HIGH-TOUGHNESS CFRP LAMINATES WITH ENGINEERED FRACTURE SURFACES: A SHARK-TEETH DESIGN

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Keywords: CFRP, Thin-ply, Finite Difference Fracture Mechanics, Toughness, Damage Tolerance

Abstract

Carefully placed patterns of micro-cuts have been designed and then used to increase the translaminar work of fracture in thin-ply composite laminates. These patterns of micro-cuts are able to deviate a translaminar crack and force the formation of large bundle pull-outs. The technique allowed to achieve a 68% increase in the laminate notched strength and a 460% increase in the laminate translaminar work of fracture when compared with the un-modified baseline material. Part of the improved performance was found to be due to the interaction of fracture mechanisms between contiguous plies with different orientation; this mechanism opens new possibilities for micro-structure design which will be explored in future works.

1. Introduction

The translaminar fracture toughness is an important property to improve the damage resistance and damage tolerance of Carbon Fibre Reinforced Plastics (CFRP) structures [1–3]. This is particularly important for thin-ply composites because the translaminar fracture toughness of composite laminates has been shown to decrease substantially with ply thickness [4, 5].

Modelling results [5] showed that the translaminar fracture toughness of long-fibre reinforced composites is largely determined by the energy dissipated via debonding and friction during the formation of bundle pull-outs from the fracture surface. These bundle pull-outs are the result of a stochastic failure process [6] and exhibit a hierarchical architecture [2, 3].

In a previous work, Bullegas et al. [7] demonstrated that patterns of precisely-placed micro-cuts can be used to promote the formation of large hierarchical bundle pull-outs in the 0° plies and increase the translaminar fracture toughness in thin-ply composite laminates. In this work, the idea of using patterns of micro-cuts is further investigated and a new micro-structure design, called “shark teeth”, is introduced.

2. Materials, manufacturing and test methods

The material system used in this work is a thin-ply UD carbon-epoxy prepreg (TR50s/K51) provided by Skyflex [8]. The prepreg comes in two grades, which correspond to two different ply thicknesses of

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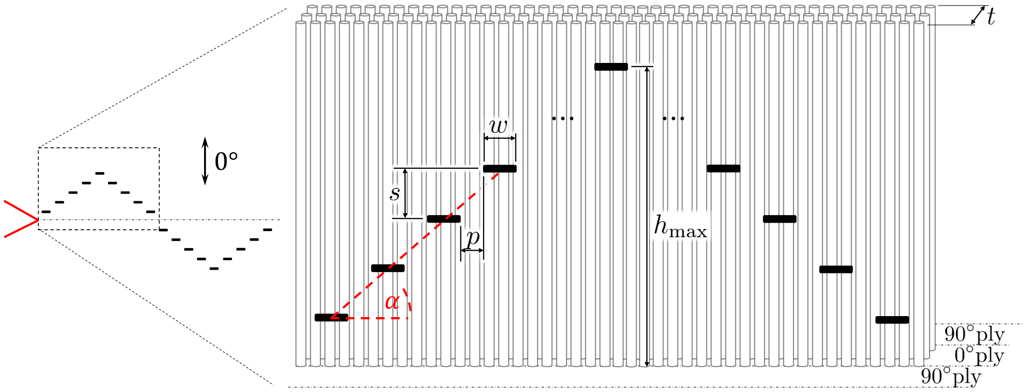

Figure 1: "Shark-teeth" micro-structure design concept: patterns of laser-engraved micro-cuts perpendicular to the fibre direction are inserted in the 0° plies of the laminate to guide crack propagation and promote the formation of large bundle pull-outs.

30 µm (grade A) and 50 µm (grade B). Individual fibres and laminatae properties used in this work can be found in Bullegas et al. [7].

The behaviour of thin-ply composites with patterns of micro-cuts during translaminar fracture propagation has been investigated using Compact Tension (CT) specimens; the CT specimens design is the same described in [7]. The specimens have a symmetric cross-ply lay-up ($[90,(0,90)_{20}]_{s}$) where the thinner prepreg material (grade A) was used for the 0° plies, and the thicker prepreg (grade B) was used for the 90° plies. Each 0° ply in the specimen contains a pattern of micro-cuts aligned with the test section of the specimen.

