On longitudinal compressive failure of carbon-fibre-reinforced polymer: from unidirectional to woven, and from virgin to recycled

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Modelling the longitudinal compressive failure of carbon-fibre-reinforced composites has been attempted for decades. Despite many developments, no single model has surfaced to provide simultaneously a definitive explanation for the micromechanics of failure as well as validated predictions for a generic stress state. This paper explores the reasons for this, by presenting experimental data (including scanning electron microscopic observations of loaded kink bands during propagation, and brittle shear fracture at 45° to the fibres) and reviewing previously proposed micromechanical analytical and numerical models. The paper focuses mainly on virgin unidirectional (UD) composites, but studies for woven and recycled composites are also presented, highlighting similarities and differences between these cases. It is found that, while kink-band formation (also referred to in the literature as microbuckling) is predominant in UD composites under longitudinal compression, another failure mode related to the failure of the fibres can be observed experimentally. It is also shown that the micromechanics of the failure process observed in UD composites is similar to that in other fibre architectures, hence encouraging the adaptation and application of models developed for the former to the latter.

Keywords: kink band; composite; fracture; unidirectional; woven; recycled

1. Introduction

Longitudinal compressive failure has been a topic of research for several decades because of its significance in structural design. Different models have been proposed, based on microbuckling of the fibres [1] and on fibre kinking [2] (figure 1). Key developments to these theories have been put forward more recently [5–7]. Figure 1c shows failure predictions for longitudinal loading (σ11) combined with in-plane shear (τ12) for several models (polynomial, e.g. Tsai–Wu and maximum stress; physically based, e.g. Puck and LaRC05); see the study of Gutkin et al. [4] for a discussion.

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The experimental, numerical and analytical results presented in this paper highlight the physical processes underlying longitudinal compressive failure for a range of composites, focusing mainly on unidirectional (UD) composites (§2). Section 2a introduces experimental observations and finite-element (FE) micromechanical modelling results that support the development of a model for fibre kinking under pure longitudinal compression (also presented). Section 2b uses a similar approach to analyse kink-band formation for longitudinal compression superposed with in-plane shear. The two approaches complement each other, with the first one based on a plasticity model suitable for ductile resins, while the second one is based on principles of finite fracture mechanics more suited to brittle resins. Section 2c finally investigates a different failure mode under longitudinal compression: shear-driven fibre compressive failure. Similar work for woven composites is presented in §3 and for recycled composites in §4. The relation between the compressive failure mechanisms is discussed in §5 and conclusions are drawn in §6.

### 2. The physics of fibre kinking in unidirectional plies

#### (a) Pure longitudinal compression

**Experimental observations**

Using scanning electron microscopy, observations of loaded kink bands during propagation (figure 2; see also [8]) reveal how their formation is related to the development of microcracks in the matrix (label ‘m’ in figure 2c), which can coalesce into splits (label ‘c’ in figure 2c), and with fibre failure appearing only relatively late in the process. Carbon fibres eventually fracture because of the formation of shear bands (figure 3). It will be noted in §2c that shear-dominated fibre failure can also lead to another failure mode at the ply level, entirely different from fibre kinking.

**Micromechanical finite-element modelling**

In order to complement the qualitative experimental data detailed in §2a(i) and gather quantitative insight on local stress and displacement fields,
Figure 2. (a) Kink band propagating from right to left. (b) Damage and localization are visible ahead of the fully formed kink band. (c) Damage in the matrix and interface [8].

Figure 3. Failure mode of carbon fibres during kinking: shear bands form on the side of higher compressive stress at an angle approximately 45° with the longitudinal fibre direction [8].

kink-band formation and propagation were simulated using two-dimensional micromechanical FE models [3]. Several modelling approaches have been used: the initial geometry of the fibres was either sinusoidal or perfectly straight (figure 4), and different constitutive laws were investigated—cohesive or plastic formulations for the matrix, and elastic or failing fibre response.

