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EVALUATION OF SHEAR TUFT RESPONSE CHARACTERISATION METHODS

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ABSTRACT

Obtaining the shear response of tufts is essential to investigate their impact on shear delamination in tufted composites. This paper will present the results of an experimental study comparing two test methods to characterize tuft shear response. To create the shear load in the samples, in the first test method, a custom compression setup with lateral guides is used while in the second test method, a test frame is actuated in a tensile manner. The load-displacement diagrams and the fracture surfaces have been studied to compare tufts' shear response and failure mechanisms in these two methods. The study shows that lateral guides control off-axis movement and bending, but increase friction and energy dissipation, leading to differing load-displacement diagrams and failure mechanisms. This test method demonstrated a higher peak load than the second method and included a plateau at the end of the load-displacement diagram. The main failure mechanism observed in both methods is tuft breakage. In the tensile loaded method, partial pull-out is also witnessed in some tufts, relating to the unconfined off-axis movement. Therefore, the compression test method with lateral guides is preferred. Still, because the obtained results depend on the conditions of lateral guides, an approach should be considered to quantify the friction and dissipated energy caused by them.

1 INTRODUCTION

Delamination represents a significant fracture mechanism within composite laminates, occurring predominantly in the interlaminar region. This phenomenon arises due to low interlaminar strength and toughness associated with the lack of fibers oriented through the thickness. To address this issue, a range of solutions has been proposed, encompassing resin toughening methods and through-thickness reinforcement (TTR) techniques, leading to the development of diverse composite variants with tailored properties. These advancements in TTR composite manufacturing techniques, such as stitching, Z-pinning, and tufting, have yielded composites with superior balance between in-plane and out-of-plane properties compared to traditional counterparts [1].

While considerable research has been devoted to Mode I fracture in TTR composites, investigations into Mode II fracture in tufted composites remain relatively scarce in the literature. The full characterization of Mode II fracture in tufted composites necessitates the shear behavior of the tufts. The latter can be performed experimentally.

Several tailored test setups have been used to investigate the shear behavior of Z-pins and tufts. In 2006, Cartié [2] studied the delamination of Z-pinned carbon fiber reinforced laminates. They applied shear loading to Z-pinned composite specimens while constraining opening displacement using a custom test rig that included lateral supports guided by a series of cylinders. This setup avoided additional friction, as the cylinder could rotate freely. Yasaee in 2014 [3] conducted experiments on a single carbon composite Z-pin to study traction-displacement relationships. The pure mode II shear testing setup involved inner blocks sliding parallel to each other within a rigid outer guide to minimize out-of-plane opening. Raised semi-circular profiles reduced friction during sliding. The fixture was designed to align the center of gravity of the blocks with the test machine's loading line to minimize opening moments. Despite efforts to constrain out-of-plane opening, achieving precise pure mode II conditions proved challenging. In 2016, M'membe [4] explored the Mode II delamination resistance of composites reinforced with inclined Z-pins. A similar experimental configuration for the single-pin test was employed, comprising two shear grips exerting a sliding force on the specimen, along with an outer guide to limit out-of-plane opening. Hui in 2022 [5] delved into examining the interlaminar shear performance of tufted preforms and composites under Mode II loading conditions. A meticulously designed and optimized T shear test, steel fixture was employed to obtain the interlaminar shear sliding behavior of the tufted samples.

Coupled with mechanical testing, different fractography methods such as optical micrography, SEM, 3D CT scan, etc. are also employed in literature to investigate failure mechanisms such as delamination, matrix cracking, fiber-matrix debonding, fiber breakage, and fiber pull-out in TTR composites [6][7][8].

All the above demonstrates that a proper test setup to characterize the Mode II shear response of tufts is challenging. When shear force is induced in a free test setup, without lateral confinement, the test setup is prone to off-axis movement, relating to bending and mode mixity. On the other hand, when a mechanism is used to control off-axis movement, the test setup will be prone to friction energy dissipation. The results of an experimental study comparing these two test setups to characterize tuft shear response are presented in this paper. In addition, fracture surfaces in the mid-plane of specimens are observed to determine the failure mechanisms involved in these two different testing methods.

