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Exploring the influence of micro-structure on the mechanical properties and crack bridging mechanisms of fibrous tufts

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ABSTRACT

A constitutive model for tufts bridging a mode I delamination is presented. The tuft is modelled as a rod, laterally supported by an elastic medium and clamped at both ends. A fracture mechanics approach is introduced to describe the progressive debonding of the tuft from the embedding laminate. The debonding model requires the identification of stiffness, strength and toughness properties, which depend both on the laminate/tuft architecture and the constituent materials. Such identification is carried out via experimental data obtained from tensile tests on single tufts inserted in a pre-delaminated non-crimp fabric composite. The experimental results are complemented by micro-scale finite element analysis. The mode I bridging law obtained from the constitutive model is implemented into a meso-scale cohesive zone formulation. This formulation is applied to predict the response to delamination of tufted Double Cantilever Beam (DCB) coupons. The cohesive zone approach is validated by means of experimental data from DCB tests. It is shown that the proposed micro- to meso-scale modelling approach yields results in good agreement with the experiments.

1. Introduction

Through-the-thickness reinforcement (TTR) is applied to 2-dimensional composites in order to control and suppress delamination. Most common TTR methods include *Z*-pinning [1], stitching [2] and tufting [3]. Tufting is the most recent among them and is performed by inserting carbon, glass or aramid threads through the thickness of a dry preform by means of a single needle. Neighbouring tufts are interconnected to each other by a seam on one side of the preform and form thread loops on the other. Once resin infused, tufts become integral parts of the preform architecture, making it locally 3-dimensional. Despite the proved potential of tufts to counteract the propagation of delamination in composite parts [4], a complete study of their crack bridging behaviour is not available in the open literature.

The aim of this paper is to identify and describe the influence of micro-structure on the mode I crack bridging response of tufts and use the observations made at the micro-scale as the basis for the development of a multi-scale modelling framework for tufted composites.

An analytical micro-mechanical model is proposed to simulate the mechanical response of tufts embedded in mode I delaminating composites. The governing equations and assumptions of the model are supported by experimental results obtained for single-tuft coupons, complemented with observations of the tuft architecture, morphology and failure mode. The suitability of this model for the prediction of the mechanical behaviour of bridged interfaces has been assessed via its implementation into the finite element model of a DCB coupon. A cohesive zone approach [5] has been adopted for this purpose and experimental data have been used to validate the overall multi-scale modelling strategy presented.

2. Bridging mechanisms of fibrous tufts

2.1. Single-tuft tests

A set of pre-delaminated single-tuft coupons has been tested under mode I conditions in order to derive the bridging law of the tuft, i.e. the relation between the relative displacement of the surfaces of a bridged crack and the force exerted by the tuft to counteract it [6,7]. The specimens were made of four layers of biaxial carbon Non-Crimp Fabric (NCF) with an areal weight of 1010

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g/m^2, stacked in a symmetric $[(0/90)_s]_2$ layup. The stack was separated at the mid-plane by a thin release film. Each 0°/90° layer contained equally arranged 24k HTS carbon fibre tows from Tenax, held together by non-structural stitching. Each coupon was tufted with commercially available 2k HTA40 carbon fibre sewing thread, having a dry cross-section area of 0.077 mm^2. Tufts were inserted orthogonally to the release film. After insertion, each tuft featured a free loop end 3–5 mm long. The tufted preform was injected with aerospace grade epoxy resin (MVR444, Advanced Composites Group) using a Vacuum Assisted Resin Transfer Moulding (VARTM) process. Injection was carried out at 70 °C and 1 bar pressure, followed by cure at 160 °C for 90 min at 4 bar. The cured panel was subjected to post-cure in the oven at 180 °C for 120 min. The final thickness was 4 (±0.01) mm, with resulting global fibre volume fraction of 56.5%. The single-tuft coupons, with dimensions 20 mm × 20 mm × 4 mm, were tested in out-of-plane tension, under displacement control, at a cross-head speed of 0.25 mm/min. A Digital Image Correlation (DIC) system was used to monitor the relative opening of the testing fixtures. Testing conditions are illustrated in Fig. 1.

