STUDY OF COMpressive FAILURE IN MULTidIRECTIONAL FIBRE-REINFORCED COMPOSITES

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Summary

In this study the compressive failure of multidirectional fibre-reinforced composites was investigated. Cross-ply (CP) and multidirectional (MD) compact compression (CC) specimens were tested to identify the failure mechanisms that occur during compressive loading. Experimental results and subsequent fractographic analysis revealed that the layup significantly influenced the performance of both CP and MD fibre-reinforced composites under compression. Delamination and in-plane shear fracture dictated the failure processes. The sequence of failure events that led to global fracture is presented. The findings have important implications for predictive modelling of compressive failure and crack arrest.

1 Introduction

Even though composites offer superior mechanical properties to other materials, their performance under compression is relatively poor. In addition to this, the anisotropic nature of composites coupled with the interactions that develop between fracture mechanisms lead to a complex failure process. In fibre-reinforced composites loaded in compression, three critical failure mechanisms have been identified, however these often act in combination[1]:

1. Damage through the ply thickness due to fibre microbuckling or kinking (translaminar fracture)
2. Matrix cracking (intralaminar fracture)
3. Delamination (interlaminar fracture)

In unidirectional composites, failure is dominated by translaminar fracture of the load-bearing (0°) fibres[2-7], which are mainly attributed to fibre microbuckling and kink band formation. During these processes, considerable matrix deformation is accompanied by a high degree of fibre rotation. There has been a debate as to whether kinking is the irreversible stage of elastic fibre microbuckling[6] or a failure mechanism in its own right[3, 5, 8, 9]. However recent studies suggested that matrix cracking (ply splitting) occur prior to fibre microbuckling and kink-band formation[7].

In multidirectional composites, the failure process is much more complex[10-16]. Whilst the load-bearing (0°) plies carry most of the stress, it is the off-axis plies that greatly influence the compressive behaviour, and these fail before the load-bearing plies. In-plane shear and ply splitting are the most dominant failure modes occurring in angle plies. Consequently the fracture in these plies dictates the failure of the load-bearing plies. MD laminates are also more prone to interlaminar fracture[17-20]. As soon as delamination develops, the laminate is split in two or more sub-laminates which consequently deform independently. Delamination is generally the most dominant failure mechanism in MD composite laminates.

Even though, there is an adequate understanding of individual failure mechanisms that can occur during compression failure, the interaction between these mechanisms and the effect of layup on these failure processes is yet to be thoroughly investigated. The study reported here aimed to address this, with the aim of supporting model development and tailoring of laminates to inhibit crack growth.

2 Experimental

2.1 Materials

For this study Hexcel IM7/8552 unidirectional pre-preg tape was used, with a nominal ply thickness of 0.125mm and fibre volume fraction of approximately 60%. This system which is widely
used in the aerospace industry, had longitudinal compressive and in-plane shear strengths of 1690MPa and 113Mpa respectively, and longitudinal compressive and in-plane shear moduli, 150GPa and 5.31GPa respectively.

2.2 Manufacturing and specimen configuration
Four panels with dimensions 430mm x 300mm were manufactured according to the supplier’s recommendations, each composed of 32 plies with different layups: two cross-ply and two multidirectional: (0/90)$_{8S}$, (90/0)$_{8S}$, (0/90/45/-45)$_{4S}$ and (-45/45/0/90)$_{4S}$.

The specimen configuration (compact compression, CC) that was used in this study, was similar to that employed by Pinho[21] to measure the translaminar fracture toughness associated with kind-band formation. To make the CC specimens, the panels were cut with a wet saw to dimensions 60mm x 65mm (Fig.1). Holes for loading pins were then drilled and a semi-circular notch, extending 31mm from the free edge, was introduced using a 4mm wide diamond-coated saw. Finally a speckle pattern was painted on the specimens’ surface to facilitate digital image correlation (DIC).

