INTERFACE EFFECTS IN MODE II INTERLAMINAR TOUGHNESS TESTING OF UNIDIRECTIONAL COMPOSITES

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Abstract

This paper reports on an investigation of the influence of friction and nesting on the Mode II toughness of unidirectional composites measured using the 4-point loaded end-notched flexure test. A special modification of this test configuration was developed which enabled the compressive force acting across the sliding interface to be reduced to zero. The results indicated that friction has a fairly small effect on the measured toughness. Specimens with different nesting characteristics were produced by using different crack starter methods. It was found that greater nesting resulted in significantly higher Mode II toughnesses, particularly at initiation. Further investigation revealed that the sliding surfaces separate in an opening mode and that the amount of separation increases with the magnitude of the nesting.

1 Introduction

Mode II interlaminar toughness testing for unidirectional laminated composites is still the focus of research despite the considerable effort that has been devoted to this topic for more than two decades. Recent studies of the end-notched flexure test specimen subjected to either 3-point or 4-point loading (respectively referred to as the ENF and 4ENF test configurations; the latter is shown in Figure 1) have shown that these test methods can yield significantly different results because of the combined influence of friction, geometric non-linearities and fixture compliance [1,2]. Another specimen proposed for evaluating the Mode II interlaminar toughness is the end-loaded split specimen (ELS) and this too has been the subject of recent research [3]. An improved data reduction strategy has been devised which overcomes the difficulties in accurately measuring crack length in mode II fracture testing by using a calculated crack length. This has shown a significant reduction in the scatter of the resulting toughness values.

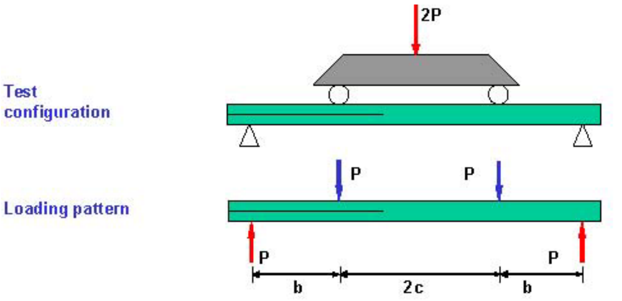
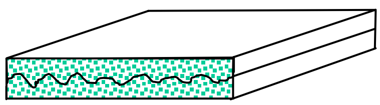
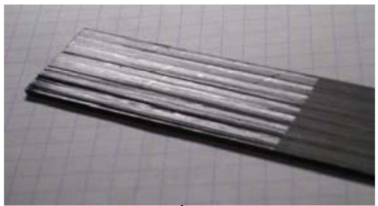


Fig. 1 Conventional 4ENF test (for the tests reported here b=30mm, c=60mm)

In the current paper an experimental technique (based on a modification of the 4ENF test) is described for directly assessing the influence of friction and initial results are presented. Another factor which could influence the interaction of the sliding surfaces is nesting. In unidirectional laminates, nesting is the tendency for fibres in one ply to 'nest' in valleys in an adjacent ply as illustrated in Figure 2.



a.



b.

Fig. 2 a) schematic of nesting b) evidence of nesting on the fracture surface of an interlaminar toughness specimen

The behaviour of 4ENF test specimens with a range of nesting characteristics is described and the significance of the results for the development of a standard test is discussed.

2. Experimental investigation

2.1 Test methods

All the Mode II interlaminar toughness measurements reported in this paper have been performed using the conventionally-loaded 4ENF [4], shown in Figure 1, or a modification of this test. An interesting feature of the 4ENF test is that it is a constant moment test i.e. for a constant applied load the moment at the crack tip, and therefore the applied energy release rate [5], is independent of crack length. The character of the R-curve will therefore be indicated by the character of the load-displacement curve e.g. a material with a critical energy release rate which remains constant will have a load-displacement curve which will form a plateau as the crack grows whereas a material with a rising R-curve will exhibit an increasing load during crack growth.

To investigate the influence of friction a modified version of the 4ENF test has been developed [6]. In the conventionally loaded 4ENF test specimen compressive stresses act at the sliding interface in the region of the applied loads and so friction will be present. In the modified loading pattern, shown in Figure 3, it is possible to reduce the compressive stresses by adjusting the value of α from zero (which gives the conventional loading pattern) to 0.5 (which will eliminate compressive stress at the interface). Figure 4 shows the loading strategy and the fixture that has been designed and built to apply this modified loading pattern.

