TWO-DIMENSIONAL MODE-II DELAMINATION GROWTH IN COMPOSITE LAMINATES

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1 Introduction

Delamination is one of the most common damage mechanisms in composite laminates, which can lead to premature structural failure. Traditional delamination experiments favor beam-like specimens that confine the fracture behavior to one dimension, i.e. the crack propagates along the longitudinal direction with fixed crack width (beam width) under certain fracture mode. However, delamination in real structures will be most likely to grow in multiple directions in the delamination plane depending on the loading condition, presenting a two-dimensional (2D) pattern. Recent works by Cameselle-Molares et al. [1,2] and the authors [3] showed that 2D Mode-I delamination growth in laminated plates not only causes different load-displacement behavior, but also exhibits larger strain energy release rate (SERR) compared to double cantilever beams (DCB) of the same material. To the best of the authors' knowledge, no relative research on characterizing 2D Mode-II delamination can be found in the literature. This work aims to experimentally investigate the 2D delamination growth in composite laminates under Mode-II fracture condition. For this purpose, a novel 2D fracture experiment was developed, using plate specimens with an embedded pre-crack. The load-deflection, crack propagation, stiffness and compliance behaviors were obtained. Based on the experimental results, the effect of the pre-crack size was discussed.

2 Experimental program

Glass fiber/epoxy laminates, consisting of 14 layers of long continuous filament mats (CFM) in the middle and 3 layers of multidirectional (quadriaxial 0/±45°/90°) sewed fabrics (MD) on each side, were selected in this study. Five specimens with a pre-crack radius of 40 mm and three with 80 mm were fabricated and cut into a circular shape; the test matrix is shown in Table 1. The specimens were semi-clamped (allowing radial slippage), by means of two steel rings, with a support radius being 150 mm, see Fig. 1. A steel cylinder of 25-mm radius with a slightly curved bottom was employed to transfer the loads. A rubber pad was placed between the cylinder and the specimens to avoid stress concentration. The specimens were loaded under displacement-control at a rate of 1 mm/s. During the experiments, a Linear Variable Differential Transducer (LVDT) was installed at the bottom center of the plates to measure the deflection. The delamination growth along three radial directions marked with rulers was filmed by a digital video camera fixed above the. Besides, a 3D Digital Image Correlation System (DIC) and a fiber optic measurement system were employed to monitor the displacement and deformation during loading.

3 Results and discussion

All plate specimens failed at the bottom center due to bending. Some of the specimens showed good concentric delamination pattern, while others exhibited asymmetric crack propagation due to the sensitivity of the experimental set-up to asymmetric loading, see Fig. 2. Increasing load–deflection curves were obtained due to the increasing crack front length during propagation. The whole loading process for 2D experiments could be divided into three stages, i.e. crack initiation, initial propagation and rapid propagation. For the plates with smaller pre-crack, both the initial and rapid crack propagation stages comprised important proportions of the structural life in terms of total deflections. The vast majority of the delamination area was created during the third stage. For the plates with larger pre-crack, the initial crack propagation stage accounted for the major proportion of the structural life in terms of total deflections. Comparable amount of delamination area was generated in the initial and rapid crack propagation stages. In general, a larger pre-crack tends to delay the crack initiation slightly, but shows no significant impacts on the ultimate load and deflection or final delamination area. Moreover, extremely long fracture process zone, including different fracture mechanisms such as fiber bridging, resin plastic deformation and micro-cracking, can be observed through microphotography. Local crack branching and kinking occurred due to the massive nesting of adjacent CFM layers, which contributed to the high fracture resistance of such material.

References

[1] A. Cameselle-Molares, A. P. Vassilopoulos, T. Keller. "Experimental investigation of two-dimensional delamination in GFRP laminates". *Enineering Fractue Mechanics*, Vol. 203, pp 152–171, 2018.

[2] A. Cameselle-Molares, A. P. Vassilopoulos, T. Keller. "Numerical simulation of two-dimensional in-plane crack propagation in FRP laminates". *Composite Structures*, Vol. 200, pp 396-407, 2018.

