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2D QUASI-STATIC DELAMINATION IN GFRP LAMINATES: EXPERIMENTAL INVESTIGATION

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1. INTRODUCTION

Composite materials are commonly used for load-bearing structural elements because of their high stiffness- and strength-to-weight ratios. The successful use of fiber reinforced polymers (FRP) in primary structural parts depends on their integrity and reliability. Delamination in laminated composites is one of the most critical types of damage. Research efforts and standards [1-2] to investigate delamination fracture behavior have focused on beam-like specimens where the crack propagates with a constant width in only the longitudinal direction. Double cantilever beam specimens have been typically employed to study delamination under opening mode (Mode I) and the derived fracture values are used in structural design [3]. However, provided that delamination in real structures is not restricted to one direction but spans all around the contour of the defect, new fracture experimental designs capable of better approaching reality are needed. In this study, the main objective was the experimental investigation of the 2D delamination behavior in GFRP plates. A novel design and experimental set-up suitable for laminates with internal disbonds and subjected to opening loads was developed. Similar out-of-plane stresses are likely to appear in real applications such as local face sheet wrinkling in sandwich panels or curved face sheets (also in sandwich panels) with interlaminar defects.

2. EXPERIMENTAL INVESTIGATION

Material and Specimen Description

Three different types of glass fiber reinforcements were used to fabricate the laminates: two types of woven fabrics with different proportions of reinforcement in the warp/weft directions (50/50 (W50.50) and 60/40 (W60.40)); and a long continuous filament mat (CFM). The experimental program was conducted on six GFRP plates, two for each type of reinforcement. The layup and geometrical description of the plates are presented in Table 1.

Table 1: Description of GFRP plates.

Plate type	No. of layers	Dimensions (mm, width x height x avg. thickness)
W50.50.1/W50.50.2	8	460x460x3.33/480x480x3.53
W60.40.1/W60.40.2	6	410x410x3.33/410x410x3.06
CFM.1/CFM.2	6	420x420x7.50/420x420x6.99

All the GFRP laminates were symmetric with respect to both the midplane and each of the halves. The plate configuration is shown in Fig. 1(a). To introduce the load, two steel inserts were placed in the center and the midplane of the reinforcements. Between them, a Teflon film was placed to introduce the pre-crack of 55-mm radial length (see Fig. 1). The procedure developed for the introduction of the out-of-plane load into the plates is detailed in Figs. 1(b, c).

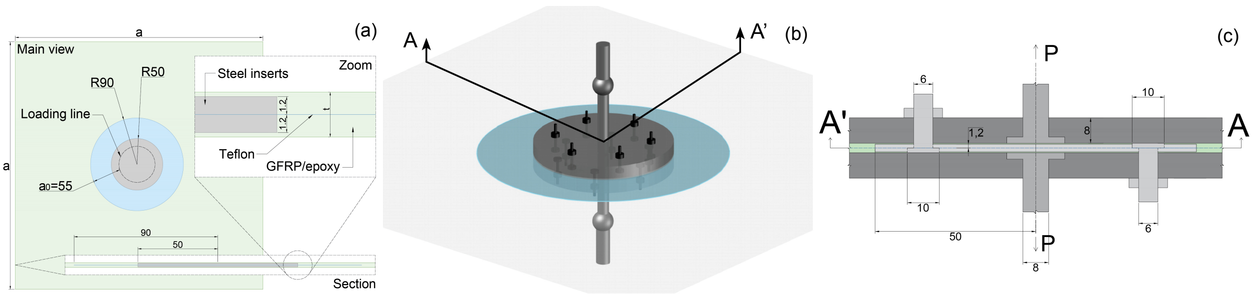

Fig. 1: (a) GFRP plate configuration; (b) general 3D view of the loading system; (c) A'A section view. Dimensions in mm.

Experimental Set-Up, Instrumentation and Measurements

The experimental set-up and instrumentation layout are shown in Fig. 2 (a, b). Once the load-introduction system was assembled, the plate was placed and fixed within the grips of the machine. Due to the difficulty of measuring the entire contour of the crack, three different measuring systems were employed: a 3D Digital Image Correlation System (DIC), a digital camera and visual measurements (see Fig. 2(c)).

