GROUPING SIMILAR FIBRE TYPES IN HYBRID DISCONTINUOUS COMPOSITE MATERIALS

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Keywords: Pseudo-ductility, hybrids, discontinuous composites, clustering

ABSTRACT

A virtual testing framework and a new manufacturing process were developed to investigate how grouping similar fibre types within a hybrid discontinuous composite affects the strength and pseudo-ductility of the material. Both the experiments and modelling showed that increasing the level of random intermingling prevents large clusters of broken fibres from forming, which maximises the strength and pseudo-ductility of hybrid discontinuous composites.

1 INTRODUCTION

Composite materials are widely used in aerospace and automotive applications due to their high specific strength and specific stiffness. However, composites are often brittle and may fail catastrophically. Consequently, there is a desire for pseudo-ductile composites that fail more gradually and offer some warning before final failure [1].

Pseudo-ductility can be achieved through hybridization of the reinforcement. Three different methods of hybridization exist: *intermingled* hybrids (mixing different fibre types at the fibre-level), *intraply* hybrids (mixing different fibre types within the same ply), and *interlaminated* hybrids (mixing different plies within a laminate) [2]. In all cases, a ductile response can be achieved through fragmentation and diffuse debonding/delamination of the low elongation reinforcement, which leads to a ductile response [3, 4].

Discontinuous reinforcements can also be used to achieve pseudo-ductility. In this case, the non-linear matrix behaviour at the reinforcement-matrix interface is used to promote gradual failure. This technology has been demonstrated at the ply-level [5, 6] and the fibre level [7, 8].

Yu et al. combined hybrid reinforcements with the High Performance Discontinuous Fibre (HiPerDiF) process [7] to produce *intermingled* hybrid discontinuous composites with near-perfectly aligned fibres [2]. The *intermingled* hybrid discontinuous composite materials showed high strength and ductility.

Various authors have shown that the grouping of similar fibre types within continuous hybrid composites affects their performance. Swolfs et al. [9] and You et al. [10] both showed that the failure strain of hybrid continuous composites was affected by the arrangement of low elongation fibres, but disagreed on which arrangement maximized the failure strain of the hybrid composites.

This paper aims to investigate the influence of grouping similar fibre types within hybrid discontinuous composite materials, with the aim of maximizing pseudo-ductility and strength of *intermingled* and *intraply* hybrid discontinuous composites.

2 EXPERIMENTAL DEVELOPMENT

Three hybrid discontinuous composite fibre arrangements were investigated as part of this study. An *intermingled* cross-section (Figure 1a) was compared against the *intraply double-blocked* (Figure 1b) and the *intraply blocked* cross-sections (Figure 1c); the size of the groups of low elongation fibres increases from the *intermingled* to the *intraply double-blocked* and to the *blocked* cross-sections. Carbon fibres (shown in light grey throughout this paper) and glass fibres (shown in dark grey) were used for all designs, with the carbon fibres exhibiting a significantly lower failure strain than the glass fibres. The volume ratio of carbon-to-glass fibres (v_c) was kept constant at 1:2. Fibre properties were kept consistent with previous work by Yu et al. [2].

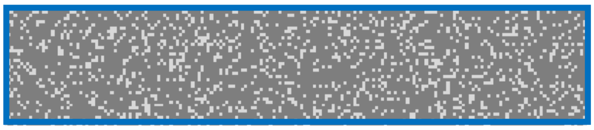


Figure 1a: *Intermingled* cross-section.

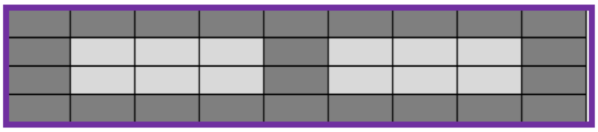


Figure 1b: *Intraply double-blocked* cross-section.

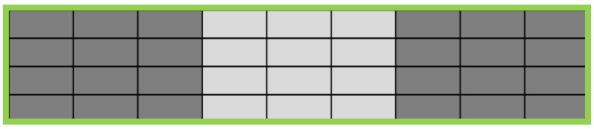


Figure 1c: *Intraply blocked* cross-section.

Figure 1: The three fibre arrangements that were studied in this investigation.