The load versus displacement curves and the stress fields obtained (figure 5) can be correlated with the sequence of events during kink-band formation: matrix failure occurs immediately prior to the peak load, and fibre failure takes...
Figure 4. Micromechanical FE models for the simulation of kink bands, highlighting the initial shape of every 10th fibre: (a) baseline model with mesh detail; (b) model for kink-band propagation into the initially defect-free fibres [3].

Figure 5. The sequence of events for fibre kinking from the FE micromechanical models [3]. (a) Load $P$ versus fibre deflection $y$ (baseline FE model). Triangle, onset of matrix yielding; circle, definition of a full yield band; plus symbol, onset of outer fibre failure; cross symbol, onset of central fibre failure. (b) Stress fields in defect-free fibres during kink-band propagation. (Online version in colour.)

place only much later (on the side of higher compressive stress), after most of the load-bearing capability has been lost. These results are supported by the experimental evidence in figure 3; in addition, the fibre displacement fields obtained numerically compare well with those observed in specimens (figure 6).
(iii) Analytical modelling

An analytical model has been developed [9] to represent the mechanisms of kink-band formation under pure longitudinal compression, as observed experimentally (§2a(i)) and numerically (§2a(ii)).

The model is based on the equilibrium of a fibre with a sinusoidal imperfection \( y_0 \) along the length \( L \). Under longitudinal compression (load \( P \)), the fibre bends (deflection \( y \) and deformed shape \( y_T \)), while being supported in shear (stresses \( \tau \)) by an elasto-plastic matrix (figure 7a). Before the onset of matrix yielding, adjacent fibres are assumed to deform in-phase (IP); therefore, at each point \( x \) along the imperfection length, elastic shear strains in the matrix layers are related to the deformation of the fibre (deflection \( y \), rotation \( \theta \) and longitudinal displacement \( u \) in figure 7b). The onset of matrix yielding defines the peak load and the transition to a softening domain, during which a central band of perfectly plastic matrix grows as compression proceeds; the kink band is considered to be fully formed when fibre stresses \( \sigma_f \) locally reach the fibre compressive strength \( X_f^c \).

The analytical model predicts the load versus displacement curve and the deflection and stress fields accurately; the main events for kink-band formation are predicted by the model, and a good quantitative correlation with FE results.
Figure 8. Results from the analytical model for kink-band formation under pure longitudinal compression [9]. (a) Load $P$ versus fibre deflection $y$ from the analytical model. Triangle, onset of matrix yielding; circle, definition of a full yield band; cross symbol, onset of fibre failure; filled square, elastic domain (fibre stresses in (b)); filled diamond, softening domain (fibre stresses in (b)). (b) Maximum fibre stresses $\sigma_f$ along the fibre: analytical (solid lines) versus FE (dashed lines) results.

is also achieved (figure 8). Moreover, the analytical model leads to a closed-form prediction of strength as a function of initial misalignments, and to the computation of the kink-band width at the onset of fibre failure [9].

(b) Combined compression and shear

(i) Experimental observations

Experimental failure envelopes for longitudinal compression and in-plane shear are not always easy to interpret because of significant scatter (figure 9). However, it is apparent that different envelopes follow different trends: while the envelopes in figure 9a, b appear to be divided into two regions with two different slopes, the envelope shown in figure 9c appears to be characterized by only one (perhaps straight) segment, while in figure 9d, the scatter is too large to extract a reasonable trend. Therefore, figure 9 raises two questions: Why do similar materials follow different trends? Could the two apparent segments observed in certain envelopes correspond to two different failure modes?

(ii) Micromechanical finite-element modelling

To gain insight on the mechanisms involved in the failure envelopes shown in figure 9, micromechanical FE models have been developed. The FE model, shown in figure 10, shares similarities with those from §2a(ii), but because of the large number of simulations required to generate the failure envelopes, a unit cell of a matrix layer between two half-fibres is preferred. Periodic boundary conditions have been applied to the model to represent actual conditions in the

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Figure 9. Comparison of failure envelopes for longitudinal compression with in-plane shear, measured by four different research groups, showing high scatter and different trends [4]. Original data from earlier studies [10–13]. (a) Carbon/epoxy; (b) carbon/epoxy (T300/914C); (c) carbon/epoxy EXAS HST/DX 6002); and (d) carbon/vinyl ester.