2 MATERIALS AND METHODS

The shear samples are cut from a composite plate, consisting of 30 plies of twill 2/2 woven E-glass (305 g/m^2) from Texonic layered orthotropically (consecutive layers of 0°/90°). The tufts are coiled 2*1k-67TEX Tenax® HTA40 carbon fiber threads, vertically inserted using a KSL RS522 tufting head at GROUP CTT. To isolate the contribution of tufts in shear testing, a full-length release film is placed at the mid-plane of shear samples during the manufacturing of the plates. Huntsman's Araldite® LY 8605/Aradur®8605 epoxy is infused into the preforms at 25°C using the VARTM method. The plates are left to cure at 25°C for 24 hours, and post-cured at 121°C for 2 hours and at 177°C for 3 hours. Six shear test samples with dimensions of 2 cm x 2 cm, containing 9 tufts with 5 mm distance from each other, are cut from the plate (Figure 1a).

Two customized test configurations are developed for this experimental study to evaluate the shear response of tufts. In both configurations, shear specimens are glued on two tailored aluminum tabs to transfer the loads. For the first test setup, the "tab/specimen assembly" is placed inside an ASTM 6484 [9] open-hole compression fixture, and compressive loading is applied to generate shear load in the samples (Figure 1b). A gap equal to the thickness of a paper sheet (about 0.1 mm) was left when attaching each lateral guide. For the second approach, the tab/specimen assembly is subjected to tensile loading, in a configuration that resembles shear lap testing, to generate the shear load (Figure 1c). A displacement-controlled condition with a rate of 1 mm/s was employed to perform the tests. Displacements are measured using the crosshead displacement of the test frame and also by the Digital Image Correlation (DIC) method. For the design of aluminum tabs, the length-to-thickness ratio was minimized while conforming to the constraints imposed by the dimensions of the fixture, grips, and samples, so that bending and off-axis movement during the tests is minimized. The length-to-thickness ratio of the designed aluminum tabs is 70/4 (mm/mm) for the compression test setup with lateral guides, and 40/4 (mm/mm) for the tensile setup test.

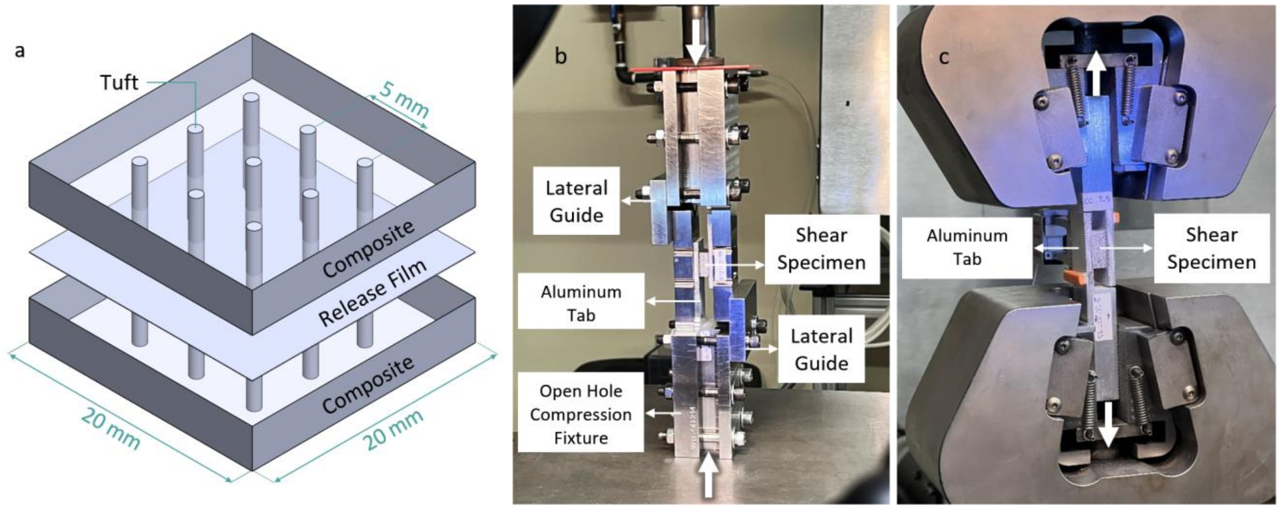

Figure 1. a) Schematic of shear specimen. b) Compression loading setup with lateral guides. c) Tensile loading setup.

