Interlaminar fracture under mixed-mode II + III and I + III

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ABSTRACT

This paper presents two new interlaminar fracture test methods for mixed-mode II + III and I + III loadings. Both involve biaxial bending of edge pre-delaminated plate specimens with a cross-ply lay-up. The tests allow the coverage of a wide range of mode mix ratios. However, they require finite element analyses (FEA) for selecting specimen configurations and experimental data reduction. Moreover, a relatively complicated fixture is needed for the mixed-mode I + III test, while geometric non-linearity is significant in the mixed-mode II + III one. Nevertheless, results for carbon/epoxy laminates gave quite realistic fracture envelopes.

INTRODUCTION

Characterisation of delamination resistance of high performance laminated composites has been subject of considerable research [1]. Several tests are nowadays well established for mode I, mode II and mixed-mode I + II loadings. However, fracture under pure or partial mode III conditions has received very little attention. The edge crack torsion (ECT) test seems to be the best method available for pure mode III [2], but its suitability has been questioned recently [3]. As for partial mode III loadings, the state-of-art is incipient in mixed-mode II + III [4,5] and, apparently, inexistent in mixed-mode I + III.

This paper describes two new tests developed for mixed-mode II + III and I + III loadings: the 6-point and the 8-point bending plate tests, hereafter designated as 6PBP and 8PBP, respectively (Fig. 1).