Figure 10. Micromechanical FE model with periodic boundary conditions.
composite; the nodes on each top and bottom external boundary of the half-fibres are constrained so that their displacements in the $x$ and $y$ directions ($u$, $v$) follow

$$\forall x \in [0, L]: \begin{cases} u(x, y = d) = u(x, y = 0), \\ v(x, y = d) = v(x, y = 0) - V, \end{cases}$$

(2.1)

where $V$ accounts for Poisson’s expansion in the $y$ direction, and $d$ is the dimension of the unit cell in the $y$ direction. The model is then subjected to several combinations of longitudinal compression and in-plane shear [4]. The softening induced by matrix microcracking is represented using an elastic–plastic constitutive law for the matrix layer (with a yield strength $\tau_Y$) and the fibres use a continuum damage model, where the stress carried by a fibre in compression is reduced following a linear softening law once its strength is reached. The effect of imperfections such as initial fibre misalignment ($\theta_0$) is also considered.

The failure envelopes obtained (figure 11) show that fibre kinking occurs in composites with large fibre initial misalignments or high fibre compressive strengths, while fibre fracture can occur for materials with less significant fibre misalignments or lower fibre compressive strength $X_f^C$ (leading in these cases to bimodal failure envelopes as in figure 9a,b). Figure 12a,b shows that the FE model is able to reproduce accurately the different trends found experimentally [10,11].

For fibre kinking, the micromechanical FE models also give the width of the localized failure zone, i.e. the width of the kink band ($w$) non-dimensionalized by the fibre diameter ($\phi_f$; figure 12c). For the specific material properties used [4], the models predict that failure only localizes into a kink band for shear stresses lower than approximately 75 MPa; for higher shear stresses, failure therefore corresponds to fibre–matrix splitting. Despite the significant change in localization predicted by the FE models, the transition from fibre kinking to fibre–matrix splitting is not apparent in the numerical failure envelopes; as, for example, in the envelopes of figure 11, which correspond to the predictions of figure 12c. This also reflects the experimental findings in the study of Jelf & Fleck [10], shown in figure 12a, where the transition from fibre kinking to fibre–matrix splitting was reported for shear stresses greater than 50 MPa without any change in the trend of the failure envelope.

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For materials that exhibit a bimodal failure envelope for longitudinal compression combined with in-plane shear, failure under pure longitudinal compression \((\tau_{12} = 0)\) is predicted as fibre compressive failure, independent of fibre kinking. In figure 3, it is also observed that failure of carbon fibres (within a kink band) results from the formation of shear bands within the fibre at angles approximately \(45^\circ\) to the fibre axis, and it was therefore inferred in §2a(i) that fibre fracture was a shear-dominated process. The numerical predictions and experimental observations of fibre compressive failure appear to have the same origins, and §2c will discuss further how this relates to macroscopic shear failure in longitudinal compression.

(iii) Analytical modelling

Several theories can be used for failure predictions under combined longitudinal compression and in-plane shear; some results from these theories are shown in figure 1c. In this section, an analytical model capable of generating such envelopes is presented [14]. The experimental observations show that kink-band initiation results from the formation of matrix microcracks and splits in the inter-fibre region (figure 2). Therefore, the formulation of the present model is based on the hypothesis that the strength of the composite associated with fibre kinking is reached when the strain energy released per unit area of crack generated between an undamaged state and a damaged state is equal to the energy required to create the cracks (fracture energy).