2.3 Experimental setup
Compressive testing was conducted in a 10-tonne servo-hydraulic Instron machine, equipped with a 10 kN load cell, using 1mm/min stroke. Linear Variable Differential Transducers (LVDT) were attached to the loading pins to record displacement during loading.

Along with load-displacement readings, Digital Image Correlation (DIC) was used to measure the surface deformations. Three specimens of each layup configuration were tested.

2.4 Post-failure examination
To facilitate fractographic examination, selected specimens were dissected using a dry saw to produce rectangular sections of 30mm x 20mm that enclosed the damaged area (Fig.2a).

Initially optical microscopy was employed to investigate the damage distribution and the positions of the dominant failure mechanisms and their interactions. To achieve this, the fracture patterns of each different configuration were examined at the notch and 15.5 mm away from the notch (Fig.2b,c). Failed specimens were then examined using Scanning Electron Microscopy to provide a more detailed insight into the various failure mechanisms and compare with the findings from the optical microscopy examination. The approach taken was to compare the fracture surfaces of a reference specimen(baseline configuration), (90/0)$_{8S}$, at the notch and 10.8mm away from the notch, with fracture surfaces from the other specimens.

Fig.2. (a) Section used for fractographic analysis; (b) Polished CC specimen configuration; (c) Optical microscopy specimen configuration; (d) Dissected CC specimen section; (e) SEM specimen configuration.

Fig.1. Compact Compression Specimen Configuration
3 Results and Discussion

3.1 Compressive testing

Cross-ply and multidirectional configurations behaved in a different manner during failure. The multidirectional configurations exhibited a stiffer elastic response than the cross-ply configurations, although for a given type (i.e. cross-ply or multidirectional), the elastic response was almost independent of the layup (Fig.3). The elastic modulus and failure load for the multidirectional configurations were approximately 20% higher than that of the cross-ply configurations, but exhibited a more complicated failure process (see Fig.3), indicating that the presence of angle plies and the different layup greatly influenced the compressive behavior.

Initially nominally identical (90/0)_{8S} specimens were compared to investigate the inherent variability on the compressive failure processes. Although the behavior was identical in the elastic region, the fracture propagation was slightly different.

In the case of the cross-ply configurations, the baseline cross-ply configuration, (90/0)_{8S} was approximately 7% stronger than the (0/90)_{8S} configuration. As can be seen in Fig.3, once the peak load has been reached, the fracture propagation was more progressive in the baseline cross-ply configuration.

However, the incorporation of the angle plies enhanced the compressive strength and stiffness although the difference between the two multidirectional configurations was not significant.

The baseline multidirectional configuration (0/90/45/-45)_{4S} was approximately 5% stronger than the (-45/45/0/90)_{4S} configuration but exhibited higher scatter.

3.2 DIC

Whilst the specimens were loaded in compression the surface deformations were recorded, using DIC. Fig.4 and Fig.5 illustrate the surface strain distributions (ε_y) in the direction of the load-bearing fibres (0°) and the in-plane shear strain distributions (γ_{xy}).

![Fig.4. DIC normal strain distribution just prior to the crack initiation in (a) (90/0)_{8S}, (b) (0/90)_{8S}, (c) (0/90/45/-45)_{4S} and (-45/45/0/90)_{4S} configurations.](image1.png)

![Fig.5. DIC shear strain distribution just prior to the crack initiation in (a) (90/0)_{8S}, (b) (0/90)_{8S}, (c) (0/90/45/-45)_{4S} and (-45/45/0/90)_{4S} configurations.](image2.png)

As can be seen in Fig.4 the normal strain distribution around the notch in the (0/90)_{8S} configuration was higher than that in the (90/0)_{8S}, but the shear strains...
were lower. As for the multidirectional configurations, the normal strains were higher than those observed in the cross-ply configurations but the shear strains were lower (Fig.5). As Fig.4 and Fig.5 clearly show, the layup greatly influenced the strain distributions, particularly close to the notch. Even though less load-bearing fibres would suggest inferior compressive performance of a laminate, the incorporation of off-axis plies actually enhanced it. This was due to the enhancement of the overall shear performance of the laminate, given that at a CC specimen configuration the compressive load transfer from the pins to the notch is shear dominated.

