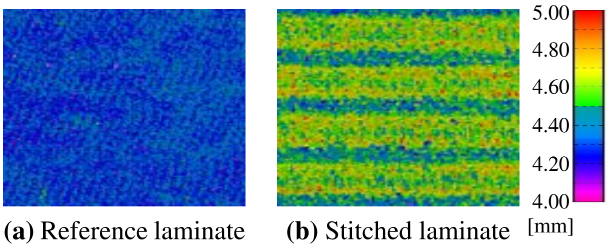
2.6. Static mechanical tests

Although several static and fatigue tests could have been chosen to evaluate the effect of OSS® on laminate damage tolerance, open-hole compression and compression after impact were selected because of their relevance for the aerospace industry. Open-hole compression was performed as per ASTM D6484/D6484M-09, procedure B. Compression after impact was done as per ASTM D7137/D7137M-12. In accordance with the standard test ASTM D7136/D7136M-12, the low velocity impact was carried out on an Instron CEAST 9350 drop tower impact system with a 16 mm hemispherical impactor. All specimens were impacted with an energy of 30 J to generate a dent of at least 2.5 mm in depth. Prior to the compression test, a post-impact ultrasonic inspection (C-Scan) was conducted on all specimens to verify the damage type and extent. One third of CAI specimens were instrumented with 4 strain gauges to validate their proper alignment in the test fixture and thus, ensure a pure compressive load.

3. Results and discussion

3.1. Effect of OSS® on laminate physical properties

The use of OSS® combined with the use of a VARTM flexible bagging resulted in a local laminate thickening (up to 0.5 mm thick) along the stitching lines (see Figure 3). A change of color in the stitches' vicinity (see Figure 4) indicates that the thickening is rich in resin.



(a) Reference laminate **(b)** Stitched laminate

Figure 3. Local laminate thickening along stitching lines as measured with the laser scan

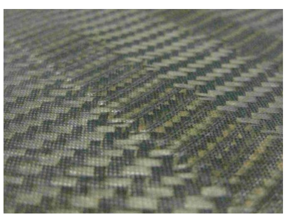


Figure 4. Resin rich thickening on the laminate's bag-side

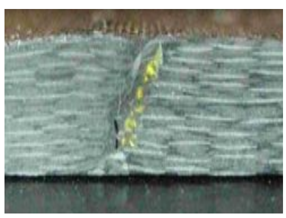


Figure 5. Porosity and resin-pocket (yellow) near Z-yarn (cross section)

As shown in Figure 5, the holes left by the stitching needles turned into resin-pockets and are conducive to the formation of large porosity. As presented in Table 2, the thickening caused an increase of the global laminate surface weight (LSW) that appears to be unaffected by the *molding strategy*, but proportionally related to the *stitching density* in the studied range. In spite of the visual observations presented in Figure 4 and Figure 5, results for constituent content measurements (see Table 2) showed that OSS® did not significantly alter void and fiber volume content.

ID	LSW		V_f		V_v	
	Avg.*	**CV** [%]	**Avg.** [%]	**SD** [%]	**Avg.** [%]	**SD** [%]
REF.	1.000	0.16	61.70	1.35	0.97	0.17
8-NF-L	1.027	0.38	61.53	1.35	1.21	0.58
8-NF-T			60.96	1.57	0.85	0.23
8-FL-L	1.029	0.04	60.61	1.43	1.08	0.14
8-FL-T			62.38	1.11	0.93	0.08
4-NF-L	1.084	0.04	60.50	1.94	1.11	0.28
4-NF-T			60.69	2.86	0.95	0.23
4-FL-L	1.084	0.13	61.99	3.21	1.25	0.26
4-FL-T			63.93	1.81	1.03	0.08

* Normalized with respect to the reference laminate (REF).

Table 2. Measured physical properties: laminate surface weight (LSW), fiber volume fraction (V_f) and void volume fraction (V_v).

3.2. Effect of OSS® parameters on laminate damage tolerance

Results normalized with respect to the reference laminate for OHC and CAI tests are detailed in Table 3[1]. In Figure 6, OHC and CAI strengths are presented in a histogram to ease the comparison between the different studied combinations of process parameters.