The CT specimens were tested using an Instron load frame with a 10 kN load cell; each specimen was loaded under displacement control at a rate of 0.5 mm/min. A video strain gauge system (Imetron) was used to measure and record the relative displacement of the load application points. The modified compliance calibrated method [2, 3] was used to calculate the laminate work of fracture from the experimental data. Note that the term work of fracture is used here instead of fracture toughness to highlight the diffuse damage introduced by this technique.

3. Micro-structure design

The micro-structure design concept devised for this study is shown in Figure 1. It is based on the idea of using a regular array of micro-cuts to deflect an incoming translaminar crack and cause the formation of a large bundle pull-out. To be able to accommodate a scenario where the position of the incoming crack is not know a priori, the patterns on micro-cuts shown in Figure 1 was repeated periodically along the test section of the CT specimens to form a design called "shark-teeth". The maximum pull-out height ($h_{\max}$), which is the most important parameter of the design, was decided upon following the predictions from an original Finite Difference Fracture Mechanics (FDFM) criterion developed for this study.

Figure 2 shows an example of a translaminar crack, propagating horizontally from left to right in the 0° ply, which is deflected along a secondary direction by the presence of an array of micro-cuts. It is assumed that the crack propagates from one micro-cut to the next in finite steps, progressively causing the debonding and pull-out of a new bundle portion. At each step along the array of micro-cuts, the

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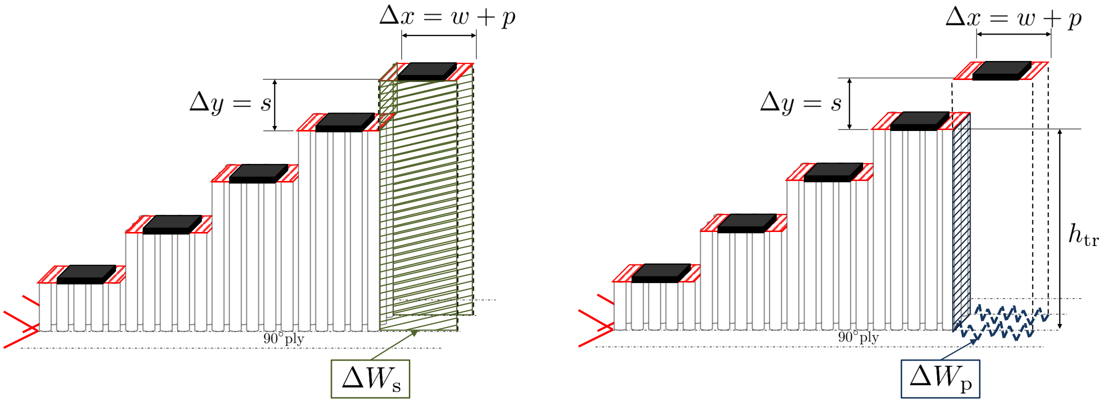
Table 1: Geometrical parameters of the patterns of micro-cuts.

Specimen	Pattern	geometrical parameters				
		w [µm]	p [µm]	s [µm]	α	h_{max} [µm]
CT1	Baseline	-	-	-	-	-
CT2	ST1	30	30	60	45.0°	600
CT3	ST2	30	30	90	62.5°	600
CT4	ST3	30	0	60	70.5°	900



(a) (b)

Figure 2: Finite Difference Fracture Mechanics can be used to predict the crack propagation path in a 0° ply with an array of pre-existing micro-cuts: (a) the crack follows the array of micro-cuts, $\Delta\mathcal{W}_{\text{s}}$ is the finite energy necessary to propagate from one micro-cut to the next; (b) the crack jumps back to the original fracture plane, $\Delta\mathcal{W}_{\text{p}}$ is the finite energy necessary for this propagation and h_{tr} is the transition pull-out height at which the two energies are equivalent.

crack has two options: it can either propagate to the nearest micro-cut and continue along the deflected direction; or it can jump back to the original crack propagation plane. In the former case, the crack needs to cause the debonding of the lateral surface of the next bundle portion (which requires the finite amount of energy $\Delta\mathcal{W}_{\text{s}}$ in Figure 2(a)). In the latter case, the crack needs to cause the debonding of the interface with the next bundle portion in the thickness direction and the translaminar failure of the fibres at the base of the bundle (which requires the finite amount of energy $\Delta\mathcal{W}_{\text{p}}$ in Figure 2(b)).

