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Predicting matrix failure in composite structures using a hybrid failure criterion

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ABSTRACT

Matrix failure in composite structures has not been widely presented in literature. Their failure has often been overlooked due to focus directed at fiber failure. With increasing attention on progressive damage models for composite structures it is important that matrix failure is well understood as this is often the characteristic of initial failure in these advanced materials. In this paper the authors perform several four point bend tests on a typical stacking sequence used in composite structures $[-45/0/45/90]_{2S}$. Inspection techniques involving a FLIR thermal camera are used to detect matrix failure. Two methods are then employed to establish a suitable failure criterion to predict matrix failure. The first compares several failure criteria at the lamina level, whilst the second uses micromechanical analysis to predict matrix failure. It was found that matrix failure was poorly predicted at the lamina level, whilst a hybrid failure criterion incorporating the 1st Stress Invariant and Drucker–Prager failure criterion at the micromechanical level gave a much better prediction. The proposed hybrid failure criterion can be used in various progressive damage models to give a better prediction of initial failure in composite structures.

1. Introduction

Composite materials are increasingly being used due to their high strength to weight ratio and high fatigue resistance. Their extensive use can be found in the recently developed military helicopters such as the Eurocopter Tiger and Bell/Boeing V22 where the airframe is made of nearly all composites. In order to ensure structural integrity in such applications, it is important to understand the material behavior at failure. However as failure in composites are characterized by different modes, namely fiber, matrix and interfacial failure [1], this has complicated their understanding. For this reason there are still many unanswered questions as to the materials' failure characteristics, one such area includes matrix failure.

Conventional laminate theory (CLT) is widely used to model composite structures [2]. CLT uses an averaging approach to combine the properties of the matrix and fiber to form what is considered to be a new homogeneous material called a lamina. The advantage of using this theory is that it is simple to use and does a good job in predicting ply failure [2]. With advances in computing resources available in industry it has been possible to extend CLT and establish a more detailed model, although modeling each strand of fiber embedded in a matrix material is still considered computationally prohibitive. One such method that is gaining popularity is micromechanical analysis where the homogenous material created using CLT is broken back down to its individual constituents using Representative Volume Elements (RVEs). Multicontinuum theory (MCT) is one of these methods [1,3].

With these advances, it has meant that further research is required to understand the behavior of the individual constituents that make up the laminate rather than stopping at the lamina level. This is where matrix failure in composites plays an important role. Despite being one of the constituents in a composite it's behavior has often been overlooked as the behavior of the fiber constituent is usually the most visible form of failure in composite structures [4,5] and often detectable on a load–displacement curve. Conversely, matrix failure is often not very visible and hard to pick up on a load–displacement curve [6]. Even if picked up on a curve it is difficult to pinpoint the location in the laminate. By establishing an experiment method that is able to pinpoint matrix failure, various matrix failure criteria can be tested for their accuracy. Once a suitable failure criterion is selected, it can be used in progressive damage models which have been gaining large interest quite recently [7–11]. In this paper the authors use a Forward-Looking Infrared Radar (FLIR) thermal imaging camera to aid in detecting failure alongside visual inspection post failure detection.

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In this paper the authors perform several four point bend tests on a laminate with a typical stacking sequence of $[-45/0/45/90]_{2S}$. The results are used to compare several well-known failure criteria [4] to predict failure of the matrix at the lamina level using CLT. The analysis method is then extended to perform micromechanical analysis where the failure criterion proposed by the authors in two previous investigations [12,13] is used for comparison purposes. In those investigations biaxial tensile tests on fiber reinforced polymer composite (FRPC) specimens and neat resin specimens were performed on the same matrix material discussed in this paper (EP280) [14]. The proposed stress based failure criterion for the matrix is tested for its validity in this paper.

The paper starts with presenting the experimental setup and results. Then the two analysis methods are described in Sections 3 and 4 followed by a final discussion comparing the prediction of the two analysis methods.

