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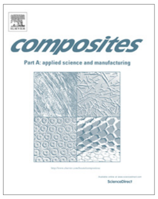

Experimental and numerical study of oblique transverse cracking in cross-ply laminates under tension

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ABSTRACT

The first damage mode in cross-ply laminates under tension is broadly accepted as transverse cracks normal to the loading direction in the 90° layers, but there is not the same agreement about the second damage mode. While most of the analytical and experimental results are based on delamination induced by transverse cracking, another type of damage, oblique cracks within the 90° layers, has also been observed as the second damage mode in $[0/90_4]_s$ laminates. To understand the cause of this phenomenon, FE analyses considering damage development at the interfaces were performed. The obtained results indicate that the main reason for the oblique cracking damage mode is the higher toughness of the material in mode-II compared with mode-I: when the value of shear toughness is close to the opening toughness, the second damage mode in cross-ply laminates under tensile loading is delamination induced by transverse cracks, however, if the difference between the two values is large, oblique cracks in the 90° layers are likely to appear. In the specific tested and analysed laminate, if the mode II toughness is double the mode I toughness, oblique cracking occurs but if the values of mode I and mode II toughness are close, delamination is the second damage mode.

1. Introduction

The damage process of cross-ply laminates has been widely investigated over many years with a variety of approaches. The first damage mode is broadly accepted as transverse cracking based on different experimental observations [1–4] and theoretical analyses [5–14]. But the observed and predicted second damage mode in cross ply laminates can be categorised in two groups. Most of the observations and analyses have shown that delamination initiating from the tips of the transverse cracks is the second damage mode after the 90° layers reach saturation with transverse cracks [3,5,15,16]. On the other hand, oblique and curved transverse cracks close to the straight ones with no delamination have been also reported as the second damage mode in cross-ply laminates in a few observations [16–18]. These damage modes are shown schematically in Fig. 1. There are reports [13,18] showing these two different kind of secondary damage modes in the same $[0/90_4]_s$ layups when the materials were different.

The occurrence of delamination induced by transverse cracks is mostly described by the stress concentration around the transverse crack tip and also the high value of strain energy release rate. Further transverse cracking and delamination initiating from the tips of existing transverse cracks are known as two competing damage mechanisms. To find the winning mechanism, the energy release rate for transverse cracking and delamination induced by transverse cracks are compared. Different mathematical approaches such as variational [7,12], shear-lag [3,6] and Finite Element Analysis (FEA) [19,20] have been introduced for calculating the energy release rates, all of which may be used in comparing the energy release rates to predict the dominant damage mode. Recently, there have been some studies modelling a longer part of the cross-ply laminate considering the randomness of transverse cracking [21,22], without the assumption of uniform transverse crack density. However, the presumed damage mechanisms in all of these analyses are confined to straight transverse cracks covering the whole thickness of the 90° layers and interlaminar cracks at the 0°/90° interface initiating from the tips of transverse cracks.

Tiny oblique cracks in the 90° layers is another damage mode reported to occur after straight transverse cracks. To the best knowledge of the authors, this kind of damage mode has not been investigated in detail and the few available descriptions such as by

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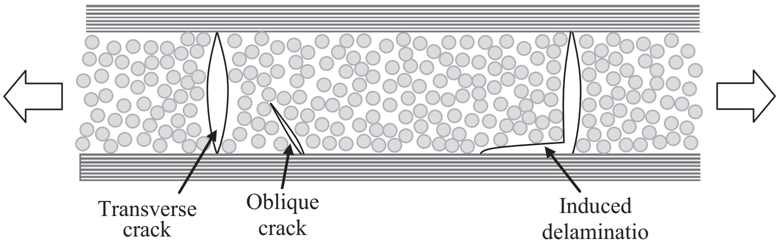

Fig. 1. Different damage modes in a cross-ply laminates.

Groves et al. [18] and Hu et al. [16] are not in agreement with each other. Hu et al. used a variational approach to find the distribution of maximum principal stress around the normal crack tips and showed that at high crack densities, the point with maximum first principal stress moves significantly away from the tips of the straight transverse cracks. However, the stress distribution obtained by Groves et al. using FEA clearly indicated that the maximum first principal stress stays at or very close to the tips of the straight transverse cracks if linear elastic material properties are applied. They proposed that taking the nonlinearity of the material response into account may improve the agreement between the obtained results and the experimental observations.

