



Identifying microstructural features initiating compressive failure in unidirectional fibre-reinforced polymers

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ABSTRACT

The industrial applicability of advanced fibre-reinforced polymers (FRPs) is limited by their compressive performance. This study aims to uncover the microstructural features that influence unidirectional (UD) FRP compressive failure. This was undertaken through computational simulation of virtual 2D UD-FRP microstructures with systematically varying fibre misalignment angle θ^f field statistical and spatial parameters. For each FRP, the location of maximum matrix plastic strain at peak global stress was taken as the failure initiation site location. Locations of maximum θ^f , maximum fibre volume fraction V^f , and minimum V^f for each FRP were also identified; the typical microstructural (θ^f and V^f) features about such locations were compared against those of the failure initiation site locations. The results showed that UD-FRP failure initiation location could not be predicted using the magnitude of θ^f or V^f alone, and must include significant consideration of local spatial variation of the property fields as well. This study has highlighted the critical role of microstructural spatial patterns, in addition to the magnitudes of θ^f and V^f , in influencing the underlying micromechanics of UD-FRP failure initiation.

1. Introduction

While fibre-reinforced polymers (FRPs) have experienced rapid market growth in recent years [1,2], FRPs are notably limited by their compressive performance [2–4]. Hence, understanding the factors that contribute to FRP compressive failure is essential to design and optimise the next generation of energy-efficient, high-performing composite structures.

Failure by kink band formation (involving a combination of matrix or interfacial shear failure and localised fibre rotation and bending) has been established within the literature as the most common compressive failure mode in unidirectional (UD) FRPs with a thermoset polymer matrix and stiff fibres [5,6]. Matrix plasticity (i.e. yielding) has been consistently shown to be a precursor to FRP failure via kink band formation, both experimentally [7,8] and computationally [6,9]; in contrast, fibre fracture has been observed to be a post-failure (i.e. post-FRP peak strength) event rather than a part of the failure initiation process [6, 10]. While FRP compressive failure is an inherently 3-dimensional (3D) process, kink band formation has been well-established to predominantly occur within a 2-dimensional (2D) plane [8]. 2D computational modelling has been used extensively throughout literature [6,9,10] to

understand fundamental characteristics of the kink band formation process, with good agreement between experimental and computational results.

The inherent variability and randomness of FRP architectures hinders the identification of clear relationships between microstructure (e.g. local fibre misalignment angle fields θ^f) and FRP performance (e.g. longitudinal compressive strength X_c). Most existing literature has addressed this challenge by either focusing on global statistics of microstructural properties (e.g. maximum misalignment angle $\theta_{\max}^f$) [2,4], or introducing known defects with greater severity than those typical of industrial composites [11,12].

In UD-FRP laminates, fibre misalignment defects reduce X_c by 15% to 50% for $\theta_{\max}^f \leq 3^\circ$ [11,12], and up to 75% for $\theta_{\max}^f \geq 10^\circ$ [2,4,11]. Fibre misalignment spatial characteristics also influence X_c , with X_c decreasing with increasing transverse width of high- θ^f regions [3,12], as well as shorter local fibre wavelengths [13].

Unlike the monotonic relationship between θ^f and X_c , the effect of fibre volume fraction V^f on X_c follows a parabolic trend [10,14]. Optimal mean values ($\overline{V^f}$) were estimated to be ≈ 0.60 for carbon-FRPs [10], and ≈ 0.45 for glass-FRPs [14]. The spatial distribution of V^f was shown (computationally) to not have a significant effect on X_c [15].

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Nomenclature

Variables

Δ	Mesh size.
δ	Spatial resolution (FRP fields).
ϵ	Failure strain.
γ	Shear strain.
ϕ	Diameter.
σ	Standard deviation.
θ	Initial local misalignment angle
Θ	Averaged θ field centred about O_{crit}
Y	Averaged V field centred about O_{crit}
$\wp$	Fibre path representation of region centred about O_{crit}
A	Cross-sectional area.
E	Young's modulus.
G	Shear modulus.
H	FRP height.
L	FRP length.
l	Physical length.
l^0	Correlation length.
n	Number of elements.
N	Number of realisations.
O_{crit}	Critical position (identified by $_{\text{crit}}$ critical criterion)
S	Stress.
t	In-plane thickness.
w	Out-of-plane thickness.
V	Initial local volume fraction.
X	Strength.

Decorations (where b = dummy variable)

$ b $	Magnitude
$\bar{b}$	Mean

Descriptors (where b = dummy variable)

b^θ	Related to fibre misalignment angle.
b_c	In compression.
b^f	Related to fibre.
b_{fail}	Related to failure initiation.
b^m	Related to matrix.
b_{max} or $\max[b]$	Maximum.
b_{min} or $\min[b]$	Minimum.
b_p	Plasticity.
b_n	Normalised values.
b_x	Longitudinal fibre direction.
b_y	Transverse fibre direction.
$b^{\mathcal{S}\{\cdot\}}$	Related to specific dataset(s).
b^h	Dummy FRP realisation.

Coordinates

(l_x, l_y)	Coordinates in virtual FRP (in units of length, e.g. mm).
(x, y)	Coordinates in virtual FRP (dimensionless: $x = l_x/\delta_x$, $y = l_y/\delta_y$).
$(\xi_{\text{crit}}, \zeta_{\text{crit}})$	Shifted coordinates in virtual FRP, $(\xi_{\text{crit}}, \zeta_{\text{crit}}) = (l_x, l_y) - O_{\text{crit}}$

Most analytical models in the literature estimating X_c from FRP microstructural features involve severe idealisations, such as in-phase fibre geometry, which limit the models' accuracy. One approach is the model for failure of an infinite kink band proposed by Budiansky [5], assuming a linear-elastic (shear modulus G^{FRP}) and perfectly-plastic (shear yield strain $\gamma_{\text{yield}}^{\text{FRP}}$) composite:

$$X_c = G^{\text{FRP}} \cdot \frac{1}{1 + (\theta^f / \gamma_{\text{yield}}^{\text{FRP}})} \quad (1)$$

The composite parameters featured in most analytical models [5,6] are commonly limited to representative values of θ^f (with some models [6] considering additional fibre rotation during loading) and the average fibre volume fraction $\bar{V}^f$; the contribution of V^f is generally overlooked, with its role limited to its effect on G^{FRP} .

Generation of realistic FRP virtual microstructures has allowed better understanding of FRP compressive failure events and mechanisms (i.e. kink band formation and fibre fracture [16]) as well as effects of FRP microstructure (e.g. θ^f standard deviation [16,17] and size of highly misaligned defects [18]). The artificial generation methods of realistic 2D FRP θ^f fields include: (i) Gaussian random fields [18], (ii) manipulation of initially straight fibre paths (using Bézier curves) to match experimental θ^f distributions [16], and (iii) defining θ^f field spatial and statistical properties via a power spectral density (PSD) function [17]. For all methods, mean compressive strengths of the generated virtual FRPs agreed well with experimental results [16–18].

Computational simulation of virtual UD-FRP microstructures have been used in identifying critical defects: (i) Liu et al. [17] discretised virtual FRPs into regions of fixed width and either $\theta^f > 0$ or $\theta^f < 0$, subsequently determining the weakest region (i.e. failure location or critical defect) based on region size and θ^f ; (ii) Sutcliffe [18] identified failure location as the location of maximum absolute shear strain at peak global stress; failure was found to consistently initiate at locations where $\theta_{\text{fail}}^f \leq \theta_{\text{max}}^f$; (iii) Wilhelmsson et al. [19] identified failure location as the location where a matrix damage parameter (based on shear strains) first reaches 1; the magnitude of θ^f was found to most strongly correlate with defect severity; (iv) Takahashi et al. [20] identified failure initiation as the area where matrix yielding first occurs (from equivalent plastic strain), which was found to coincide with a location of high local V^f . However, the interaction between θ^f and V^f has been largely neglected in current critical defect models in the literature; spatial characteristics of regions around failure initiation sites (and their sensitivity to FRP microstructural variations) also remain inadequately characterised.

This work aims to uncover the underlying microstructural features influencing UD-FRP compressive failure, in terms of location and strength, through computational simulation of virtual 2D UD-FRPs with random fibre waviness. Nine UD-FRP datasets, with varying θ^f field statistical and spatial parameters, were studied. For each dataset, the microstructural (θ^f and V^f) features of FRP failure initiation sites, both at the localised point and in the region of interest surrounding it, were examined. Similar to the works of [18,20], the location of each FRP failure initiation site was taken as the location of maximum matrix plastic strain at failure (i.e. peak FRP global stress). Critical FRP locations based on literature-derived failure-promoting criteria (e.g. maximum θ^f) were also identified; the typical microstructure (θ^f and V^f) around such locations was compared against that of the true failure initiation site locations. The effect of FRP microstructure at critical FRP locations on compressive strength X_c was also examined. Engineering implications of the work's findings and directions for future work were discussed.

