Structural integrity assessment of tufted textile composite and its comparison with laminated textile composite

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Abstract

Three dimensional composites have been used in aerospace industry to improve interlaminar strength. This paper evaluates the 3D tufted composites from aspect of their mechanical properties. The tufted composite panel was manufactured based on polyester resin as well as an untufted laminated composite for comparison purposes. Experiments show that specimens with transverse tufting suffer slighter reduction in the tensile strength than longitudinal tufting. The tufted composites are found lower tensile strength compared with laminated composite samples accompanied with slight improvement in the compression strength and high strain rate tensile strength. The experimental results presented in this paper should be valuable to achieve desired property of tufted composites for specific aerospace applications.

1. Introduction

Composite materials have been successfully used for structural applications, due to their structural advantages for high specific strength and stiffness. The first generation of composite is 2D laminates. Although, these types of composites are characterized by high stiffness and strength properties, they suffer from weak out-of-plane properties, and a more time-consuming fabric lay-up process. Over the last decades, three-dimensional (3D) textile structures have been developed to overcome those disadvantages of 2D laminates [1]. The development of 3D textile composites has been undertaken largely by NASA [2]. Mostly, the development of 3D textile composites has been driven by the needs of reducing fabrication cost and improving mechanical properties. 3D textile composites containing textile preforms have the following mechanical characteristics: improved stiffness and strength in the thickness direction, elimination of the interlaminar surfaces due to integrated structure, possibilities of near-net-shape design and manufacturing [3,4]. 3D Textile composites based on textile preforms are manufactured by several processing techniques, resin infiltration, and consolidation techniques. Textile preforms can be divided into four groups according to their manufacturing techniques: Braiding [5], Weaving, Stitching [6] and Knitting. These textile processes have the potential to reduce significantly the cost of manufacturing of many composite components and produce structures to improving mechanical performance in critical design cases such as the impact [7] and fatigue [8,9]. Tufting process or modified one side stitching is new developed technique to insert through thickness reinforcement inside fabrics [10-12]. Mostly, two main aspects of tufted composites could cause research questions: manufacturing cost and mechanical properties. Damage in tufted preforms and subsequent tufted composite failures due to static or dynamic loading [13,14] are a major concern to their aerospace applications [15,16]. Therefore, understanding the behaviour of a tufted composite structure subjected to mechanical loadings in particular fatigue loads [17,18] is vital task. In this paper, we discuss on mechanical properties of tufted composites during static testing. Damage in tufted preforms and subsequent composite failures subjected to static loading are discussed. Furthermore, an insight in the mechanical properties of composite samples at high strain rate was done to study effect of strain rate in compare to those samples at low velocity tensile testing. Finally, X-ray technique along with optical and electron scan microscopy are applied to characterize the microstructural variations of composite samples and damages states.

2. Experimental material and equipment

The preforms were composed of eleven layers of twill woven glass fabrics with a quasi-isotropic lay-up. The woven fabrics have the areal weight of 305 g·m^{-2}. These fabrics were tufted with a twisted 240 Tex polyester thread using a KUKA 6-axis robot head

equipped with a commercial tufting head at CTT group center, Canada as shown in Figure 1. The tufting rows were oriented at 0° in direction of woven fabrics, with a tufting spacing of 4 mm and pitch of 4 mm. The preforms were impregnated with polyester resin using vacuum infusion process. The tufted composite panel thickness was 2.8 mm giving a fibre volume fraction around 60%.


Figure 1. Microscopic image of tufted composites.

Tensile test of composite specimens in accordance with ASTM 3939 standards was experimentally carried out by an MTS testing machine with a load cell capacity of 100 KN. The tensile tests were carried out on specimens cut in perpendicular and parallel of tufting direction. The sample size for the tensile tests was 25 mm × 250 mm, and the test speed was 2 mm·min^{-1} for all samples. Furthermore, static tension test was conducted on open hole tufted composite to determine the reduction of strength and stiffness because of hole in diameter size of 6mm in center of coupon. Tabbed samples used in the compression tests measured in 40 mm wide and 100 mm long. When sample mounted in the testing machine the length of unsupported section was 38 mm. Compression Tests was conducted on MTS machine equipped with hydraulic grips at a crosshead speed of 1mm/min. For characterizing the samples, X-ray Micro CT scanning was conducted using a commercial scanner at Jesse Garant & Associates Company in Canada consisting of a micro focus X-ray tube at 36KV within spot size of 0.005 mm and 2376 projections. For this research, the sample size of 20 mm × 20 mm was prepared from each composite plate to provide high resolution scanning around 0.045 mm. The scanner created two dimensional images of composite sample, and a specific software program constructed 3D map from these 2D X-ray images. The 3D reconstructed CT data were analysed using the VG studio toward damage characterization purposes.