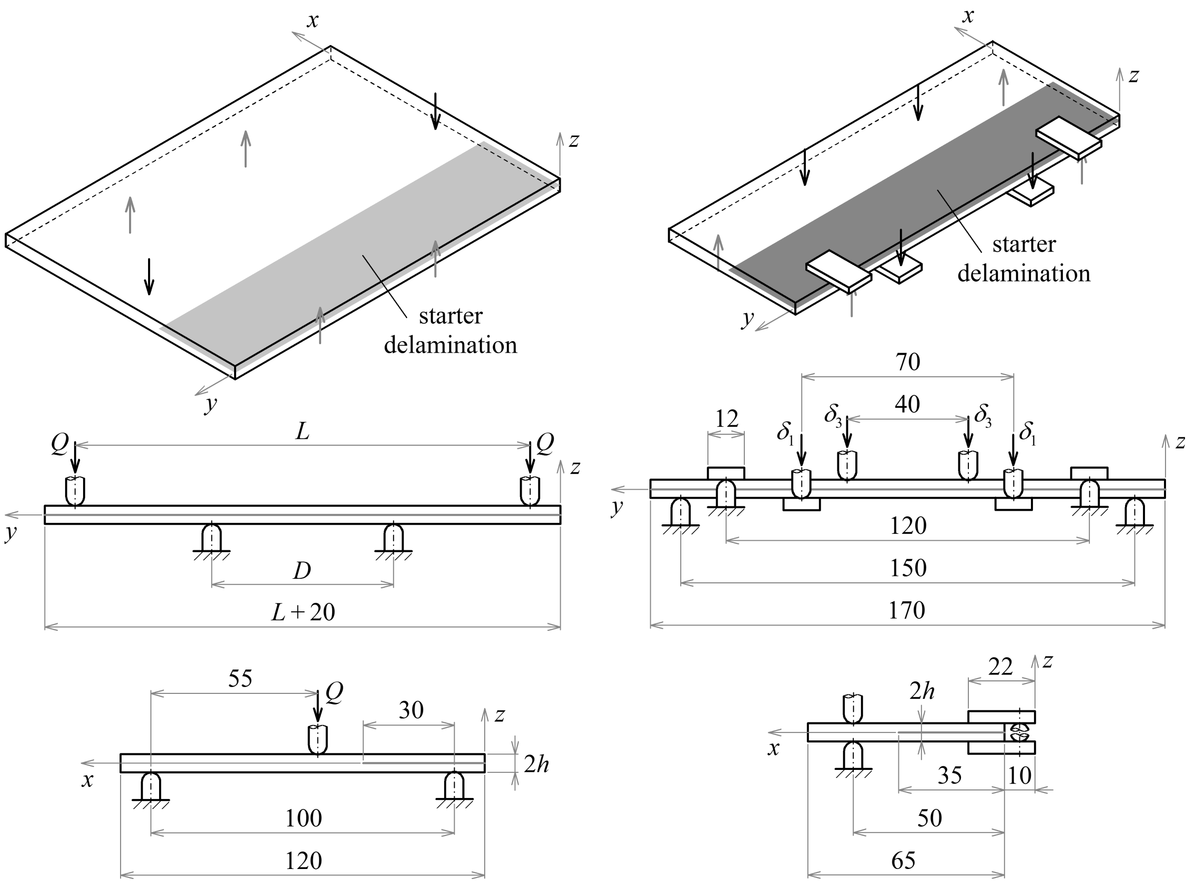

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Fig. 1. Representation of the 6PBP (left) [5] and 8PBP (right) tests.
Both tests involve biaxial bending of edge pre-delaminated plate specimens with a cross-ply lay-up and the standard 0/0 interface. Moreover, only transverse loads are involved, thus avoiding the high stiffness and severe geometry constraints of split cantilever beam type loadings [4]. In addition, the tests developed allow the coverage of a wide range of mode mix ratios. In the 6PBP test this is achieved by changing the *L* and *D* distances (Fig. 1), while in the 8PBP test a lever system is used to apply different δ_1 and δ_3 displacements. As seen in Fig. 1, the latter test requires bonded tabs for mode I load transmission.

ANALYSIS

The development of the above tests was based on extensive FEA using the ABAQUS® code. Figs. 2 and 3 exemplify FE models used, which only considered half-specimen due to the symmetry of loadings and lay-ups.

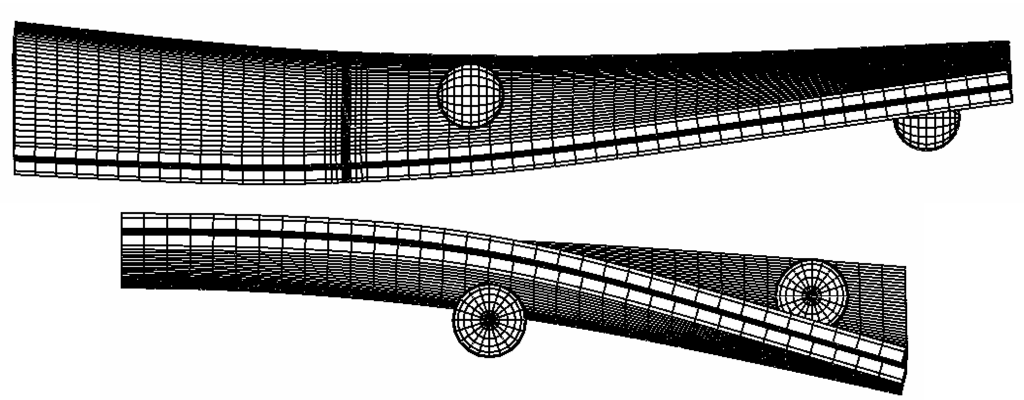


Fig. 2. FE model of the 6PBP specimen: views of the deformed configuration in the *yz* (top) and *xz* (bottom) planes of Fig. 1 [5].

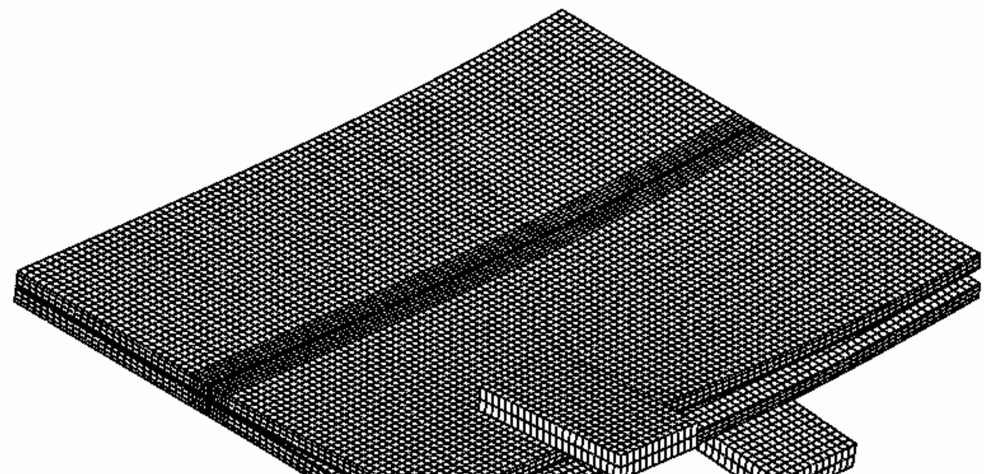


Fig. 3. FE model of the 8PBP specimen: perspective view of the deformed configuration.