The existing HiPerDiF method for *intermingled* hybrid discontinuous composites [2] (Figure 2**)** was modified to enable the manufacture of *intraply* hybrid discontinuous composites. This was achieved by using separate tanks to pump carbon or glass fibres into specific locations in the specimen cross-section, as shown in Figure 3. The *intraply* HiPerDiF method was used with the aim to manufacture the *intraply* hybrid cross-section designs shown in Figures 1b and 1c.

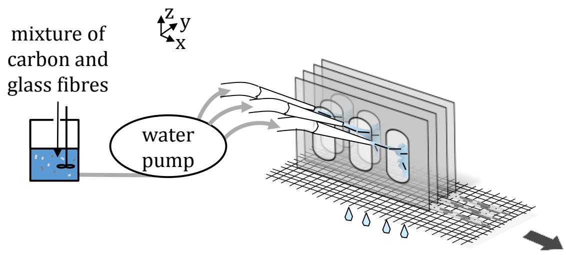


Figure 2: The HiPerDiF process uses a single tank to pump the same mixture of carbon and glass fibres to every nozzle to form the *intermingled* cross-section.

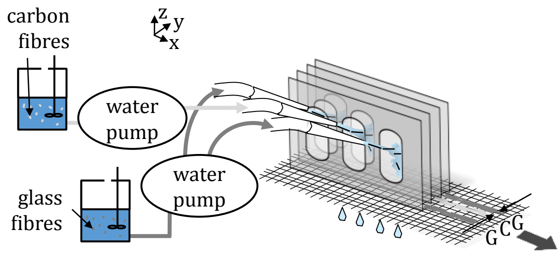
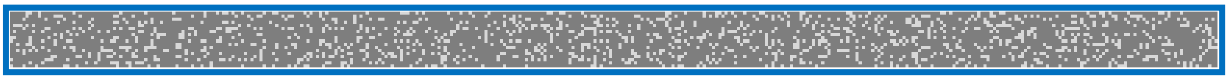


Figure 3: The HiPerDiF process uses separate tanks to pump glass or carbon fibres to each nozzle to form the *intraply* cross-sections.

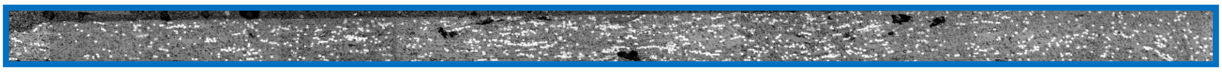
3 MODEL DEVELOPMENT

Fibre arrangements representative of the intended cross-sections were created for modelling work, as shown in Figures 4a to 6a. The modelled *intermingled* cross-section showed good agreement with the experimental cross-section produced using the *intermingled* HiPerDiF method, as shown in Figure 4b. However, the experimental *double-blocked* and *blocked* cross-sections, produced using the *intraply* HiPerDiF method, evidenced a significant deviation from the intended design, as shown in Figures 5b and 6b. Consequently, a fibre migration algorithm [11] was used to simulate the movement of the different fibre types during the *intraply* HiPerDiF manufacturing process; the simulated migrated cross-sections are shown in Figures 5c and 6c.

A virtual testing framework was developed to simulate the response of specimens with *intermingled* (Figure 4a), *double-blocked* (Figure 5c), and *blocked* (Figure 6c) cross-sections; this virtual testing framework was based on that proposed by Henry and Pimenta [12] for *intermingled* hybrid discontinuous composites. However, the grouping of low-elongation fibres in the *intraply* designs required modification of the framework's fracture criterion, in order to determine the ultimate strength and failure strain of each specimen. Failure is governed by fracture mechanics, i.e. once a cluster of broken fibres reaches a certain size, further failure of the surrounding fibres will lead to unstable propagation of fibre failures, leading to fracture of the complete specimen.



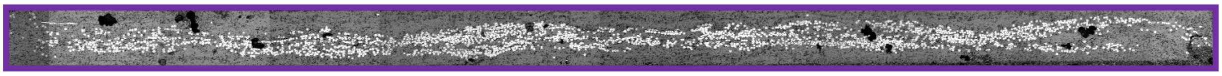
(a) Intended *intermingled* cross-section.



