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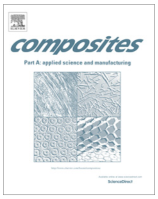

Matrix failure in composite laminates under compressive loading

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ABSTRACT

The failure envelope of the matrix in composite laminates under compressive loads has not received much attention in literature. There are very little to no experimental results to show a suitable failure envelope for this constituent found in composites. With increasing popularity in the use of micromechanical analysis to predict progressive damage of composite structures which requires the use of individual failure criteria for the fibre and matrix, it is important that matrix behaviour under compression is modelled correctly.

In this study, off-axis compression tests under uniaxial compression loading are used to promote matrix failure. Through the use of micromechanical analysis involving Representative Volume Elements, the authors were able to extract the principal stresses on the matrix at failure. The results indicated that hydrostatic stresses play an important role in the failure of the matrix. Thus, Drucker–Prager failure criterion is recommended when modelling compressive matrix failure in composite structures.

1. Introduction

Fibre reinforced polymer materials commonly known as composites are increasingly being used due to their high strength to weight ratio and high fatigue resistance. In order to ensure structural integrity of the components which they form, it is important to understand their behaviour at failure. However as failure in composites are characterised by different modes, namely fibre, matrix and interfacial failure [1], this has complicated the understanding of the failure behaviour. For this reason there are still many unanswered questions as to the materials' failure characteristics, one of which includes matrix compression failure.

In an ideal situation, a composite would be modelled with each strand of fibre surrounded by a polymeric matrix. This would allow for the stress and strain states of the fibre, matrix and interface to be extracted separately. However, this is obviously computationally prohibitive. One method that has greatly assisted in simplifying this analysis is Classical Laminate Theory (or CLT) [2]. This theory combines the properties of the fibre and the matrix through an averaging approach to form what is considered to be a new homogenous material called a lamina. CLT is widely used by researchers in the field and given its simplicity, it does a good job at modelling the stiffness of a laminate including linear load behaviour up to the point of failure. One improvement that can be made to this theory would be the ability to separately examine the fibre and the matrix. This can be done using micromechanical analysis.

For failure assessment, micromechanical analysis can be used to separate the stress–strain states in the matrix and fibre components from a Representative Volume Element (or RVE). The relationship can then be used in a structural analysis to predict matrix or fibre failure. One popular analysis method that uses micromechanical analysis is Multicontinuum Theory (or MCT) [3,4]. MCT predicts failure at the fibre and matrix level by obtaining the volume averaged stress states in the fibre and the matrix. Here, matrix failure is assumed to be influenced by all six of the matrix average stress components in a 3D analysis, whilst a quadratic function is used to find the average stress of the fibre [3]. This particular theory greatly assists with understanding matrix failure and fibre failure in a composite, especially when it comes to progressive damage models [5–8]. However, the assumption of averaging the overall stresses in the individual constituents can be improved on. An analysis method that does this is the Amplification Technique [9–11]. Unlike MCT, where the stresses in each constituent are averaged, the amplification technique calculates the principal stresses and strains at several locations to identify a critical location. Using this separation technique allows the fibre and matrix failure to be examined in detail.

Fibre failure has been quite extensively researched in the field of composites, whilst at a micromechanical level, matrix failure has not received the same amount of attention. Matrix failure is typically known to take place well before the fibre in matrix

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dominated load cases and can be characterised by three main modes; tension, compression and shear failure. Some authors have proposed these modes of failure to be characterised by dilatational failure and distortional failure [10,12]. In this paper the authors focus on distortional matrix failure in composites.

Matrix failure under tension loading has received some attention in literature. The most commonly known form of this test is the 10° off-axis tension test on a uniaxial composite to find the shear modulus of the lamina [13,14,15]. Others have also performed a range of off-axis tests on uniaxial composites where the fibre direction changes [14,15]. The authors have also explored this form of failure through several biaxial tension tests under different loading ratios [16,17]. Through the use of micromechanical analysis, some have proposed the tension quadrant of a principal stress based failure envelope to be truncated [9,10,16,17]. This idea is not new in the field of isotropic materials, where existing failure criteria have proposed this. The simplest example is maximum stress theory which predicts failure when the stress state in the material exceeds its tensile strength. Others include: Drucker–Prager, Mohr–Coulomb, and recently, SIFT (First Strain Invariant) or Onset Theory [18].