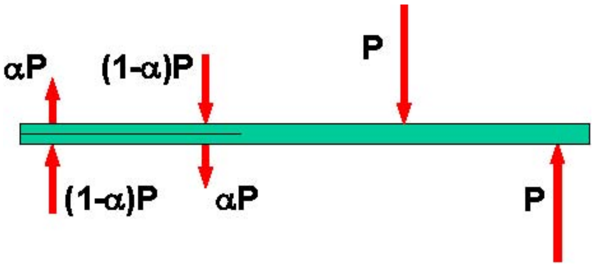


Fig. 3. Modified 4-ENF loading configuration

2.2 Test specimens

Unidirectional Mode II interlaminar toughness specimens were prepared using two carbon epoxy prepreg systems manufactured by Hexcel. For the friction tests T300-914 was used and for the nesting studies IM7-8552 was used. The nominal specimen dimensions were 3mm thick, 20mm wide and 170mm long. For the friction tests a non-stick FEP film was used to create the starter crack. To investigate the influence of nesting, three other delamination starter methods were also used. These consisted of an aluminium foil coated with release

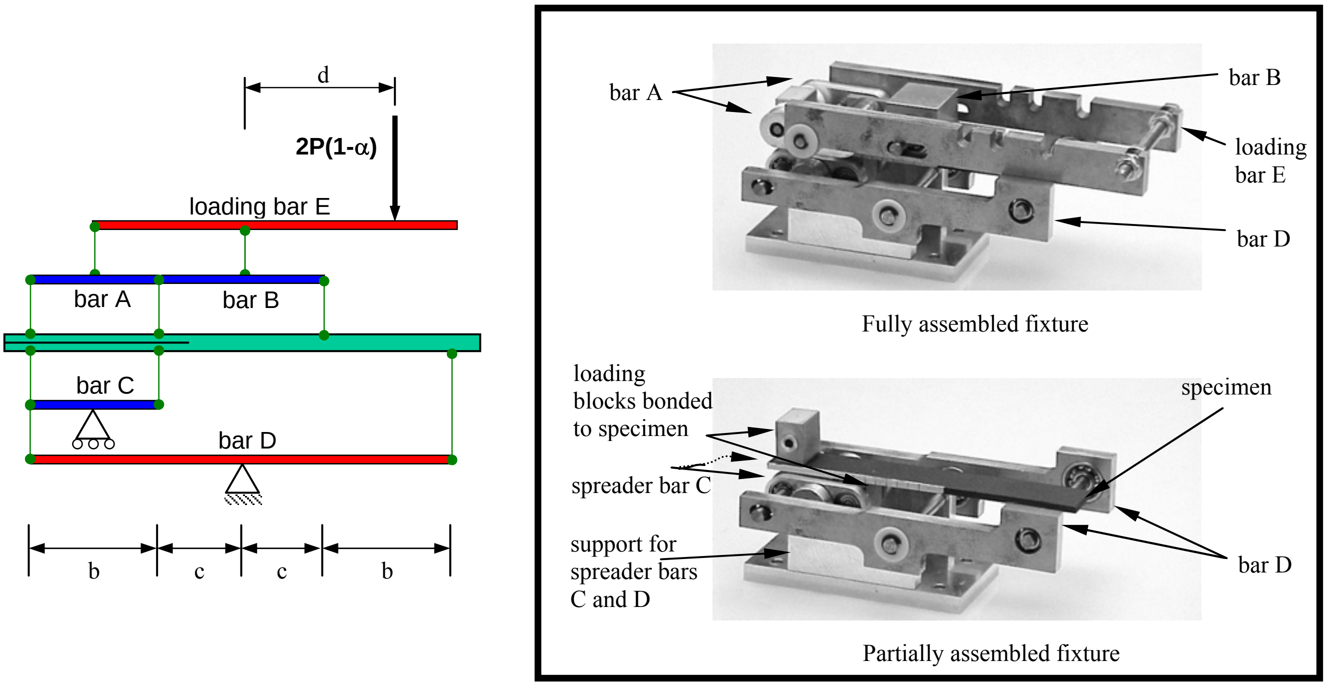


Fig. 4. Loading strategy and test fixture for modified 4ENF

agent, a release spray applied directly to the surface of the prepreg and a 'natural' starter crack - one which was formed without the use of an 'insert' material. This was created using the technique indicated in Figure 5.

