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IMPLEMENTING STRUCTURAL FUSES IN CFRP COMPONENTS VIA MICROSTRUCTURALLY-ENGINEERED CRACK PATHS

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Abstract: *This study aims to develop and implement actual carbon fibre-reinforced polymer (CFRP) solutions for realising structural fuses in real components. To this end, we have developed various concepts for structural fuses, applied to generic idealised components and aimed at engaging different in-plane and through-the-thickness damage propagation mechanisms. Micro-cut patterns (MCPs) / crack path combinations have been engraved on thin-ply CFRP prepregs (by using a laser cut machine) for manufacturing CFRP specimens. Afterwards, we have carried out a series of experimental studies to evaluate the fracture properties of various MCPs under three-point bending (3PB). Then, 3PB results were used to refine and down-select our concepts, for use in our generic idealised component design to test them under indentation test using a cantilever beam rig. The test results demonstrated that MCPs can provide significant control over the fracture locus and path, additionally allowing the failure initiation load and energy dissipation to be tailored.*

Keywords: Microstructure design; Carbon fibre-reinforced polymer (CFRP); Structural fuse; damage-control; crack path

1. Introduction

Carbon fibre-reinforced polymer (CFRP) composites are being increasingly used in various industries such as aeronautics due to their high performance to weight ratio. Nonetheless, because of their inherently brittle nature, CFRPs are susceptible to sudden uncontrolled failure, which can endanger the integrity of entire CFRP components [1]. When a CFRP component separates into two parts due to fracture, typically, the actual fracture path is a consequence of the geometry of the component and of the loading, rather than a characteristic designed into the component. However, in many applications (e.g. fan blade-off events) there are significant advantages in controlling the fracture path via a form of structural fuse (e.g. to reduce the portion of the blade ejected) to reduce the energy transmitted into the casing.

Thin-ply CFRPs provide greater design possibilities, improved homogenization and more possible stacking sequences than conventional thick plies-based counterparts [2]. As extensively studied in the literature, the ply thickness affects the initiation and propagation of micro-cracks as well as delamination [3]. It is known that translaminar fracture depends on the microstructure (in particular on the crack path shape) [4] and that applying micro-cut patterns (MCPs) on thin-ply CFRP prepregs is a powerful tool for developing engineered CFRP micro-structures with

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enhanced fracture performance [5]. In a previous study, we demonstrated that applying MCPs can increase the fracture toughness of the laminates up to 180% compared to that of QI laminates in a compact tension (CT) test [5]. However, new tests and concepts are needed to examine the behaviour of engineered micro-structures when applied as structural fuses for real CFRP components. Hence, the main goal of this study is to propose innovative designs of engineered crack paths with tailored properties for practical applications. To this end, we have proposed an innovative microstructure design through various studies and down-selected potential MCP concepts to create a predictive controlled failure along a chosen (crack) path, while retaining the strength and toughness of the structure (compared to that of the baseline (quasi-isotropic (QI)) material. These engineered crack paths can be used to promote or prevent selected failure mechanisms.

2. Experimental Procedure

Unidirectional thin-ply SkyFlex USN20A prepregs (a 20gsm UD fabric of TR30S, high strength carbon fibres from Mitsubishi with K51 epoxy resin from SK Chemicals) with an uncured thickness of 0.05 mm are used in this study. To manufacture panels, we have cut each thin-ply prepreg at the desired angle (using an automated cutting table) and placed on top of each other ply with the help of alignment holes to guide the layup (Figure 1, a). While laying up, micro-cut patterns (MCP) (see Figure 1, e-f) were engraved using the Oxford Lasers Diode Pumped Solid State micro-machining system with specific patterns in each ply (Figure 1, b) to manufacture CFRP specimens with the stacking sequence of $\left[(0,45,90,-45)_{16},0_{1/2}\right]_s$. Then, we cured the panels at 125 ℃ under 5 bar pressure in an autoclave machine. After curing, we cut the specimens via the abrasive waterjet cutting method and tested them under three-point bending (3PB) as well as indentation tests (Figure 1, c-d).