3 RESULTS AND DISCUSSION

3.1 Load-Displacement Diagrams

The load-displacement diagrams, featuring displacements obtained from both crosshead (Cr.) and DIC for both test setups, are illustrated in Figure 2. The comparison of Cr. and DIC measurements shows that both test setups are significantly compliant. Consequently, neither configuration permits the use of displacements from the crosshead to derive the damage energy related to tuft failure, mandating the adoption of methods such as DIC for precise displacement determination.

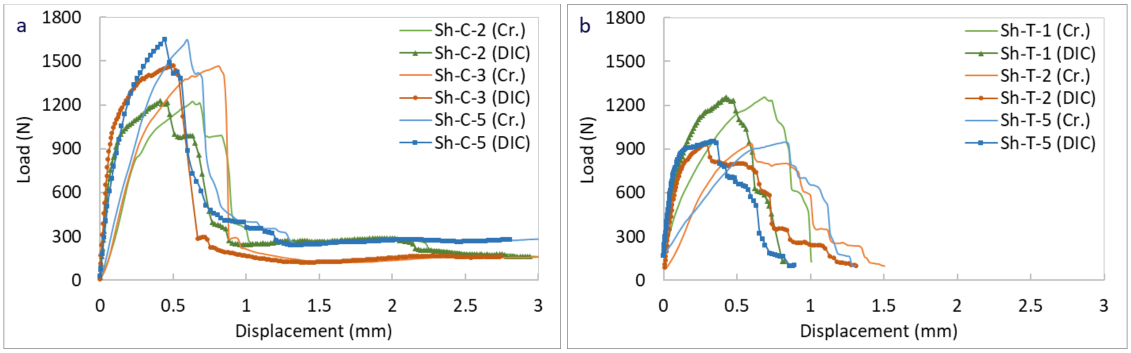

Figure 2. Load-displacement diagrams from Crosshead (Cr.) and DIC measurements for a) Compression test setup with the lateral support, b) Tensile test setup.

The load-displacement diagrams obtained from DIC for these two test setups and average diagrams for each test setup are depicted in Figure 3. Both diagrams reach their yield load with a practically similar steep slope. The average peak load for the compression test setup with lateral guides is 41% higher than for the tensile test setup. For the tensile load setup, the end of the diagrams is governed by the machine's stop when loading is lower than the initial load required to hold the tabs inside the grips (defined before the start of the test). In the compression setup, a plateau can be seen at the end of the diagrams, relating to the presence of lateral guides in this configuration. The tests are stopped manually when the crosshead displacements reach about 3 mm. For the tensile configuration minor tuft support is still present after the test stop, as described further in section 3.3.

As seen in Figure 3b, the absorbed energy is higher in the compression test setup with lateral guides. In particular, the energy absorption in the first part of the diagrams (prior to the plateau) is 33% higher for this setup, indicating different failure mechanisms, acknowledging the fact that we are not in contact with the lateral guides in this part (see Figure 4d and Figure 4e). The absorbed energy in the plateau may include friction contribution due to the presence of lateral guides, including frame and friction between the failure surfaces of the specimens.