In existing literature similarly focused on identifying microstructural features of FRP failure initiation location (commonly referred to as the 'critical defect') [17,19], multiple potential defects are often first identified using some arbitrary thresholds, where one would be subsequently defined as truly 'critical'. However, this type of approach

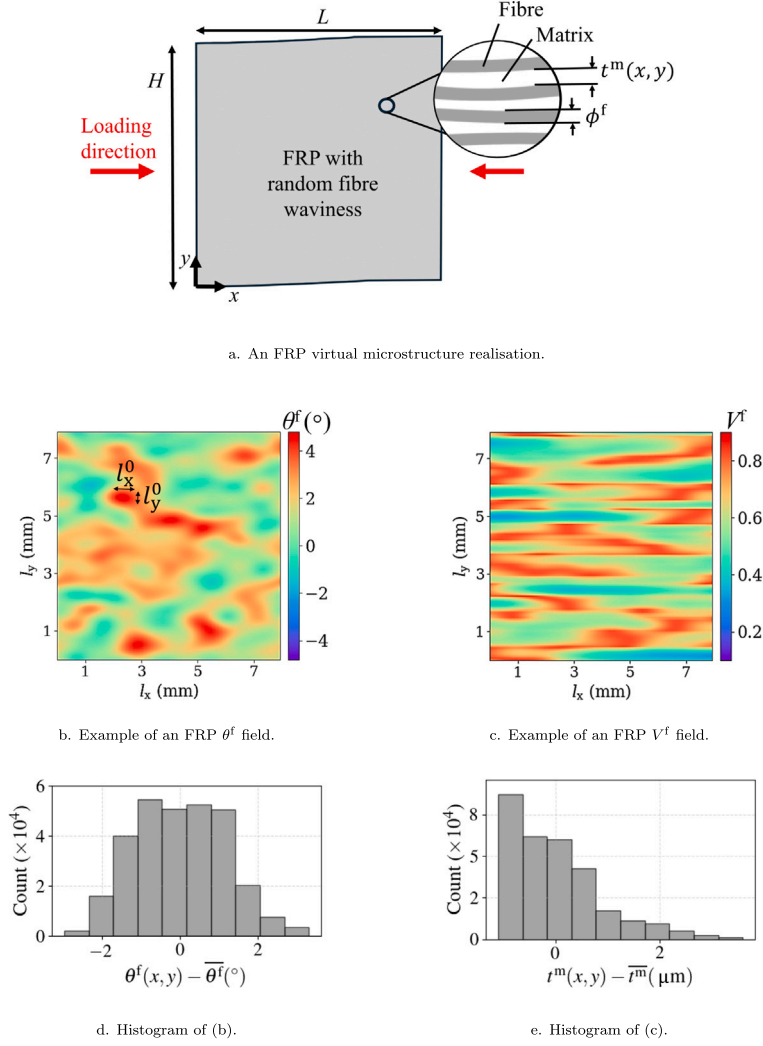


Fig. 1. Examples of an FRP virtual microstructure realisation.

imposes an implicit bias of how potential FRP failure initiation locations should be identified (e.g. a region where all $|\theta^f|$ magnitudes are above some threshold [19]), which may not be accurate. The approach presented in this work mitigates this bias by utilising a spatial averaging process (see Section 2.4), in which the microstructural features about the failure initiation location across multiple FRPs are averaged to reveal underlying common microstructural features.

2. Method

2.1. Virtual microstructure geometry

Virtual 2D FRP microstructures (Fig. 1(a)) were created to represent unidirectional FRPs, with geometrical parameters of Table 1.

The FRP coordinate system was defined with the x -axis aligned with the nominal longitudinal fibre direction, and y -axis with the transverse direction. The FRP property (θ^f and V^f) fields have $n_x = \frac{L}{\delta_x} = 324$ and $n_y = \frac{H}{\delta_y} = 920$ discretisations, with spatial resolutions $\delta_x = 3.5 \cdot \phi^f$ and $\delta_y = \phi^f + \bar{t}^m$, in the x - and y - directions respectively. (x, y) refers to the discretised dimensionless coordinate; $(l_x, l_y) = (x \cdot \delta_x, y \cdot \delta_y)$ refers to a spatial coordinate with dimensions of length.

The generation of the virtual FRP microstructures was based on the design of their $\theta^f(x, y)$ field (Fig. 1(b)), which follows the work of Liu

Table 1

FRP geometrical parameters.

Fibre diameter ϕ^f	Mean matrix thickness $\bar{t}^m$	Mean fibre volume fraction V^f	Length L	Height H
7 μm	1.6 μm^a	0.6	7.938 mm	7.912 mm

^a The nominal inter-fibre spacing of hexagonally-packed fibres with $V^f = 0.6$.

et al. [17]. FRP fibre paths were then determined by enforcing a fixed minimum matrix thickness $t_{\min}^m$ between each pair of adjacent fibres; the value of $t_{\min}^m$ was adjusted until the mean FRP matrix thickness $\bar{t}^m$ (defined in Table 1) was achieved. The $V^f(x, y)$ field of the FRP (Fig. 1(c)) was subsequently calculated. A more detailed description of the FRP microstructure definition method is presented in Appendix A.1.

The normal distribution of $\theta^f(x, y)$ (Fig. 1(d)) and exponential distribution of $t^m(x, y)$ (Fig. 1(e)) in the FRPs generated matched experimental observations of real FRPs [5,15].

2.1.1. Datasets

The baseline FRP dataset S{BL} had $N = 200$ FRP realisations. The θ^f field statistical and spatial parameters used (Table 2) were consistent with experimental observations of manufactured FRPs.

Table 2Parameters of θ^f field for baseline (S{BL}) FRPs [2,21].

Mean θ^f ($^\circ$)	Standard deviation σ^θ ($^\circ$)	x correlation length l_x^0 (mm)	Correlation length aspect ratio l_y^0/l_x^0
1.5	1.2	1.35	0.54

Table 3

FRP material parameters [22–24].

	Modulus (GPa)			Major Poisson's ratio
	Longitudinal	Transverse	Shear	
T300 carbon fibre	230	27.6	10.9	0.3
Epon862 epoxy	2.9	2.9	–	0.4

Table 4Matrix behaviour at characteristic points along the $S_{VM}^m - \epsilon_{VM}^m$ curve [24].

	Von Mises stress S_{VM}^m	Von Mises strain ϵ_{VM}^m	Matrix plastic strain ϵ_p^m
Peak	95.2 MPa	0.102	0.069
End	100.5 MPa	0.410	0.375

The spatial parameters defined were correlation lengths; correlation length l^0 (in a given direction) is a measure of the distance over which θ^f values remain similar, defining half the typical size of a high- or low- θ^f region within the FRPs (in that direction).

Eight variation datasets (with $N^{S\{Var\}} = 100$ FRP realisations each) were explored. The variation datasets were named according to the parameter changed (from Table 2) and the new value assigned:

- | | |
|--|-------------------------------------|
| (i) $S\{\bar{\theta}^f : 0.75^\circ\}$ | (v) $S\{l_x^0 : 1.08 \text{ mm}\}$ |
| (ii) $S\{\bar{\theta}^f : 3.0^\circ\}$ | (vi) $S\{l_x^0 : 1.69 \text{ mm}\}$ |
| (iii) $S\{\sigma^\theta : 0.5^\circ\}$ | (vii) $S\{l_y^0/l_x^0 : 0.4\}$ |
| (iv) $S\{\sigma^\theta : 1.5^\circ\}$ | (viii) $S\{l_y^0/l_x^0 : 1.1\}$ |

2.2. Materials

The virtual FRP microstructures were modelled as transversely isotropic linear elastic carbon fibres in an isotropic non-linear elastic-plastic epoxy matrix, with properties defined in Tables 3 and 4, and Fig. 2. Fibre failure was not considered, as FRP failure (given the materials defined) was expected to be matrix-dominated. Results supporting this assumption is later shown in Section 3.2.1.

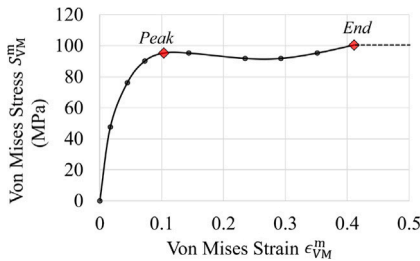


Fig. 2. Epoxy $S_{VM}^m - \epsilon_{VM}^m$ behaviour [24]; characteristic peak and end points highlighted.

2.3. Computational simulation

Finite element analyses (FEA) of the virtual FRP microstructures were performed using ABAQUS 2023. To allow for the most realistic representation of the failure initiation process, both fibre and matrix elements were modelled explicitly with continuum plane strain elements (element type CPE4R). The FEA computational model parameters are

Table 5

FRP computational model parameters.

Out-of-plane thickness ^a		Element size ^b		
Fibres	Matrix	Longitudinal	Transverse (fibres)	Transverse (matrix)
$\frac{A^f}{\phi^f}$	$\frac{1}{r^m} \cdot \left(\frac{A^f}{V^f} - A^f \right)$	δ_x	$0.5 \cdot \phi^f$	r^m

^a The fibre cross-sectional area is $A^f = \pi \cdot (0.5 \cdot \phi^f)^2$.

^b A mesh sensitivity study was conducted (Appendix B).

shown in Table 5. The matrix was simulated using Von Mises plasticity in ABAQUS. Material orientation for the anisotropic fibres was set to follow individual fibre paths.

To mitigate against edge-induced stress concentrations and premature edge-failures, transition regions (of size 10% L) with exponentially reducing θ^f (to 10% of initial value) were added to the transverse edges of each FRP. Uniform longitudinal compressive displacement loading was then applied at the transverse edges of the FRP microstructures (Fig. 1(a)). A single node at the bottom left corner of each FRP mesh was fixed in the transverse fibre direction to prevent rigid body motion. Riiks analysis, the most suitable method in ABAQUS for capturing unstable nonlinear failure, was used. An FRP model $h \in \{1 \dots N\}$ was deemed to have failed when a drop in longitudinal global reaction force R_x^h was observed, after which the following outputs were recorded:

- (i) FRP compressive strength

$$X_c^h = \frac{\max[R_x^h]}{n_y \cdot \left(\bar{r}^m \cdot w^m + A^f \right)} \quad (2)$$

where w^m is the out-of-plane matrix thickness defined in Table 5.