To assess the optimum geometrical properties of MCP, we investigated a large range of MCPs to evaluate the variation of fracture parameters in a compact tension (CT) test [6]. An example of ST MCP is illustrated in Figure 1, e-f. The rationale behind selecting various MCPs / crack path combinations is mainly based on: (1) studying the ability of the MCP to deflect the crack away from the inherent (critical) stress path; (2) promoting desirable failure mechanisms, mainly delamination; (3) protecting uncut plies so that they act as crack stopping barriers; and (4) designing MCP properties so that the specimen does not fail under other unwanted failure modes (namely compressive failure). With these in mind, we have carried out multiple studies in terms of various MCP parameters / crack path combinations (as shown in Figure 2 and Table 1) and presented some of which here to address the aforementioned objectives.

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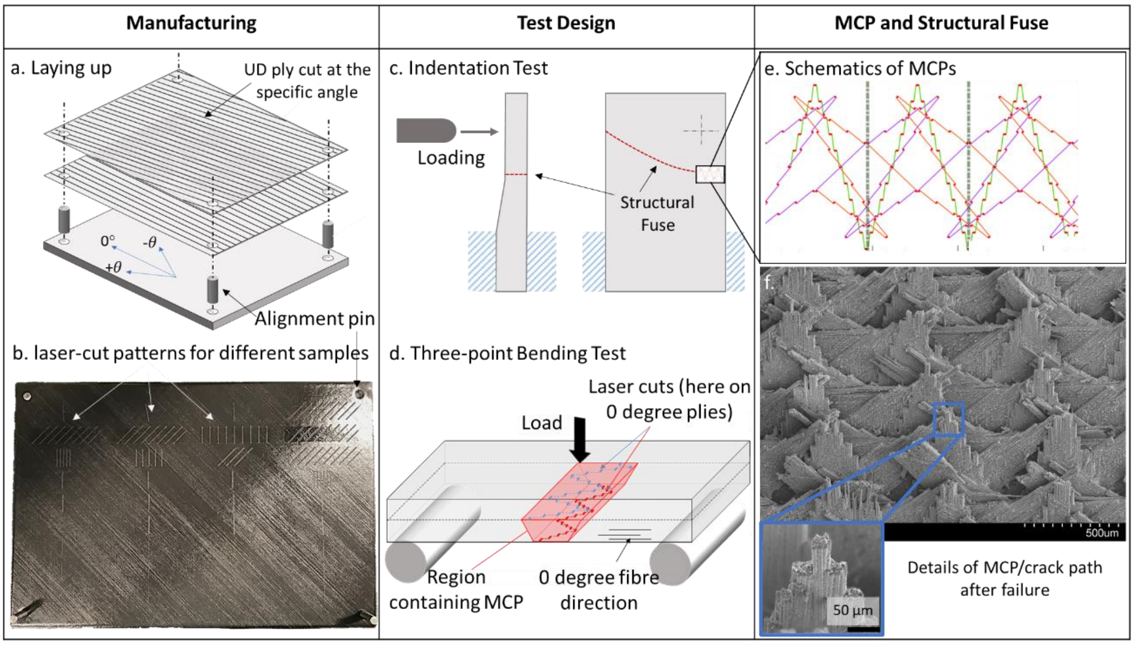

Figure 1: Design, manufacture, and test of engineered structural fuses made of CFRP composites

