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Scaling of fracture response in Over-height Compact Tension tests

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ABSTRACT

An experimental investigation into in-plane scaled Over-height Compact Tension (OCT) $[45/90/-45/0]_{4s}$ carbon/epoxy laminates was carried out to study the scaling of fracture response. The dimensions of the baseline specimens were scaled up and down by a factor of 2. Interrupted tests were carried out for specimens of each size in which the tests were stopped after certain load drops in order to study the failure mechanisms. X-ray Computed Tomography (CT) scanning was applied after the interrupted tests to examine the damage development and its effect on the fracture response. The test results showed that the scaling of the initial propagation of fracture follows Linear Elastic Fracture Mechanics (LEFM), but the development of the damage process zone differs with specimen sizes. The OCT specimens were found to be not large enough to generate a self-similar damage zone during propagation, and so no conclusions could be drawn regarding the *R*-curve effect.

1. Introduction

Fracture toughness is an important parameter for composite structures. Though test standards are available for the measurement of plane-strain fracture toughness for metallic materials [1] and trans-laminar fracture toughness for composite materials [2], the fracture response of composite laminates is still not well understood in terms of damage development and scaling. The Over-height Compact Tension (OCT) test was developed to determine fracture properties of composite laminates. The OCT specimen is regarded as being compact, exhibiting stable damage growth and allowing a post-test investigation of the damage evolution [3]. Damage development in OCT tests was investigated by Floyd [4], Williams et al. [5] and Li et al. [6]. Previously, a series of centre-notched tensile tests has shown that the scaling of in-plane dimensions of notched quasi-isotropic composite laminates shows a corresponding scaling of the damage zone with the size approaching a constant at large notch lengths [7]. The fracture toughness approaches an asymptote, as expected, based on LEFM. However, with such a specimen configuration, the progressive fracture cannot be captured after the damage zone is fully developed because specimens fail catastrophically. To study the scaling of the post-initiation fracture response, in-plane scaled OCT specimens are tested in the present study.

Gonzáles and Knauss [8] investigated the scaling of global fracture behaviour of large laminated composites by testing in-plane scaled compact tension specimens of two different stacking sequences and three different sizes. Structural scale compact tension specimens with notch lengths of 55.0 mm, 110.0 mm and 165.0 mm were tested. The results indicated that scaling can be related to the square root of the linear specimen or crack dimension. They also examined the damage at the 'global crack front' through 2-D X-ray images. Laffan et al. [9] studied the in-plane size effects in scaled cross-ply compact tension laminates. Compact tension specimens with scaled crack lengths of 26.0 mm, 32.0 mm and 37.0 mm were tested. They concluded that the *R*-curves for the three sizes are similar [10], which implies the scaling follows LEFM.

In the present paper, scaled quasi-isotropic OCT specimens are studied with notch lengths of 16.5 mm, 33.0 mm and 66.0 mm, covering coupon scale as well as structural scale laminates. Furthermore, more detailed damage development within each ply is examined through CT scanning. In particular, a fracture scenario is presented in which the damage development and fracture propagation are clearly distinguished. The applicability of the *R*-curve concept is also discussed.

2. Test setup

A schematic of the baseline OCT specimens is shown in Fig. 1. All baseline specimen dimensions are scaled down and scaled up by a factor of 2, so the in-plane scaled OCT specimens have notch lengths of 16.5 mm, 33.0 mm and 66.0 mm as shown in Table 1. The specimens were cut on a water jet cutting machine with

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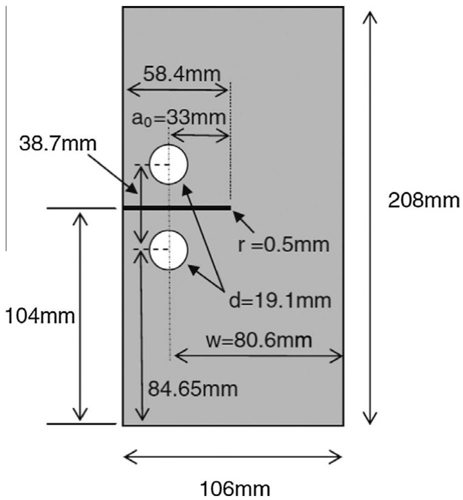

Fig. 1. Schematic of the baseline OCT specimen.

Table 1
Dimensions of the in-plane scaled OCT specimens tested (mm).