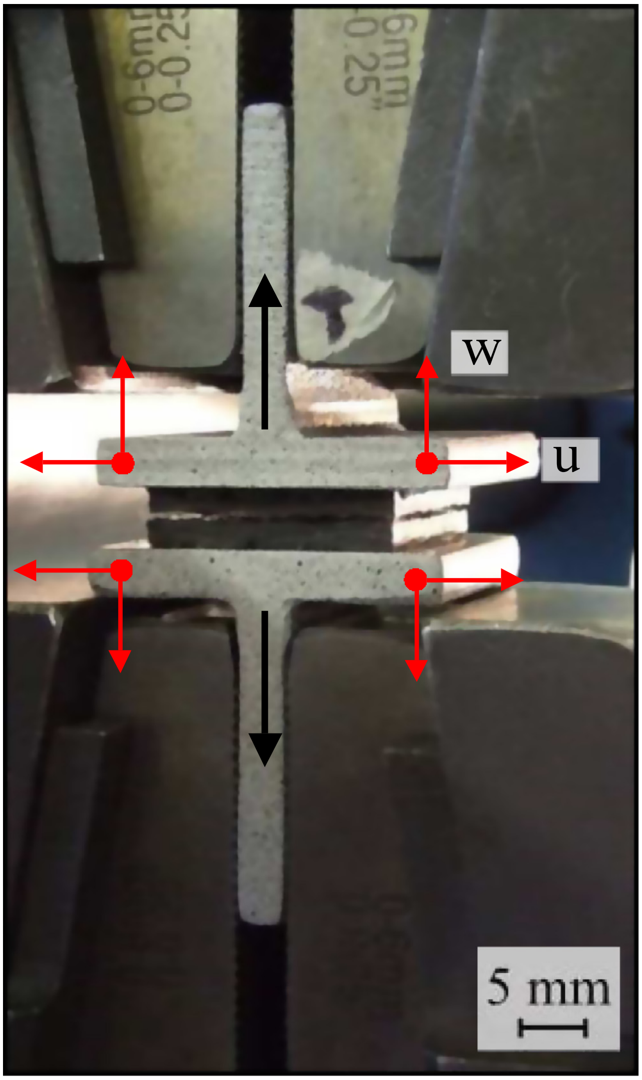

Fig. 1. Mode I test on single-tuft specimen. The test is carried out in displacement control with an Instron 5500R and a 5 kN load cell. The arrows at the fours corners of the T-tabs identify the monitored displacements. Two cameras, one on the front and one at the back of the specimen, have been used at this purpose. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Tuft morphology

Micrographic analysis was carried out to assess the post-cure tuft morphology, as shown in Fig. 2a. The insertion of tufts in a preform causes a local disruption of the in-plane fibre architecture, resulting in the formation of resin-rich regions around the through-thickness reinforcement. This is consistent with what has been reported for other TTR types in the open literature [7,8]. The cross section of the tuft is modelled by both the fabric architecture and the preform layup. Micrographs have revealed resin-rich regions characterised by maximum and minimum diameters of 5.6 mm (Coefficient Of Variation (COV) = 14.3%) and 0.55 mm (COV = 14.5%), respectively. The average impregnated cross-sectional area of the tuft, measured at 25% and 75% thickness of the samples, was 0.27 mm^2 (COV = 11%). Sectioning of the specimens has shown further that tufts are characterised by curved profiles and a random arrangement of their constituting thread segments, as in Fig. 2b. Such complex inherent features render a topological definition of tufts very difficult, and help explain the large experimental scatter in the derived bridging laws, as in Fig. 3a.

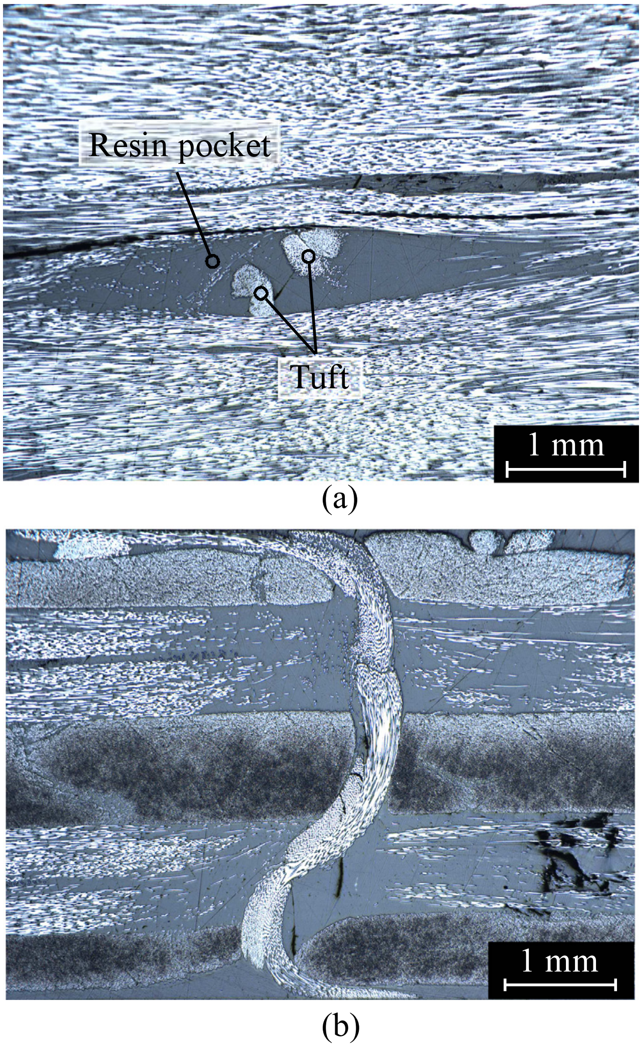

Fig. 2. In-plane (a) and out-of-plane (b) tuft morphology in a NCF composite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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