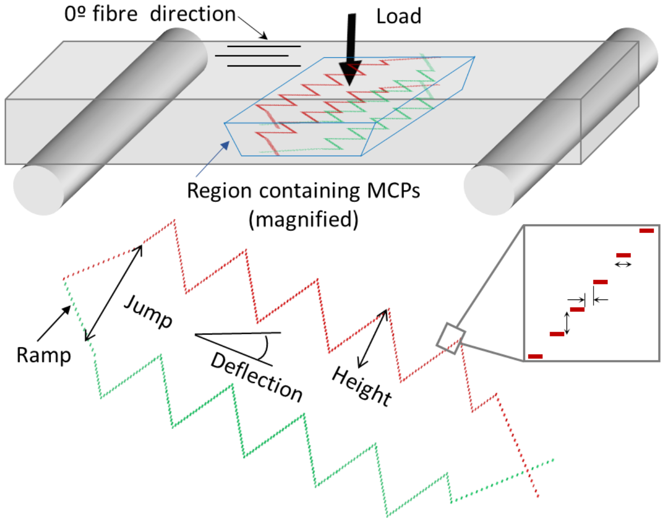

Figure 2: Schematic of a shark teeth (ST) MCP and associated parameters

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Table 1. Various parameters of micro-cut patterns (MCPs) investigated in this study

Study	Parameter	Specimen number
1	Jump size	Sp1-Sp4
2	Ramp up and Jump Size	Sp5-Sp8
3	Deflection and amount of fibres cut	Sp9-Sp12
4	MCP height and type	Sp13-Sp16
5	Using 45°/-45° plies	Sp17-Sp20

3. Results and discussion

Study 1 investigates the effect of jump size from 1.0 mm to 2.0 mm on the fracture path as well as delamination size/jump. For study 1, we observed that increasing the jump size from 1.0 mm to 2.0 mm results in more significant delamination, see Figure 3-b. By comparing the fracture paths of Sp2-Sp4 (see Figure 3-a, b) with those of the baseline material (Sp1) without micro-cut patterns (MCPs), we have noticed that MCPs give microstructures the ability to guide the crack along its engineered path, while the baseline material without MCPs lacks such characteristic and shows an uncontrolled brittle path after failure, Figure 3-a,b. In addition, measured strength and energy dissipation are still close to those of the non-engineered material, although Sp4 still shows a 15% and 13% decrease in work of fracture and peak stress compared to those of the baseline material, respectively, Figure 4, a-b.

Study 2 (through Sp5-Sp8) investigates the effect of ramp-up and jump value on the fracture properties. By comparing the results to those of study 1, we conclude that ramping up is a successful tool that promotes failure in 90° plies and shows a potential for improvement of delamination jump. It is also concluded that the baseline ramp is a good balance of a few cuts and also can guide the crack. Test results demonstrate that adding targeted partial cuts in the 45°/-45° can help guide the crack. However, applying Teflon or silicon spray to weaken the interface to promote delamination does not seem to affect the behaviour. Moreover, the challenge with this particular MCP is that the crack does not alternate sign and create delamination in every block (similar to non-engineered material). Hence, the MCP could be modified so that it would alternate every two or three blocks to make sure the crack always follows the pattern and increases delamination, Figure 3-c. Nonetheless, by comparing to Study 1, we can observe that normalised work of fracture and peak stress values improve slightly, see Figure 4. a-b.

