THE INFLUENCE OF DEFECTS AND VARIABILITY IN DISCONTINUOUS COMPOSITE MATERIALS

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Abstract

A virtual testing framework was further developed to investigate the influence of defects and variability on the structural performance of various aligned discontinuous composite material systems. The virtual testing framework identified the most critical sources of variability as (i) fibre strength, (ii) the distance between fibre ends, or (iii) the level of fibre-type intermingling, depending on the material system. Fibre vacancy defects were shown to also have a significant influence on the strength and ductility of aligned discontinuous composites.

1. Introduction

Composite materials are widely used in the aerospace industry due to their high specific strength and specific stiffness. However, like most materials, composites are sensitive to defects and variability. Various authors have shown that the performance of continuous composite materials is negatively influenced by variability in inter-fibre distance / local volume fraction, fibre strength and Young's modulus, and matrix interfacial shear strength.

Aligned discontinuous composites (ADCs) are a sub-class of composite that offer tailorable structural properties which can be controlled by manipulation of the composite microstructure. For example, short-fibre ADCs exhibit a pseudo-ductile response due to non-linear matrix yielding at the fibre-ends, while long-fibre ADCs are stronger and stiffer because the longer fibres are able to recover more load through shear of the matrix [1]. Hybridisation of different fibre-types also offers additional mechanisms for structural tailorability due to the combination of fibres with different failure strains [2]. While the performance of these composites is very promising, the additional complexity in the microstructure will lead to many more sources of variability and defects. Examples of additional variability may include differences in the distance between fibre-ends, matrix strength variability, and a random fibre-type arrangement [2]. Defects may include fibre misalignment, fibre-damage due to handling (i.e. residual fibre fragmentations), residual interface failures, and voids (e.g. fibre vacancies)

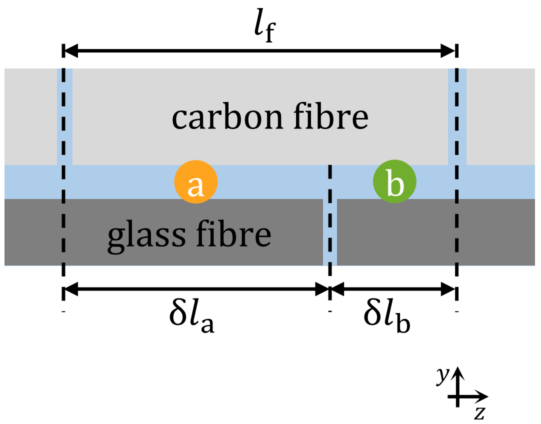
There has been no accurate yet efficient assessment of how variability and defects may influence the strength, stiffness, and pseudo-ductility of composites, and ADCs in particular. This lack of research is primarily down to the complexity of the problem and the number of results that need to be generated to form a statistically relevant analysis. Final failure of hybrid and non-hybrid discontinuous composites requires knowledge of how failures at the fibre-level propagate to cause failure of the complete specimen, essentially creating a multi-scale modelling problem. Finally, many model runs need to be completed to generate a distribution of specimen performance to fully understand how stochastic effects such as variability affect the properties of these materials.

This paper aims to explore how variability and defects affect the strength, stiffness, and ductility of aligned discontinuous composites. This aim will be achieved through the use of an accurate yet efficient virtual testing framework, which captures the influence of micro-scale stochastic variability and defects.