To calculate the energy balance, a two-dimensional model with unit thickness is used. The two-dimensional model consists of a representative element of the kink band, i.e. a fibre of length \(w\) (kink-band width) embedded in a matrix (figure 13a), onto which compressive \((P)\) and shear \((S)\) loads are applied. The bending contribution of the fibres is neglected and the resin is assumed to carry only shear stresses \((\tau)\). The model can also account for fibre misalignment through the introduction of the variable \(\theta_0\) as well for a nonlinear response in shear. Further details on the derivations can be found in Gutkin et al. [14].

The model leads to an interaction between longitudinal and shear loading as shown in figures 13b and 14. Figure 13b shows that the analytical predictions compare well against the results from the micromechanical FE model presented.
Figure 13. (a) Equilibrium of a fibre under a longitudinal compressive force and a shear force at each end, as well as a distributed shear force across the length. (b) Comparison between analytical (§2b(iii)) and numerical (§2b(ii)) failure envelopes for linear and nonlinear shear responses [14].

Figure 14. Failure envelopes predicted by the analytical model (§2b(iii)) [14] against experimental data [10,11].

in §2b(ii) and figure 14 shows a good agreement of the analytical model against experimental results from the literature [10,11]. In figure 14b, the different levels of initial fibre misalignment corresponding to different datasets are suggested as the reason underlying the apparent scatter observed experimentally.

(c) Another failure mode for longitudinal compression: shear-driven fibre compressive failure

(i) Experimental observations

Another failure mode—brittle shear fracture at 45° to the fibres (figure 15)—was observed experimentally [8] through developments that allowed for a greater control over the loading process during initiation. For different layups and loading rigs, the 45° fracture plane is seen to form, propagate and only then degenerate into a kink band. The transition between shear-driven fibre compressive failure and fibre kinking is particularly sharp (figure 15).
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Figure 15. (a–d) Shear-driven fibre compressive failure as an independent failure mode that eventually leads to kink-band formation. (e) Bending failure of a fibre during kink-band formation. (f) Broken fibre in the shear-driven fibre compressive failure region [8].

It is hypothesized that this type of failure may be more common than expected, given that its occurrence is easily masked or lost because of the catastrophic and crushing nature of compressive failure. The different failure modes leave different features on the cross section of the broken fibres (figure 15e, f). For instance, fibre ends at the kink-band edges show a typical bending failure pattern, with

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transition: compressive shear failure to kinking

\[ X_C = 2500 \text{ MPa} \]

\[ X_C = 1300 \text{ MPa} \]

Figure 16. Complete failure envelope prediction for combined longitudinal compression and in-plane shear [14].

tensile (label ‘T’ in figure 15e) and compressive (label ‘C’ in figure 15e) failures separated by a neutral axis, while for shear-driven fibre compressive failure, the fibre ends are smooth and show significant abrasion (figure 15f).

(ii) Modelling

The modelling of shear-driven fibre compressive failure can be easily achieved using a maximum shear criterion in the first instance, resulting in combined envelopes for shear-driven fibre compressive failure/fibre kinking/splitting as shown in figure 16.

3. Compressive failure in woven composites

(a) Experimental observations

Experimental studies analogous to those on UD composites were carried out for woven composites [15].

Different reinforcement architectures were tested under compression: 2 × 2 twill and five-harness (5H) satin. Kinking was identified as the mechanism responsible for the failure of the load-aligned tows (figure 17a). The latter has a structural role within the reinforcement architecture, highlighted in figure 17b, where tows are observed to fail individually. Moreover, the reinforcement architecture was seen to affect the failure morphology and immediate sequence of events [15]. One of the observed differences in failure morphology is highlighted in figure 18; while 2 × 2 twill tows tended to fail at the centre of the crimp region (\(d \approx 0\)), 5H satin tows failed systematically at a distance \(d \neq 0\) from it.

In a two-dimensional woven laminate, shifting between adjacent layers is usually not controlled, leading to a random configuration (figure 19a). Upon
Figure 17. (a) Tow failed by kinking; (b) several tows failing individually [15].