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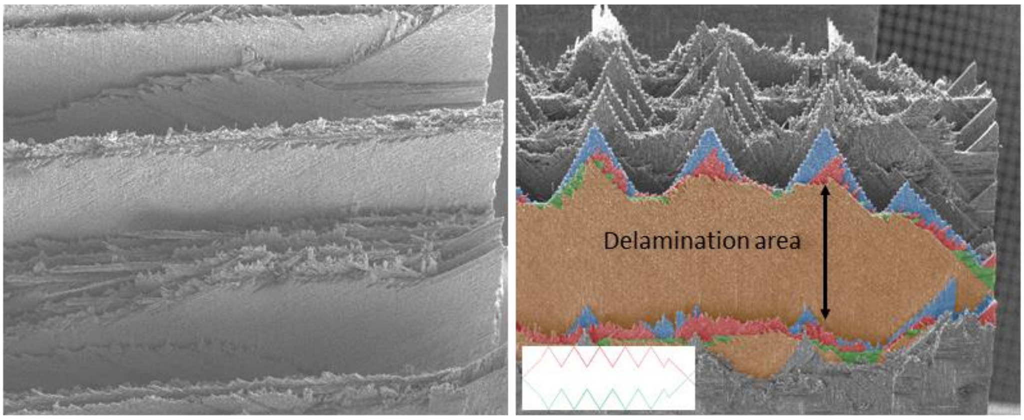
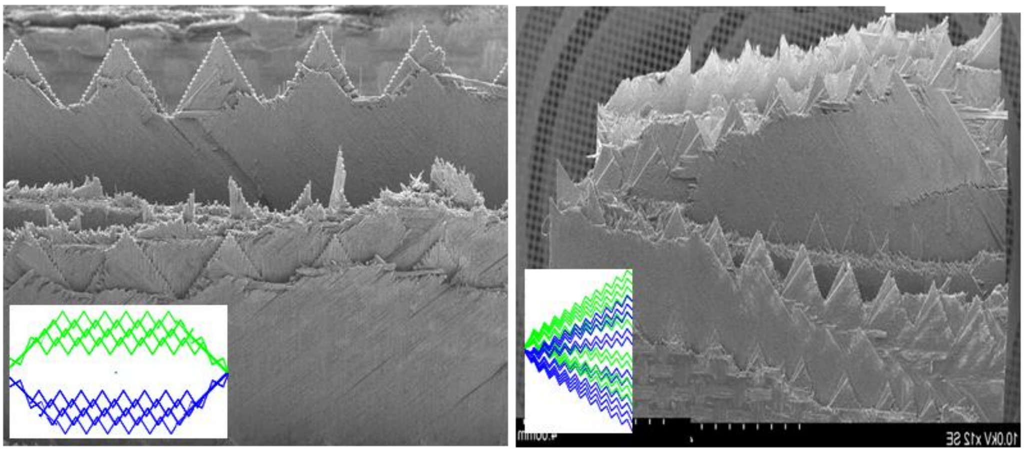


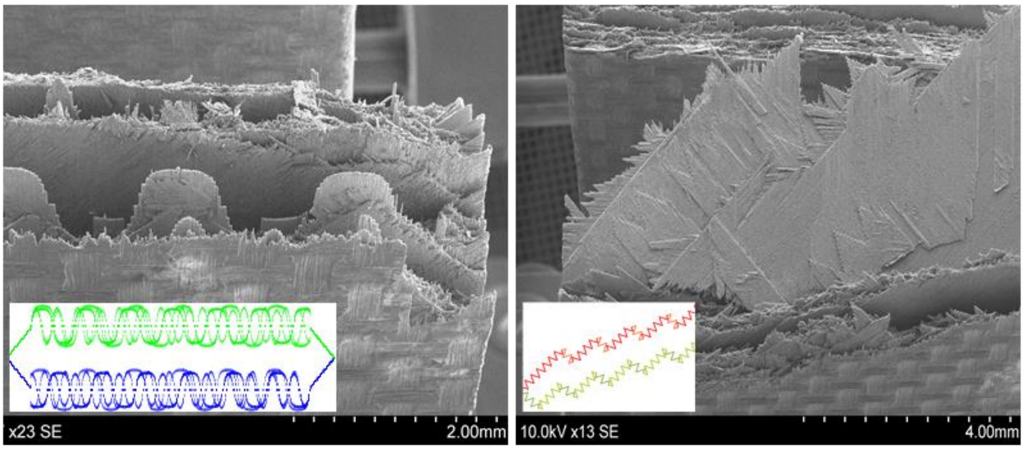
a. Baseline without MCP

b. The effect of Jump Size (Study 1)



c. The effect of Ramp up and Jump (Study 2)

d. The effect of Deflection and amount of fibres cut (Study 3)



e. The effect of MCP height and type (Mogul field) (Study 4)

f. The effect of Using 45°/-45° plies (Study 5)