In this study, 14 tensile specimens of a cross-ply laminate have been used to assess the damage initiation and propagation at different stages of loading. Similar to all other works, the first observed damage mode was transverse cracking normal to the loading direction but the second observed damage mode was oblique cracking. No delamination was observed. The occurrence of this damage mode is then investigated using FE analyses considering the nonlinear shear behaviour of the 0°/90° interface. Finally, the question why two different second damage modes might occur in a laminate with similar geometry is considered.

2. Experiments

2.1. Test procedure

A cross-ply laminate, $[0/90_4]_s$, with a thick middle 90° layer has been made out of Hexcel IM7/8552 pre-impregnated carbon fibre sheets. Cross-ply glass/epoxy end-tabs 2.5 mm thick were bonded after curing and then the plate was carefully cut into fourteen $1.25 \times 10 \times 300$ mm specimens using a diamond wheel saw.

To examine the damage progress, different load levels were selected for each of the specimens. One of the specimens was loaded up to final failure which is due to fibre failure of the 0° layers. The load levels of the other specimens were selected accordingly to cover the different stages of damage development. The specimens were then loaded in displacement control at a rate of about 0.2 mm/min up to their predefined load level. At this point, loading was stopped and the specimens were unloaded. An Instron extensometer with 50 mm gauge length was used for strain measurements.

The edges of the specimens after testing were polished in different stages after removing the end-tabs. The removed material due to polishing was roughly 1 mm in the width direction. Then a ZEISS Axio Imager 2 microscope was used to view the edge of the samples. To obtain the crack pattern over the length of the specimen, individual photos taken from the edge of the specimens were stitched together with the Axio Vision software. Crack measurements were also performed on the overall stitched image of the specimen using the same software. To quantify the damage pattern, the distance of all of the transverse cracks were measured at the mid-plane of the specimens. For a limited number of specimens, the variation of crack pattern through the width of the specimen was investigated by re-grinding and re-polishing the edge of the specimens in two separate stages by removing about 3 mm from the edge of the specimens and it was found that the damage pattern stayed approximately constant in the width direction.

2.2. Test results–transverse cracking

A summary of the measured transverse cracking distances in the different specimens in addition to the maximum stress and strain are shown in Table 1. Fig. 2 indicates the maximum stress and strain in different specimens in addition to the stress–strain curve of specimen no. 14 with the largest applied load. Specimen no. 1 was not loaded but was polished and then viewed via the microscope to make sure that there were not any unpredicted cracks in the specimens before load application due to the process of making the test samples, e.g. curing and cutting. Specimen no. 14 was loaded up to final failure and because of fibre failure of the 0° layers, it was not examined via microscopy. The other specimens were carefully viewed and snapshots were taken of their edges. No damage was observed in specimens no. 2 and 3, while a few of randomly distributed straight transverse cracks started to be observed in specimen no. 4 at a maximum applied strain of 0.3%.

Fig. 3 indicates the average, maximum and minimum measured distances between the transverse cracks in samples no. 4–13. In the initiation stage of the transverse cracking (low values of strains), the crack distances are higher and the difference between minimum and maximum distances are considerable. As the load is increased, the remaining space for new cracks becomes more restricted and the distance between transverse cracks decreases. The large difference between maximum and minimum crack spacing also decreases and they both tend to converge toward the average value. The difference between maximum, minimum and average value of distances between cracks can be used to judge how evenly the cracks are spread over the specimens. Fig. 3 clearly shows that crack spacing in the early stages of crack initiation is significantly non-uniform but becomes more even at larger strains.

The crack density of each laminate was calculated independently by dividing the counted number of transverse cracks by the specimen length, and is depicted in Fig. 4 for specimens no. 1–13. The density of transverse cracks increases with a decreasing rate up to the strain of 1.16% when final failure occurs.

The Coefficient of Variation (CV) of the crack spacing is shown in Fig. 5. At low values of strain, it is large, but as the load increases, it decreases to about 40% which is still significant and indicates a quite non-uniform distribution of transverse cracking even at high values of strain. However, this large CV remains almost constant at strains larger than 0.65%.

The crack pattern taken from the edge of specimens no 8, 9, 11 and 13 is shown in Fig. 6. The crack density is obviously increasing with the applied load. Furthermore, all of the cracks in specimens no. 8 and 9 are straight and perpendicular to the loading direction,