Figure 18. Differences in failure location between different reinforcement architectures: 2 × 2 twill and 5H satin [15]. (a) 5H satin: tows failed at a distance $d \neq 0$ from the centre of the crimp region. (b) 2 × 2 twill: tows failed at a distance $d \approx 0$ from the centre of the crimp region.

Figure 19. Cross sections of (a) random-stacked, (b) IP and (c) OP laminates. (Online version in colour.)
compression, adjacent layers will naturally interact. This interaction, namely the out-of-plane support provided by the adjacent layers, was also investigated. Several specimens were produced with carefully aligned adjacent layers in an IP configuration, i.e. all load-aligned tows of adjacent layers are IP (figure 19b). Figure 20 shows that the failure morphology changes significantly with the support provided by the adjacent layers. As highlighted previously, tows behave as structural elements within the reinforcement architecture; under compression, the out-of-plane support provided by the adjacent layers affects the bending of the tows and consequently the failure morphology. This effect was also seen to be a function of the reinforcement architecture [15].
At the microscale, compressive failure of woven composites occurs according to the process previously described for UD composites: microcracking/plasticity of the matrix between fibres (within the tows or at the interface between tows and pure matrix regions) leading to kinking/splitting (figure 21).

(b) Numerical and analytical modelling

An FE model of a $2 \times 2$ twill reduced unit cell (rUC) was developed [16] (figure 22a). The rUC used is the smallest possible domain that can be used to analyse a $2 \times 2$ twill geometry, while applying the correct periodic boundary conditions both in-plane and out-of-plane [19]. In the out-of-plane direction, two sets representing different cases of out-of-plane support were applied: (i) in-phase (IP), where all load-aligned tows of adjacent layers are IP, and (ii) out-of-phase (OP), where all load-aligned tows of adjacent layers are OP (figure 19b,c), respectively. These two cases define practical limits of support that any layer can have within a laminate, where adjacent layers are randomly shifted. The tows are modelled as an orthotropic material, with the material orientations following the central path of the tow. The matrix is considered to be an elasto-plastic material and its response is modelled using a linear Drucker–Prager plasticity model. Additionally, the debonding between tows and matrix is accounted for and modelled through the definition of cohesive contact. The longitudinal compressive failure is predicted using a kinking model [20], developed for UD materials, applied at the tow level. The use of such a model to predict the compressive failure of woven composites is in agreement with what is found...
experimentally, where compressive failure is seen to occur by kinking of the load-aligned tows (figure 17). The material is assumed to fail when failure of the load-aligned tows is detected using the referred criterion.

With the insight gathered from both experimental and numerical investigations, an analytical model was also developed \[17,18\] (figure 22b). It consists of an Euler–Bernoulli beam supported by an elastic foundation. The beam represents the load-aligned tow and is regarded as a UD composite. The elastic foundation provides both normal and torsional support, and its properties are derived from kinematic models that account for: weave effect, case of support provided by the adjacent layers (IP or OP), and elastic properties of the tows and matrix (figure 23).

The weave effect (figure 23a) is accounted for by considering that the IP adjacent tows affect the deflection of each other through the shearing of the matrix connecting them. The latter is obtained by realizing that the deflection of adjacent tows can be related, taking into account that equivalent positions in adjacent tows displace in the same fashion \[19\]. Having determined the shearing of the connecting matrix, the distributed load exerted in a given tow by the adjacent tows can be approximated by

\[
p_{\text{weave}}(x) = 2 \left( y_0 + \bar{t}_{\text{tow}} \right) \frac{G_m}{g} v(x),
\]

where \( y_0 \) is a geometrical parameter (figure 22b), \( \bar{t}_{\text{tow}} \) represents the average tow thickness over the cross section of the tow, \( g \) is the gap between adjacent tows, \( G_m \) is the shear modulus of the matrix and \( v(x) \) is the deflection of the tow.