- (ii) Matrix equivalent plastic strain $\epsilon_{p, fail}^{m, h}(x, y)$ field at the loading increment corresponding to $\max[R_x^h]$.
 (iii) Location $O_{crit}^h = (x_{crit}^h, y_{crit}^h)$ of the following critical points:

- Point with maximum $\epsilon_p^{m, h}$ at X_c^h , used as proxy for the true failure initiation site of FRPs as FRP failure (by kink-band formation) is well-established in the literature to be matrix-failure-dominated [6–9], labelled as $O_{fail}^h = (x_{fail}^h, y_{fail}^h)$. Results supporting this assumption is later shown in Section 3.2.1.
- Point with maximum θ^f , widely considered to be significant in FRP failure initiation, labelled as $O_\theta^h = (x_\theta^h, y_\theta^h)$.
- Point with maximum V^f , to investigate the role of high V^f on FRP failure initiation, labelled as $O_V^h = (x_V^h, y_V^h)$.
- Point with minimum V^f , to investigate the role of low V^f on FRP failure initiation, labelled as $O_v^h = (x_v^h, y_v^h)$.

2.4. Determination of microstructural features typical of critical points

After the identification of critical points $O_{crit} \in \{O_{fail}, O_\theta, O_V, O_v\}$ for each virtual FRP, a spatial averaging process (similar to that employed in [25]) was conducted across each FRP dataset to highlight the associated microstructural features about such critical points (Fig. 3; more details in Appendix A.2.1). The outputs of this spatial averaging process are:

- $\bar{\theta}^f(\xi_{crit}, \zeta_{crit})$: the average θ^f field centred about critical point O_{crit} .
- $\bar{V}^f(\xi_{crit}, \zeta_{crit})$: the average V^f field centred about critical point O_{crit} .

The coordinate system $(\xi_{crit}, \zeta_{crit}) = (l_x, l_y) - O_{crit}$, with units of length. Hence, $O_{crit} = (x_{crit}^h, y_{crit}^h) = (\xi_{crit} = 0, \zeta_{crit} = 0)$.

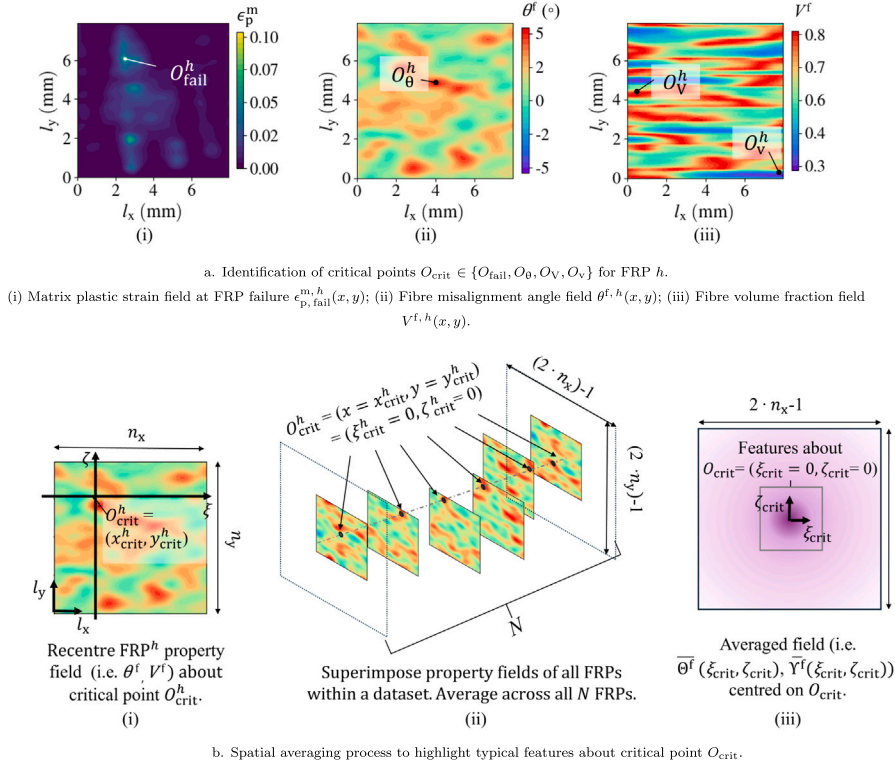


Fig. 3. Post-processing procedures.

The FRP property fields were also normalised (i.e. standard scaled) prior to the spatial averaging process, with output averaged fields $\bar{\theta}_n^f(\xi_{crit}, \zeta_{crit})$ and $\bar{Y}_n^f(\xi_{crit}, \zeta_{crit})$. In Sections 3 and 4, reference to high- and low- θ^f will refer to points where $\bar{\theta}_n^f > 0$ and $\bar{\theta}_n^f < 0$ respectively. Similarly, reference to high- and low- V^f will refer to points where $\bar{Y}_n^f > 0$ and $\bar{Y}_n^f < 0$ respectively.

Fibre path representations $\wp(\xi_{crit}, \zeta_{crit})$ of the averaged regions around the critical points were generated to illustrate their typical microstructure (method explained in Appendix A.2.2). The θ^f or V^f region of interest about the critical points was identified as the region about $O_{crit} = (\xi_{crit} = 0, \zeta_{crit} = 0)$ where $\bar{\theta}_n^f(\xi_{crit}, \zeta_{crit})$ or $\bar{Y}_n^f(\xi_{crit}, \zeta_{crit})$ magnitudes show significant variation respectively, with magnitudes ≈ 0 beyond its boundaries.

3. Results

3.1. Typical microstructure around critical microstructural points (O_θ, O_V, O_v)

Fig. 4 shows the typical microstructural features of the region of interest about critical points O_θ, O_V, O_v .

As shown in $\bar{\theta}_n^f(\xi_\theta, \zeta_\theta)$ of Fig. 4(a)(i), points of O_θ were typically within a high- θ^f region, as expected, of size $2 \cdot l_x^0$ by $2 \cdot l_y^0$. Points of O_V typically occurred within a high- V^f region, as expected, with low- V^f regions above and below it (Fig. 4(b)(ii)). Conversely, O_v typically occurred within a low- V^f region with high- V^f regions above and below it (Fig. 4(c)(ii)). In the transverse ζ direction, the size of the region of interest about both $\bar{Y}_n^f(O_v)$ and $\bar{Y}_n^f(O_v)$ was $\approx 3 \cdot l_y^0$, with the respective central high- and low- V^f portion being 1 to $1.5 \cdot l_y^0$. For both $\bar{Y}_n^f(O_v)$ and $\bar{Y}_n^f(O_v)$ regions of interest, no clear size in the longitudinal fibre direction could be established.

Fibre path representations $\wp(\xi_{crit}, \zeta_{crit})$ of the region of interest surrounding each critical point is shown in Fig. 4. $\wp(\xi_\theta, \zeta_\theta)$ (Fig. 4(a)(iii)) shows a bundle of highly misaligned fibres, with fibres away from this

central bundle (both above and below) being increasingly more aligned. This geometry creates the antisymmetric pattern of high and low fibre volume fraction observed longitudinally about $\bar{Y}_n^f(O_\theta)$ (Fig. 4(a)(ii)).

As shown in Figs. 4(b)(iii) and 4(c)(iii), locations of both O_V and O_v correlate well with locations between two adjacent fibre bundles, where one of which has a predominant fibre path that is perfectly antisymmetric to that of the other. These antisymmetric fibre paths are reflected in the pattern of high and low θ_f observed longitudinally about $\bar{\theta}_n^f(O_v)$ (Fig. 4(b)(i)), and the inverse of that pattern about $\bar{\theta}_n^f(O_v)$ (Fig. 4(c)(i)).

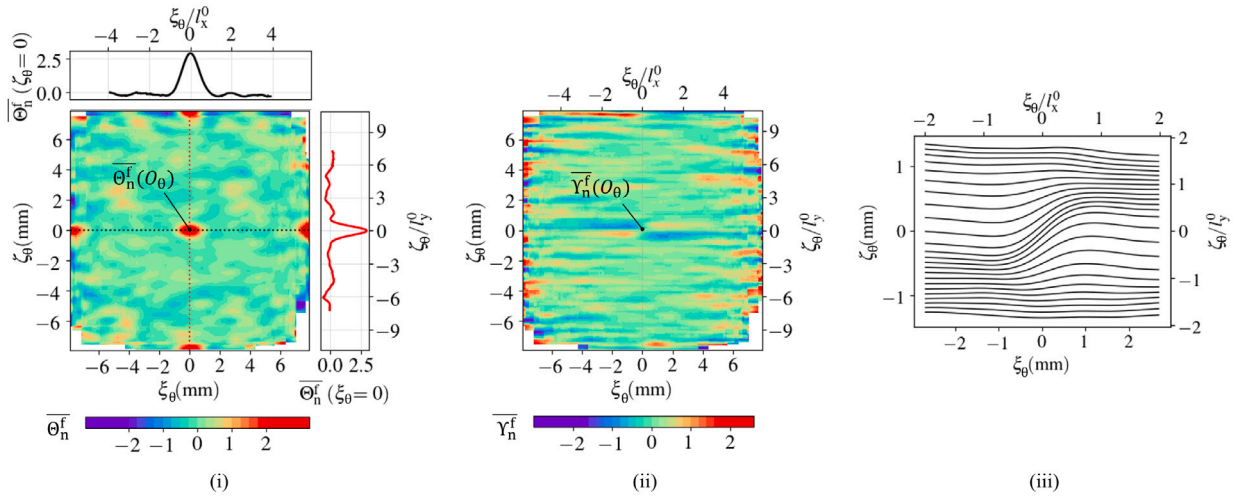
Similar observations about critical points O_θ, O_V, O_v were seen across all FRP variation datasets studied in this investigation (see Section 2.1.1).