By comparing the energies required by these two finite fracture processes, it is possible to determine at which step the crack would stop following the array of micro-cuts and jump back to the original fracture plane. This approach therefore allows determining the pull-out height h_{tr}, which is a function of the material properties, the bundle geometry and the deflection angle α. The complete development of the FDFM method can be found in [9].

For this study, three different patterns of micro-cuts have been defined following the “shark teeth” design concept. All patterns have $w = 30\,\mu\text{m}$ long micro-cuts perpendicular to the fibre direction, but different values of the interspace p and of the vertical distance between the micro-cuts s, which then determine the

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Table 2: Results of the CT test for the four specimens. $\Delta P_{\max}$ is the increase in notched strength and $\Delta \mathcal{G}_{\mathrm{If}}$ is the increase in work of fracture with respect to the baseline material.

Pattern	$P_{\max}$ (kN)	$\Delta P_{\max}$ %	$\mathcal{G}_{\mathrm{If}}^{\mathrm{lam}}$ (kJ/m^2)	$\Delta \mathcal{G}_{\mathrm{If}}$ %
Baseline	0.99	-	12.6	-
ST1	1.49	+51	50.5	+300
ST2	1.61	+63	58.1	+361
ST3	1.66	+68	70.6	+460

deflection angle α. The FDFM criteria was used to determine the transition pull-out length h_{tr} for each pattern design, and then $h_{\max}$ was selected such that $h_{\max} \leq h_{\mathrm{tr}}$. This approach guarantees that the crack would always follow the pattern without jumping back to the original fracture plane. The dimensions of the three patterns are reported in Table 1.

4. CT test and results

Four CT specimens were tested in this work (specimen CT1 to CT4). Specimen CT1 was manufactured without any pattern of micro-cuts and was used as baseline for the behaviour of the un-modified material, while specimen CT2 to CT3 contain the different pattern designs as defined in Table 1. The details of the specimens' geometry and manufacturing, and the test procedure are reported in Section 2.

Figure 3 shows the four different fracture surfaces obtained from the CT test. By comparing Figure 3(b),(c) and (d) to Figure 3(a), it is clear that all the patterns of micro-cuts promoted the formation of large bundle pull-out during the fracture process. It is also possible to notice that, while the 90° plies in specimen CT1 failed on a well defined fracture surface; the 90° plies in the specimens with the patterns of micro-cuts (CT2 to CT3) present multiple splits and tensile failures of the fibres.

Figure 4 shows the quantitative results of the CT tests for the four specimens. From the load vs. displacement plot in Figure 4(a), it is possible to notice that the crack propagation behaviour goes from unstable (in the case of the baseline material) to stable (for the specimens with the patterns of micro-cuts), with a substantial increase in the notched strength (up to 68%). Accordingly, the laminate work of fracture vs. opening displacement plot (Figure 4(b)) shows greatly improved performances for the laminates with engineered micro-structures. In particular, the specimens with the engineered micro-structures show a strong R-curve effect in the initial portion of graph (related to the formation of a cohesive zone); then the curves level out during steady state crack propagation and the work of fracture of the laminate (defined as the average of the values in this flat region of the curve) is up to 460% higher than that of the baseline material. A summary of the test results in terms of maximum load and steady state laminate work of fracture can be found in Table 2.

4.1. Discussion

It is clear from Figure 3 that the micro-structure design technique was successful and allowed to obtain the designed fracture surfaces in the 0° plies. The corresponding micro-mechanic failure mechanism led to a different macro-mechanical response of the laminate during the test.