(b) Experimental *intermingled* cross-section.

Figure 4: The experimental *intermingled* cross-section (Figure 4b) matched well with the intended *intermingled* cross-section (Figure 4a).

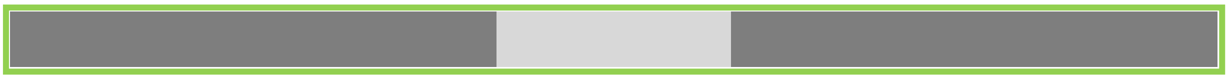
(a) Intended *intraply double-blocked* cross-section.



(b) Experimental *intraply double-blocked* cross-section.

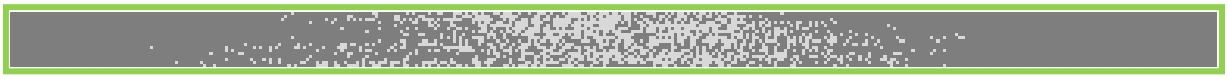
(c) *Intraply double-blocked* cross-section after application of fibre migration algorithm

Figure 5: The experimental *intraply double-blocked* cross-section (Figure 5b) showed significant fibre migration when compared to the intended cross-section design (Figure 5a), and therefore a fibre migration algorithm was applied to the modelled cross-section (Figure 5c).



(a) Intended *intraply blocked* cross-section.

(b) Experimental *intraply blocked* cross-section.



(c) *Intraply blocked* cross-section after application of fibre migration algorithm.

Figure 6: The experimental *intraply blocked* cross-section (Figure 6b) showed significant fibre migration when compared to the intended cross-section design (Figure 6a), and therefore a fibre migration algorithm was applied to the modelled cross-section (Figure 6c).

The fracture criterion followed the method proposed by Finley et al. [11], which is briefly summarised in the flowchart in Figure 7. The method starts with the applied strain set to zero. The strain is then increased; for each strain increment, the fibre stresses are determined, and the clusters of broken fibres (i.e. the fibres which carry zero load) are identified. The strain energy release rate associated with every broken cluster is evaluated, along with the fracture toughness of the material surrounding each cluster. If the strain energy release rate of any cluster exceeds its associated fracture toughness, the analysis stops and the stress-strain curve is trimmed to this fracture strain. Otherwise, the strain is increased further and the analysis loop continues.