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Figure 23. Kinematic models used to derive the properties of the elastic foundation [17,18]. (a) Weave effect: shearing of the matrix connecting in-plane adjacent tows (of the same woven layer); \( v_l \), \( v_c \) and \( v_r \) represent the deflections of the tows \( T_l \), \( T_c \) and \( T_r \), respectively; \( \gamma_{cl} \) and \( \gamma_{cr} \) are the shear strains of the matrix connecting \( T_c \) to \( T_l \) and \( T_r \). (b) In-phase: shearing of the material between load-aligned tows of adjacent layers. (c) Out-of-phase: straining (through-thickness direction) of the material between tows of adjacent layers. (Online version in colour.)

The kinematic model that accounts for the IP support is illustrated in figure 23b. In this case, the support is essentially provided by the shearing of the material (matrix and transverse tows) between load-aligned tows. Assuming that all load-aligned tows from adjacent layers displace in an identical fashion (figure 23b), the shear strain of the material between tows can be obtained from
geometrical considerations, as a function of the tow deflection. Knowing the shear strain, the shear stress applied to a given tow can be determined by

$$\tau_{\text{IP}}(x) = G_h \left(1 + \frac{\bar{t}_{\text{tow}}}{h}\right) \frac{dv}{dx}, \quad (3.2)$$

where $G_h$ is the modulus of the material between tows, homogenized using the rule of mixtures, and $h$ is the average thickness of the material between tows. Additionally, the gradient of equation (3.2) leads to a direct pressure applied to the tow given by

$$p(x) = -\frac{d\tau}{dx} h b_{\text{tow}}, \quad (3.3)$$

where $b_{\text{tow}}$ is the width of the tow. This gradient is obtained from the equilibrium of the material between tows [18].

In the OP configuration (figure 23c), the support is mainly provided by the straining of the material between load-aligned tows because of their deflection in opposite directions. Similar to the IP case, the strain of the region between tows can be obtained from geometrical considerations (figure 23c). Knowing the strain, the pressure $p_{\text{adj}}$, applied by the load-aligned tows of the adjacent layers, is obtained by:

$$p_{\text{adj}} = 2v(x) b_{\text{tow}} \left(\frac{E_h^{\text{Top}}(1 - \nu_h^{\text{Top}})}{(1 - \nu_h^{\text{Top}})(1 - 2\nu_h^{\text{Top}})h_{\text{Top}}} + \frac{E_h^{\text{Bot}}(1 - \nu_h^{\text{Bot}})}{(1 - \nu_h^{\text{Bot}})(1 - 2\nu_h^{\text{Bot}})h_{\text{Bot}}}\right), \quad (3.4)$$

where $E_h^{\text{Top/Bot}}$ and $\nu_h^{\text{Top/Bot}}$ are the homogenized Young’s moduli and Poisson’s ratios, and $h_{\text{Top/Bot}}$ is the distance between the adjacent tows. The superscripts ‘Top’ and ‘Bot’ refer to the regions above and below a given tow, respectively.

Finally, the governing differential equation is derived in a general fashion from the analysis of the equilibrium of a beam element (figure 24):

$$\frac{d^4 v(x)}{dx^4} + \lambda_{1,\text{IP/OP}}^2 \frac{d^2 v(x)}{dx^2} + \lambda_{2,\text{IP/OP}}^2 v(x) = -\lambda_3^2 \frac{d^2 y_0(x)}{dx^2}, \quad (3.5)$$

where $\lambda_{1,\text{IP/OP}}$ are a function of the case of support (IP/OP) considered, and $y_0(x)$ is the initial shape of the tow.