However, both tests have relevant drawbacks. First, FEA are needed for selecting specimen configurations and for data reduction, including geometrically non-linear analyses of 6PBP specimens. Second, they lead to non-self-similar crack growth in limited regions, and thus only allow the measurement of initiation critical strain energy release rates G_c. As exemplified in Fig. 4, initiation was assumed to occur within y_a distances over which *G* was at least 90 % of the maximum value. A highly localised peak at the edge detected in some configurations was excluded from y_a. G and G_{III}/G values adopted for data reduction were average values along y_a. Although the definition of y_a is somewhat arbitrary, it was judged much more appropriate to use y_a-averages instead of peak values, in order to consider a significant volume of highly strained material. In fact, y_a distances were at least 20 mm and thus as wide as the usual mode I and mode II specimens [1]. Moreover, the mode mix ratio G_{III}/G was practically constant inside y_a.

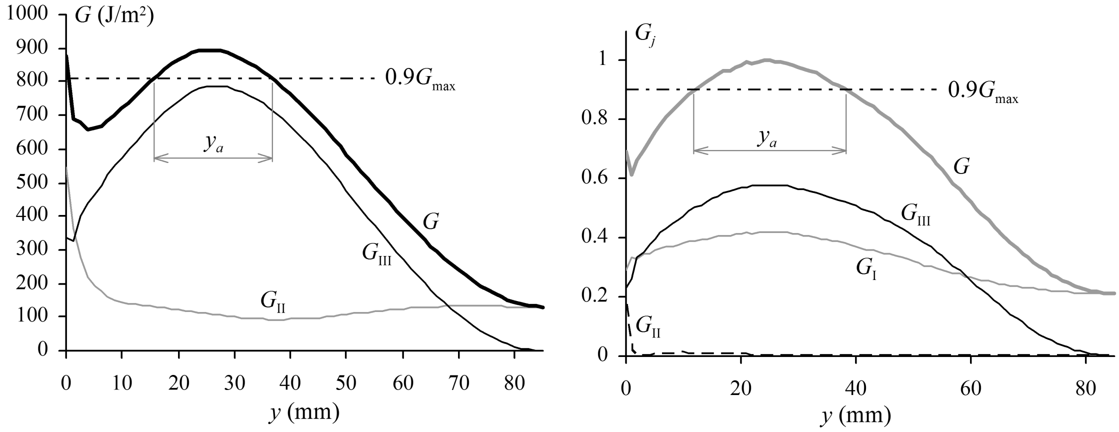


Fig. 4. Examples of widthwise distributions of strain energy release rates in 6PBP (left) [5] and 8PBP (right) specimens. The plots include the definition of y_a distances used to establish G and G_{III}/G values.

In the end, the above drawbacks seemed acceptable in the current state-of-the-art. Moreover, they can be considered challenging for application of fracture mechanics under conditions that are closer to those of actual applications.

EXPERIMENTAL

Laminated plates with the $[(90/0)_{3s}/0]_s$ lay-up were manufactured by hot plate pressing from the HS 160 REM prepreg. A 13 μm thick PTFE film was inserted during lamination to generate the starter crack. Specimens were cut from the plates by water jet and subjected to dimensional control, so that true specimen dimensions could be subsequently inputted in FE models. Test were carried out in a Shimadzu 50 kN-AG machine at 2 mm/min crosshead speed (Fig. 5). A special rig was designed to obtain several displacement ratios δ_I/δ_3 in 8PBP specimens. In both tests, specimens were loaded and supported by high-strength screws with machined 8 mm diameter hemispherical heads. This enabled the adjustments needed for an initial levelled position with contact at all points.