Specimen	Width	Height	Notch length	Notch radius	Hole diameter
Scaled down	53.0	104.0	16.5	0.5	9.6
Baseline	106.0	208.0	33.0	0.5	19.1
Scaled up	212.0	416.0	66.0	0.5	38.2

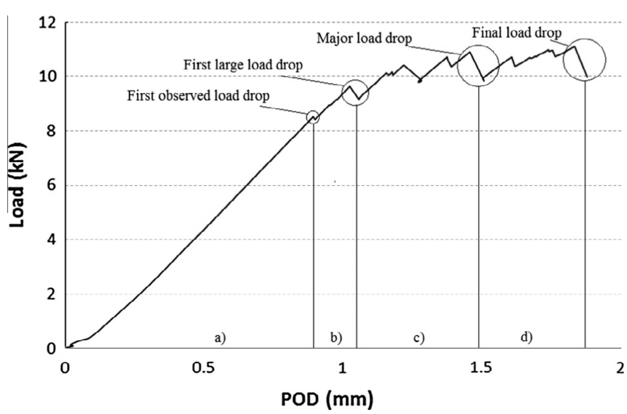

Fig. 2. Typical load–POD curve from the baseline OCT test. (a) Linear loading; (b) damage process zone development; (c) fracture propagation; (d) fracture zone expansion.

finishing at the notch tip by a 1 mm-diameter cutter on a milling machine. The last three scaled up OCT specimens were manufactured with improved drilling quality for the holes, in order to achieve a better fit between the loading pins and the holes. An extensometer was attached to the loading pins to measure the Pin Opening Displacement (POD). The radii of the notch tips were $r = 0.5$ mm for all the OCT specimens. According to Camanho and Catalanotti [11] who used $[90/0/\pm45]_{3s}$ laminates and the same material in a compact tension test, the above notch radii are sharp enough for the results not to be affected by the notch tip radius.

The material used in this test was the Hexcel HexPly® IM7/8552 carbon-epoxy pre-preg with a nominal ply thickness of 0.125 mm. The lay-up for all the OCT specimens was $[45/90/-45/0]_{4s}$. The nominal overall thickness is 4 mm, which is very close to the actual thickness.

A steel test jig was developed to hold the OCT specimens in place, with arms to apply the vertical tensile load through loading pins. It was attached to an Instron hydraulic-driven test machine with a 100 kN load cell. The specimens were tested under displacement control with scaled loading rates with regards to the specimen dimensions (a loading rate of 1 mm/min was used for the baseline specimens). A pair of anti-buckling bars was used in the baseline and the scaled-up OCT tests. They lightly clamped the rear end of those specimens to prevent potential buckling due to the high compressive stress caused by the in-plane bending of the specimens.

Interrupted tests, in which the tests were stopped after the first observed load drop, the first large load drop and a major load drop on the plateau of the load displacement curves were carried out as shown in Fig. 2. CT scanning was used to study the damage development in a single specimen from each interrupted test that was stopped at the different load levels. The samples from interrupted tests were soaked in a bath of zinc iodide penetrant for 3 days. A Nikon XTH225ST CT scanner was used to scan the scaled composite specimens from the interrupted tests. It has a 1 μm focal spot size and 225 kV, 225 W microfocus X-ray source.

3. Load–POD response

The fracture response in the baseline OCT test is divided into four stages on the typical load–POD curve in Fig. 2, which are linear loading, damage process zone development, fracture propagation, fracture zone expansion followed by final failure.

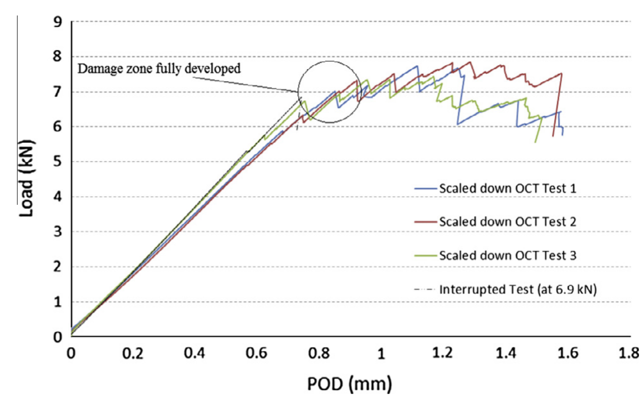

Fig. 3. Load–POD curves from the scaled down OCT tests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

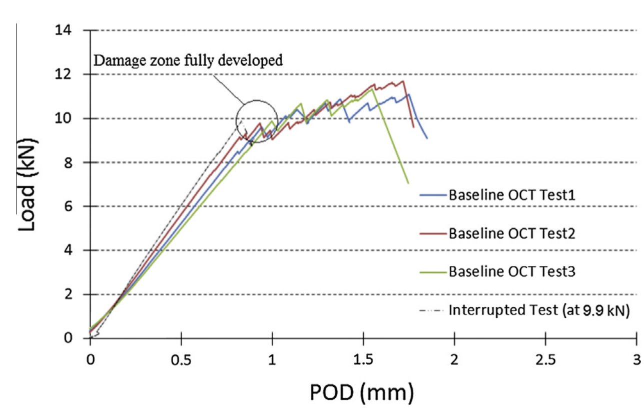

Fig. 4. Load–POD curves from the baseline OCT tests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)