3.2. FRP compressive performance

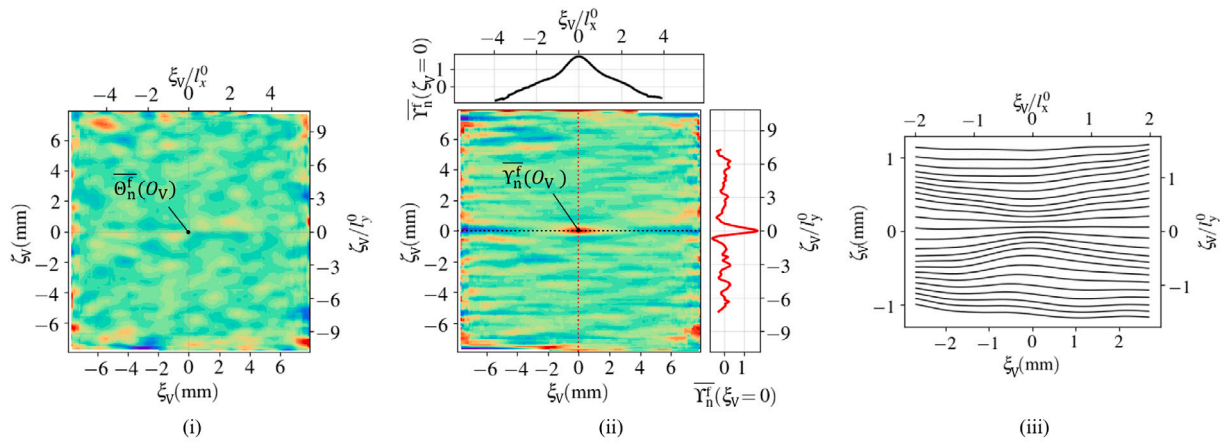
3.2.1. Stress-strain behaviour and compressive failure mode

The global stress-strain behaviour of a typical FRP realisation h under longitudinal compression is shown in Fig. 5(a). Corresponding matrix plastic strain $\epsilon_{p, fail}^{m, h}(x, y)$ and fibre longitudinal stress $S_{11}^{f, h}(x, y)$ fields at three distinct load increments are shown in Fig. 5(b).

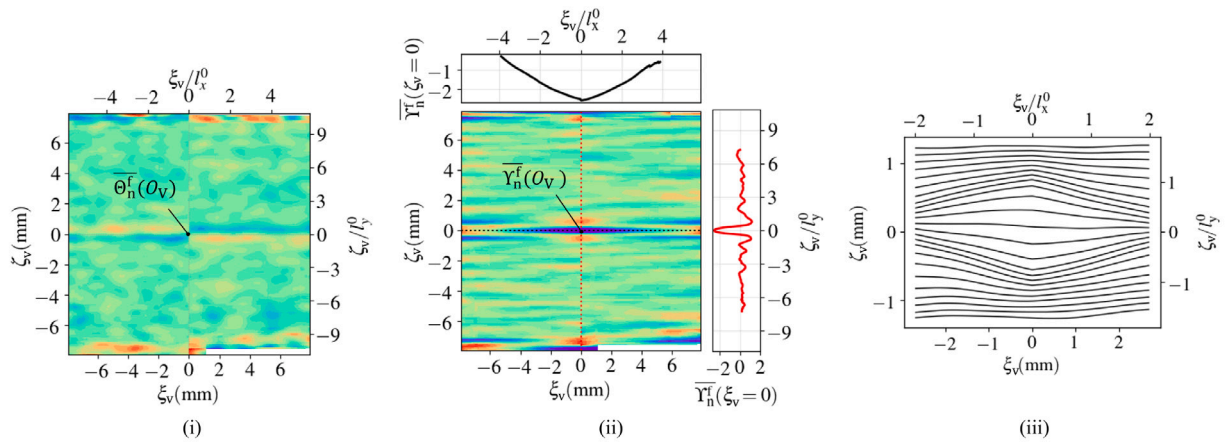
For the FRP of Fig. 5, at peak global stress (loading increment (ii)), $\max[S_{11}^{f, h}(x, y)] = 3.5$ GPa. With T300 carbon fibre strength of 3.7 GPa [22], fibre failure would not occur before the peak global FRP stress was reached. Across all FRPs studied, at peak global stress, $\max[S_{11}^{f, h}(x, y)] < 3.7$ GPa, justifying the omission of fibre failure in the FEA simulations. Therefore, failure of the FRP is matrix-dominated, due to kink-band formation (Fig. 5(b)); this kink-band initiates from the point of $\max[\epsilon_{p, fail}^{m, h}(x, y)]$ at X_c^h , as shown in Fig. 5(b)(ii). Similar results were seen across all the FRPs studied, which justified the selection of the failure initiation site O_{fail}^h of each FRP as the location of $\max[\epsilon_{p, fail}^{m, h}(x, y)]$. Fig. 6 show typical $\epsilon_{p, fail}^{m, h}(x, y)$ fields of the FRP datasets studied, which show similar localisations of matrix plastic strain at FRP failure.



a. Centred about O_θ : (i) average θ^f field $\overline{\Theta}_n^f(\xi_\theta, \zeta_\theta)^*$; (ii) average V^f field $\overline{\Upsilon}_n^f(\xi_\theta, \zeta_\theta)^*$; (iii) fibre path representation of the region of interest about O_θ $\phi(\xi_\theta, \zeta_\theta)$.



b. Centred about O_V : (i) average θ^f field $\overline{\Theta}_n^f(\xi_V, \zeta_V)$; (ii) average V^f field $\overline{\Upsilon}_n^f(\xi_V, \zeta_V)^*$; (iii) fibre path representation of the region of interest about O_V $\phi(\xi_V, \zeta_V)$.



c. Centred about O_v : (i) average θ^f field $\overline{\Theta}_n^f(\xi_v, \zeta_v)$; (ii) average V^f field $\overline{\Upsilon}_n^f(\xi_v, \zeta_v)^*$; (iii) fibre path representation of the region of interest about O_v $\phi(\xi_v, \zeta_v)$.

Fig. 4. $\overline{\Theta}^f(\xi_{\text{crit}}, \zeta_{\text{crit}})$, $\overline{\Upsilon}^f(\xi_{\text{crit}}, \zeta_{\text{crit}})$, and $\phi(\xi_{\text{crit}}, \zeta_{\text{crit}})$ associated with $O_{\text{crit}} \in \{O_\theta, O_V, O_v\}; \text{S[BL]}\}$. For clarity, only 10% of fibres are plotted in all $\phi(\xi_{\text{crit}}, \zeta_{\text{crit}})$ figures; $\phi(\xi_{\text{crit}}, \zeta_{\text{crit}})$ is not to scale. Colourbars in (a) apply to all $\overline{\Theta}_n^f(\xi_{\text{crit}}, \zeta_{\text{crit}})$ and $\overline{\Upsilon}_n^f(\xi_{\text{crit}}, \zeta_{\text{crit}})$. *For the characterisation of the region of interest size about O_{crit} , variation of $\overline{\Theta}_n^f$ and $\overline{\Upsilon}_n^f$ along (the central 75% of) axes $\xi_{\text{crit}}=0$ and $\zeta_{\text{crit}}=0$ is shown.

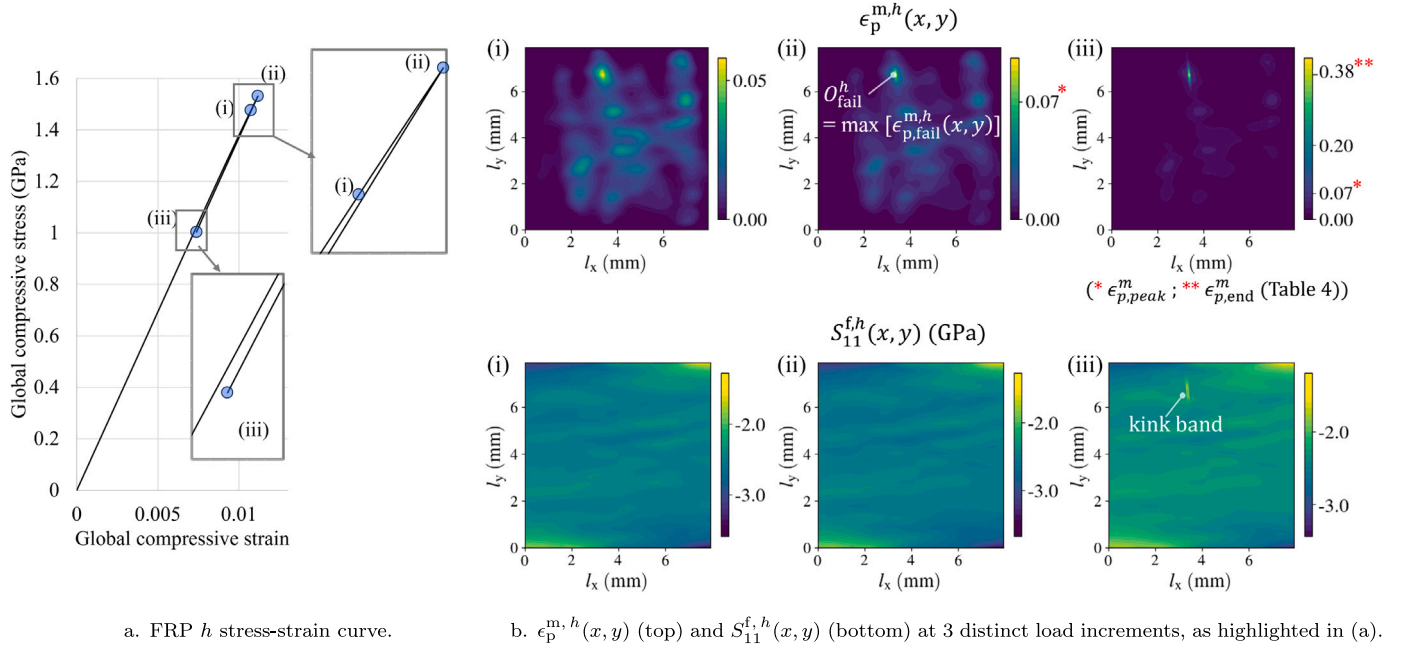


Fig. 5. Failure behaviour of a typical FRP (S{BL}). Load increments highlighted include: (i) just before peak global stress X_c^h , (ii) at X_c^h , (iii) when $\max[\epsilon_p^{m,h}(x,y)] \approx \epsilon_{p,end}^m$.