Figure 3: Fracture surfaces of the failed specimens in different studies

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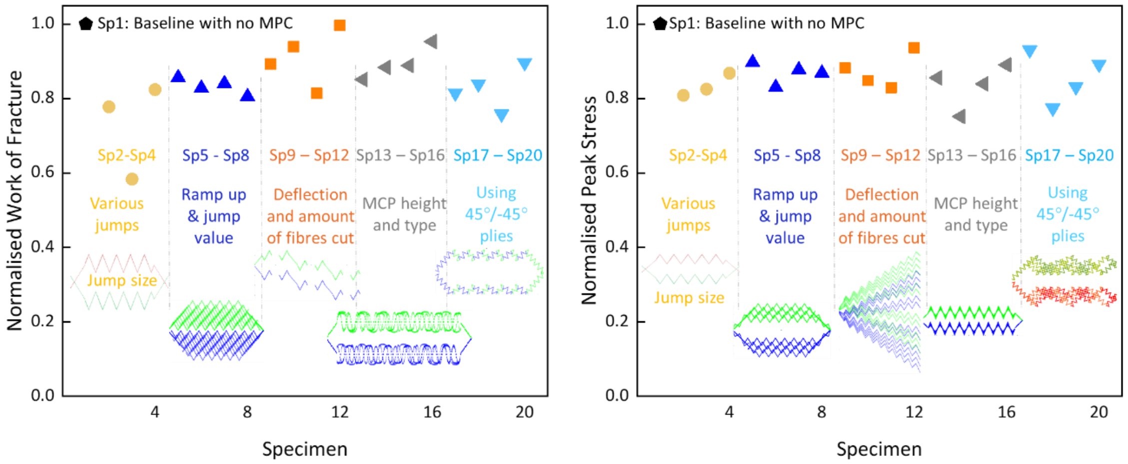

a. Normalised work of fracture

b. Normalised peak stress

Figure 4: Normalised (a) work of fracture and (b) peak stress values of engineered crack path specimens under three-point bending (3PB)

To demonstrate one of the promising design concepts, the force-displacement curves for study 3 specimens (Sp9-Sp12) are depicted in Figure 5-a. We have examined the variations of deflection and amount of fibres cut, showing that this particular design is successful to deflect the in-plane crack, see Figure 3-c and Figure 5,c-d. Moreover, partially cut MCPs can still guide the crack and increase strength and energy dissipation (see Sp 12 values in Figure 5, b). The test results suggest that there is a potential for a partial cut of MCPs in 0° plies. In the fourth study, we investigate the roles of MCP height and type on fracture performance. Regarding the type of MCPs, in addition to ST MCPs, we also apply mogul field (MF) MCP to examine its feasibility and performance. By analysing Figure 3-d and Figure 4 a-b, we can observe that changing a MCP type can have a positive effect in deflecting the crack, while retaining fracture properties. By comparing the results in Figure 4-a,b, we can confirm that slightly higher shark-teeth (ST+) patterns can be used, though it does not significantly increase the fracture properties. As a result, we can conclude that there is still some room for using longer features in the MCPs if needed; however, the limited effect of the MCP used should be examined to that of ramp/crack jump height.