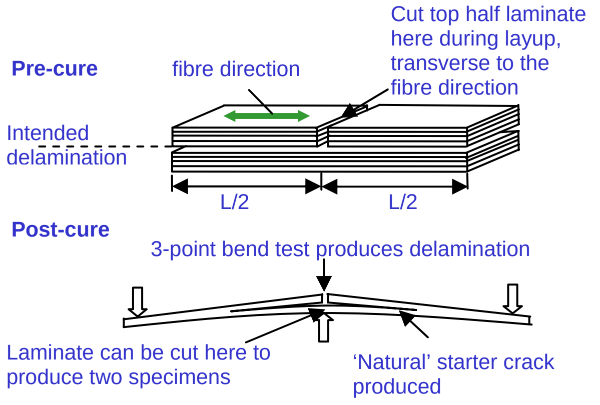


Fig. 5. Method for producing natural starter crack

A novel interlaminar specimen, the 'gap' specimen shown in Figure 6, was also used in the modified 4-ENF fixture for the case of α=0.5. This ensured absolutely that there was no contact between the sliding surfaces at the start of the test.

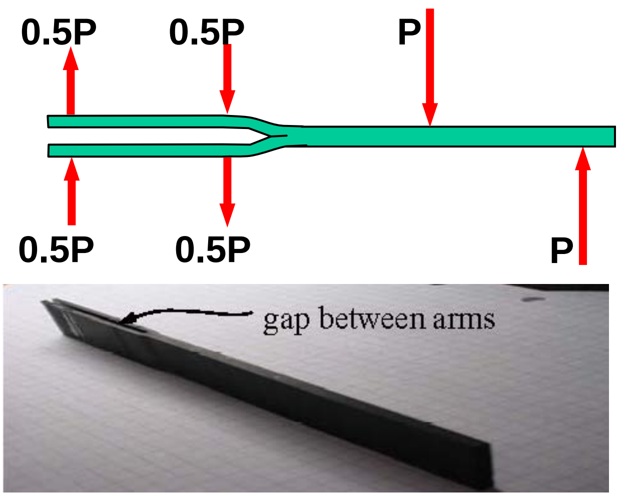


Fig. 6. 'Gap' specimen used in modified 4-ENF specimen

For the conventional 4ENF test no loading blocks were required but for the modified version it was necessary to adhesively bond two loading blocks at the positions of the αP loads shown in Figure 3.

2.3 Data reduction

The fracture toughness was determined from the applied load at failure by using the following beam theory equation:

$$G_{IIc} = \frac{18M^2}{E_{1f}B^2h^3}$$

where M is the bending moment within the inner span (i.e. from figure 1 M=Pb), B is the specimen width, h the specimen thickness and E_{1f} is the longitudinal flexural Young's modulus.

2.4 Test results

2.4.1 Friction

The Mode II toughnesses measured using the conventional 4 ENF test and the modified 4-ENF test (for α = 0, 0.4 and 0.5) for specimens with an FEP film starter crack are shown in Figure 7.

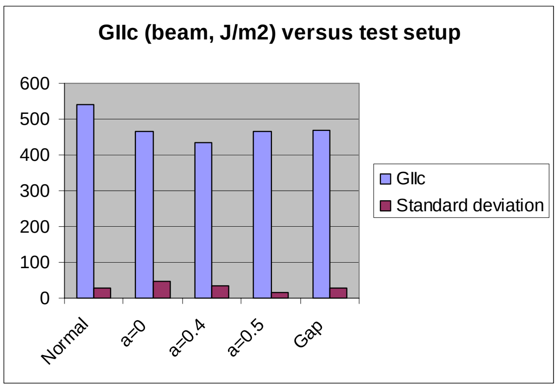


Fig. 7. Measured G_{IIc} for conventional and modified 4-ENF tests

The results for the gap specimens (tested in the modified 4ENF test with α = 0.5) are also shown in this figure. There is some difference between the toughness of the conventional 4ENF test (labelled 'normal' in Fig. 7) and that measured in the modified test with α=0 (which should be equivalent) and this is being investigated further. The other results indicate very little change in toughness as the compressive force acting across the specimen is reduced which indicates that friction has little influence on the measured toughness. This is in agreement with the following simple formula which gives the energy release rate at the crack tip in the conventional 4ENF specimen in the presence of friction ($G_{friction}$) in terms of the energy release rate given by the simple beam theory used for the data reduction ($G_{no\ friction}$).