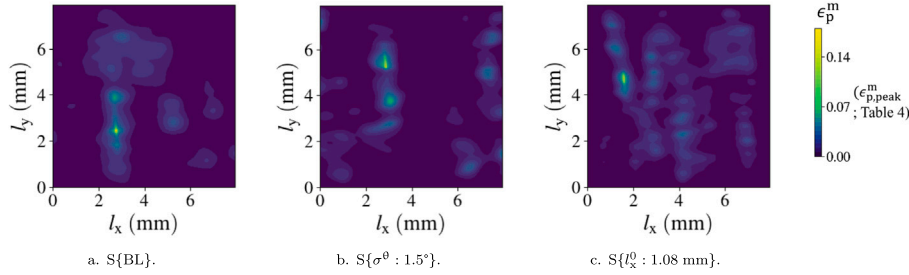


Fig. 6. $\epsilon_{p,fail}^m(x,y)$ fields for a typical realisation across several FRP datasets.

3.2.2. Effect of the microstructure of critical points on X_c

Figs. 7(a) and 7(b) show the relationship between X_c and $\bar{\theta}^f(O_{crit})$, where $O_{crit} \in \{O_\theta, O_{fail}\}$ respectively, for all FRP datasets studied. No meaningful trend between X_c and $\bar{\theta}^f(O_{crit})$ at any critical point studied was found (see Appendix C.2).

As expected from analytical models [5,6], there was a general inverse relationship between $\bar{\theta}^f(O_\theta)$ and X_c across the datasets explored (Fig. 7(a)). Notable observations were:

1. Datasets with varying $\bar{\theta}^f$ had the strongest inverse relationship between $\bar{\theta}^f(O_\theta)$ and X_c , followed by datasets with varying σ^θ , and subsequently datasets with varying l_x^0 (but see point 4).
2. Datasets with varying l_y^0/l_x^0 were an outlier to the general inverse trend, as X_c increased with $\bar{\theta}^f(O_\theta)$.
3. For $\bar{\theta}^f$, σ^θ , and l_y^0/l_x^0 variation groups, the $X_c - \bar{\theta}^f(O_\theta)$ relationships observed were found to be statistically significant. Statistical significance was evaluated by calculating the p -value for the linear-regressed $X_c - \bar{\theta}^f(O_\theta)$ slope (for each variation group) and testing if it differs significantly from zero; variation groups with trendline p -values < 0.01 were deemed statistically significant. Linear regression was used to assess the presence of meaningful relationships between the microstructure of FRP critical points and X_c for each FRP variation group (within the range of FRP microstructural parameters studied).

4. For datasets with varying l_x^0 , the large standard deviations in both $\bar{\theta}^f(O_\theta)$ and X_c (relative to the narrow range of mean values) cause the $X_c - \bar{\theta}^f(O_\theta)$ relationship observed to not be statistically significant.

Fig. 7(b) also showed a similar general negative correlation between $\bar{\theta}^f(O_{fail})$ and X_c , but with no outliers (i.e. all variation groups showed similar trends of decreasing X_c with increasing $\bar{\theta}^f(O_{fail})$). Aside from datasets with varying l_x^0 , all other $X_c - \bar{\theta}^f(O_{fail})$ relationships observed were found to be statistically significant. All datasets had larger standard deviations for $\bar{\theta}^f(O_{fail})$ than $\bar{\theta}^f(O_\theta)$.

Figs. 7(c) and 7(d) more clearly show how X_c is influenced by the spatial parameters l_x^0 and l_y^0 , which govern the size and aspect ratio of regions with correlated θ^f magnitudes. Fig. 7(c) shows the effect of size of such correlated regions, with opposing trends for the two dataset variation groups shown. Fig. 7(d) shows the effect of the aspect ratio of correlation regions, where a clear decreasing trend in X_c with increasing aspect ratio is observed. This suggests that the aspect ratio l_y^0/l_x^0 of correlated θ^f regions is a more significant microstructural parameter in influencing the compressive strength of FRPs than the size $l_y^0 \cdot l_x^0$ of such regions.

To compare the relative influence of each microstructural parameter on X_c , Fig. 8 shows the change in X_c across the range of each microstructural parameter explored. For effective comparison, the range

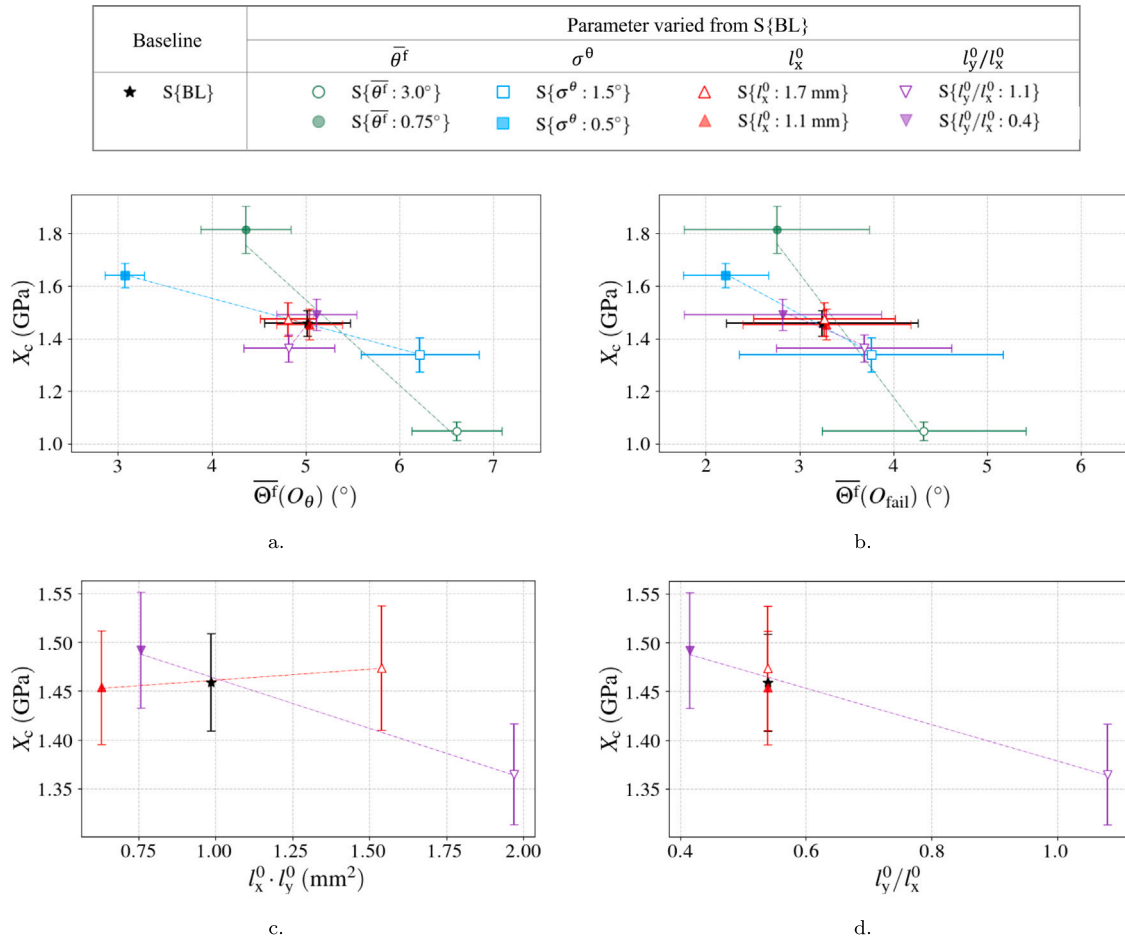
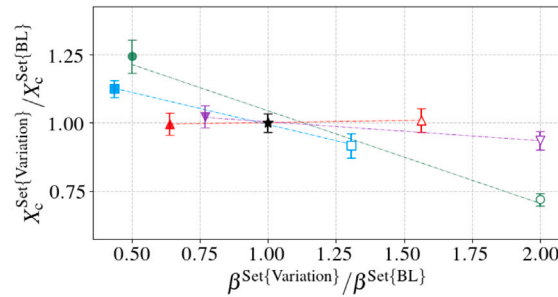


Fig. 7. Effect of the microstructure of critical points (a and b) and FRP spatial parameters (c and d) on X_c . Data points indicate mean values (calculated across each dataset), with error bars of $\pm$ one standard deviation. FRP datasets are grouped by variation in microstructural parameter; for all figures, dashed lines show linear regression for each variation group (all variation groups include S{BL}). Please note that the X_c -range is larger in subfigures a. and b. in comparison to c. and d.



	Parameter varied from S{BL} (β)			
	$\bar{\theta}^f$	σ^θ	l_x^0	l_y^0/l_x^0
Datasets	○ $S\{\bar{\theta}^f: 3.0^\circ\}$ ● $S\{\bar{\theta}^f: 0.75^\circ\}$	□ $S\{\sigma^\theta: 1.5^\circ\}$ ■ $S\{\sigma^\theta: 0.5^\circ\}$	△ $S\{l_x^0: 1.7 \text{ mm}\}$ ▲ $S\{l_x^0: 1.1 \text{ mm}\}$	▽ $S\{l_y^0/l_x^0: 1.1\}$ ▼ $S\{l_y^0/l_x^0: 0.4\}$
Trendlines*	—	—	—	—
Slope	-0.336	-0.237	0.015	-0.068
Std. dev.(slope)	0.005	0.006	0.006	0.004
p-value (with null hypothesis of slope =0)	$< 10^{-50}$	$< 10^{-50}$	0.0079	$< 10^{-50}$

* All trendlines consider ★ S{BL}

Fig. 8. Proportional effect of FRP θ^f microstructural parameters on X_c . For each parameter β , dashed lines show linear regression between $X_c^{S\{Var\}}/X_c^{S\{BL\}}$ and $\beta^{S\{Var\}}/\beta^{S\{BL\}}$ (all variation groups include S{BL}); the slope and associated standard deviation for each linear-regressed β trendline are quantified. Linear regression was used to test for the presence of a meaningful association between FRP θ^f microstructural parameters and X_c for the range of parameters explored, and is not suggestive of the underlying relationship being inherently linear.

of each microstructural parameter is presented as the ratio between the changed parameter value for each dataset and the corresponding baseline value (as in Table 2). A proportional change in microstructural parameter θ^f was shown to have the strongest effect on X_c , followed by σ^0 , and subsequently l_y^0/l_x^0 ; changes in l_x^0 had minimal effect (slope of trendlines in Fig. 8). All relationships were found to be statistically significant (trendline p-values < 0.01).

