Composite Structures 135 (2016) 61–73

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Matrix failure in composite laminates under tensile loading

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ARTICLE INFO

Article history:
Available online 25 September 2015

Keywords:
Matrix failure
Composites
Biaxial tension
Truncation
Failure envelope

ABSTRACT

The failure envelope of the matrix in composite laminates under tensile 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 in composite structures, it is important that matrix behaviour under tension is modelled correctly. In this paper, the authors present and test a new biaxial specimen design to investigate tensile matrix failure in composite structures. Through the use of micromechanical analysis, the authors developed a method in which the matrix stresses at failure can be extracted. Comparing to the existing off-axis test, it was shown that the presented specimen design and test methodology can improve the accuracy of the obtained matrix failure stresses, i.e., the matrix failure envelope for EP280 resin. Additionally, the results indicate that matrix failure takes place earlier than that predicted by von-Mises failure criterion and that the 1st Stress Invariant criterion can better predict matrix failure under tensile loading.

1. Introduction

Fibre reinforced polymer materials are increasingly being used due to their high strength to weight ratio and high fatigue resistance. Despite this, there are still many unanswered questions as to the materials' failure characteristics as composites can be characterised by fibre, matrix and interfacial failure [1].

It is computationally prohibitive to model a composite structure with each strand of fibre despite being able to extract the stress and strain states of the fibre, matrix and interface separately. One method that has greatly assisted in simplifying this analysis is Classical Laminate Theory (CLT) [2]. This theory combines the properties of the fibre and the matrix through an averaging approach to form 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.

Micromechanical analysis can be used to separate the stress and strain in the matrix and fibre from a representative volume element (RVE). These can then be used to predict matrix or fibre failure in a structural analysis. One popular analysis method that uses micromechanical analysis is Multicontinuum Theory (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 [5–7]. 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 [8–10]. 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 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 [8,9,11]. In this paper the authors focus on tensile matrix failure in composites.

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http://dx.doi.org/10.1016/j.compstruct.2015.09.022
0263-8223/

Matrix failure under tension loading has received some attention in literature where some have performed a range of off-axis tests on uniaxial composites [12]. However improvements to this method can be made. For example testing a 45° off axis specimen can only give the user one data point for failure, in order to obtain several more failure points, the fibre angle should be varied. However, as more angles are tested, the difference between them is minimal and subject to manufacturing errors. For example: two specimens; one with 45° fibre orientation and the other with 47° fibre orientation. Along with this others have stated how the off-axis tensile tests suffer from premature failure due to the way the specimens are constrained when being loaded [13–15]. This raises the question of whether the measured data from off-axis tests are accurate. One method in which these tests can be improved is through performing biaxial tension–tension tests. This would mean that for a given fibre orientation, the load ratios can be varied to obtain more than one data point for failure. Biaxial test results and specimen designs have been presented in literature [16–18]. The findings from these can be used to create a new test specifically examining matrix failure.

In the past, experimental data for isotropic materials has been used to propose various failure criteria. Some of which include maximum stress theory, von-Mises, Drucker–Prager, and Mohr–Coulomb. The availability of data has allowed certain models to be refined. For example, maximum stress theory, Drucker–Prager, and Mohr–Coulomb all suggest a truncation in the tensile quadrant of a principal stress based failure envelope [8,9]. However the lack of experimental data to explain the onset of failure (matrix failure) in composites under tensile stress states has hindered research in composites. Through the use of micromechanical analysis and by designing and testing a biaxial fibre reinforced specimen, this void of information can start to be populated.

In this paper the authors aim to design and test a fibre reinforced biaxial specimen by overcoming some of the difficulties presented in literature with performing such tests [19]. The authors use a modified version of a specimen design previously presented to test isotropic materials under biaxial loads [20,21]. Uniaxial off-axis tests are also performed using the same material to highlight the significance of performing biaxial tests. The study is concluded by comparing against a third set of experiments performed on a biaxial specimen made of the matrix material called EP280 [22].