Unlike matrix tensile failure, there are few papers that explore shear and compression failure of the matrix at a micromechanics level. One of the few failure criteria that utilises micromechanical analysis to predict matrix failure is that proposed by Gosse and Christensen called Onset Theory [9,10]. Their criterion uses von Mises failure criterion to predict what they term as distortional failure of the matrix [9]. This implies that they consider both shear and compressive failure in composites to be modelled by von Mises. With the assumption that a matrix can be treated as an isotropic material, literature has shown that in the shear quadrants of a stress based material failure envelope, von Mises failure criterion does a good job in predicting failure [17]. However, it should be noted that von Mises theory does not consider hydrostatic stresses, which is known to play an important role in the failure of isotropic materials under compression. To account for this phenomenon, von Mises failure criterion was modified to account for hydrostatic stresses. One of these theories is Drucker–Prager failure criterion which has been quite successful in modelling shear and compression failure in monolithic isotropic materials [19]. Thus, the authors aim to perform a set of experiments using Classical Laminate Theory and micromechanical analysis to examine the importance of considering hydrostatic stresses when a matrix fails due to compression.

2. Uniaxial compression

2.1. Experiment methodology

There are three main types of antibuckling rigs used for compression tests: (1) the modified ASTM D 695 standard; (2) the IITRI compression test method; and (3) the combined loading test methods [20]. Out of the three test methods, the latter two have been shown to considerably reduce end crushing when compared to the modified ASTM D695 test method. This is due to the fixture's ability to transfer the loads through shear. In the case of the experiments considered in this study, the authors are interested in matrix failure, which occurs at much lower loads compared to layups examining fibre failure. Thus, end crushing is not as prominent in these set of experiments which enabled the authors to use the modified ASTM D695 test fixture. The procedure outlined in the modified ASTM D695 standard was followed for these experiments [21]. Failure was confined to the gauge region for all the specimens (shown in Fig. 2), which demonstrated that the tests were successful.

The prepared specimens were machined according to the modified ASTM D695 standard [21]. In total ten different fibre orientations were examined. The geometry of the specimen is shown in Fig. 1 and Table 1. W is the width of the specimen, T is the minimum thickness of the specimen, θ is the angle of the fibre direction relative to the loading direction, G is the length of the gauge section and L is the length of the tabs. It is important to oversize the gauge region when testing matrix failure, as this prevents the fibres extending from one tabbed region to the other. One consideration that must be noted in specimens containing tabs is that extending the gauge region implies that the specimen is more susceptible to buckling as this region is unsupported by the anti-buckling rig. In order to prevent this, the thickness of the specimens should be chosen according to Eq. (1) [22]. The material ultimate compressive strength ($F^{cu} = 610$ MPa), flexural modulus ($E^f = 131$ GPa), and interlaminar shear modulus ($G_{xz} = 4.73$ GPa) were found in another investigation by the authors [23]. The values were either provided by the material supplier [24] or obtained experimentally using ASTM D695, and ASTM D5379. A conservative design was chosen by making the steep fibre testing angles (e.g. 10–45 degrees) thicker as their designs incorporated tabs implying the support jig would not be supporting their gauge regions. Specimens with fibres positioned at angles between 50 and 90 degrees did not require tabs as they were found not to suffer from end crushing.

$$T \geqslant \frac{G}{0.9069\sqrt{\left(1 - \frac{1.2F^{cu}}{G_{xz}}\right)\left(\frac{E^f}{F^{cu}}\right)}} \tag{1}$$

where T = specimen thickness, mm; G = length of gage section, mm; F^{cu} = expected ultimate compressive strength, MPa; E^f = expected flexural modulus, MPa; G_{xz} = through the thickness (interlaminar) shear modulus, MPa.

The material being used is a carbon prepreg material called EP280 Prepreg, supplied by GMS Composites [24]. Several plates of varying thickness (made according to Table 1) were laid up on aluminium plates placed on the top and bottom to maintain a flat geometry during cure. Care was taken to ensure that the fibres were aligned in the same directions. The gap between the two plates was sealed using high temperature scotch tape to prevent any resin escaping during the cure. The specimens were then cured according to the manufacturer recommendations [24] in an autoclave. A CNC was used to cut out the specimens at the desired angles. Final grinding of the sides was performed on a diamond wheel to minimise any machining defects.

Acceptable modes of failure under compression are presented in both the ASTM D 3410 and ASTM D 6641 [22,25]. They include; (a) axial splitting, (b) fibre kinking, and (c) shear failure. Global buckling is the fourth failure mode which is considered to be unsuccessful. Axial splitting and fibre kinking are typical fibre modes of failure [26]. As these experiments are examining matrix failure, the authors consider the shear failure mode to be the only acceptable behaviour.

Fig. 2 and Table 2 present the final forces at failure. It is observed that the specimens with angles between 90 and 45 degrees are found to fail suddenly with a shear mode of failure, whilst specimens with fibre angles between 30 and 10 degrees tended to slowly stop carrying load. These specimens have their fibres aligned close to the loading direction, which from Fig. 2 (h)–(j) indicate failure to have taken place due to fibre kinking. This behaviour is known to take place in 0° composites due to local instability at the fibre level when the lamina is axially loaded. Here, the elastic deformation of the fibres progresses to actual fibre fractures [26].