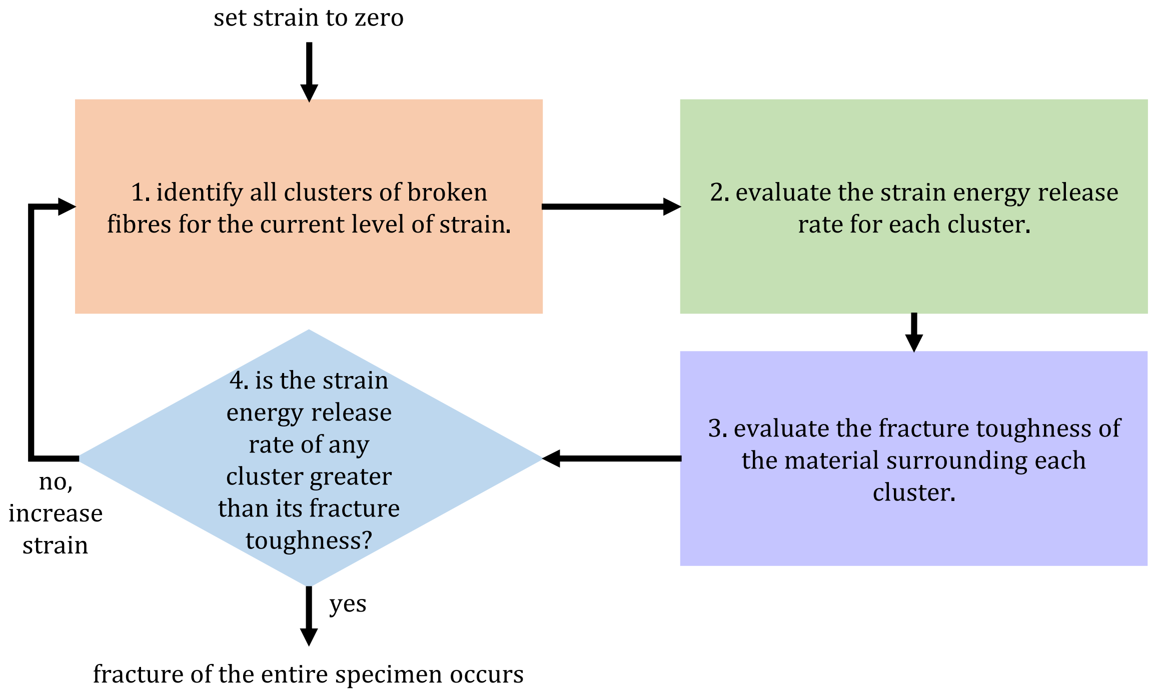


Figure 7: A flowchart illustrating how the fracture-based failure criterion is implemented.

4 RESULTS

4.1 Model validation

Figure 8 to 10 show both the modelled and experimental stress-strain curves for the *intermingled*, *intraply double-blocked*, and *intraply blocked* configurations, respectively. There is a good agreement between the model and the experiments in each case.

The *intermingled* cross-section has the highest ultimate strength and failure strain, whilst the *intraply blocked* configuration has the lowest. This indicates that the strength and ductility of hybrid discontinuous composites can be maximized when groups of low elongation fibres are avoided or kept to a minimum size.

Figure 11 shows that the *intermingled* cross-section has the smallest critical cluster of broken fibres, whereas the *intraply blocked* configuration has the largest critical cluster. Configurations with larger groups of low elongation fibres will create large clusters of broken fibres, which will lead to a higher strain energy release rate. A higher strain energy release rate leads to premature fracture of the specimens, therefore grouping of low elongation fibres should be minimized in order to delay failure and thus maximize the strength and pseudo-ductility of hybrid discontinuous composites.

4.2 Effect of intermingling

Figure 12 shows that increasing levels of random intermingling of the intended *intraply blocked* cross-section increased the strength and pseudo-ductility of the hybrid discontinuous composite. Figure 13 shows that the size of the critical clusters reduced as the level of random intermingling is increased. Random intermingling of low elongation fibres is therefore an effective technique to maximize the strength and ductility of hybrid discontinuous composites; as the amount of intermingling is increased, groups of low elongation fibres become smaller and more isolated from one-another, thus preventing large clusters of broken fibres from forming. A brittle response is observed for low levels of intermingling, whereas an increasingly more ductile response is seen when the amount of random intermingling is increased over 50%.

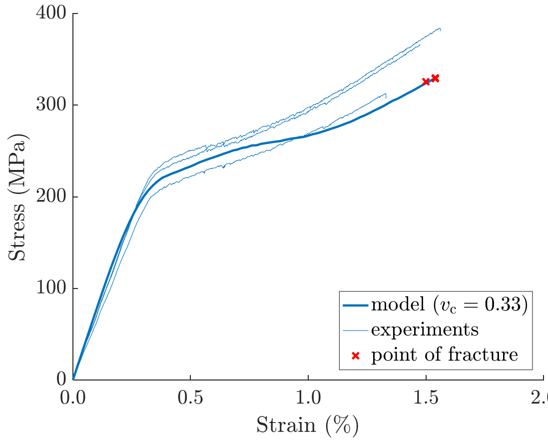


Figure 8: Experimental and analytical stress-strain curves for the *intermingled* cross-section.

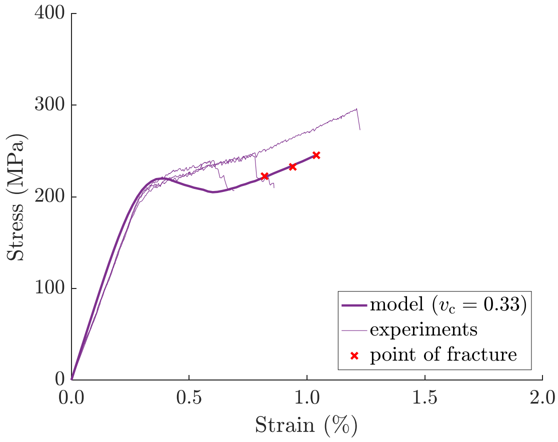


Figure 9: Experimental and analytical stress-strain curves for the *intraply double-blocked* cross-sections.