$$G_{friction} = G_{no\ friction}\left(1 - \frac{4\mu h}{3b}\right)$$

For the geometry used this formula gives:

$G_{friction} = 0.96\ G_{no\ friction}$ for $\mu=0.3$

$G_{friction} = 0.93\ G_{no\ friction}$ for $\mu=0.5$

The flexural Young's modulus can be determined from the slope of compliance versus crack length and the resulting values are shown in Fig. 8. It can be seen that there is no clear pattern to the variation of modulus with test configuration. The results may be effected by difficulties in consistently monitoring the crack length in Mode II interlaminar toughness tests.

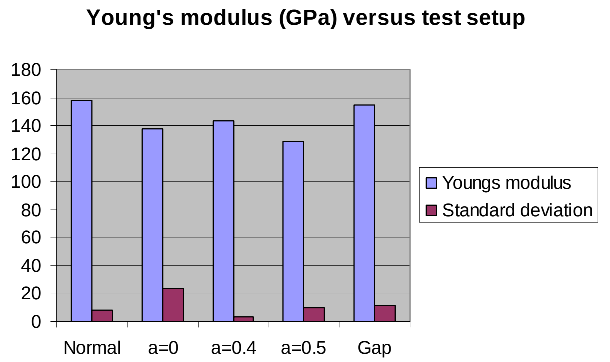


Fig. 8. Flexural Young's modulus from conventional and modified 4-ENF tests

2.4.2 Nesting

Load-displacement traces for tests using the film and natural starter crack methods are shown in Figs. 9 and 10 respectively.

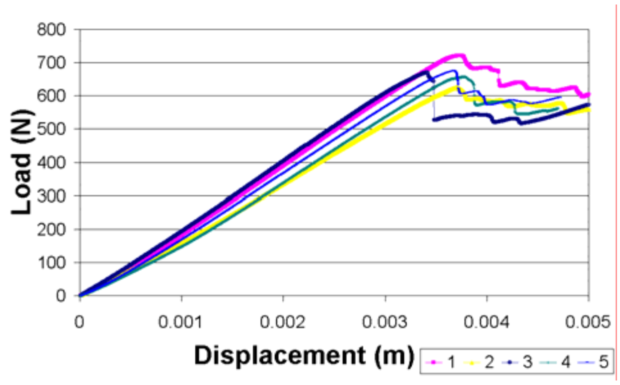


Fig. 9. Load-displacement plots for film insert specimens

There are very obvious differences between these plots; the natural starter crack specimens have lower initiation loads and have much smoother curves as the crack grows with much less variation between specimens. Recalling that for this constant moment test the load-displacement curve indicates the character of the G_{IIc} R-curve, then it is clear that

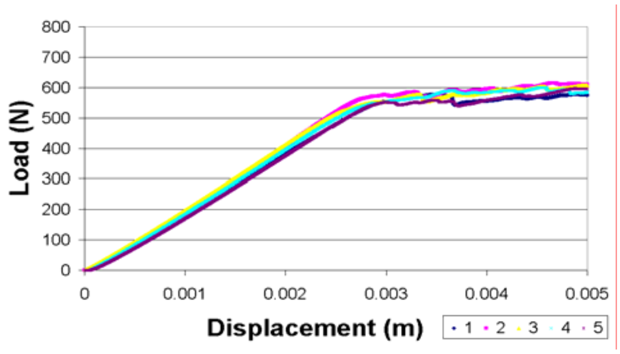


Fig. 10. Load-displacement plots for natural starter crack specimens

there is a significant difference in the toughnesses exhibited by these specimens.