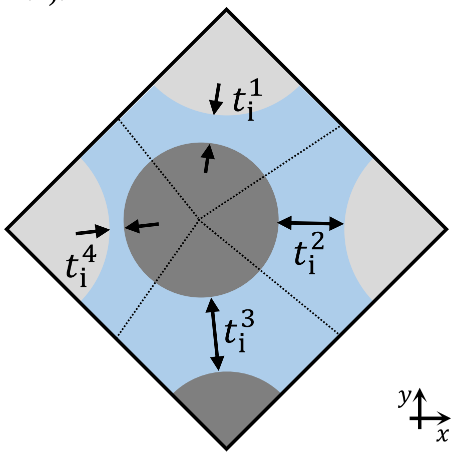
2. Model development

2.1 The virtual testing framework

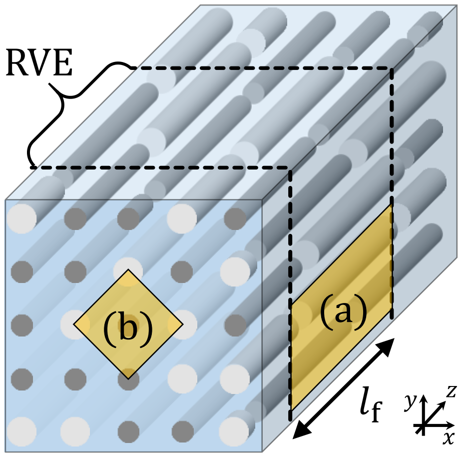
The stress-strain response of each specimen is built up using a multiscale Virtual Testing Framework (VTF) [1-4]. Firstly, the stress-strain curve of each fibre-fibre overlap is calculated; the overlaps are then combined in series to give the stress-strain curve of a single fibre-fibre interaction (Figure 1a). A co-ordination number of four is assumed, meaning that four fibre-fibre interactions are combined in parallel to give the stress-strain response of a single fibre (Figure 1b). The stress-strain response of every fibre in the cross-section are combined in parallel to give the stress-strain response of the Representative Volume Element (RVE, Figure 1c). Finally, the RVEs are combined in series to give the stress-strain response of the complete specimen (Figure 1d). Final failure of the specimen is determined by a fracture mechanics-based failure criterion (more details in Section 2.4).



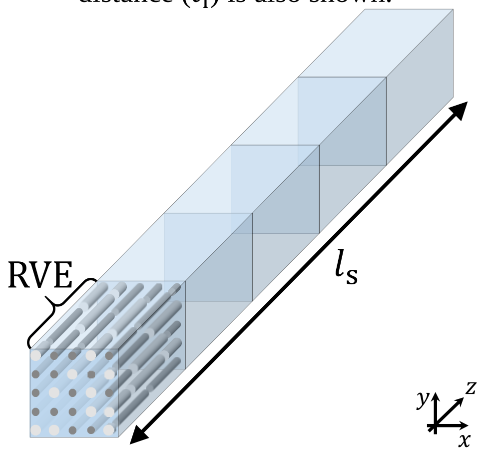
(a) The stress-strain response of overlaps *a* and *b* are combined in series to give the stress-strain response of a single fibre-fibre interaction.



(b) The stress-strain response of four fibre-fibre interactions are combined in parallel to give the fibre stress-strain response. The inter-fibre distance (t_i) is also shown.



(c) All fibre stress-strain responses are combined in parallel to give the stress-strain response of a RVE.



(d) All RVEs are combined in series to give the stress-strain response of the full specimen.

Figure 1: The stress-strain response of the composite is calculated on multiple length scales to find the overall stress-strain response of the material.

Non-linear matrix shear behaviour is captured using a piecewise linear constitutive law. All fibres are linear elastic, with the strength of each fibre governed by a Weibull distribution. Fibre-end locations are determined by a uniform random distribution, while the arrangement of different fibre-types is determined using either a uniform random distribution or a specific fibre arrangement (coupled with a fibre migration algorithm [2]).

2.2 Additional sources of variability

Three additional sources of variability were added to the VTF to understand which source of variability had the biggest impact on structural performance:

- Matrix interfacial shear strength variability was measured from single fibre pull-out data and fitted to a Weibull distribution. In the VTF, the shear strength of the matrix constitutive law for each interaction was sampled from this Weibull distribution.
- Fibre modulus variability was measured using T300 single fibre tensile test data; while different fibre types were used for this study, it was assumed that the coefficient of variation in fibre modulus remained similar for all fibre types. Fibre modulus variability was then added to the VTF by sampling the stiffness of each fibre in a RVE from a Normal distribution.
- Variability in the inter-fibre distance (t_{i}, Figure 1b) was captured by sampling each inter-fibre distance from a modified Poisson-Voronoi tessellation process. The inter-fibre distances were then used to calculate stress concentrations between the neighbouring fibres according to a power law. More details for this derivation can be found in work by Finley et al. [5].