3.3 Fractographic Analysis

3.3.1 Optical Microscopy

Optical and scanning electron microscopy were employed to identify the fracture mechanisms that had occurred during compression and glean the sequence of events that led to the catastrophic failure. The fracture morphology at the notch and 15.5mm away from the notch are shown in Fig.6 and Fig.7 respectively. As Fig.6 illustrates, although the fracture morphologies were quite different there were some similar features, which indicate that similar failure modes occurred in all specimens.

The two dominant failure mechanisms which occurred in all the specimens were delamination and through-thickness in-plane shear fracture. In particular, in the baseline (90/0)₈S cross-ply configuration, delamination was the first mode which had then triggered the in-plane fracture, whereas in the (0/90)₈S configuration in-plane shear had then triggered interlaminar fracture.

In the two multidirectional configurations, the fracture morphologies were more complicated, which made the interpretation more difficult. In the baseline (0/90/45/-45)₄S multidirectional configuration in-plane shear fracture was the first event to have occurred, whereas in the other multidirectional configuration, (-45/45/0/90)₄S, delamination triggered the failure process. Even though the failure mechanisms were similar, as can be clearly seen from Fig.6 and Fig.7, the failure process was more complex in the multidirectional configurations, since secondary failure modes caused further damage.

In Fig.7, the failure morphologies 15.5mm away from the notch are shown. Clearly, the damage was less extensive and which was because the fracture at the notch was “older” and significantly less post-failure damage was present. Hence the failure process had to be interpreted by taking into account the fracture morphologies at both points.

Fig.6. Optical micrographs illustrating the fracture propagation at the notch in (a) (90/0)₈S, (b) (0/90)₈S, (c) (0/90/45/-45)₄S and (-45/45/0/90)₄S configurations(x5).

Fig.7. Optical micrographs illustrating the fracture propagation 15.5mm away from the notch in (a) (90/0)₈S, (b) (0/90)₈S, (c) (0/90/45/-45)₄S and (-45/45/0/90)₄S configurations (x5).
3.3.2 Scanning Electron Microscopy
The electron microscopy supported the observed differences in the compressive performance and verified the findings of the optical microscopy. The following figures illustrate the various failure mechanisms that were observed in the different cross-ply and multidirectional configurations. Although scanning electron microscopy confirmed the findings of the optical microscopy, it also enabled a more thorough examination of the failure mechanisms and their interactions. From the fractographic analysis, the sequence of events that can lead to the catastrophic failure of composite laminates was deduced. Since delamination was identified as the most important failure mode, premature formation of this failure mode can play a vital role to the failure process.

In case where delamination is the first event to occur, the laminate is split to two sub-laminates and leads to a loss of the lateral support. The two sub-laminates then behave independently and the loss of the lateral support induces secondary failure modes. Upon increased load, these secondary failure modes lead to global instability and the laminate fails catastrophically. Alternatively, if delamination does not occur first, through-thickness in-plane shear fracture develops. The lateral sliding of the laminate due to in-plane shear triggers secondary failure modes which then lead to the global fracture of the laminate.

4 Conclusions
In this study the failure mechanisms that occurred in cross-ply and multidirectional composite laminates were identified and the effect of the layup on compressive behaviour was studied. In addition to mechanical testing, surface strains were recorded and fractographic analysis was employed to confirm the experimental findings.

Regarding the compressive behavior, multidirectional configurations exhibited a stiffer response in comparison to the cross-ply configurations. The introduction of off-axis plies and the layup greatly influenced the compressive performance. Whilst the multidirectional configurations exhibited a stiffer compressive response due to the CC specimen geometry, the failure process was also more complex and susceptibility to delamination was significantly higher. Finally, the fractographic analysis revealed that delamination and in-plane shear fracture were the dominant failure modes throughout the different configurations and that the multidirectional configurations were more prone to delamination and post-failure damage.

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6 References