3.3. Microstructural features of failure initiation sites O_{fail}

3.3.1. Region of interest features

Fig. 9 shows the typical microstructural features of the region about O_{fail} ; FRP failure initiation was shown to typically occur in regions of high- θ^f , though $\bar{\theta}_n^f(O_{fail}) < \bar{\theta}_n^f(O_0)$, as well as of high- V^f ($\bar{Y}_n^f(O_{fail}) \approx \bar{Y}_n^f(O_V)$).

The patterns of θ^f common to the failure initiation sites O_{fail} (Fig. 9(a)) were in stark contrast to those of O_0 (Fig. 4(a)(i)), in terms of both shape and size. The size of the longitudinal region of interest about $\bar{\theta}_n^f(O_{fail})$ was ≈ 2 to $4 \cdot l_x^0$, with a high- θ^f ($\bar{\theta}_n^f > 0$) portion of $\approx 1.5 \cdot l_x^0$ (Fig. 9(a)). The size of the overall longitudinal region of interest about $\bar{\theta}_n^f(O_{fail})$ is larger than that of the region of interest about $\bar{\theta}_n^f(O_0)$; another key difference is the region of interest about $\bar{\theta}_n^f(O_{fail})$ has low- θ^f regions (Fig. 9(a)). Unlike the clear transverse size ($\approx 2 \cdot l_y^0$) for the region of interest about $\bar{\theta}_n^f(O_0)$ (Fig. 4(a)(i)), which is true across all FRP datasets, the transverse size of the region of interest about $\bar{\theta}_n^f(O_{fail})$ was inconsistent between datasets, with high- θ^f region transverse widths being typically $> 3 \cdot l_y^0$ (Fig. 9(a)).

In contrast, the patterns of V^f (Fig. 9(b)) typical of the region about O_{fail} were similar to those of O_V (Fig. 4(b)(ii)). Similar to the region of interest about $\bar{Y}_n^f(O_V)$ (Fig. 4(b)(ii)), the transverse size of the region of interest about $\bar{Y}_n^f(O_{fail})$ was ≈ 2 to $3 \cdot l_y^0$, with a high- V^f ($\bar{Y}_n^f > 0$) portion of $\approx 1.5 \cdot l_y^0$; sizing in the longitudinal fibre direction was also inconsistent between datasets, with the high- V^f portion being $> 3 \cdot l_y^0$ (Fig. 9(b)).

The averaged high- θ^f region about O_{fail} (Fig. 9(a)) was shown to be significantly wider transversely than longitudinally, indicating a region where many adjacent fibres are locally misaligned in-phase (Fig. 9(c)). Additionally, the regions of low- θ^f observed on either side (longitudinally) of the central high- θ^f region (Fig. 9(a)) indicate a region with sharp longitudinal changes in θ^f (i.e. short local fibre wavelengths). These geometric features are captured in $\varphi(\xi_{fail}, \zeta_{fail})$ (Fig. 9(c)).

The averaged high- V^f region about O_{fail} was shown to be significantly wider longitudinally than transversely (Fig. 9(b)). Low- V^f regions were observed above and below the central high- V^f region. These findings are suggestive of FRP failure localising within a region between two adjacent fibre bundles (with antisymmetric predominant fibre paths), where many (≈ 100) fibres are locally in close proximity while surrounding (above and below) regions have distinctly fewer fibres (Fig. 9(c)).

3.3.2. Relationship between microstructural features of different critical points

Considering all datasets, $\bar{\theta}^f(O_{fail}) \approx 0.63 \cdot \bar{\theta}^f(O_0)$ (Fig. 10(a)) and $\bar{Y}^f(O_{fail}) \approx 0.97 \cdot \bar{Y}^f(O_V)$ (Fig. 10(b)). This is consistent with results of Section 3.3.1, where O_{fail} was shown to typically occur in regions of high (but significantly lower than maximum) θ^f as well as high V^f .

For datasets with varying l_y^0/l_x^0 , $\bar{\theta}^f(O_{fail})$ decreased with increasing $\bar{\theta}^f(O_0)$, contradicting the general trend (Fig. 10(a)), though this relationship was not statistically significant. Even so, this suggests that changes in $\bar{\theta}^f(O_0)$ may not be a reliable predictor of changes in $\bar{\theta}^f(O_{fail})$ in the absence of changes in FRP θ^f field statistical distribution (i.e. mean or standard deviation). There were no such contradicting trends between $\bar{Y}^f(O_{fail})$ and $\bar{Y}^f(O_V)$ (Fig. 10(b)).

4. Discussion

4.1. Microstructural features typical of failure initiation locations

The main microstructural features identified to be associated with FRP failure initiation sites (for longitudinal compressive failure) were:

- | | |
|--------------|---|
| Feature I: | Higher magnitudes of θ^f . |
| Feature II: | Local θ^f field spatial patterns (Fig. 9(a)). |
| | <ul style="list-style-type: none"> • larger transverse width of high-θ^f region, than in the longitudinal direction. • shorter θ^f variation in the longitudinal fibre direction, than in the transverse direction. |
| Feature III: | Higher magnitudes of V^f . |
| Feature IV: | Local V^f field spatial patterns (Fig. 9(b)). |
| | <ul style="list-style-type: none"> • larger longitudinal width of high-V^f region, than in the transverse direction. • shorter V^f variation in the transverse fibre direction, than in the longitudinal direction. |

Feature I is the failure-associated feature most strongly suggested by literature for FRPs under uniaxial compressive loads [2,4,11]. However, if FRPs largely failed at O_0 (location with maximum θ^f), Figs. 4(a) and 9 would be similar.

From $\varphi(\xi_0, \zeta_0)$ of Fig. 4(a)(iii), the typical microstructure of the region about O_0 can be described as a distinct severely misaligned bundle of fibres, with bundle size (i.e. number of fibres) and wavelength defined by the correlation lengths of the FRP (l_y^0 and l_x^0 respectively). In contrast, from Fig. 9(c), the typical microstructure of the region about O_{fail} can be described as the region between two adjacent fibre bundles which have predominately antisymmetric fibre paths, but are locally in-phase and misaligned across a short fibre length. This creates regions of negative $\bar{\theta}_n^f$ on either side (longitudinally) of O_{fail} , which is not observed in the typical region about O_0 ; additionally, the size of the high- θ^f region about O_0 is notably wider than that of O_{fail} longitudinally, but less wide transversely (Figs. 4(a)(i) and 9(a)).

Therefore, it is clear that FRP compressive failure initiation typically does not occur in the same high- θ^f regions that contain O_0 , but rather occur in high- θ^f regions of lower magnitudes. This infers that the magnitude of fibre misalignment angle alone does not govern FRP compressive failure initiation location, and that the local θ^f field spatial patterns (Feature II), together with V^f field characteristics (Feature III and IV), also play a highly significant role. In existing literature [4, 12,20,26], FRP failure initiation has been observed to initiate from a region with a high density of misaligned, in-phase fibres, which is consistent with Features I-III identified in the present work.

For regions with higher V^f , or lower r^m , less fibre rotation would be needed for the local matrix region to experience high shear strains and undergo unstable shear deformation (resulting in failure localisation) than other regions with similar θ^f values but lower V^f . From the critical defect models in the literature, matrix shear strain is commonly used to identify critical failure initiation locations [18,19]. Hence, higher V^f magnitudes (Feature III) seem reasonable as a feature of FRP failure initiation sites.

The strong similarity between $\bar{Y}_n^f(O_V)$ (Fig. 4(b)(ii)) and $\bar{Y}_n^f(O_{fail})$ (Fig. 9(b)) suggest that the V^f spatial patterns identified (Feature IV) may be an incidental effect of Feature III, and not an independent failure-influencing microstructural feature. The FRP generation method used (Section 2.1) causes a direct link between the $\theta^f(x, y)$ and $V^f(x, y)$ fields of each FRP. Hence, the V^f spatial patterns (Feature IV) identified as typical of the region about O_{fail} may also be incidental of the θ^f spatial patterns identified (Feature II).

