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A phenomenological analysis of Mode I fracture of adhesively-bonded pultruded GFRP joints

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A B S T R A C T

The fracture behavior of adhesively-bonded pultruded joints was experimentally investigated under Mode I loading using double cantilever beam specimens. The pultruded adherends comprised two mat layers on each side with a roving layer in the middle. An epoxy adhesive was used to form the double cantilever beam specimen. The pre-crack was introduced in three different depths in the adherend in order to induce crack initiation and propagation between different layers and thus investigate the effect of these different crack paths on the strain energy release rate. Short-fiber and roving bridging increased the fracture resistance during crack propagation. Specific levels of critical strain energy release rates could be attributed to each of the crack paths, with their levels depending on the amount of short-fiber bridging and the presence of a roving bridge. The different levels of critical strain energy release rate could be correlated to the morphology of the fracture surface and the strain energy release rate can thus be determined visually without any measurement.

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1. Introduction

The limited number of existing standards and testing protocols for the Mode I fracture mechanics investigation of composite materials and adhesively-bonded joints concerns either the fracture of the adhesive in joints e.g. [1,2] or the interlaminar fracture toughness of unidirectional composite laminates e.g. [3,4]. There are a significant number of publications on both subjects [5–10]. The specimen most commonly used for Mode I fracture is the double cantilever beam (DCB) [3]. Other types of composite laminates and adhesively-bonded joints were also examined [11–15] based on existing standards and protocols. Their applicability for the interpretation of the fracture mechanics data obtained from non-standardized asymmetric fracture joints has been validated in [16].

In principle, the strain energy release rate (SERR) of composite materials is considered equal to that of their matrix, however an increased SERR is caused by fiber bridging that delays the propagation of delamination in the case of most fiber architectures and types of loading. This increasing SERR is usually described by the resistance curve (R-curve) describing the relationship between the crack length and the corresponding SERR. Extensive experiments have been performed involving ceramic [13,14] and polymer matrix composites [9,10,13] in order to examine the effect of fiber bridging on the SERR. The results showed that fiber bridging is observed in both delamination and crack propagation perpendicular to the fiber direction and affects the shape of the R-curve. The ideal R-curve presents an initially increasing SERR before reaching a plateau, although its shape is strongly dependent on the material concerned and joint configuration [13]. If large-scale fiber bridging

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occurs as mentioned in [17], that is, if the bridging length is comparable to or exceeds one of the dimensions of the specimen, the R-curve behavior may depend on the specimen dimensions.

Modeling of the fiber bridging effects on delamination resistance has also been performed and the results are presented in [14,15]. Kaute et al. [14] observed fiber bridging and attributed it to fiber waviness. Bridging fibers are always observed during the fracture of composite laminates, although their number varies according to the fiber volume fraction, fiber misalignment, fiber architecture, and crack opening. Zok and Hom [15] studied the influence of fiber bridging on the R-curve behavior of brittle materials reinforced with ductile fibers (polymethylmethacrylate (PMMA) reinforced with continuous, aligned Al wire) and brittle materials reinforced with brittle fibers (laminated lithium aluminum silicate glass reinforced with SiC (Nicalon) fibers). In both cases the R-curves obtained from small specimens were found to overestimate the true resistance behavior due to large-scale bridging effects.

Post mortem observation of the fractured surfaces also provides information regarding the fracture toughness of the examined material. The fracture surface morphology was correlated to the calculated SERR values obtained after Mode I delamination failure of DCB specimens made of two carbon fiber epoxy systems: T300/5208 (a brittle resin) and T300/BP-907 (a ductile resin) [18]. Generally, the observed fracture assumed a variety of forms, depending on ply orientation, specimen geometry and matrix toughness. It is mentioned in [18] that the multiplanar character of failure surfaces is responsible for the increase in the fracture energy compared with the value found for a planar, interlaminar-type surface.

Previous studies have been conducted mainly for the aerospace and the automotive industries and focused on the delamination resistance of carbon fiber-reinforced polymer (CFRP) laminates and/or fracture mechanics joints made of this type of material. However, in civil engineering structures, joint dimensions are significantly larger mainly due to the pultruded structural glass fiber-reinforced polymer (GFRP) adherends of thicknesses above 5 mm and adhesive layer thicknesses of between 1 and 3 mm to compensate for tolerances. Only Zhang et al. [16] investigated the behavior of fracture mechanics joints with pultruded adherends. In [16] the Mode I and Mode II fracture behaviors of adhesively-bonded joints composed of pultruded GFRP laminates was investigated using DCB and End Loaded Split (ELS) specimens. The authors used a video extensometer in addition to visual observation and obtained similar SERR values from all standardized methods as well as from 3D finite element models, with the exception of simple beam theory. In [16], an almost ideal R-curve was derived for Mode I fracture and the mean value of the plateau of the R-curves was considered as being the critical SERR for crack propagation. The laminate architecture in [16] consisted of three main layers, one roving layer in the middle and one mat layer on each outer side. The same authors numerically investigated the effect of crack depth on the SERR in the case of crack propagation in double-lap joints and single-lap joints [19]. The highest values were obtained for a path between the mat and the roving layer, while the lowest values resulted from a path between the veil and first mat layer. Since the critical SERR of the individual paths was unknown, however, no conclusion concerning the real location of the crack path could be deduced from the results.

The objective of the present study is therefore the experimental investigation of the crack propagation at different depths in pultruded GFRP adherends of DCB specimens and the effect of this crack propagation path and the associated fiber bridging on the level of the critical SERR.

2. Experimental set-up

2.1. Material description

Pultruded GFRP laminates supplied by Fiberline A/S, Denmark were bonded together using an epoxy paste adhesive (Sika-Dur 330 from SIKA AG, Switzerland) to form the DCB specimens. The laminates consisted of E-glass fibers embedded in an isophthalic polyester resin and had a width of 40 mm and thickness of 6.0 mm. The laminates comprised two outer combined mat layers and a roving layer in the symmetry plane. The combined mats consisted of two outer chopped strand mats (CSM) and an inner woven 0°/90° fabric, all three stitched together. On the outside, a polyester surface veil (40 g/m^2) was added to protect against environmental attack. The layer architecture can be seen in Fig. 1, which shows a photo of half

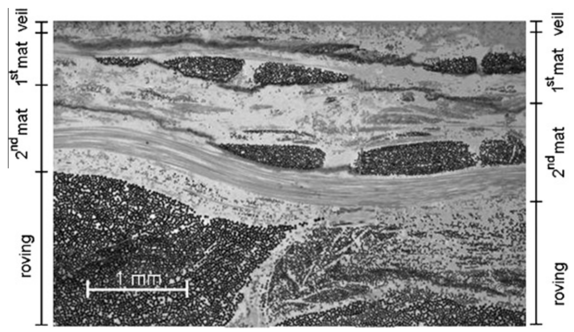

Fig. 1. Fiber architecture of upper half of laminate cross section (transverse to pultrusion direction).

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