All of the three micro-structure designs tested in this study lead to a completed bundle pull-out over the entire surface of the specimen. Since the allowable pull-out height for each design was decided upon

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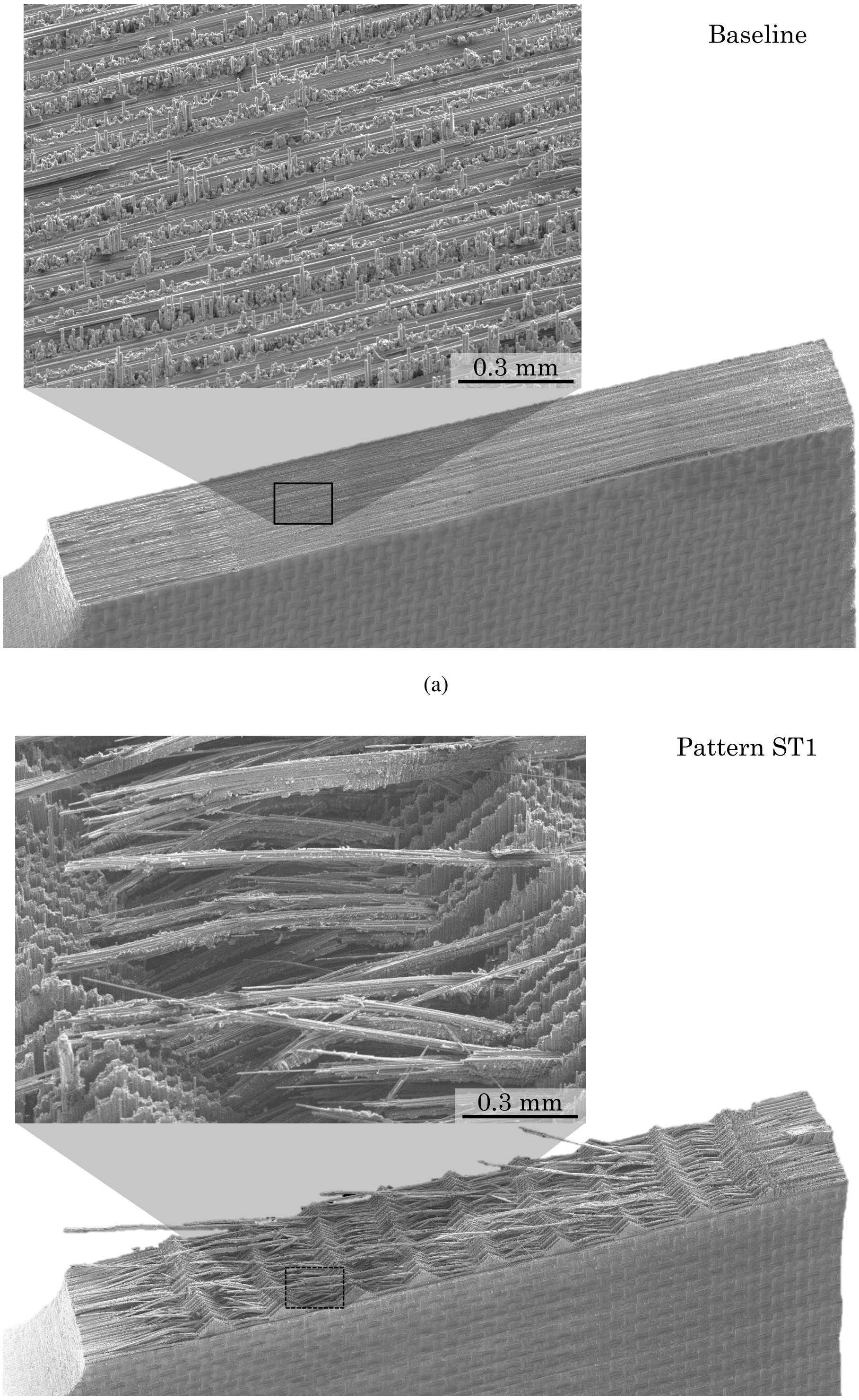