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Table 1 Specimen list

Specimen	Pre-crack radius (mm)	Thickness (mm)
CP40-1	40	16.92
CP40-2	40	16.77
CP40-3	40	14.99
CP40-4	40	16.57
CP40-5	40	16.01
CP80-1	80	15.79
CP80-2	80	17.24
CP80-3	80	17.21

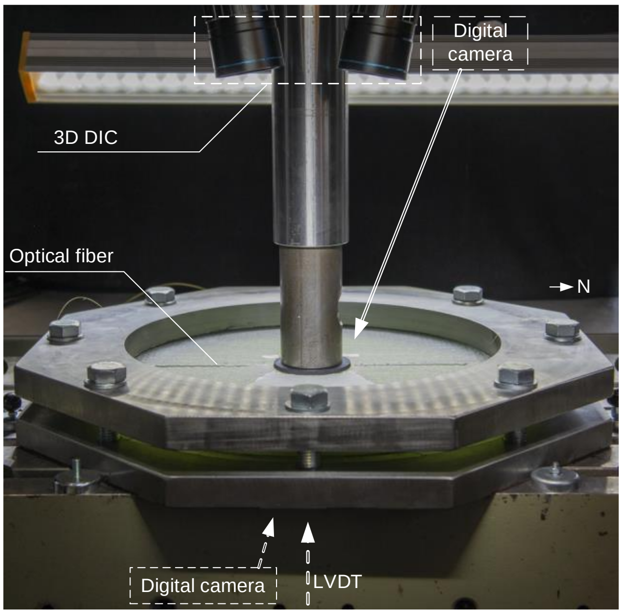

Fig. 1. Experimental set-up

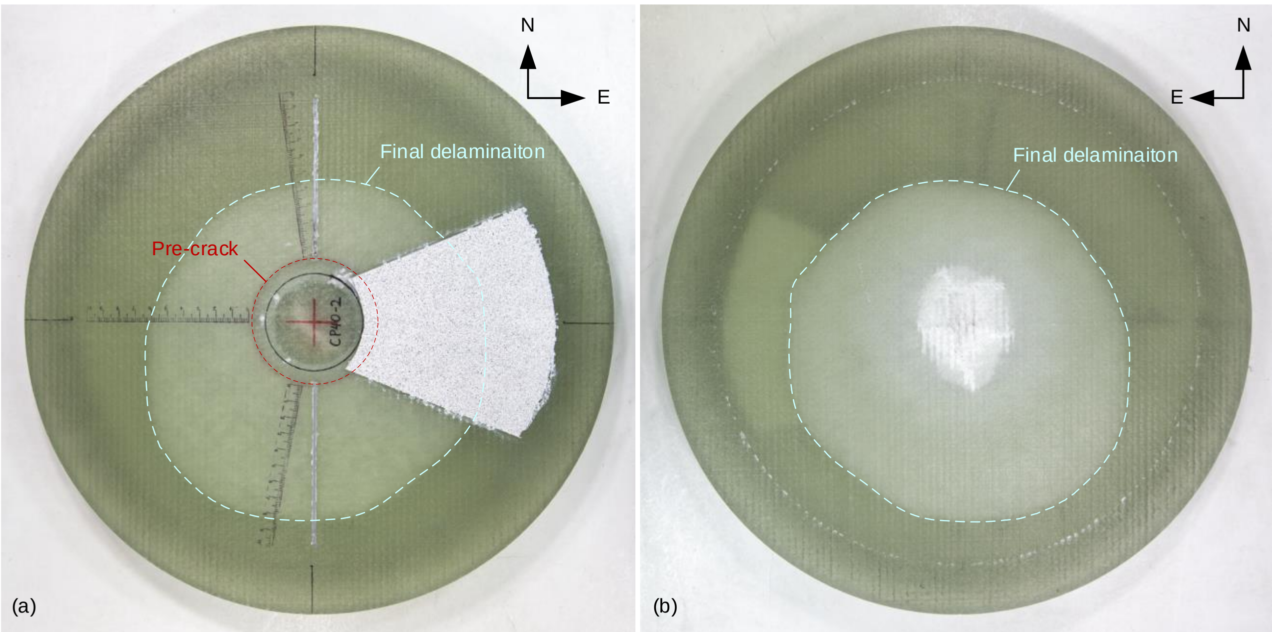

Fig. 2. Failure mode and delamination pattern of specimen CP40-2