2.3 Adding defects to the VTF

The capability to model several types of defects was added to the VTF; the details for each type are described below:

- Residual fibre fragmentation defects (created, for example, from mishandling or damage during manufacture) were modelled by inserting a controlled number of fibre fragmentations at a random length along some fibres before the start of the simulation. This has the effect of reducing the length of the overlaps (δl_{a} and δl_{b} in Figure 1a) between two fibres.
- Residual interface defects (created from matrix porosity or contamination) were simulated by setting a controlled number of fibre-fibre interaction stress-strain curves to zero (thus preventing stress transfer between specific pairs of fibres) and adjusting the number of active neighbouring fibres in the region of each defect.
- Fibre vacancy defects (created from poor local volume fraction changes and/or poor consolidation) were replicated by removing fibres from the simulation; this was achieved by setting the stress-strain response for a controlled number of fibres to zero and reducing the number of active neighbouring fibres for all fibres surrounding the fibre vacancy. This method effectively treats certain fibres as a matrix within the VTF, thus simulating the presence of fibre-sized voids.
- Misalignment of the fibres (created during the manufacturing process) was simulated at the specimen-level using misalignment probability density function data from Yu et al. [6] and Sanadi [7]. The loss of specimen stiffness due to misalignment was calculated using the equivalent laminate method. Finally, Euler's method was used to find the cumulative influence of misalignment on the complete stress-strain curve.

2.4 Accurately predicting final failure

A new fracture mechanics-based failure criterion was developed to predict the final failure of aligned discontinuous composites (ADCs). Unlike previous work [2], this new criterion captures the effect of not only fibre damage, but of all forms of relevant damage (including matrix yielding / debonding, and defects), in all types of ADC.

The criterion follows the flowchart in Figure 2. Firstly, the strain applied to the virtual specimen is set to zero. Next, the damage state of every fibre in the RVE is calculated as the loss of stiffness of each fibre, relative to its initial stiffness; a damage state of 0 implies an undamaged fibre, while a value of 1 implies a fully damaged fibre that can no longer carry any load. Next, a damage threshold is selected (between 0 and 1), whereby any fibres with a damage state greater than or equal to the damage threshold are considered part of a damaged cluster. For every cluster, the strain energy release rate is calculated and compared against the fracture toughness of the material. The process is repeated for every value of the damage threshold between 0 and 1 for the current strain level, and the minimum reserve factor (i.e. the lowest ratio of the composite fracture toughness to the cluster strain energy release rate, SERR) is calculated. If the reserve factor is greater than 1, the remote strain is increased; if the reserve factor is less than 1, the RVE has fractured at the current remote strain. This whole process is repeated for every RVE, and the fracture strength of the specimen is defined as the lowest stress at which any of the RVEs fracture. The size and location of the *critical cluster*, i.e. the cluster of damaged fibres which led to final fracture of the specimen is recorded for later analysis.

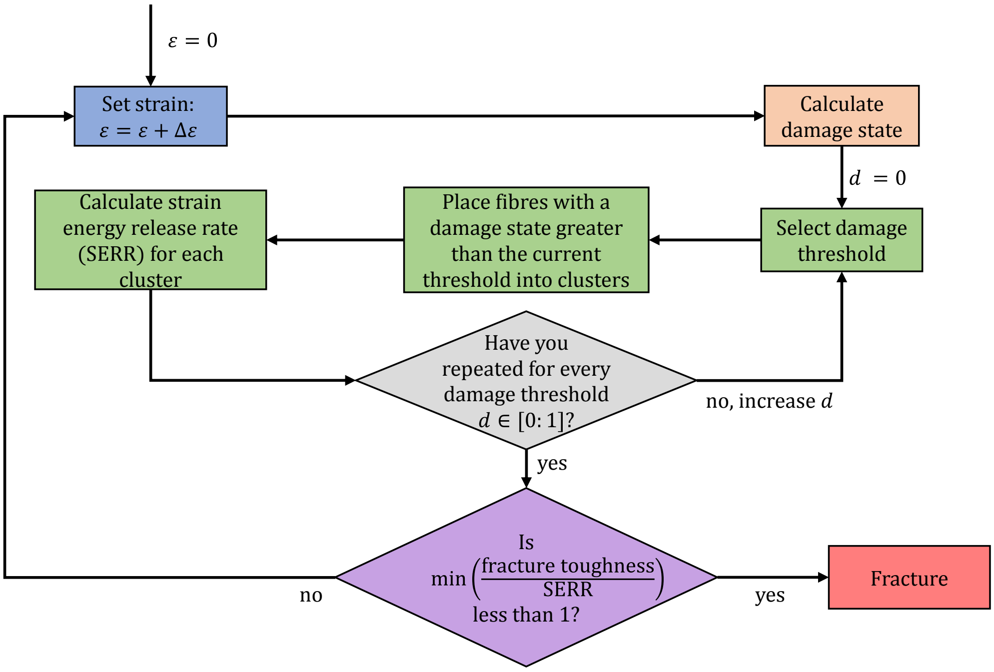


Figure 2: The flowchart to find the fracture strain of a single RVE in the specimen. The overall specimen fracture strength is calculated as the smallest stress at which RVE fracture occurs.