Figure 3

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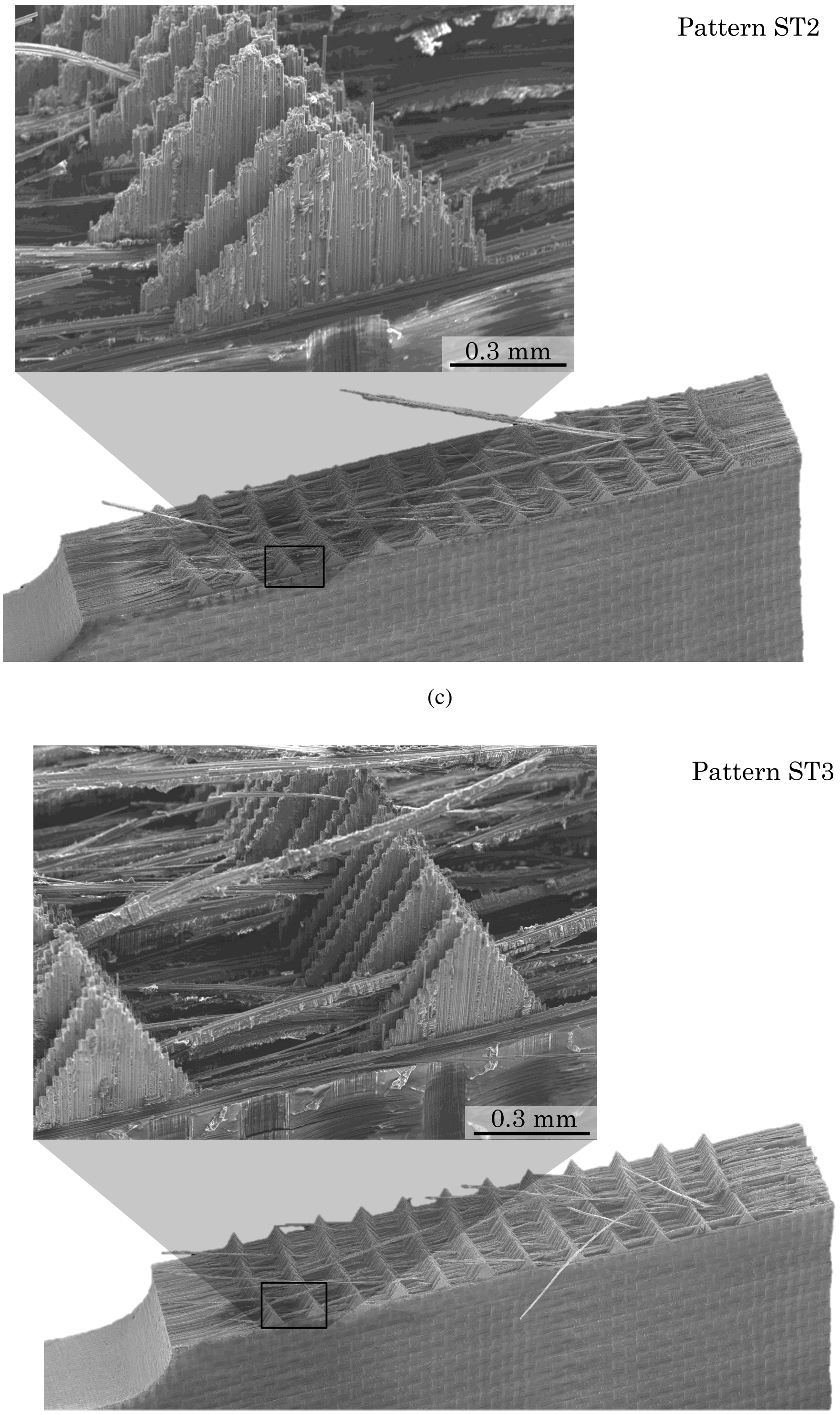

Figure 3: SEM micrographs of the fracture surfaces of four CT specimens showing a comparison of the baseline un-modified thin-ply material with the engineered thin-ply material: (a) baseline material without any micro-cut; (b) thin-ply laminate with micro-cuts pattern ST1; (c) micro-cuts pattern ST2; (d) micro-cuts pattern ST3.