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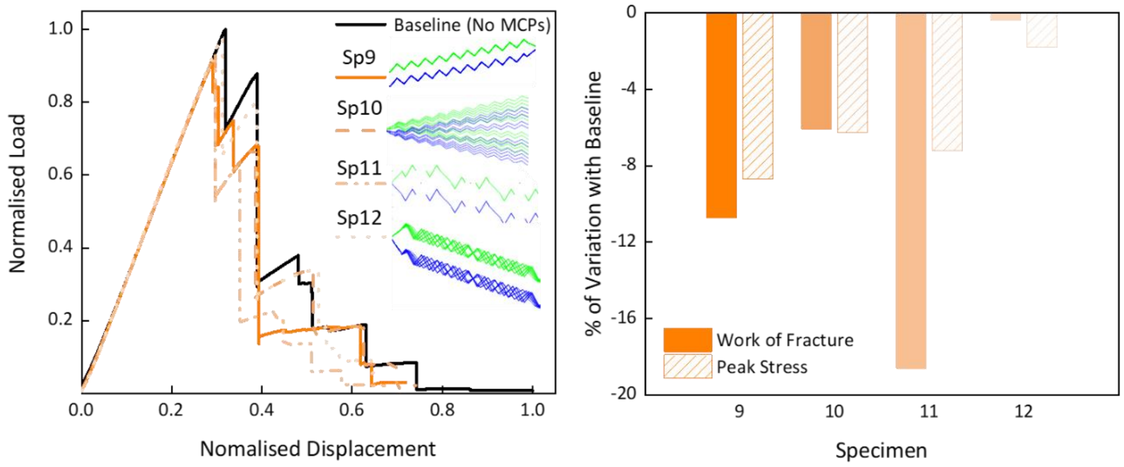
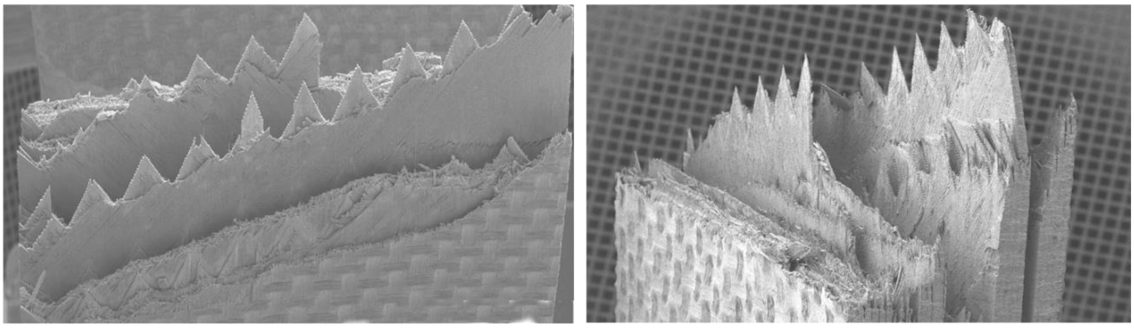


a. Force-displacement results under 3PB (Study 3)

b. Variation of normalised work of fracture and peak stress (Study 3)



c. Constant deflection through the thickness (TTT) in Sp9 (Study 3) - front view

d. Constant deflection TTT in Sp9 (Study 3) - side view

Figure 5: (a) Force-displacement curves of study 3 specimens and corresponding MCP schematics, (b) their percentage of variation (in terms of work of fracture and peak stress) with the baseline, and (c-d) fracture surface of one of the samples in study 3 (Sp9)

In the last study, we examined using MCPs on 45°/-45° plies on the fracture performance. The fractographic analyses of failed specimens (Figure 3-e) show that using MPCs on the 45°/-45° may be somewhat less effective at controlling the crack position in those plies. Comparing the work of fracture and peak stress values reveals that using MCD on 45°/-45° plies does not improve the performance significantly compared to previous studies. In addition, we did not observe any strong knock-off of the strength/work of fracture despite micro-cuts being present in every two plies (versus every four plies in Sp4). This concept is perhaps less promising than MCPs in 0° plies to control the crack; however, targeted MCP in 45° still can be used to help deflect the crack.

To further evaluate the feasibility of applying these engineered crack paths to real applications, such as blade-off events in engines, engineered crack paths are applied to more realistic specimens and will be investigated under indentation test using a cantilever beam test, which its results will be provided at the conference.

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4. Conclusion

In this paper, we carried out multiple studies to design concepts of structural fuses made of thin-ply carbon fibre-reinforced polymer (CFRP) for generic idealised components. A series of micro-cut patterns (MCPs) and crack path combinations were engraved on multiple CFRP specimens and we tested them under three-point bending (3PB). It was concluded that:

1- carefully-designed micro-cuts can be applied to create engineered crack paths in thin-ply composite structures, which can deflect the crack away from the inherent (critical) path and steer it along chosen planes;
2- MCPs can be used to promote desired failure mechanisms, namely delamination, to retain energy dissipation, not necessarily present in the baseline material;
3- engineered crack paths can be applied so that the specimen does not fail under unwanted failure modes (namely compressive failure); and
4- by applying engineered crack paths, uncut plies are protected so that they can act as crack stopping barriers.

These results motivate ongoing work where we are investigating this structural fuse concept in more complex structures.

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