3. Results and Discussion

3.1 The influence of variability on structural performance

In order to understand which sources of variability most influence the failure of composite materials, the average material properties of the *critical cluster* were compared against that of the bulk composite material. Four types of ADC were tested using the VTF: 6 mm fibre high strength carbon (HSC)/epoxy ADC, 0.5 mm fibre HSC/epoxy ADC, 6 mm fibre high modulus carbon/E-glass/epoxy (HMC/EG/epoxy) hybrid ADC, and 0.5 mm fibre HMC/EG/epoxy hybrid ADC. For each ADC material system, 4000 virtual specimens were tested, and the *critical cluster* and material properties were recorded for each specimen. The RVE containing the *critical cluster* for each of the virtual specimens (the critical RVE) is then concatenated ontop of each of the other critical RVEs, and translated such that the centroids of the *critical clusters* were aligned along a single axis (Figure 3). The material properties (Young's modulus, fibre strength, matrix strength, inter-fibre distance, etc.) were then averaged along the alignment axis, giving a `heat map' of the average properties of the critical cluster in the centre of the map, and the properties of the bulk composites around the edges.

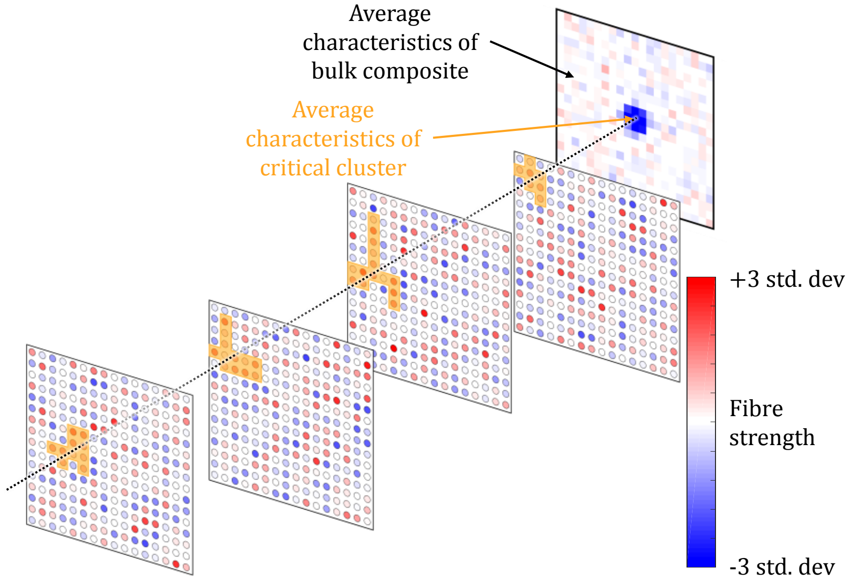


Figure 3: Each specimen is arranged such that the properties of the critical cluster can be averaged, enabling a comparison between the properties of the critical cluster and the bulk material to be made.

Figure 4 shows that the critical source of variability (i.e. the source of variability that leads to failure of the material) changes with each material system. 6 mm high strength carbon ADCs are susceptible to variability in carbon fibre strength (and also fibre overlap length, not shown); this is because fibre fragmentations (and matrix debonding) are caused by weaker fibres and shorter overlap lengths, which lead to final failure of this material. The 0.5 mm HSC/epoxy ADC is very dependent on the fibre-fibre overlap length, as short overlap lengths lead to widespread debonding in this case. Both long- and short-fibre hybrid ADC material systems were strongly dependent on the fibre-type arrangement; this is because grouping of low-elongation fibre-types creates large clusters of failed fibres at relatively low strains, leading to premature failure.

3.2 The influence of defects on structural performance

Figure 5 shows the influence of residual fibre fragmentation defects (ζ_{rff}), interface defects (ζ_{ri}), fibre vacancy defects (ζ_{v}), and fibre misalignment on the structural performance of aligned discontinuous composites. As shown in Figure 5a to Figure 5c, fibre vacancies are by far the most detrimental defect to the structural performance of all types of ADC. Figure 5d shows that small levels of misalignment (as in when the HiPerDiF method is used) have negligible influence on the stress-strain curve, whereas poor misalignment has a larger effect (but still not as significant as fibre vacancy defects).