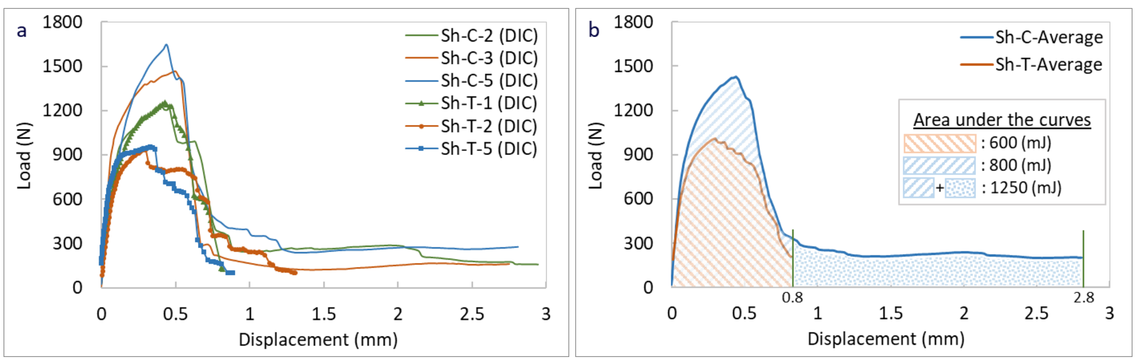

Figure 3. Load-displacement diagrams for a) Both test configurations, b) Average of each test configuration, with corresponding dissipated energy.

3.2 Lateral Displacement

The lateral displacement and off-axis movement in the specimens during the tests are illustrated in Figure 4. The maximum distance between two lines coinciding with the two outer surfaces of the specimen is considered a measure of lateral displacement.

Figure 4a and Figure 4b display the lateral displacement during the test in the compression setup with lateral guides and in the tensile setup for five applied displacement segments (i.e. 0, 0.1, 0.4, 0.6, and 0.8 mm). As presented in Figure 4a, Figure 4b, and Figure 4c, the application of compression and tensile loads to generate shear in the mid-plane of specimens (L), induces a clockwise bending moment in the aluminum tabs of compressive test setup with lateral guides, and a counterclockwise bending moment in tensile test setup. The magnitude of this bending moment is equal to "L·d", where "d" is the distance between the mid-plane of the specimen and the neutral axis of the aluminum tab. The recorded lateral displacement results from the sliding of fractured surfaces without excluding some tuft bending caused by partial pull-out. The inevitable moments induced by the setups may have some contributions to the lateral displacements. In the compressive configuration, the bending moment pushes the crack planes together, while in the tensile configuration, it creates separation and crack opening.

In the tensile setup, specimens exhibit a higher maximum lateral displacement (point 5 in Figure 4) attributed to flexure, as the test frame is free to move. On the contrary, off-axis movements and flexure during the test are better controlled when using lateral guides. However, the test results will depend on the conditioning of this test setup and the relative degree of pre-load of lateral guides.