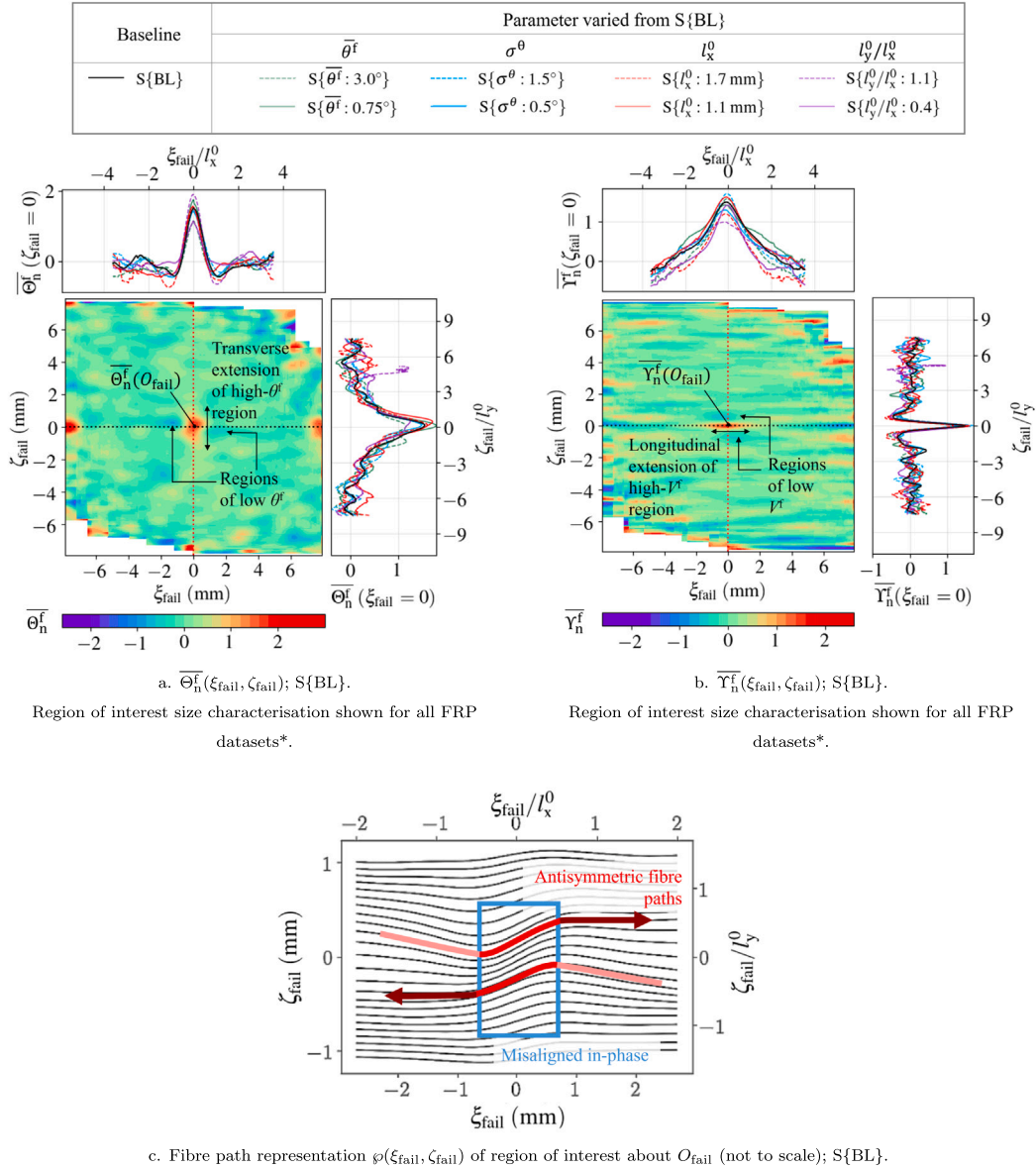


Fig. 9. Characterisation of region about failure initiation site O_{fail} .

*For effective characterisation of the region of interest size about O_{fail} across all datasets, the variation of $\bar{\theta}_n^f$ and $\bar{\gamma}_n^f$ values along axes $\xi_{fail} = 0$ and $\zeta_{fail} = 0$ for each dataset is shown against the normalised dimensionless parameters of ξ_{fail}/l_x^0 and ζ_{fail}/l_y^0 respectively. Averaged fields $\bar{\theta}_n^f(\xi_{fail}, \zeta_{fail})$ and $\bar{\gamma}_n^f(\xi_{fail}, \zeta_{fail})$ of the variation FRP datasets are shown in Appendix C.1.

4.2. Microstructural features influencing X_c

Both spatial (l_y^0/l_x^0) and statistical ($\bar{\theta}^f$ and σ^θ) microstructural parameters have been identified as influential on X_c (Fig. 8). With their likely interaction and interdependence in real FRPs, this might explain why there is often a large scatter in results for experimental studies aimed at correlating X_c to the variation of any single microstructural feature [2,4].

As predicted by analytical models for X_c [5] and long-established in the literature, increasing either $\bar{\theta}^f$ or σ^θ of FRPs negatively affects X_c (Fig. 8), as both increase $\bar{\theta}^f(O_0)$ (Fig. 7(a)), though $\bar{\theta}^f$ is more influential.

The negative trend between l_y^0/l_x^0 and X_c observed (Fig. 8) is in agreement with the conclusions of other works [3,19]. While Wilhelmsson et al. [19] reported the relative impact (on X_c) of $\bar{\theta}^f$ vs. the transverse width of high- θ^f regions being 2 vs. 1, the results of the current study indicate a ratio closer to 5 vs. 1 (as seen by the slope

of the trendlines shown in Fig. 8). The computational models used by [19] were based on θ^f observations from 2D non-crimp fabric FRP slices, which would likely have more distinct high or low θ^f regions and higher absolute θ_{max}^f values than the FRPs generated in this study, which may have had some influence on their conclusions.

The mild correlation between X_c and $l_x^0 \cdot l_y^0$ for datasets with varying l_x^0 (Fig. 7(c)) is primarily attributed to dataset S{ l_x^0 : 1.08 mm} containing more high- θ^f regions and hence more potential failure sites within the FRP model space than S{ l_x^0 : 1.69 mm}, leading to slightly lower X_c values. This suggests the effect of the overall size of correlated θ^f regions on X_c is purely statistical, rather than an effect on failure mechanisms.

While X_c generally decreased with increasing $\bar{\theta}^f(O_0)$ (Fig. 7(a)), the inverse trend was observed for datasets with varying l_y^0/l_x^0 ; the strength of this $X_c - \bar{\theta}^f(O_0)$ trend also differed between the FRP variation groups.

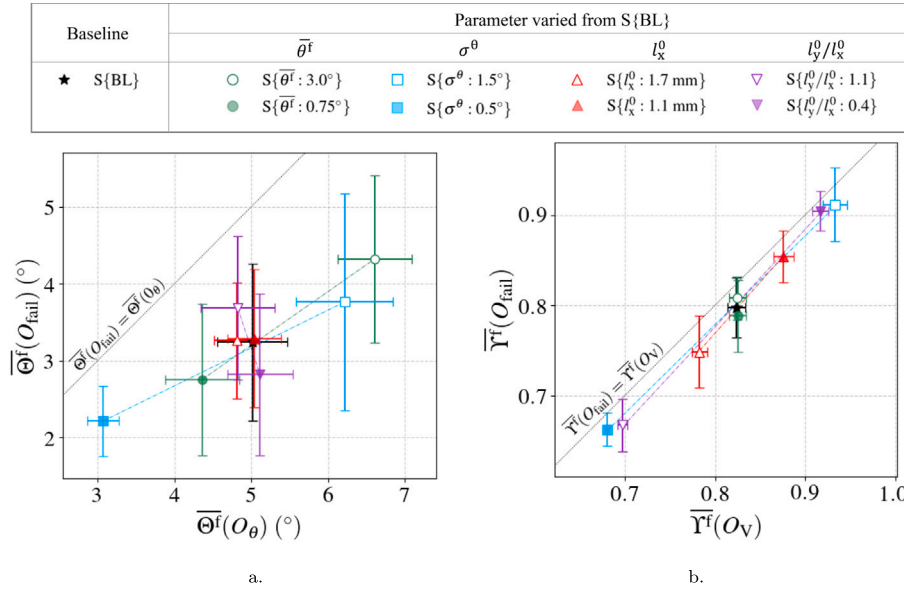


Fig. 10. Relationships between microstructural features of different critical points. Data points indicate mean values (calculated across each dataset), with error bars indicating $\pm$ one standard deviation. FRP datasets are grouped by variation in microstructural parameter; dashed lines show linear regression for each variation group.

These findings contradict the common conclusion within existing literature of $\bar{\theta}^f(O_0)$ (i.e. maximum fibre misalignment angle) being a strong or accurate predictor of FRP compressive strength [2,4].

The consistent trend of decreasing X_c with increasing $\bar{\theta}^f(O_{fail})$ (Fig. 7(b)) suggests that accurate identification of $\bar{\theta}^f(O_{fail})$ from the initial θ^f field of an FRP may be the most effective method to predict X_c , in comparison to using $\bar{\theta}^f(O_0)$ or any other statistical measure of θ^f fields. However, the identification of $\bar{\theta}^f(O_{fail})$ is clearly complex, as FRP failure initiation is shown to be influenced by multiple microstructural features (as described in Section 4.1), and its location cannot be captured by the value of θ^f at a single point; this is reflected in the large $\bar{\theta}^f(O_{fail})$ error bars of Fig. 7(b).

As no consistent trends between X_c and $\bar{Y}^f(O_{crit})$ at any critical point studied were found (see Appendix C.2), local volume fraction at critical points $O_{crit} \in \{O_{fail}, O_V, O_v\}$ can be concluded to not play a role in influencing FRP strength.

4.3. Engineering implications

Improving the understanding of microstructural factors influencing FRP failure is key to enabling safer and more efficient engineering solutions.

- In industry, FRP component quality assessments often rely on quantifiable maximum allowable defects. While θ_{max}^f is commonly considered [1], a more robust evaluation should include all microstructural features influencing FRP failure, in terms of both location (Section 4.1) and strength (Section 4.2). Existing evaluations of manufacturing methods [27] commonly involve the measurement of θ^f fields, with statistical measures such as $\bar{\theta}^f$ and σ^θ used to quantify the statistical distributions; inclusion of spatial measures (e.g. correlation lengths) in such studies would extend the usefulness of the data measured, providing a more robust overview of the method's manufacturing quality and effect on FRP strength (see Fig. 7(d)). Additionally, process- or manufacturing-based simulations are commonly conducted for critical automotive components, where the fibre misalignment angle field of the component can be estimated at the design or prototyping phase [28]; identification of potential failure initiation locations (via spatial correlation to the failure-promoting microstructural

spatial patterns of Section 4.1) during the early design phase can aid in the mitigation of catastrophic component failure as well as determination of the most suitable manufacturing parameters.