2. Experiments

2.1. Experiment setup

The experiments were performed using a four point bend test fixture. The procedure outlined in ASTM D7264 [15] was followed. The material used is called EP280 Prepreg [14], with material properties presented in Table 1. The specimen layup consisted of 16 plies with a symmetric stacking sequence given by $[-45/0/45/90]_{2S}$. The dimensions and material coordinate system are shown in Fig. 1. A plate made up of the prepreg material was cured in an autoclave at 120 °C for 60 min with a ramp up rate of 2 °C/min. Care was taken to ensure that the fiber directions were aligned correctly. The specimens were machined from the cured plate using a CNC milling machine. Final machining of the specimen sides was performed on a diamond wheel to minimize damage from the milling process.

In total 8 specimens were tested on a 5 kN Instron test machine. The span between the two bottom supports and the two top supports were 128 mm and 64 mm respectively. A loading rate of 4 mm/min was used resulting in failure taking place at 3–5 min from the start of loading.

Four of the eight specimens tested had strain measurements recorded. Instead of using a conventional strain gauge, strain was measured along the length of the specimen by bonding a fiber optic cable [16,17] in the thickness of the specimen as shown in Fig. 2. The advantage of using the fiber optic cable to measure the strain is that the relative size (width) of the specimen to a strain gauge is smaller so a more localized strain in our experiments can be compared against our FE model.

In conjunction with the strain measurement, a FLIR thermal imaging camera was used to capture any thermal spikes that result from failure of the specimen. However this technique is only able to observe failure on exposed faces of the specimen and cannot capture any internal damage or damage on surfaces that aren't facing the view of the camera.

Table 1
Prepreg material properties.

Property	
E11	131 GPa
E22	6.20 GPa
E33	6.20 GPa
v12	0.28
v23	0.40
v13	0.28
G12	4.73 GPa
G23	1.44 GPa
G13	4.73 GPa

2.2. Experiment results

The time at failure picked up by the FLIR thermal camera was used as the basis for analyzing the results. Fig. 3 shows an example of the temperature spike picked up by the FLIR camera for specimen 2. Table 2 records the displacements at failure for the 8 experiments performed.

From Table 2 it can be seen that the overall consistency of the observed point at failure was good with a standard deviation of 0.90 mm and mean of 7.66 mm.

3. Method 1: failure at the lamina level

3.1. Finite element analysis

Finite element analysis was used to process all the experimental results to establish which ply had failed and to obtain the stress and strain states on the matrix. The finite element package ABAQUS 6.13 was used [18]. Each of the 16 plies were modeled with 4 elements through their thickness. The top and bottom nodes of each ply were tied together to assume a perfect contact. 8-node linear brick elements with reduced integration and hourglass control were used for the specimen (C3D8R) [18]. In total there were 39168 elements and 46865 nodes. The material properties listed in Table 1 were assigned to each Ply with an orientation specified through ABAQUS GUI. A frictionless tangential constraint was applied between the top loading pins and the specimen whilst a zero displacement constraint along the x-direction was applied in the positions of the bottom supports. Fig. 4 shows the boundary conditions applied to the FE model.

The strain along path AA (ε_x) shown in Fig. 4 was extracted and plotted in Fig. 5. These strains were extracted from 4 of the experiments (specimens: 5–8) at 100s from the start of loading. The corresponding displacements at this time were used in the FEA models to obtain a comparative strain state. Our FEA model matched our experiment values to within 10%, thus it was considered appropriate for the remainder of the analysis.

3.2. Results

The strain state (along path BB) of the specimen shown in Fig. 5, is extracted for each ply and is shown in Tables 3 and 4. The inner plies were found to experience lower order values and were not considered to fail before any of the four outer plies. They are excluded for the remainder of this analysis.

3.3. Failure Prediction at the Lamina Level

Conventional analysis techniques have usually stopped at the laminae level [4,19,20]. To provide an idea of predicting matrix failure at this level, various failure criteria are compared. The following criteria are considered:

1. Maximum Stress failure criterion.
2. Maximum Strain failure criterion.
3. Tsai–Hill's failure criterion.
4. Tsai–Wu's failure criterion.
5. Hashin–Rotem failure criterion.

These lamina level failure criteria require information about the stresses at failure for the lamina (EP280 Prepreg) used in this investigation. Thus, several experiments were performed on the lamina material to obtain its critical failure stresses which are shown in Table 5. Where 'F_{ij}' is the critical failure stress, 'i' is the material direction and 'j' represents whether the stress is