3. Results and discussion

The static tensile loading of composite coupons was applied until the failure of samples. Typical stress–

strain curves of tufted composite with longitudinal (tufting direction is parallel to tensile loading direction) and transverse tufting are shown in Figure 2. As seen in this figure, the stress-strain curves are composed of two regions, inelastic and plastic deformation regardless the tufting orientation. The stress-strain responses in elastic region are approximately linear until initiation of damages. The transition from elastic region to plastic deformation is typically observed for all tufted composites accompanied with the formation of transverse cracks in matrix and interface of fabrics in particular around tufting region.
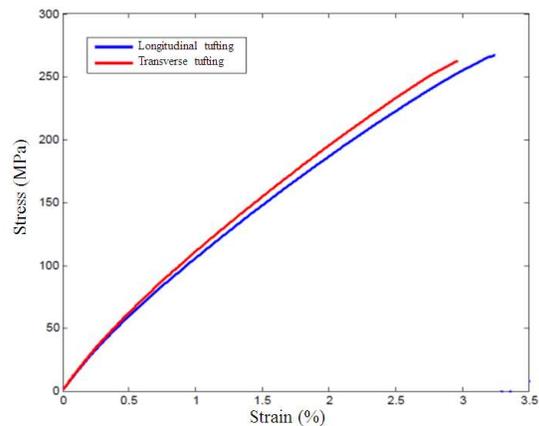
Figure 2. Stress-strain graph of tufted specimen under tensile loading: longitudinal tufting and transverse tufting.

Figure 3 depicts the behavior of laminated composite subjected to static tensile loading. It is evident that untufted composite specimens exhibit nonlinear curves up to its final failure same as tufted composites. The slope of the curve for both tufted and untufted specimens can be seen to gradually decrease for strains higher than about 1%, and almost remains linear up to failure. It is observed from the stress–strain plot that there is a sudden small drop in magnitude of the stress near to final rapture point. This point, at which the macroscopic failure occurs, was followed by loss of load carrying capability. The stress at this point could be considered to be the failure stress. Upon continued loading after this drop, the stress tends to get redistributed, but further failure follow and the sample lost its structural integrity along that loading direction.

As a whole, neither the strain nor the strength caused differed considerably for the longitudinal and transverse tufting. It frequently appeared that composite sample with transverse tufting had lower strength than longitudinal tufted sample, however the difference between them was around 3%.

Furthermore, experimental data indicated that tufting process had little influence on the tensile response of composite samples in comparison with laminated composites. Figure 4 depicts the quasi-static tension tests results related to tufted specimens with and without open hole. During tensile testing, the stress strain graph was nonlinear and samples was ruptured from hole region due to high stress concentration on this area. It should be noted that the failure strength of untufted composite was below the strength of tufted sample. It seems that stress concentration due to hole in tufted composites is less than untufted composite. It could be because of arresting damages such as delamination adjacent to the hole by tufts.
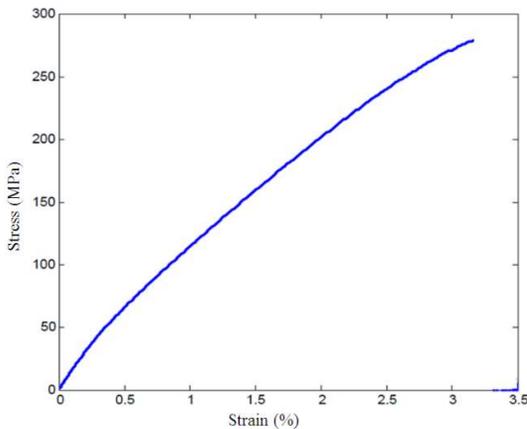