- For accurate digital twin construction or defect-effect studies of FRPs, both global statistics and spatial distributions of microstructural properties must be preserved to realistically capture failure behaviour. Hence, in the generation of realistic virtual FRPs, it is insufficient to simply ensure equivalent θ^f statistical distribution, as has been previously assumed in the literature [16].
- Improved understanding of FRP microstructural features influencing failure location and X_c can provide insights into how manufacturing processes affect performance. For example, the superior strength of thin-ply FRPs (by $\approx 10\text{--}20\%$ [29]) in comparison to standard-ply FRPs may be due to not only lower magnitudes of $\bar{\theta}^f$ or θ_{max}^f , but also from smaller aspect ratio of the correlated high misalignment regions l_y^0/l_x^0 in the out-of-plane direction (due to reduced ply thickness).

4.4. Limitations and future work

As kink band formation has been well-established in the literature to predominantly occur within a 2D plane [7,8,30], the present work has used 2D FE modelling to identify the microstructural features influencing FRP failure via kink band formation.

Even so, in real FRPs, the identification of this 2D kink plane is a 3D phenomenon. In other words, while kink bands do form within a 2D plane, their initiation has been shown to be 3D in nature (with 3D effects such as twisting being observed experimentally [8]). Hence, the findings of the present work can be further developed by extending the analysis to 3D computational models. However, this extension is not trivial, as (i) for the spatial averaging process (as described for the 2D case in Section 2.4) to reveal meaningful features, the kinking plane must be aligned between all FRPs, (ii) the high computational cost of 3D FE simulations (e.g. the micromechanical simulation of a 3D virtual FRP had been reported to require approximately 2 weeks with FRP microstructure size significantly smaller (40 fibres and 343 μm long) than those studied in the present work (see Section 2) [20]), and (iii) the complexities of generating 3D virtual FRP microstructures.

Unlike 2D θ^f fields, the generation of artificial 3D θ^f fields (which can be used to explicitly define fibre-matrix geometry) is complex

due to the interdependence of θ^f magnitude and phase. More practical methods of generating realistic 3D virtual FRP microstructures include (i) direct reconstruction of micro-CT (computed tomography) scans of real FRPs [8] and (ii) physics-based generation of random microstructures such as the method proposed by Seon and Makeev [31]. Characterisation of the FRP microstructural parameters (e.g. correlation lengths) would then be conducted after FRP generation.

The present work involved ≈ 1000 independent FE simulations of FRP failure; for a similar 3D analysis, more FRP realisations may be needed. To mitigate the time-intensive nature of 3D FRP modelling, more time-efficient modelling approaches could be used, such as the 'shell-beam' approach proposed by Bikos et al. [32].

The present study can also be extended via the consideration of other FRP microstructural defects, such as voids, as well as the effect of fibre (e.g. ϕ^f) and matrix (e.g. strength) material parameters on FRP failure.

5. Conclusions

Through computational simulation of 2D UD-FRP virtual microstructures and subsequent analysis of their compressive behaviour, microstructural (fibre misalignment angle θ^f and fibre volume fraction V^f) features influencing UD-FRP compressive failure location and strength have been identified and discussed. Key findings include:

- Aside from high θ^f values, features found to promote failure initiation include: (I) θ^f field spatial patterns: larger transverse width of high- θ^f region and shorter longitudinal θ^f wavelengths; (II) high V^f values; (III) V^f spatial patterns: larger longitudinal width of high- V^f region and shorter transverse V^f variation. These features were consistent across FRPs with varying microstructural parameters.
- The typical microstructure around FRP failure initiation sites differed significantly from that around points identified via literature-derived failure-promoting criteria: $\theta_{\max}^f$, $V_{\max}^f$, $V_{\min}^f$.
- FRP compressive strength X_c decreased with increasing aspect ratio (I_y^0/I_x^0) of correlated fibre misalignment regions, whereas changes in correlated region size ($I_y^0 \cdot I_x^0$) alone (without aspect ratio changes) had no significant effect.

Results from this investigation can be used to enhance predictions of FRP failure initiation, as well as guide the development of tailored microstructural designs to improve FRP compressive performance.

CRedit authorship contribution statement

H.L. Khoo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **R.S. Trask:** Writing – review & editing, Supervision. **S. Pimenta:** Writing – review & editing, Supervision, Methodology, Conceptualization. **P. Robinson:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.ijmecsci.2026.111709>.

Data availability

Data will be made available on request.

References

- [1] Kulkarni P, et al. An overview of the formation of fibre waviness and its effect on the mechanical performance of fibre reinforced polymer composites. *Compos Part A* 2020;137.
- [2] Wilhelmsson D, et al. An experimental study of fibre waviness and its effects on compressive properties of unidirectional NCF composites. *Compos Part A*. 2018;107:665–74.
- [3] Fleck NA, Shu JY. Microbuckle initiation in fibre composites: A finite element study. *J Mech Phys Solids* 1995;43:1887–918.
- [4] Joyce PJ, Moon TJ. Compression strength reduction in composites with in-plane fiber waviness. *Compos Mater: Fatigue Fract* 1998;7:76–96.
- [5] Fleck NA. Compressive failure of fiber composites. *Adv Appl Mech* 1997;33:43–113.
- [6] Pimenta S, et al. A micromechanical model for kink-band formation: Part II — analytical modelling. *Compos Sci Technol* 2009;69:956–64.
- [7] Pimenta S, et al. A micromechanical model for kink-band formation: Part I — Experimental study and numerical modelling. *Compos Sci Technol* 2009;69(7):948–55.
- [8] Wang Y, et al. Evolution of fibre deflection leading to kink-band formation in unidirectional glass fibre/epoxy composite under axial compression. *Compos Sci Technol* 2021;213.
- [9] Davidson P, Waas AM. Mechanics of kinking in fiber-reinforced composites under compressive loading. *Math Mech Solids* 2016;21:667–84.
- [10] Zhou L, et al. A micromechanical model for longitudinal compressive failure in unidirectional fiber reinforced composite. *Results Phys* 2018;10.
- [11] Nair SN, et al. Failure behavior of unidirectional composites under compression loading: effect of fiber waviness. *Materials* 2017;10:909.
- [12] Adams DO, Bell SJ. Compression strength reductions in composite laminates due to multiple-layer waviness. *Compos Sci Technol* 1995;53.
- [13] Kyriakides S, et al. On the compressive failure of fiber reinforced composites. *Int J Solids Struct* 1995;32:689–738.
- [14] Taheri-Behrooz F, et al. A new model for the determination of optimum fiber volume fraction under multi-axial loading in polymeric composites. *Iran Polym J* 2018;28.
- [15] Méchin P, et al. Influence of microstructure randomness on the shear behaviour and compressive strength of continuous carbon fibre composites. *Appl Compos Mater* 2024;31.
- [16] Varandas LF, et al. Micromechanical modelling of the longitudinal compressive and tensile failure of unidirectional composites: The effect of fibre misalignment introduced via a stochastic process. *Compos Struct* 2020;203.
- [17] Liu D, et al. Compressive strength of fibre composites with random fibre waviness. *J Mech Phys Solids* 2004;52:1481–505.
- [18] Sutcliffe M. Modelling the effect of size on compressive strength of fibre composites with random waviness. *Compos Sci Technol* 2013;88:142–50.
- [19] Wilhelmsson D, et al. Compressive strength assessment of fibre composites based on a defect severity model. *Compos Sci Technol* 2019;181.
- [20] Takahashi T, et al. Simulation on kink-band formation during axial compression of a unidirectional carbon fiber-reinforced plastic constructed by X-ray computed tomography images. *Adv Compos Mater* 2019;28(4):347–63.
- [21] Sutcliffe M, et al. Measurement of fibre waviness in industrial composite components. *Compos Sci Technol* 2012;72:2016–23.

- [22] Ueda M, Akiyama M. Compression test of a single carbon fiber in a scanning electron microscope and its evaluation via finite element analysis. *Adv Compos Mater* 2018;28:58–71.
- [23] Duan S, et al. Determination of transverse and shear moduli of single carbon fibres. *Carbon* 2020;158:772–82.
- [24] Sorini C. Multiscale modelling of polymer and ceramic matrix composites (Ph.D. thesis), Arizona State University; 2021.
- [25] de Geus T, et al. Microstructural topology effects on the onset of ductile failure in multi-phase materials – a systematic computational approach. *Int J Solids Struct* 2015;67–68:326–39.
- [26] Lemanski SL, Sutcliffe MPF. Compressive failure of finite size unidirectional composite laminates with a region of fibre waviness. *Compos Part A: Appl Sci Manuf* 2012;43(3):435–44.
- [27] Yurgartis SW. Measurement of small angle fiber misalignments in continuous fiber composites. *Compos Sci Technol* 1987;30(4):279–93.
- [28] Romanenko V, Duhovic M, Schommer D, Hausmann J, Eschl J. Advanced process simulation of compression molded carbon fiber sheet molding compound (C-SMC) parts in automotive series applications. *Compos Part A: Appl Sci Manuf* 2022;157:106924.
- [29] Galos J. Thin-ply composites a review. *Compos Struct* 2020;236.
- [30] Ueda Masahito, Mimura Kento, Jeong Tae-Kun. In situ observation of kink-band formation in a unidirectional carbon fiber reinforced plastic by X-ray computed tomography imaging. *Adv Compos Mater* 2016;25:31–43.
- [31] Seon G, Makeev A. A computer graphics-based method for efficient generation of 3D micromodels of CFRPs and investigation of the effect of random fiber misalignment phase on fiber-direction compressive strength. *Compos Sci Technol* 2026;277:111545.
- [32] Bikos D, Poh F, Trask RS, Robinson P, Pimenta S. Shell-Beam micromechanical models to improve the efficiency of simulations of composites under longitudinal compression. *Compos Struct* 2025;354:118830.