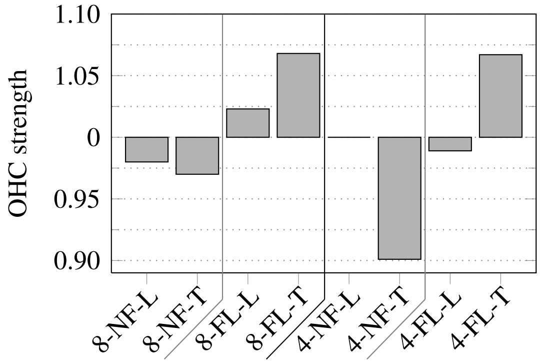
ID	OHC				CAI					
	Strength		Strain at break		Strength		Strain at break		Modulus	
	Avg.*	**CV** [%]	**Avg.***	**CV** [%]	**Avg.***	**CV** [%]	**Avg.***	**CV** [%]	**Avg.***	**CV** [%]
REF.	1.000	1.77	1.000	2.04	1.000	3.46	1.000	3.61	1.000	3.83
8-NF-L	0.980	2.01	0.993	4.31	0.983	5.69	0.988	6.95	1.023	2.97
8-NF-T	0.970	1.84	0.930	3.01	1.051	4.27	1.044	4.45	1.013	4.18
8-FL-L	1.023	1.45	1.055	2.36	0.995	5.18	0.981	2.55	1.022	3.20
8-FL-T	1.068	6.95	1.077	6.55	1.000	3.19	1.003	6.11	1.002	2.97
4-NF-L	1.000	2.34	1.012	2.99	1.042	6.52	1.081	3.94	1.007	2.94
4-NF-T	0.901	2.90	0.897	3.34	1.047	4.61	1.010	5.36	1.038	1.27
4-FL-L	0.989	2.56	0.996	3.16	1.046	6.25	1.054	6.85	1.021	4.29
4-FL-T	1.067	2.69	1.137	4.09	1.026	5.98	1.036	6.78	1.008	1.80

* Normalized with respect to the reference laminate (REF).

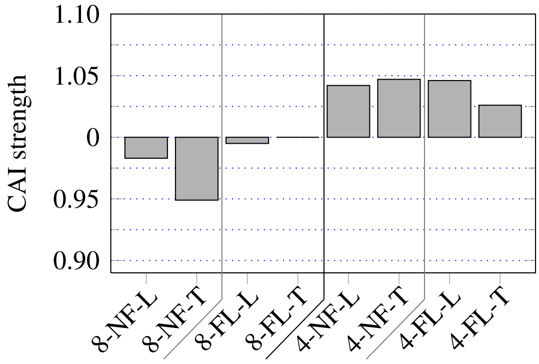
Table 3. Results for open-hole compression (OHC) and compression after impact (CAI) standard tests

As shown in Figure 6(a), under OHC, the *molding strategy* appears to be the most influential parameter: each preform that was flipped in the VARTM process had a similar or higher strength

[1]For comparison purposes against the reference laminate, the laminate thickening caused by OSS® was not considered as a part of the effective section for stress calculation.



(a) Open-hole compression (OHC)

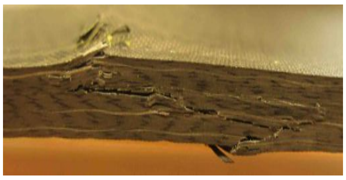


(b) Compression after impact (CAI)

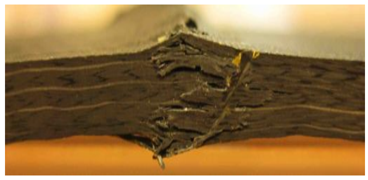
Figure 6. Residual compressive strength normalized with respect to the reference laminate (REF)

and strain at break than its equivalent non-flipped preform. Effect of *stitching orientation* on OHC strength appears to be dependent on the molding strategy: each longitudinally stitched preform exhibited a higher strength than its equivalent transversely stitched preform when preforms were non-flipped, and conversely, each transversely stitched preform showed a higher strength than its equivalent longitudinally stitched preform when preforms were flipped. This relation is likely to be due to the combined effects of severe fiber misalignment on the preform bottom side and laminate surface irregularity (thickening) on the laminate's bag-side, both caused by OSS®.