Figure 3. Tensile test response of laminated composite.
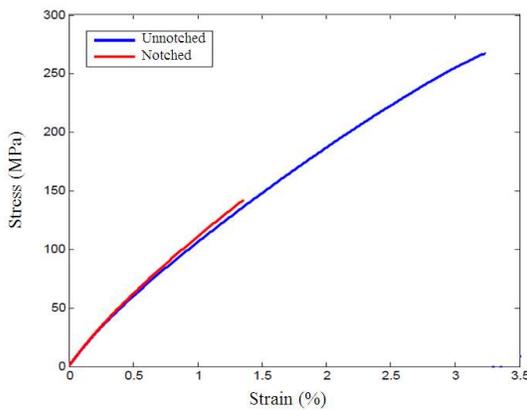

Figure 4. Stress- stain graphs of tufted specimens with open hole.

In addition to tensile test at low crosshead speed, tension tests at high strain rate around 0.1 s^{-1} was done to investigate the influence of strain rate on stress strain curves of tufted and laminated composite. As shown in Figure 5, It was concluded that high strain rate could cause specific increase in mechanical performance of tufted up to 18% while laminated composite didn't have such increase. These phenomena can be explained with the assumption that small damage at interface of fiber and matrix and resin rich regions at high strain rate loading does not find sufficient time to develop.
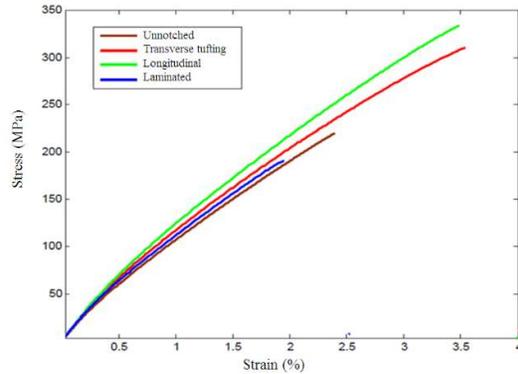

Figure 5. High strain rate tensile test of composite samples.

Figure 6 indicates the composite sample's strength plot under compression loading. The unnotched tufted composite sample was loaded in at tufting direction (0°). The failure behaviour of tufted sample is generally the same with laminated composite while the tufting process increasing the compression strength. Therefore, it could be said that the tufting has positive impact on composite performance and improved the damage resistance of sample. However, more research should be done to verify this event in particular for the case of high tufting density at different directions.
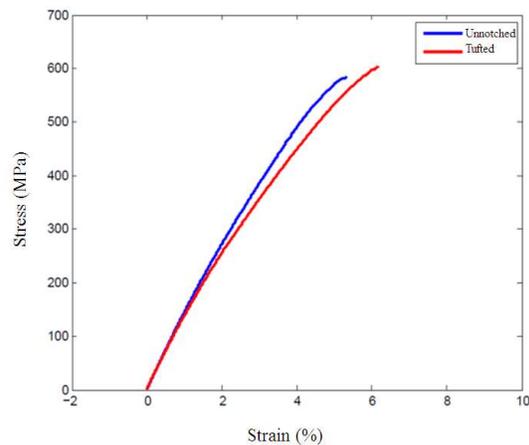

Figure 6. Strain plot of samples subjected to compressive loading.

The specimens with transverse tufting were usually raptured along the tufting lines while the specimen with longitudinal tufting was raptured in angular direction to the tensile loading direction. At the initial