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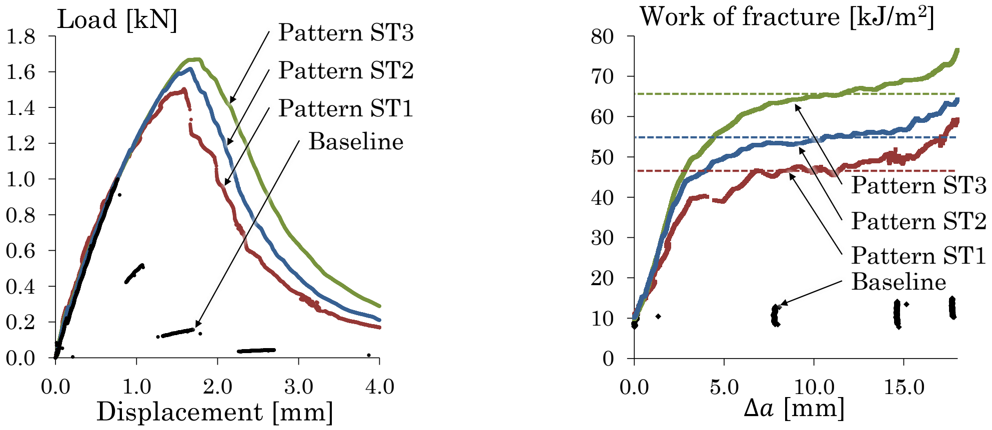

(a) (b)

Figure 4: Results of the CT tests for the four specimens.

so that it did not exceed the transition height h_{tr} determined using the FDFM criterion, these experimental results demonstrated that this criterion is useful in identifying a conservative lower boundary of applicability of the crack deflection technique. More studies are needed to confirm the upper boundary.

The test demonstrated an interaction between different ply orientations: the presence of the patterns of micro-cuts in the 0° caused multiple splits and tensile failures in the 90° plies. It is possible to conclude that this considerably increased the contribution of the latter to the total work of fracture of the laminate if compared to the baseline material.

5. Conclusions

The results presented in this work demonstrate that patterns of micro-cuts perpendicular to the fibre direction can be successfully used to engineer the translaminar fracture behaviour, and drastically increase notched strength by up to 68% and the work of fracture by up to 460% in thin-ply laminates. In particular, the following conclusions can be reached:

- patterns of micro-cuts in the 0° plies are successful in steering the crack from its original propagation plane and in causing the formation of large pull-outs. These pull-outs dissipate energy through debonding and friction, thus increasing the toughness of the laminate;
- the presence of the patterns of micro-cuts in the 0° plies does not just cause crack deflection in the 0° plies, but also causes multiple splits and tensile failures in the 90° plies, considerably increasing the contribution of the latter to the toughness of the laminate;
- Finite Difference Fracture Mechanics (FDFM) criteria can be used to determine maximum allowable height of these pull-out structures and therefore are useful in the design of the patterns of micro-cuts.

Although the increase in the laminate work of fracture achieved in this paper is already remarkable (460%), it is likely that this technique has the potential to lead to a more significant increase in the damage tolerance of CFRP laminates for two main reasons:

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- the upper boundary of the applicability of the FDFM criterion was not demonstrated experimentally and it is possible that longer bundle pull-out than those prototyped in this work might be achieved;
- the interaction between plies with different orientation opens new possibilities for micro-structure design that can be used to maximize energy dissipation.

Acknowledgments

The first two authors are grateful to the funding from EPSRC under grant EP/M002500/1. The third author acknowledges the support from the Royal Academy of Engineering for her Research Fellowship on Multiscale discontinuous composites for large scale and sustainable structural applications (20152019). The authors are also grateful to Steve Harrison from Triple-H Composites for supplying the prepreg material used in this study.

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