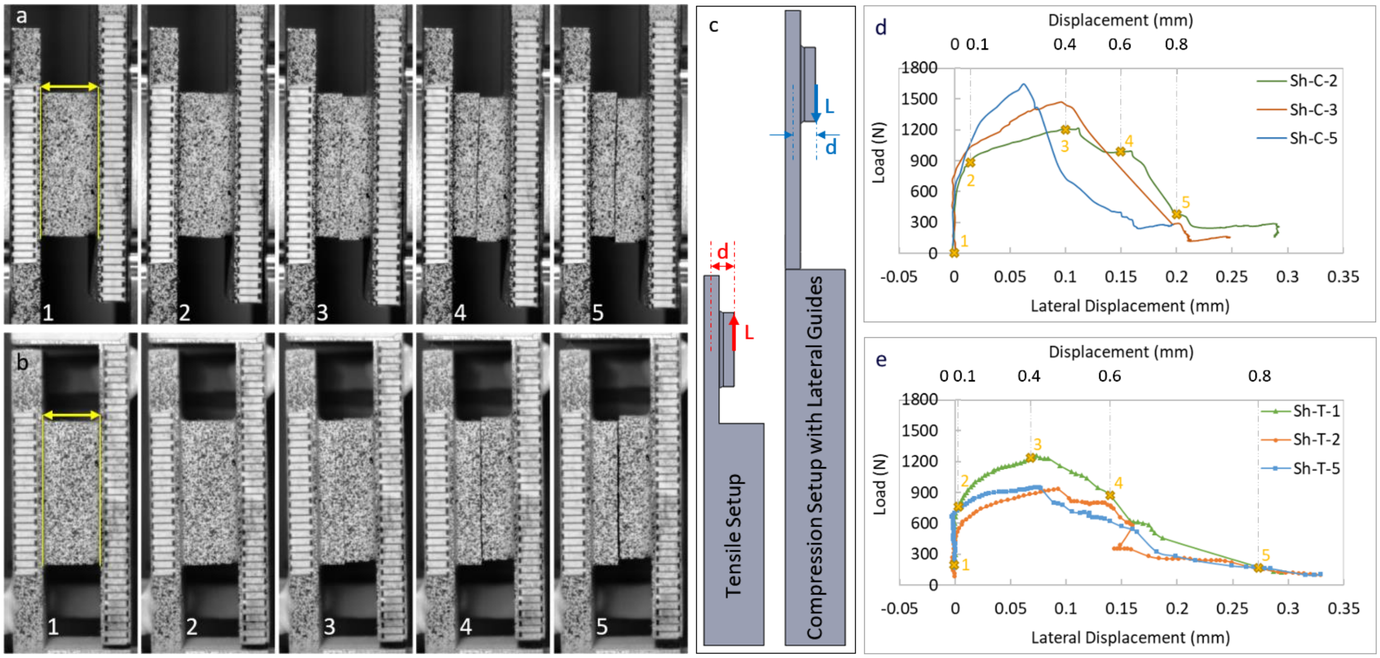

Figure 4. Lateral displacement during the test in a) Compression setup with lateral guides, b) Tensile setup. c) Schematic of load and resulting bending moment in half of the tensile and compression tab/specimen assembly. Load-lateral displacement diagrams for d) Compression setup with lateral guides, e) Tensile setup.

3.3 Failure Mechanisms

Upon observing the fracture surfaces of the tested samples, as shown in Figure 5, it is evident that the tuft breakage failure mechanism occurs in both test configurations. The failure mechanism is shear-dominated, yet some local pull-out is witnessed when using the tensile test setup correlating to the introduction of mixed mode conditions due to the minor tuft bending before the ultimate shear failure, affecting the failure mechanism.

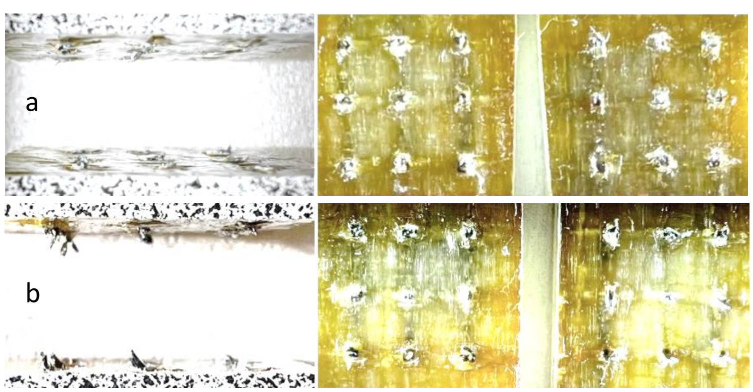

Figure 5. Fracture surface of the specimen tested by a) Compression test setup with lateral guides, b) Tensile test setup.

4 CONCLUSIONS AND OUTLOOK

Characterizing the shear response of tufts is important to quantify the effect of tufts on shear delamination and allow for precise modeling that will enable damage-tolerant design approaches. However, employing an appropriate test setup to assess the Mode II shear response of tufts is challenging. The results of this experimental study show that the shear behavior of tufts may differ, depending on the characterization base, i.e. tensile or compression test setup with lateral guides. The attested tensile setup provides reduced constraint of off-axis movement and bending, resulting in lower damage energy dissipation but also friction. The lateral guides in the compression test setup provide controlled off-axis movement and bending of the tab/specimen assembly, resulting in higher energy dissipation, potentially associated with some friction, which is anyhow expected in bending-dominated shear delamination [10]. Thus, the compression test setup with lateral guides provides a better controlled test method to characterize the shear behavior of tufts, yet the results depend on the condition of the lateral guides.

In future work, the focus will be on quantifying the friction load due to the presence of lateral guides employing flexible pressure sensors in the compression test setup with lateral guides. Accordingly, the friction caused by the lateral guides and the friction between the composite surfaces in the mid-plane of the specimens can be differentiated. This solution facilitates the application of an ideal test method to obtain accurate results for the shear behavior of tufts.

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