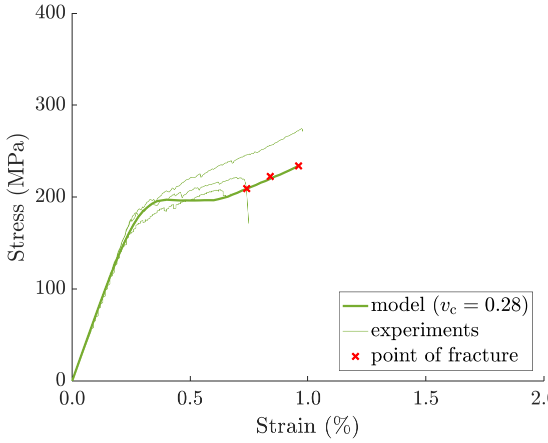
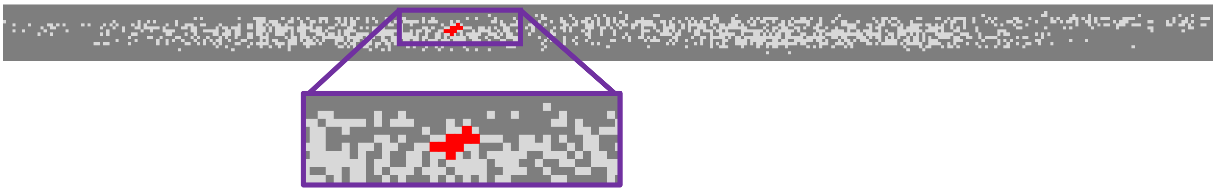
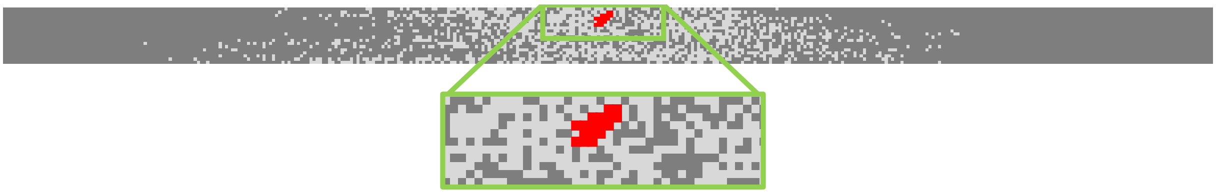


Figure 10: Experimental and analytical stress-strain curves for the *intraply blocked* cross-sections.

(a) The critical cluster in the *intermingled* cross-section is small,
and includes both carbon and glass fibres.



(b) The critical cluster in the *interplay double-blocked* cross-section is medium-sized,
and contains only carbon fibres.



(c) The critical cluster in the *intraply blocked* cross-section is larger than the *intermingled* and *intraply double-blocked* cross-sections and only contains carbon fibres.

Figure 11: Cross-sections for the *intermingled* and *intraply blocked* configurations.
Critical clusters (i.e. clusters of broken fibres that lead to fracture of the specimen) are shown in red (carbon fibres shown in bright red, and glass fibres shown in dark red).