The influence of the starter crack method (and the associated nesting) on the initiation and propagation values of toughness can be seen in Figs. 11 and 12. There is a clear variation of initiation toughness (determined using the onset of non-linearity) with starter crack method; in particular the specimens with the release spray and natural starter crack

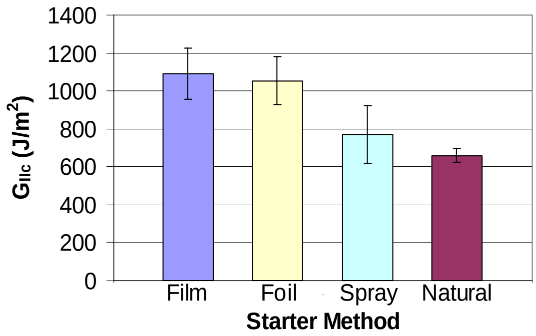


Fig. 11. Initiation values of G_{IIc} for various starter crack methods

methods can be seen to have initiation toughnesses which are significantly lower than those for the film and foil insert specimens. The standard deviation is for the natural starter crack specimens is the smallest for all the specimen types. There is a less significant

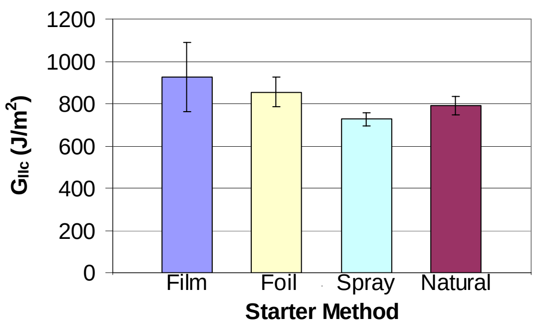


Fig. 12. Propagation values of G_{IIc} for various starter crack methods

effect on the propagation toughness values but again the spray and natural starter crack specimens have lower toughnesses and both exhibit quite small standard deviations.

2.4.3 Further investigations of the nesting specimens

Fig. 13 shows that the sliding surface of the

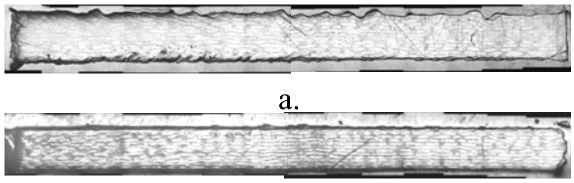


Fig. 13. Transverse micro-sections showing surface profile for a) film insert and b) natural starter crack

specimens is very dependent on the crack starter method. The surface produced by the natural starter crack method appears much flatter than that of the film insert specimen. This is probably due to the effect of the high expansion coefficient of the FEP film (approx 70×10^{-6} /°C) which causes the film to wrinkle at elevated temperature during the composite cure process (see Fig.14).

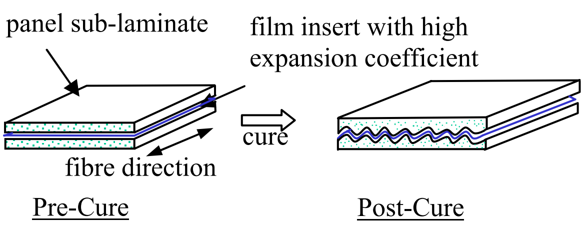


Fig. 14. Schematic showing possible mechanism of nesting production in film insert specimens

It is clear from the cross sections in Fig. 13 that nesting of varying severity has been produced in the specimens that were tested. If the nesting profile remained constant along the specimen length then it is unlikely that it would significantly influence the behaviour in the Mode II test. However further micro-sectioning has shown that the nesting is not

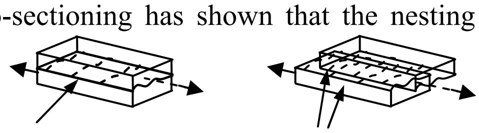


Fig. 15. Effect of nesting on separation of sliding surfaces

constant and so, as illustrated in Fig. 15, for the contacting surfaces to slide over each other the surfaces will have to separate in an opening mode. To investigate this effect further the miniature 4ENF test shown in Fig. 16 was manufactured so that any separation of the sliding surfaces could be observed. The miniature specimens were 1mm thick, 4mm wide and 65mm long and were machined from the same composite plate as the full size specimens to ensure that the nesting characteristics remained unchanged.