Figure 7. Severe fiber misalignment on bottom side of a dry preform



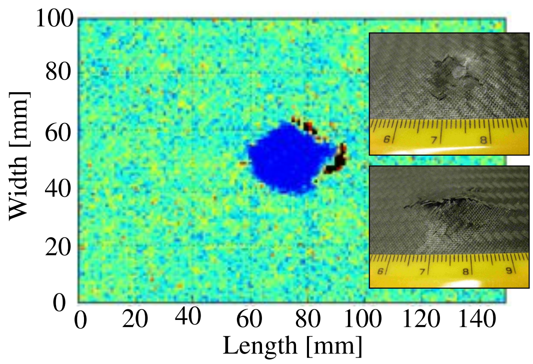
(a) Reference CAI specimen



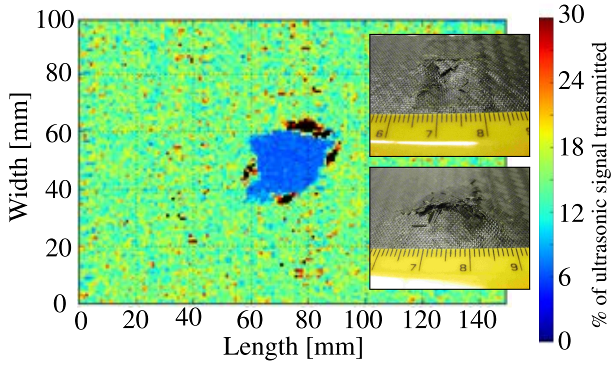
(b) Stitched CAI specimen

Figure 8. Post-mortem physical examination of CAI specimen edge

For CAI specimens, the impact caused a dent on the impacted surface and a rupture of the fibers on the opposite surface without being a through penetrant damage. Post-impact C-Scans showed no significant delamination extending around the impact dent (see Figure 9). Thus,



(a) Reference laminate



(b) Stitched laminate

Figure 9. Example of post-impact damage observed with C-Scan

damaged area simply corresponds to visually observable damaged area. In this case, OSS® did not affect the laminate impact resistance (i.e. damaged area). To reveal or enhance the possible effects of the Z-yarns on the laminate impact resistance, a larger impactor could be used to promote delamination through interlaminar shear.

Post-mortem physical examination of reference CAI specimen edges (see Figure 8(a)) showed longitudinal splitting, sign of a typical compressive local sublaminate buckling failure mechanism. On stitched specimens (see Figure 8(b)), the closing traction provided by stitch fiber bridging significantly reduced sublaminate buckling and therefore, fiber kinking became the main failure mode. As evidenced by Figure 6(b), CAI strength increased (with respect to the reference laminate) among all laminates stitched using a pitch of 4 mm, thus showing that OSS® can improve damage tolerance by reducing local sublaminate buckling. However, as observed with laminates stitched using a pitch of 8 mm, when the *stitching density* is too low, the degradation of intralaminar properties caused by OSS® appears to undo its benefits on interlaminar properties. The present results support Tan *et al.*'s observation: there is a critical *stitching density* below which stitches fail to bridge the delaminated area and, thus, do not improve CAI strength [9].

At this point, it is worth noting that OSS® stitches are relatively large compared to the size of the standard specimens and the size of the damaged area. Hence, OHC and CAI residual compressive strength may be sensitive to the arrangement of the stitches in the specimens and the exact position of the damage (e.g. hole or impact center) relative to the stitches. To minimize such possible effects, it is recommended to conduct tests on much larger coupons and full-size components.

4. Conclusions

Based on the premise that stitching affects the laminate mechanical performances, the objective of the present study was to measure the effect of three process parameters — the *stitching pitch*, the *molding strategy* and the *stitching orientation* — on the damage tolerance of laminates preformed using OSS®.

While the *molding strategy* was found to be the most influential process parameter under OHC, CAI strength was mostly affected by the *stitching pitch*. OSS® did not affect the laminate void and reinforcement volume fractions, but the use of OSS® combined with the use of a VARTM flexible bagging caused a resin rich thickening of the laminate along the stitching lines that resulted in an increase of the global laminate surface weight. A different molding strategy should therefore be considered when surface irregularity and weight gain caused by OSS® must be avoided.

While the use of OSS® may not be worth for the only purpose of improving a laminate's damage tolerance, it can be used to develop a more cost-effective manufacturing process for complex parts while assuming that in-plane mechanical properties could be maintained.

Finally, considering the macroscopic defects induced by OSS® (resin-pockets and fiber distortion) and knowing that, in the presence of a defect, angled plies are useful to redistribute the load in the vicinity of the defect, it would be relevant to test laminates that contain much higher or much lower proportions of angled reinforcements to see if stitches would alter mechanical properties (more) significantly.

Acknowledgments

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