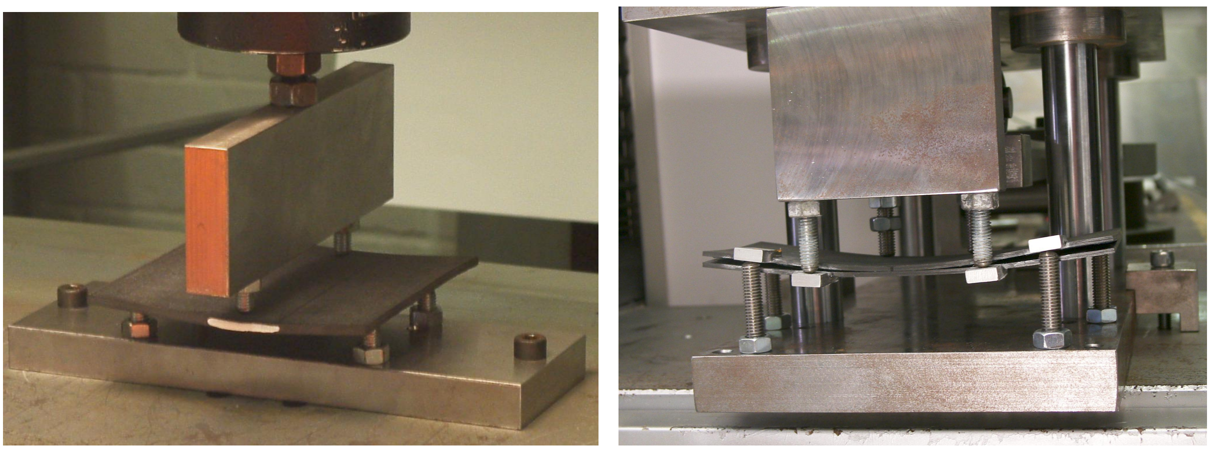
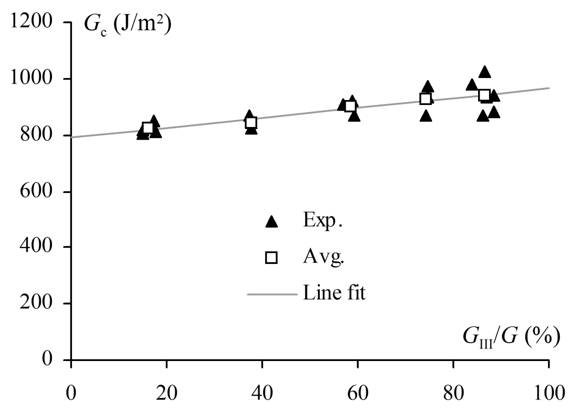


Fig. 5. Pictures of experimental 6PBP (left) and 8PBP (right) tests.

Results obtained from both tests were quite realistic (Fig. 6). 6PBP tests suggested a quasi-linear evolution of G_c with the G_{III}/G mode mix ratio, which was consistent with previously measured G_{IIc} values and expected $G_{IIIc} > G_{IIc}$. On the other hand, results of 8PBP tests showed a linear increase of initiation G_c values with $G_{III}/G \geq 42$ %, while fracture in higher mode I setups seemed to occur when $G_I = G_{Ic}$.



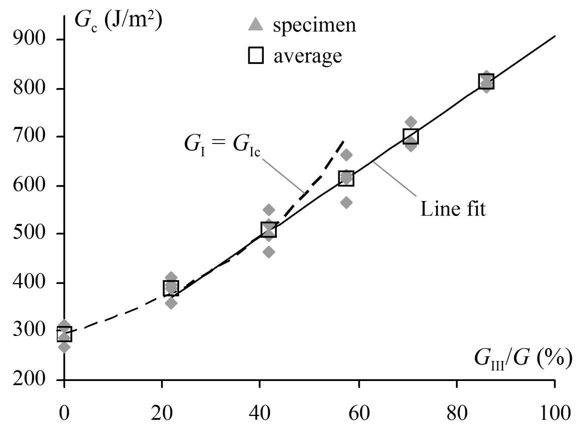


Fig. 6. Experimental results of 6PBP (left) and 8PBP (right) tests.

CONCLUSIONS

Two new interlaminar fracture tests were developed for mixed-mode II + III and I + III loadings. The tests involve biaxial bending of edge pre-delaminated plate specimens with a cross-ply lay-up. Both tests require finite element analyses (FEA) based experimental data reduction and are only suitable for measuring initiation fracture toughness. Yet, results for carbon/epoxy allowed a reasonable characterisation of mixed-mode I + III and II + III fracture. Nevertheless, considerable research is still needed, including the development of improved test methods.

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