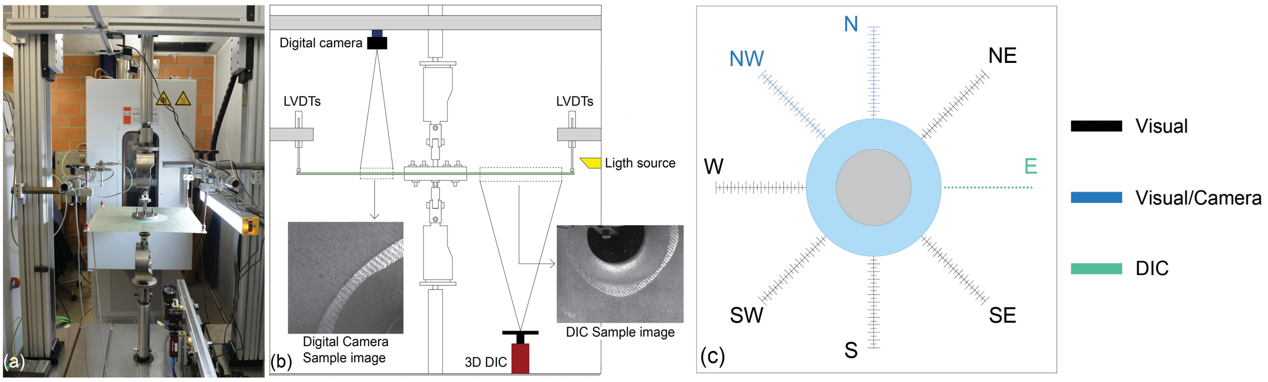

Fig. 2: (a) Experimental set-up; (b) instrumentation layout; (c) layout of crack measuring system.

EXPERIMENTAL RESULTS AND DISCUSSION

Load-Displacement Responses and Crack Propagation Measurements

Continuously increasing load-opening displacement curves were obtained for all the experiments (Fig. 3) as a result of the disproportionate growth of the crack area, whose increments were higher as the crack advanced, forcing the load to increase to continue the propagation of the crack. Only one specimen of each pair of plates is shown here. The other specimen of each pair of plates behaved similarly.

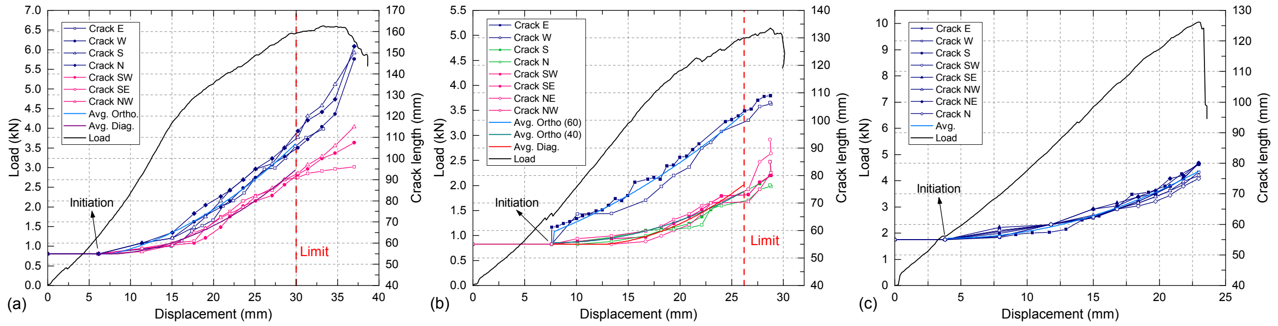

Fig. 3: Load and crack lengths vs opening displacement curves: (a) W50.50.1; (b) W60.40.1; and (c) CFM.1.

The crack lengths vs opening displacement response of the W50.50.1 plate is shown in Fig. 3(a). The blue lines represent the orthogonal directions and the magenta lines represent the diagonal directions. It can be observed that the measured lengths along the diagonal directions remained fairly consistent with each other as well as for the orthogonal directions, indicating a practically symmetric growth of the crack front. The limit of the symmetric behavior corresponded to a 30-mm opening displacement and is marked with a dashed vertical red line. The same representation is shown in Figs. 3(b, c) for the W60.40.1 and CFM.1 plates respectively. For the first, the blue lines represent the orthogonal directions with 60% reinforcement, the green lines the orthogonal directions with 40% of reinforcement and the magenta lines the diagonal directions. For the CFM.1, due to the concentric growth of the crack, the values of the crack lengths showed the same trend.

Crack Propagation Patterns

Crack propagation in the W50.50 and W60.40 plates advanced symmetrically to the orthogonal axes up to the symmetric limit (see Fig. 3). The shapes of the crack fronts for the last symmetric contours are drawn in blue in Figs. 4(a, b). For the CFM laminates, Fig. 4(c), a concentric circular crack front propagation was observed.

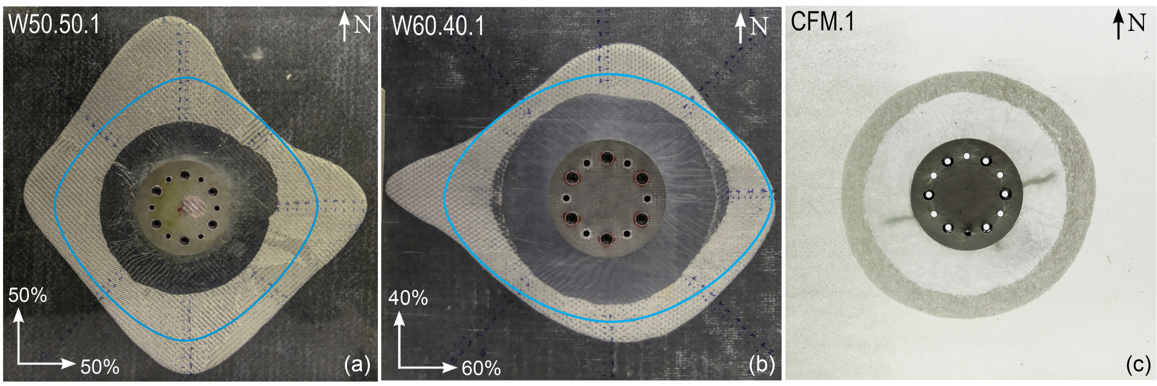

Fig. 4: Crack propagation pattern for (a) W50.50.1; (b) W.60.40.1; and (b) CFM.1.