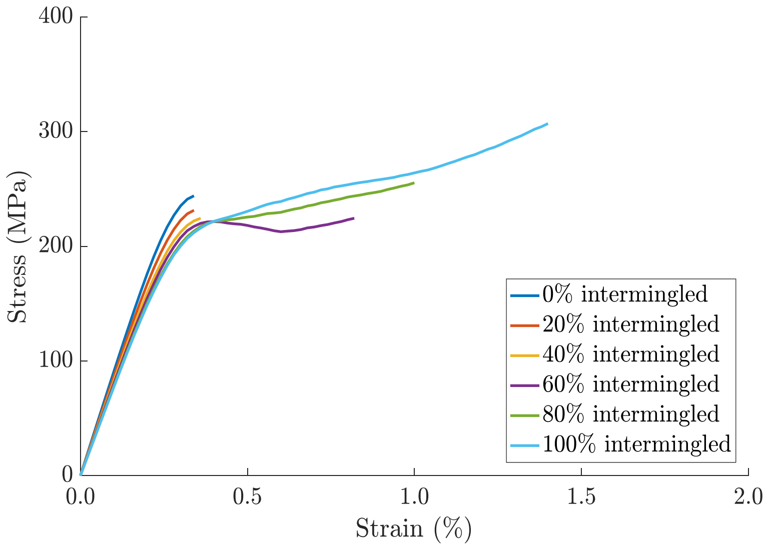
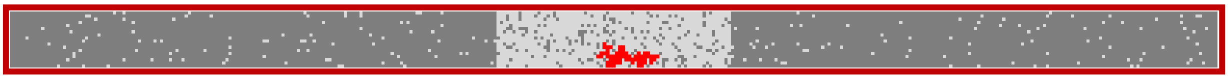
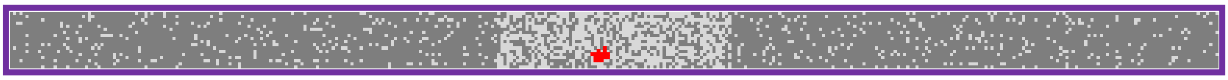


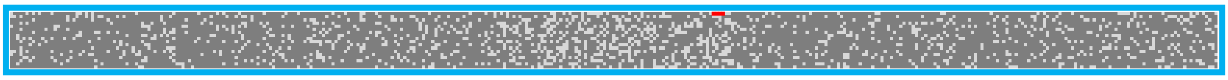
Figure 12: Increasing levels of intermingling increases the strength and ductility,
but decreases the initial stiffness of the *intraply blocked* hybrid discontinuous composite.



(a) *Intraply blocked* cross-section with 20% random intermingling.
A large critical cluster of broken fibres is formed (in red).



(b) *Intraply blocked* cross-section with 60% random intermingling.
A medium-sized critical cluster of broken fibres is formed (in red).



(c) *Intraply blocked* cross-section with 100% random intermingling.
A small critical cluster of broken fibres is formed (in red).

Figure 13: Increasing levels of random intermingling reduces the size of critical clusters within the *intraply blocked* cross-section.

5 CONCLUSIONS

This study investigated the effects of grouping similar fibre types within aligned hybrid discontinuous composites, with the aim of maximising strength and pseudo-ductility. A virtual testing framework was developed alongside a new HiPerDiF manufacturing method to analyse both *intermingled* (i.e. not grouped) and *intraply* (i.e. grouped) hybrid discontinuous composites.

Intermingled and *intraply* hybrid discontinuous composites were successfully manufactured, although the *intraply* cross-sections showed a significant deviation from the intended cross-sections. A fibre migration algorithm was therefore used in the model to account for fibre movement during the manufacture of the *intraply* hybrid specimens. A new fracture criterion proposed by Finley et al. [11] was used to predict final fracture of both the *intermingled* and *intraply* specimens. These two modelling features enabled a good agreement between the virtual tests and the experiments.

The *intermingled* hybrid discontinuous composite showed the highest strength and pseudo-ductility of all the specimen designs. This was because the intermingled cross-section featured much smaller groups of low elongation fibres, which led to smaller clusters of fibre breaks and therefore avoided premature failure.

Increasing intermingling proved to be an effective technique to increase the strength and pseudo-ductility of hybrid discontinuous composites, by reducing the size of low elongation fibre groups. Consequently, this study proves the HiPerDiF method is the current state-of-the-art for producing ductile hybrid discontinuous composites, as this method is the only available technique to achieve the high levels of intermingling required to maximise the ductile response.

Future work will investigate how further isolation of the low elongation fibres can further improve the strength and pseudo-ductility of hybrid discontinuous composites.

ACKNOWLEDGEMENTS

This work was funded under the UK Engineering and Physical Sciences Research Council Programme Grant EP/I02946X/1 on *High Performance Ductile Composite Technology*. Soraia Pimenta acknowledges the support from the Royal Academy of Engineering in the scope of her Research Fellowship on *Multiscale discontinuous composites for large scale and sustainable structural applications* (2015-2019).

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