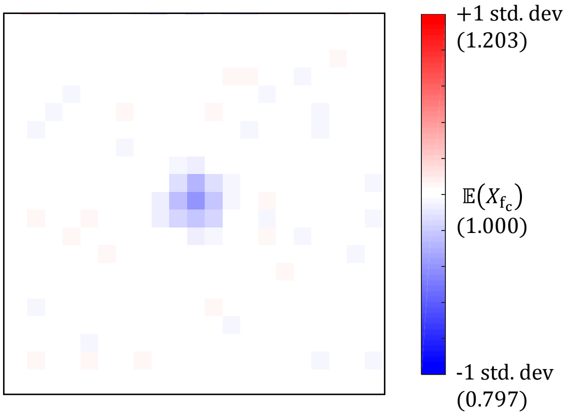
4. Conclusions

This paper further developed an efficient yet accurate Virtual Testing Framework to investigate the influence of variability and defects on the structural performance of aligned discontinuous composites. The following conclusions were drawn:

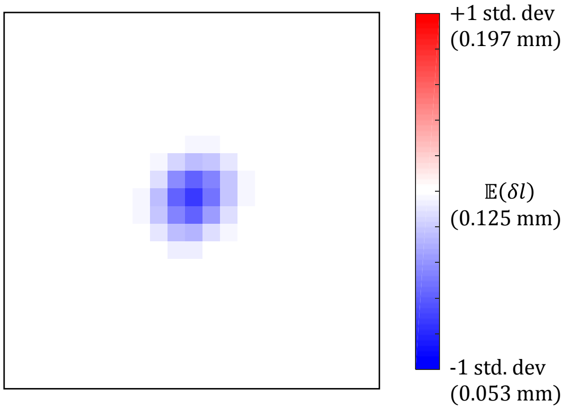
- A new fracture mechanics-based failure criterion was developed to predict not only fibre damage, but all forms of relevant damage (including contributions from matrix yielding / debonding, fibre fragmentation, and defects), hence achieving an accurate prediction of final failure in any type of aligned discontinuous composite (ADC).
- Property `heat maps' were used to identify the critical source of variability in each material system; using this technique it was proven that the critical source of variability (i.e. the source of variability that contributes most to final failure) changes with each material system. Long-fibre ADCs were most sensitive to fibre strength variability and the fibre overlap length, short-

fibre ADCs were most susceptible to the fibre overlap length, while both hybrid ADC material systems were dominated by the fibre-type arrangement.

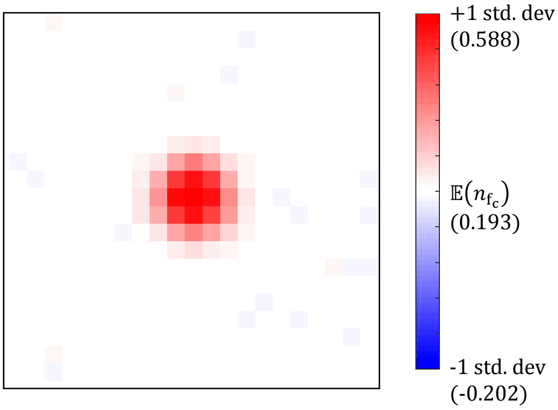
- Fibre vacancy defects proved to be the most critical defect (i.e. the defect that most readily promoted final failure). However, it was shown that hybrid ADCs are less sensitive to defects than non-hybrid ADCs.



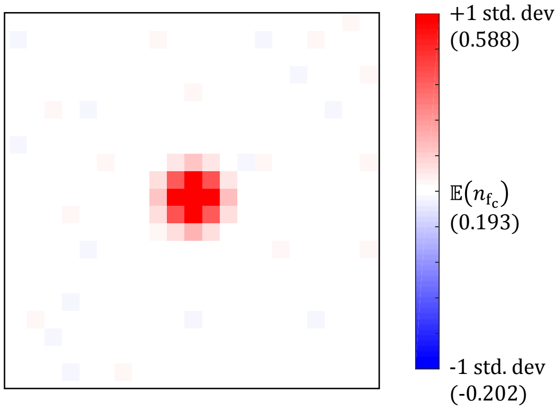
(a) 6 mm HSC/epoxy ADCs are susceptible to variability in (normalised) fibre strength (X_{f_c}).



(b) 0.5 mm HSC/epoxy ADCs are strongly dependent on variability in fibre overlap lengths (δl).