2. Matrix failure in CFRP under biaxial tensile loading

The main objective of this paper is to establish the tensile failure envelope for the matrix. In order to do this the authors have modified an existing biaxial specimen design created for testing isotropic materials [20,21,23]. The specimen design was found to achieve a 98% higher stress state at the centre gauge region compared to anywhere else in the specimen allowing for a successful biaxial test [23]. The biaxial tests were performed on a machine designed by the authors which uses two computer controlled actuators placed on a set of linear bearings which allows the specimen to deform in a uniform manner which is important in such tests [21].

2.1. Experiment methodology

The material being tests is called EP 280 Prepreg which has a ply thickness of 0.25 mm. The authors use two plies within the centre gauge region and a further 10 plies to form the surrounding geometry. It is important to have ply drop-offs at each layer in order to avoid introducing significant out of plane peal stresses. The final specimen design is shown in Fig. 1. The diameter of the holes in each ply can be chosen so that a smooth conical transition can be achieved. If a different thickness material is used or different centre gauge thickness is requires, then through the use of Eqs. (1) and (2); the required punch diameters can be calculated. The authors used existing imperial and metric sized punches to produce these holes, thus the uneven reduction in hole diameters. This uneven transition does not affect the overall specimen geometry as the external surfaces are pressed against two aluminium moulds to ensure that the geometry is maintained to the same dimensions as that used by the authors previously [20,21,23].

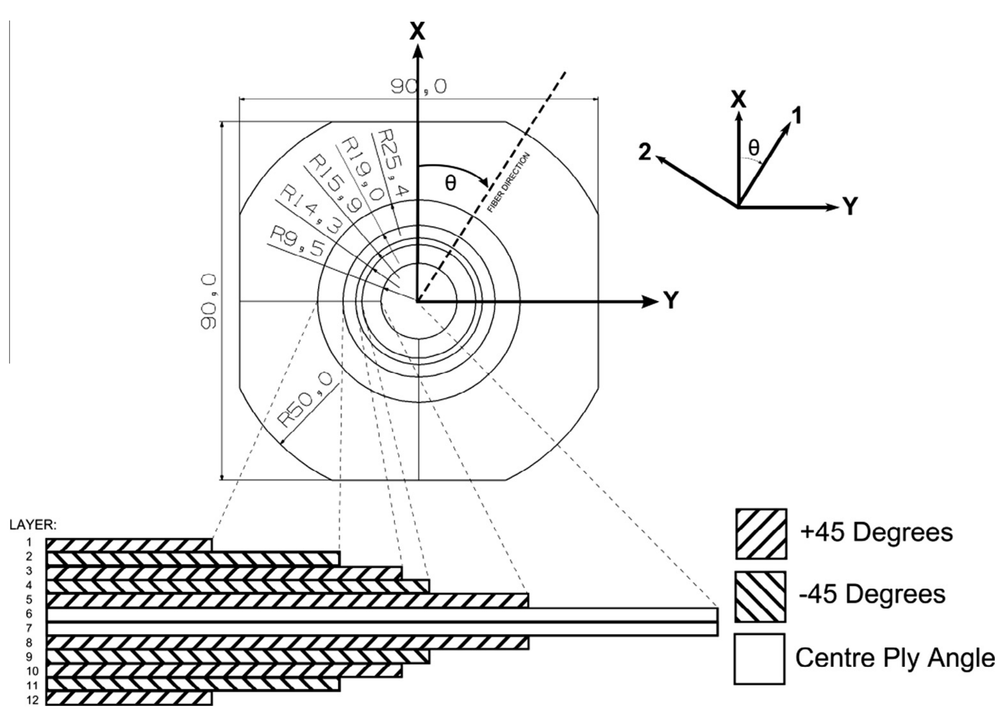

Fig. 1. Specimen design (top view) with lamina orientation and ply drop offs (0.25 mm ply thickness).