Figure 25a compares the numerical and analytical results for the shear along the tow centreline obtained for the IP case. The good agreement indicates that the analytical model developed captures well all the key features of the weave response under compression. Figure 25b compares the numerical and analytical compressive strength predictions with the experiments. The numerical and analytical predictions are obtained by averaging the strength predictions for the IP and OP cases. The analytical and numerical models show accurate strength predictions (within the scatter of the experiments). Nevertheless, the numerical model shows better agreement with experiments. This is attributed to the more accurate stress fields obtained numerically and to the modelling of the nonlinear response of the matrix. It is worth highlighting that the nonlinear material response can be included in the analytical model. However, the governing differential equation would have to be solved iteratively or numerically, thus...
4. Compressive failure in recycled composites

(a) Introduction

In recent decades, the exponential increase in the use of carbon-fibre-reinforced polymer (CFRP) has motivated the development of recycling technologies for the ever-increasing amount of CFRP waste produced. It is suggested that recycling...
CFRP can bring environmental and economic benefits over the traditional methods of landfilling and incineration. Recent studies [21] have also shown that recycled (r-) CFRP can replace traditional materials, with weight savings in selected structural applications, such as non-safety-critical components in the aeronautical and automotive industries currently manufactured with aluminium or glass-fibre.

Recycled composites are manufactured by re-impregnating recycled carbon fibres with a new resin. The recycling step typically consists of a thermal or chemical process to break down the matrix and release the valuable carbon fibres, either from end-of-life components or from manufacturing waste.

Owing to the reprocessing, recycled composites present distinct features from those of their virgin precursors, namely regarding the micromechanical properties of constituents (fibres and interface) and the reinforcement architecture. Such specificities require the development of dedicated material models and design methods for rCFRPs. However, despite their significant differences, the mechanisms involved in the compressive failure of recycled composites share many features with UD and woven composites (detailed in §§2 and 3). This section discusses similarities and differences between the compressive failure of two types of rCFRP and their virgin counterparts.

(b) Short-fibre recycled composites

Most rCFRPs have a short-fibre randomly oriented architecture. However, in contrast to most virgin short-fibre composites, the recyclates typically present a multi-scale reinforcement architecture, with individually dispersed fibres and fibre bundles; these bundles are held together by residual matrix not removed during the recycling (figure 26).
Compressive failure of recycled composites with such architecture is complex [17]. In areas with no bundles (figure 27a,b), a fracture plane starts to form at low angles ($\beta < 20^\circ$) and then rotates up to approximately $54^\circ$ through plastic deformation of the matrix. In areas with bundles, the failure process resembles the failure of tows in woven composites: isolated bundles fail by bending (figure 27c), while kink bands are formed whenever neighbouring bundles provide sufficient support (figure 27d).

(c) Woven recycled composites

To further investigate the effect of fibre recycling on the performance of rCFRPs, samples of out-of-date woven prepreg were recycled under different pyrolysis conditions, and re-impregnated into woven rCFRPs, mimicking the architecture of the virgin composite (the 5H satin analysed in §3). Both virgin and recycled materials were characterized at the filament and composite levels [23].
Figure 28. Mechanical response of a woven rCFRP: the compressive performance at the recycled composite level is shown to be insensitive to fibre strength degradation, occurring in the most aggressive recycling conditions. (a) Recycled fibre properties: retention of modulus ($E_T$) and strength ($X_T$) relative to virgin fibre. (b) Recycled CFRP tensile properties: retention of modulus ($E_T$) and strength ($X_T$) relative to virgin composite. (c) Recycled CFRP compressive properties: retention of modulus ($E_C$) and strength ($X_C$) relative to virgin composite. (d) Morphology of compressive failure.

In spite of the severe fibre strength degradation that occurs during the most aggressive reclamation cycles, fibre stiffness remained relatively unchanged (figure 28a); these results at the filament level were directly replicated on the tensile performance of the composite (figure 28b). However, the compressive strengths of the rCFRP and virgin CFRP were statistically the same (figure 28c), and the failure features are remarkably similar (figure 28d).