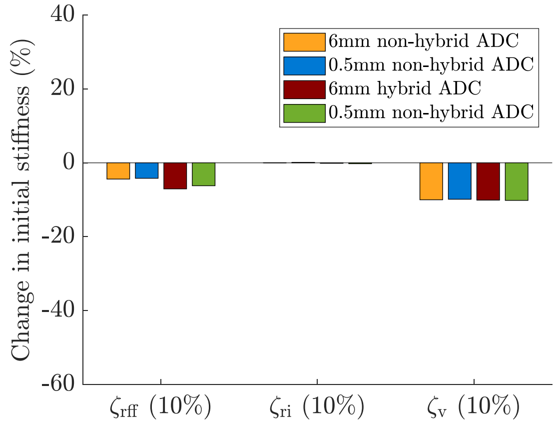


(c) 6 mm HMC/EG/epoxy hybrid ADCs are sensitive to variability in fibre-type distribution (where n_{f_c} is the number of carbon fibres).

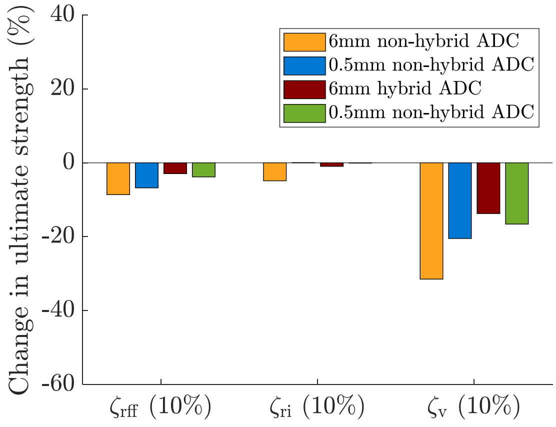


(d) 0.5 mm HMC/EG/epoxy hybrid ADCs are also sensitive to the fibre-type distribution (where n_{f_c} is the number of carbon fibres).

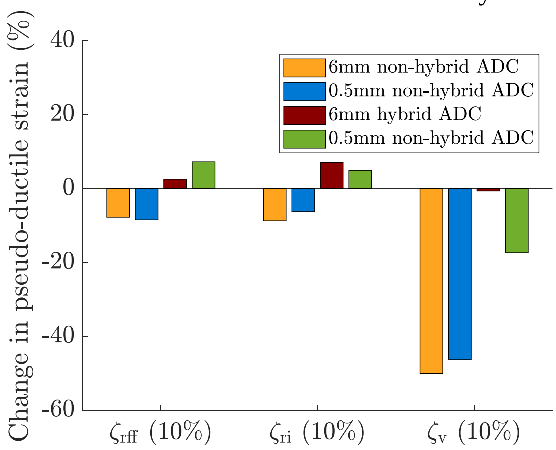
Figure 4: Different ADC material systems are most sensitive to different sources of variability.



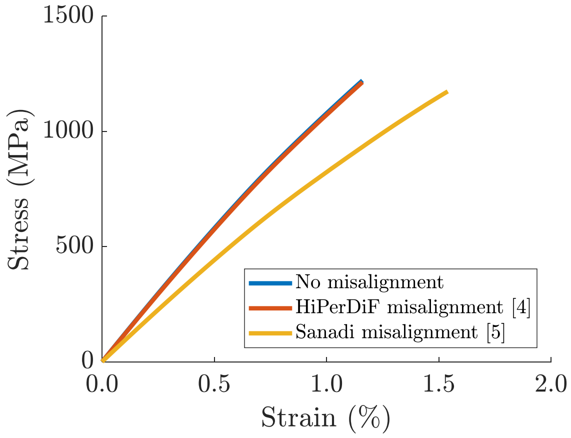
(a) The influence of residual fibre fragmentation defects, interface defects, and fibre vacancy defects on the initial stiffness of all four material systems.



(b) The influence of residual fibre fragmentation defects, interface defects, and fibre vacancy defects on the ultimate strength of all four material systems.



(c) The influence of residual fibre fragmentation defects, interface defects, and fibre vacancy defects on the pseudo-ductile strain of all four material systems.



(d) The HiPerDiF process produces good alignment and has little influence on the stress-strain curve of a 3mm fibre length HSC/epoxy ADC. The same cannot be said for other cases where alignment is poor.

Figure 5: Fibre vacancy defects provide the most significant reduction in material performance, while fibre misalignment has negligible influence provided the misalignment is small.

Acknowledgements

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