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The influence of through-thickness reinforcement geometry and pattern on delamination of fiber-reinforced composites: Part I – Experimental results

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ABSTRACT

This experimental study reports effect of tuft geometry i.e., standard tufts and loops milled-down, and tufting pattern on Mode I interlaminar fracture in a GFRP. Standard tufting geometry is responsible for an increase in fracture resistance by 3.5–6 times than the neat composite, depending on the areal pattern. Based on 5 mm squared tufting pattern on DCB specimens with a full-length release film at laminate mid-plane and non-tufted ones, the individual contribution to fracture of tufts and ply delamination are isolated. For this pattern their superposition matches well the total fracture resistance of the normal tufted composite. Extrapolation of this simple superposition to other patterns underestimates the experimental results. Experiments also show that delamination mechanisms in tufted composites are significantly affected by tuft geometry, with a 65% increased resistance for the loop-less against the standard tufted specimens. This is attributed to the large amount of energy required for tuft pull-out compared to tuft rupture during delamination, which also triggers more extended ply delamination.

1. Introduction

Layered fiber reinforced polymer (FRP) composite materials are defined by their very high specific in-plane stiffness and strength. However, they show very low resistance in delamination, especially in Mode I loading conditions, which can be easily induced in a structural component after a low-energy impact, during normal use. In order to reduce the effect of this weakness in delamination, through-thickness reinforcement (TTR) techniques such as z-pinning, stitching and tufting can be applied in layered composites. A wide range of studies conducted during the last 20 years demonstrates that TTR methods can significantly improve through-thickness properties and post impact resistance, often at the expense of degrading in-plane stiffness or strength characteristics, depending on the type and the density of the TTR [1–5].

In particular, recent developments in automated assembly techniques for dry-fiber textiles facilitate the production of complex through-thickness reinforced preforms, to be used in various liquid molding composite material fabrication processes. Amongst the many assembly techniques, tufting is successfully used in industrial applications for its simplicity and effectiveness as a TTR method (e.g. the Latecoere/Boeing 787 door [6]). Moreover, studies in damage tolerance and compression after impact (CAI) behavior demonstrate that even though all TTR methods have a positive effect [2,7], tufting TTR is expected to have the best performance compared to low-pretension stitching, high-pretention stitching and z-pinning, with minimal in-plane strength decay [3]. Other studies also show a small effect of tuft or stitching density on material's strength [8–10].

The majority of the already mentioned studies are dealing with the effect of tufting on the ultimate tensile, compressive, flexural, CAI and interlaminar shear strength behavior, while fracture toughness, which is critical in defining the complete failure of a structural component, has not been fully addressed. Thus, characterization of the different failure mechanisms involved in interlaminar fracture, still remains a challenge at this stage of research, since just a few studies specifically focus on crack bridging behavior of tufted composites, where analytical and/or numerical modeling are employed towards understanding the behavior of tufts and their role as TTR in composites [11].

The objective for this study is to identify the effects of tuft geometry and tufting patterns, on a woven glass fiber reinforced polymer (GFRP), in terms of Mode I, interlaminar fracture resistance and calculate the corresponding traction-separation relations, following a systematic delamination testing program. To do so, the neat GFRP composite is first characterized before the tufted ones, by means of double cantilever

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beam (DCB) specimens. Next, the contribution of tufts in interlaminar fracture is isolated using tufted DCB specimens with a full-length release film at laminate's mid-plane with a reference 5 mm squared tufting pattern. To investigate the effect of tuft geometry, standard tufted (i.e. with top and bottom surface loops) Mode I DCB specimens are tested and compared against specimens with surface loops removed. Moreover, three different tufting patterns are investigated in total, to identify the effect of tuft density and pattern on interlaminar fracture.

This extensive study is split in two parts, with the current one consisting of the experimental methods' description and results, including the elastic material properties evaluation and the calculated energy release rates (ERR) with the corresponding resistance curves (R-curves) for all investigated cases.

The second part of this study [12], deals with the identification of the traction-separation relations that describe the delamination process along with the force-separation relations that correspond to the failure process of the two experimented tuft geometries (with and without surface loops). In addition, FE-models, using cohesive elements to represent the delamination at crack plane and connector elements to represent the contribution of discrete tufts, are built and compared against experimental results, for all patterns and geometries.

2. Materials and experimental methods

2.1. Materials and specimens

The material under investigation is fabricated using five $400 \times 600\,\text{mm}^2$ flat, tufted preforms produced by CTT GROUP (textile research center in Québec, Canada), using a KSL (Keilmann Sondermaschinenbau GmbH) RS 522 tufting head. These preforms comprise 30 cross-plies (0/90) of twill 2/2, E-Glass fabric (TG-09-T ($305\,\text{g/m}^2$)) from Texonic Inc. (Québec, Canada). In particular regions, the plies are tufted together, with twisted 2 × 1k-67TEX Tenax® HTA-40 carbon fiber threads from Schappe Technique (see Fig. 1), using three patterns with different areal tuft density, $\rho_{tufting}$. Specimens are uniformly distributed and sufficiently spaced on these five preforms, to obtain a similar amount of tufting on each plate and limit bundle drag-out due to tufting. The tufting loops are cut down to 2-3mm using a hair trimmer device, to reduce their effect on the thickness of the final plates (Fig. 1(c)). The fabricated preforms are vacuum infused at room temperature on a flat plate, using Huntsman's Araldite® LY 8615/Aradur® 8615 epoxy (100:50, mass ratio) resin system to produce the composite laminates. An aluminum caul plate is placed above the preform during infusion (see Fig. 2), to ensure a consistent fiber volume content for each specimen and eliminate the typical laminate thickness increase above tufted areas [13]. The infused composite is initially cured at 40 °C for 24 h and later post-cured at 180 °C for 3 h as proposed by the manufacturer of the resin [14]. The cured plates have a thickness of 7.5 ± 0.5 mm with the tufted regions corresponding to the thicker domains. Later, they are cut to the desired dimensions using a diamond coated disk saw to create, not only the DCB specimens presented in this paper and the necessary specimens for the acquisition of the elastic engineering constants, but also the tuft pulling test coupons presented in [12]. The plates comprise six different types of regions: i) neat (Nt)