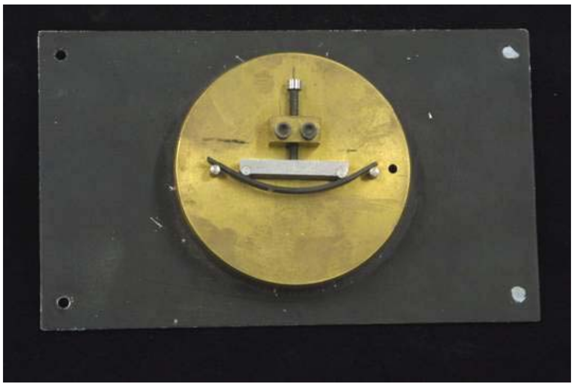


Fig. 16. Microscope stage and miniature 4ENF test

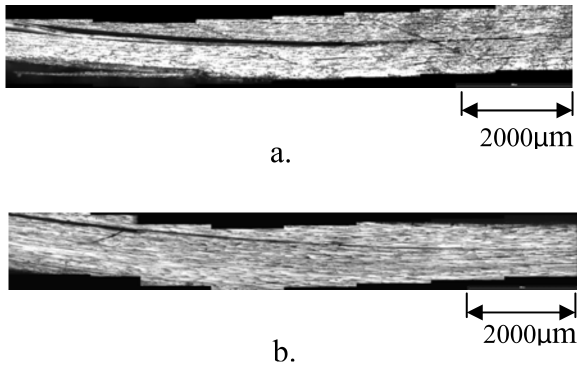


Fig. 17. Micrographs of the edge of the miniature 4ENF specimen: a) film insert specimen b) natural starter crack specimen

Fig. 17 shows micrographs of the longitudinal edge of two specimens during the miniature 4ENF test. The specimen with the film insert clearly shows more crack opening than the specimen with using the natural crack starter technique. This is as would be expected from the nesting profiles shown earlier in Fig. 13. In Figure 18 the opening profile of the crack is plotted for one specimen of each of the four crack starter methods. It is clear that the opening is much smaller for the release spray and natural starter crack specimens.

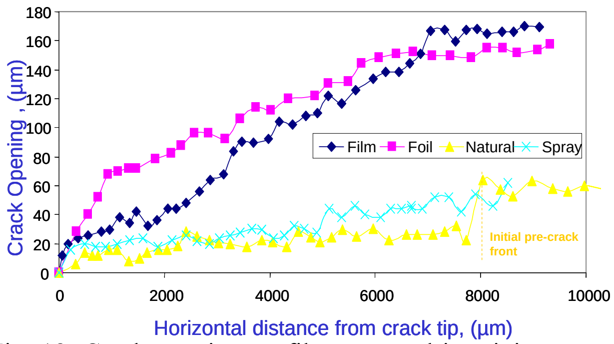


Fig. 18. Crack opening profile measured in miniature 4ENF specimens

In Fig. 19 the maximum value of the crack opening displacement is plotted against the height of the nesting profile. As expected the specimens with 'flatter' nesting exhibit less opening.

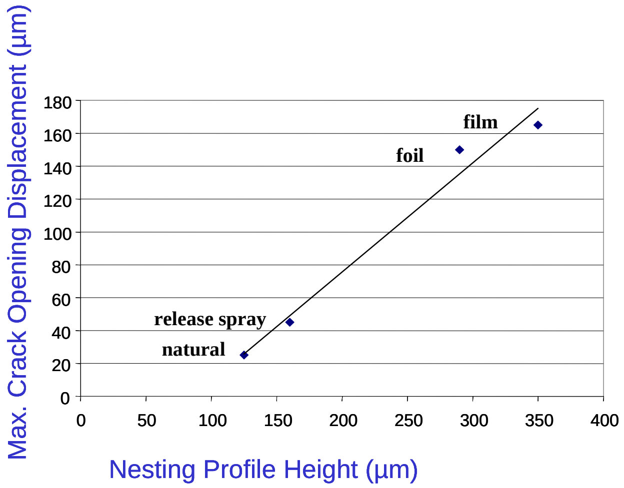


Fig. 19. Maximum crack opening displacement versus height of nesting profile

3 Discussion

The reduction of the compressive load in the modified 4ENF test produced little variation in Mode II interlaminar toughness and this was confirmed by the use of a novel 'gap' specimen. This observation agrees with theoretical predictions which indicate that friction has little effect in the 4ENF test.

Variation in starter crack methods produced a more significant effect on the measured Mode II toughness. A subsequent investigation has suggested that this may be due to the different amounts of nesting that are produced by these different starter methods - larger nesting appears to give higher initiation and propagation toughnesses.

The influence of nesting clearly is of a concern to 'single value' tests like the three-point loaded version of the ENF specimen. This effect also calls into question the relevance of unidirectional Mode II toughness data to Mode II delamination failures in real structures – these normally occur at 0/θ interfaces which will not exhibit the type of nesting observed in unidirectional specimens.

References

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