The fact that the compressive strength of a woven CFRP is independent of its tensile strength—at both fibre and composite levels—sugests that fibre kinking is indeed governed by the failure of the resin or fibre–matrix interface, rather than by the tensile failure of the fibres themselves. Moreover, it was shown that rCFRPs can assume unique combinations of mechanical properties, underlining the need for specific models and design methods for these materials.
5. Overall discussion

It is found that there are two competing mechanisms for longitudinal compressive failure in UD composites: the widely documented kink-band formation (also referred to in the literature as microbuckling), and (the much less documented) shear failure of the fibres at an approximately 45° angle to the loading direction. Both mechanisms can be described analytically by resolving the stress field at the fibre and matrix level, with the fibres idealized as beams, leading to predictions for failure stresses and morphologies in agreement with experimental observations.

Despite their more complex architecture, woven composites under longitudinal compression exhibit similar failure morphologies to those in UD composites, thus suggesting similar mechanisms (compare figures 2 and 15 for UD to figures 20 and 21 for woven). The analytical treatment is in this case made more difficult not only by the morphology of the weave, but also by the uncertainty related to the exact stacking configuration, and hence through-the-thickness support provided to a given layer. Analytical models for extremes of this support (IP and OP stacking), whereby the tows are idealized as beams, are however shown to accurately capture the stress fields within the tows. In turn, combining these stress fields in the tows with models for fibre kinking originally developed for UD composites lead to compressive strength predictions in agreement with experiments and FE results. This confirms that the failure mechanisms for UD and woven composites under longitudinal compression are intrinsically physically similar.

Recycled composites that preserve the original woven architecture of the weave hold the potential to provide further insight into the validity of analytical models. In fact, a common denominator for fibre kinking models (those presented herein but also most in the literature) is that strength depends strongly on the strength/toughness of the matrix and interface, but not on the strength of the fibres. By varying the thermo-chemical parameters of the recycling process, it is possible to manufacture different recycled woven composites that are essentially the same, but with varying fibre strength. Experimentally, it was found that reducing the fibre strength by approximately 80 per cent has virtually no effect on the compressive strength of the composite (figure 28a–c), while it has, obviously, dramatic effects in tension. Additionally, the morphology of the failure process in these woven composites with much lower tensile fibre strength (figure 28d) is remarkably similar to that in virgin woven composites (figures 20 and 21). This finding, obtained using recycled composites, provides a strong indication for the wide range of applicability of the models currently available for fibre kinking in virgin UD and woven composites.

Recycled composites also present a wealth of novel reinforcement architectures; this offers new challenges for both understanding and modelling their compressive failure. One such type of architecture consists of a matrix reinforced by randomly dispersed short fibres and bundles of different dimensions (figure 26), effectively providing reinforcement to the matrix over several scales. The bundles in these materials exhibit failure mechanisms similar to those in UD (compare figure 27 with figures 2 and 15) and woven composites (compare figure 27 with figures 20 and 21). This suggests that analytical models for compressive failure of these novel materials ought to be based on the same principles adopted for the traditional architectures.
6. Conclusions

The first part of this paper presents experimental and micromechanical FE studies, which were conducted with the aim of developing analytical models for longitudinal compressive failure in UD composites. Predictions from such models are shown to compare favourably with the numerical and experimental results. The existence and importance of a shear-driven fibre compressive failure mode under longitudinal compression is highlighted, as it is shown to be critical for explaining different trends observed in experimental failure envelopes.

Woven composites show some similarities to UD composites in their longitudinal compressive failure modes. In particular, it is shown that, once the stress field is resolved in the tows, fibre kinking models originally developed for UD composites can be successfully applied to woven composites. However, in obtaining the stress field in the tows, woven composites also show some added complexity, such as the dependence of the failure process on the through-the-thickness support provided by the adjacent layers.

Experimental results using woven composites with very weak recycled fibres suggest that the longitudinal compressive strength of woven composites does not depend on tensile fibre strength. This finding is in agreement with the models presented, which do not depend on that variable for fibre kinking. The similarities in the longitudinal compressive failure processes of different materials, regardless of their exact microstructure, suggest that knowledge and experience gathered in recent decades in analysing advanced composites appears to be very valuable for the analysis of novel types of composites, such as recycled composites with multi-scale fibre bundle reinforcement.

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References

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