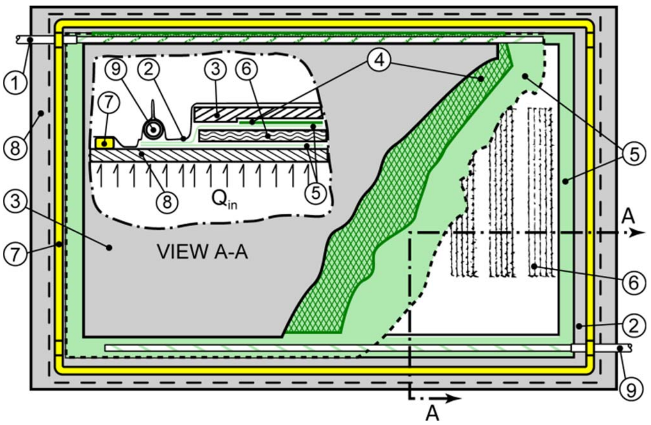

Fig. 2. Vacuum infusion set-up: ① Inlet, ② Vacuum bag, ③ Caul plate, ④ Flow medium, ⑤ Peel ply, ⑥ Fiber preform, ⑦ Sealer tape, ⑧ Heated mold, ⑨ Outlet.

GFRP regions, ii) Nt GFRP regions with a 13 μm thick ethylene tetrafluoroethylene (ETFE) film, introduced in specific regions of the preform to create the necessary symmetric pre-cracks, for the DCB delamination experiments, iii) tufted regions with a 5 mm squared (5-SQ) pattern ($\rho_{5-SQ} = 4\,\text{tufts/cm}^2$), iv) pre-released regions using the ETFE film on the mid-plane, held together only with a 5-SQ pattern tufts, v) tufted regions with a 4 mm squared (4-SQ) pattern ($\rho_{4-SQ} = 6\,\text{tufts/cm}^2$), and, vi) tufted regions with a 5 mm staggered (5-ST) pattern ($\rho_{5-ST} = 7.2\,\text{tufts/cm}^2$). The effect of tuft geometry on the delamination resistance is also investigated in this work, and for this reason, some plates are milled down on both sides in order to create loop-less tufts, free from any mechanical anchoring as shown in Fig. 1(d). This machining stage is conducted on a 3-axis CNC milling machine, using a 10 mm 4-flute (45°), diamond coated, solid carbide end-mill, at a cutting speed of 180 m/min. The final thickness of the milled down plates is 5.85 ± 0.06 mm for all investigated patterns.

In order to identify the effect of tufting patterns and geometry on the investigated GFRP system, the Nt GFRP composite DCB specimens are initially characterized. Moreover, 5-SQ tufting pattern DCB specimens with full-length pre-released surfaces at laminate's mid-plane (noted as 5F-SQ) are tested and compared against the normal 5-SQ specimens and the reference non-tufted specimens. Subsequently, DCB specimens with 4-SQ and 5-ST patterns are also tested and compared with the 5-SQ series. The same procedure is repeated for all tufted milled down loop-less series. Three specimens per pattern and geometry are tested, for all tufted series. Table 1 summarizes the description of the specimens as reported in the following paragraphs and the nomenclature used throughout this series of papers (see also [12]).

Preliminary DCB experiments on the tufted composite demonstrate that, for the reported dimensions, bending failure of the arms precedes complete delamination and full tufting breakage. Therefore, stiffening reinforcement of the DCB arms is required in order to successfully complete a DCB experiment with the tufted material. This stiffening is achieved by two symmetrically bonded polymethyl-methacrylate (PMMA) beams with thickness, h_2 of 14.6 ± 0.2 mm for the standard series and 11.6 ± 0.15 mm for the milled-down ones, with a width,

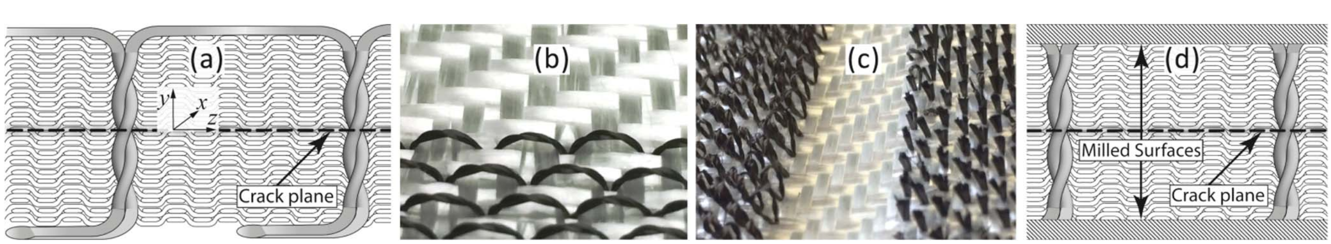

Fig. 1. (a) Cross-section of standard tuft geometry (schema). (b) Top view of tufted preform. (c) Bottom view of tufted preform with loops intact (left) and shaved (right). (d) Cross-section of loop-less tuft geometry (schema).