Compliance Behavior and Stiffness-Related Mechanisms

The compliance plotted against the crack area is shown for W50.50, W60.40 and CFM plates in Figs. 5(a, b and c respectively). All laminates exhibited comparable behavior, i.e. first a descending branch down to a minimum and then an ascending branch corresponding respectively to a stiffening and subsequent softening of the system.

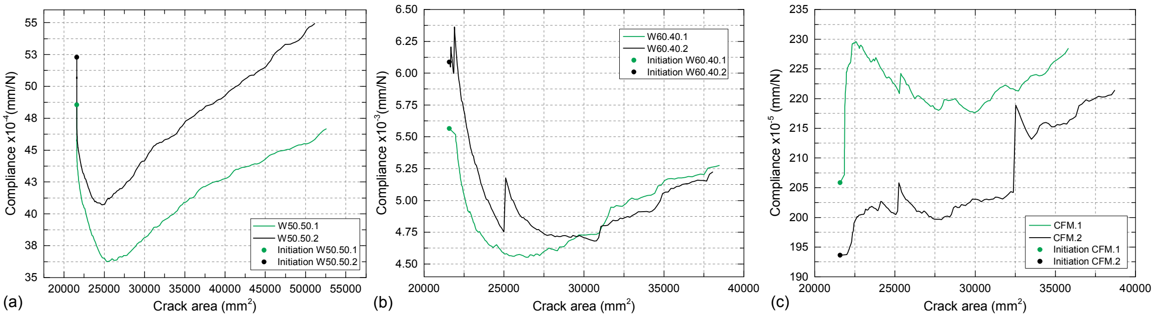

Fig. 4: Compliance vs crack area for (a) W50.50; (b) W60.40; and (c) CFM pairs

Based on the compliances, two main different regions could be differentiated, i.e. A and B in Fig. 6(a). In region A, a decreasing behavior of the compliance was observed (i.e. stiffening of the plate) down to a minimum value (transition point, TP). From the TP onwards (Region B), the compliance started to increase (i.e. softening of the plate). The changes in the stiffness were caused by three different mechanisms activated during the opening of the plates: stretching, fiber-bridging and crack propagation. The boundary conditions of the plates led to the radial and circumferential stretching of the out-of-plane deforming open part of the plates. Once the crack started propagating, the other two mechanisms were activated: the fiber-bridging, contributing to the stiffening of the plate, and the crack propagation itself, causing the softening of the system. The stiffening mechanisms prevailed over the softening up to the TP. Beyond the TP, the softening was the dominant mechanism. These two regions can be likewise identified in the load-displacement curves (see Fig. 6(b)). The same differentiation procedure in the compliance vs crack curve can be established for the W60.40 and CFM plates.

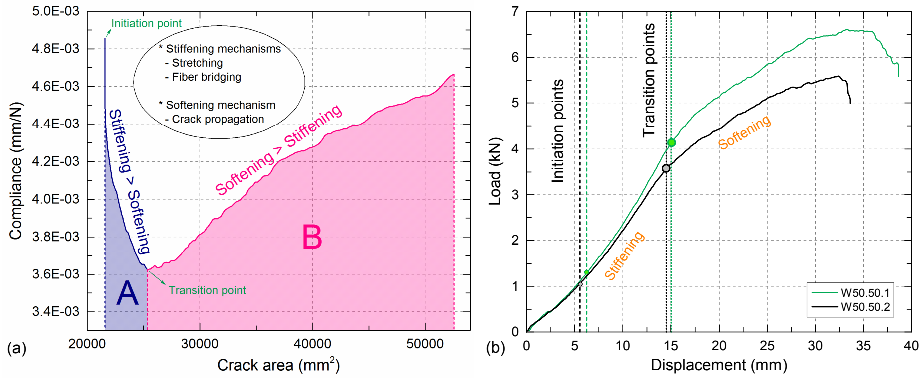

Fig. 6: Stiffening and softening regions on W50.50: (a) compliance vs crack area; (b) load vs displacement.

CONCLUSIONS

The 2D delamination behavior of composite laminates with a circular embedded pre-crack under quasi-static out-of-plane loading has been experimentally investigated. The following conclusions were drawn:

1. An experimental design suitable for investigating the 2D propagation of an embedded pre-crack under out-of-plane opening loading was successfully developed.
2. Increasing loads were obtained as a result of a continuously increasing crack front length and a consequently disproportionate increase in the propagation area.
3. As the plates started to deform, stretching stresses appeared in both the radial and circumferential directions as a result of the geometrical constraints. Consequently, the plates were subjected to a dual stiffening effect.
4. Stretching of the specimens and fiber bridging (both stiffening mechanisms) were capable of delaying the general softening of the system that typically occurs once the crack starts to propagate.

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