stage of loading, when the tensile loading exceeded a threshold value of 3 kN, damage appeared in surface of composite in the proximity of tufting thread region shown in Figure 7. For the tufted specimens, microcracking was audible at load levels between 7 and 9 kN while, microcracking inside untufted composite was audible at load levels between 4 and 6 kN.
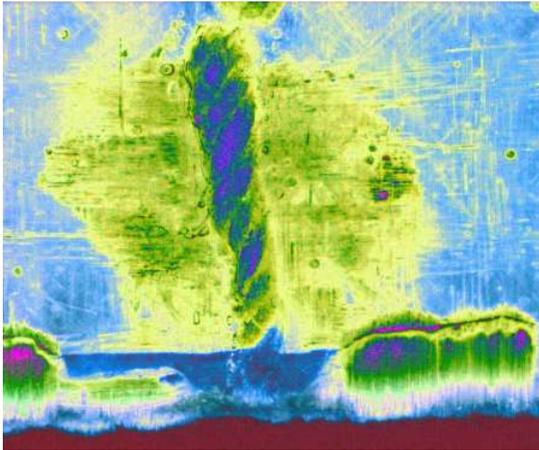
**Figure 7.** SEM images of delamination crack occurred during fatigue loading for tufted composites.

Figure 8 presents X-ray CT images of raptured tufted specimen. Figure 8a represents cross sectional x-ray images correspond to moving the cutting plane in thickness direction, while 8 depicts the sectioning of notched sample stopped at 80% of failure strength. White area indicates fibers and dark region indicates matrix and cracks. The distributions of major damages in through-the-thickness direction of tufted composites were dissimilar at different regions. In the fractured tufted specimen, largest damages including delamination and fiber fractures are seen at the center of the composite coupon. In notched sample, the damages were initiated from the tufting thread region, and the largest damages prior to full rapture is seen at the top and bottom surfaces.

Examination of cross-sectional X-ray computer tomography clearly presented the shear failure happened and fabrics moved from their original direction near the tufting thread. With respect to the obtained X-ray images, the specimen rapture tended to occur by combination of most significant damage including fibre breakage and transverse shear. Tufting thread decreased delamination but increased the kind banding and fiber misalignment and out of plan weaviness waviness. While shear failure and kink bands damages have been commenced in the vicinity to the tufting thread, but no precise correlation could be proved between them.

4. Conclusions

Experimental investigation on the effect of through-thickness tufting on the static tension and fatigue composite has been performed. Two cases are studied in present tufted investigation, namely longitudinal and transverse tufting. Laminated composite without tufting and longitudinal tufting composite revealed little larger strength than transverse tufting. The experimental results indicated that the untufted specimens are far superior to tufted specimens in fatigue. At 60% of the static failure strength of untufted specimens, the tufted specimens easily survive 2500 hundred cycles whereas the untufted specimens can last only about 2000 cycles. Although, tufting did cause some problems on the tensile strength including stress concentration at the tufting point, fibre misalignment, and fibre breakage arising from needle perforation, however it may be possible the composite sample with higher tufting density appear with low static tensile strength and fatigue performance.
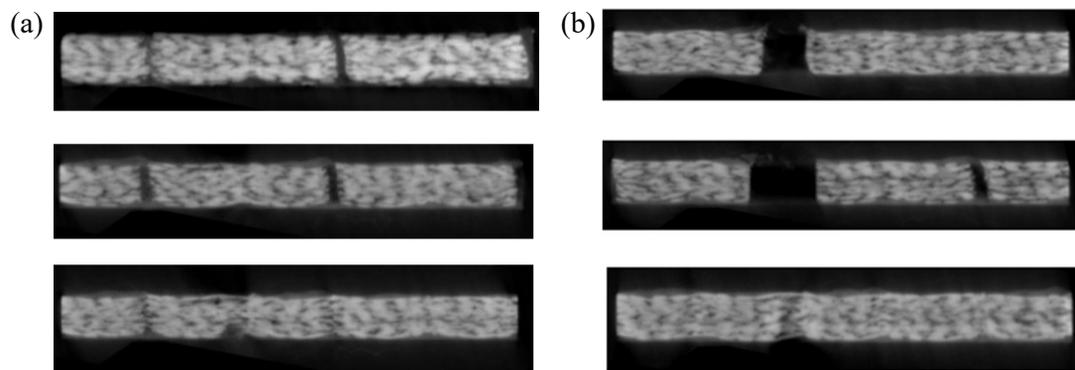
Figure 8. Reconstructed 2D X-Ray images correspond to moving the cutting plane in thickness direction (a) Cross sectional images of fractured specimen in static tension test and (b) Cross sectional images of notched sample stopped at 80% of failure strength.

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