

In-situ structural health monitoring of glass fiber reinforced composites by tufted reinforcement

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Abstract. Through-the-thickness reinforcement (TTR) techniques have been increasingly applied to fiber-reinforced polymer composite laminates to reduce the issues caused by the weak out-of-plane properties which can reduce significantly their load-bearing capacity. The present work investigates the electrical response of carbon tuft threads as reinforcements of GFRP omega stiffened panel. Besides the mechanical contribution of the tuft reinforcements to the composites structures, this study focuses on the evaluation of the electrical response on the tufted yarns as a means of monitor the structural health. The first studies consisted of evaluating GFRP composite laminate plates reinforced with carbon tufts by means of the electrical response through tufts to damage generated by multiple low-velocity impacts. Once the tufts exhibited their ability to respond continuously while increasing damage, pull-off mechanical tests were performed in the omega stiffeners assisted by electrical resistance measurements as well as acoustic emission (AE) and Digital Image Correlation (DIC). The results showed that the measures of electric resistance on the yarns are capable to distinguish important events during the mechanical tests, as the delamination and tuft failure. Furthermore, they are in common agreement with the cumulative energy on AE and strain field response on DIC.

1. Introduction

Conventional composite laminates exhibit moderate fracture toughness especially due to reduced mechanical properties of the polymer matrix and its interaction with fiber reinforcements. Therefore, they are susceptible to interlaminar damages especially by delamination that is one of the major damages in laminate composites and can reduce considerably the load-bearing of a structure. It can be induced when submitted to out-of-plane loading (static or impact loading) and typically combined with stress concentrations (related with structure geometry) or discontinuities such as manufacturing defects, ply drops or free edges [1].

Improving the resistance to crack initiation and propagation throughout fabric plies can improve considerably the interlaminar fracture toughness. Several methods have been developed to counteract the susceptibility of the composite laminates to delamination and can be classified into matrix toughening or 3D fiber architecture. Interesting results can be achieved by performing through-the-thickness reinforcements (TTR). Among the several methods to reinforce transversally the laminate composites, the main methods are the 3D weaving, stitching, tufting, z-anchoring, and z-pinning.

Tufting method is a one-sided stitching process which consists of inserts needle with the reinforcement yarn is pushed into the fabrics preform and afterward, tufts are held mainly to the friction imposed to the yarn by the fabrics. This method is known by its low-tension under reinforcement which



results in a reduction of the penalty effect in the in-plane properties of the stitching process [2]. In general, the tufts firstly contain the crack tip during the structure loading. Subsequently, the fissures are branched by the tufted yarns and finally, they fail as well as the composites. Tufting reinforcement has been shown to enhance the fracture toughness under both modes I [2]–[4] and II [5] loading conditions. Significant improvements to impact resistance and compression after impact strength have also been reported [6]–[8].

The present work reports the manufacture and mechanical characterization of omega stringers made of GFRP and reinforced through-thickness by tufting. The main goal was to monitor the structural health during pull-off tests by means of the electric resistance measurement from the tufted carbon threads. The tests were assisted by Digital Image Correlation (DIC) and Acoustic Emission (AE) in order to validate the electric resistance response. An investigation before to the pull-off tests in omega stiffened panels was performed with GFRP laminate plates so as to evaluate the electric resistance behavior in the carbon tufts when damage is generated intentionally by low-velocity impact tests. Besides the main interest to reinforce transversally a laminate composite with tufts such as increasing the interlaminar fracture toughness, this approach showed capable to acquire in-situ resistance measurements and detect the major damage events and, may avoiding the insertion of sensors into the laminate which can diminish mechanical properties.

2. Materials and methods

2.1. Materials

2.1.1. Laminated composite plates

The plates were manufactured with a stacking sequence of $[0]_6$ in glass fibers 2x2 twill weave fabrics and areal density of 280 g/m^2 . The dry preform was stitched following the warp direction of the fabrics with carbon/PBO threads (2K Tenax-J HTA 40 carbon thread wrapped by two PBO yarns). The tufting loops were adjusted to be as smaller as possible avoiding their contact that could change the electrical measurements by means of percolation. Similarly, the tufting density was $10 \times 10 \text{ mm}$ arranged in a square pattern to avoid this concern. The composite plates were molded by VARTM process with EPOLAM 5015 epoxy resin system. During infusion process, the vacuum pressure was about -1000 mBar at room temperature. The cure cycle was carried out at room temperature for 24 hours and post-cured at 80°C for 16 hours. Specimens with $100 \text{ mm} \times 150 \text{ mm}$ dimensions, with the warp direction aligned with longitudinal side, were prepared for the impact tests.

2.1.2. GFRP omega stiffened panel

Non-crimp fabrics (NCF) made with unidirectional layers of glass fiber tows (0/90) and areal density of 600 g/m^2 were employed to manufacture the omega stringers. The structure layup consisted of $[0]_{10}$ to the stiffener and $[0]_{12}$ to the skin part. The dry preforms were reinforced by tufting with carbon/PBO threads following the weft direction and stitch pitch of 7 mm . VARTM process was also employed with EPOLAM 5015 resin system by maintaining the same parameters of cure cycle as described for the plates. The tufts position and dimensions of the molded specimens are exhibited in Figure 1, with specimens width of 30 mm prepared to pull-off tests.

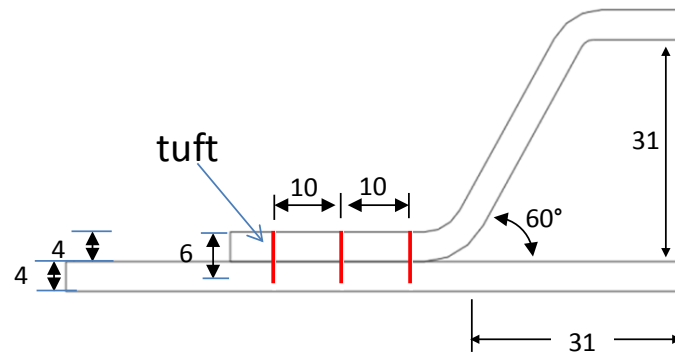


Figure 1. Schematic illustration of the final dimensions of the omega stiffened composites.

2.2. Testing methods

The laminated composite plate was manufactured to evaluate the feasibility of the carbon threads to respond to the damages created by multiple impact tests. Therefore, they have been submitted to various impact loading with energies of 5J, 5J, 10J and 10J so as to create the progressive damage. It was performed by Instron Dynatup 9250HV drop-weight impact machine, using a hemispherical indenter of 50.8 mm diameter and weight impactor adjusted to 14.2 kg. The electrical resistance of the tuft rows (6 tufted lines in the middle of the specimens) was measured before each impact test by using 4-wire sensing to perform more accurate response. The external points (pairs of current-carrying) injected a controlled direct current of 1mA while the internal points (voltage-sensing electrodes) each one placed 10 mm from the external probes, measured the electrical resistance. Moreover, a specific analysis consisted to evaluate the damaged area and heat dissipation before the impact loadings. The heat dissipation was investigated by the infrared camera during the current injection of 400mA between the 6 tuft rows in the middle of the specimen. The damaged area was characterized by C-Scan technique, scanning a zone of 50 mm x60 mm (width x length) centralized in the impact point via ultrasonic. The steps utilized for this approach are shown in Figure 2.

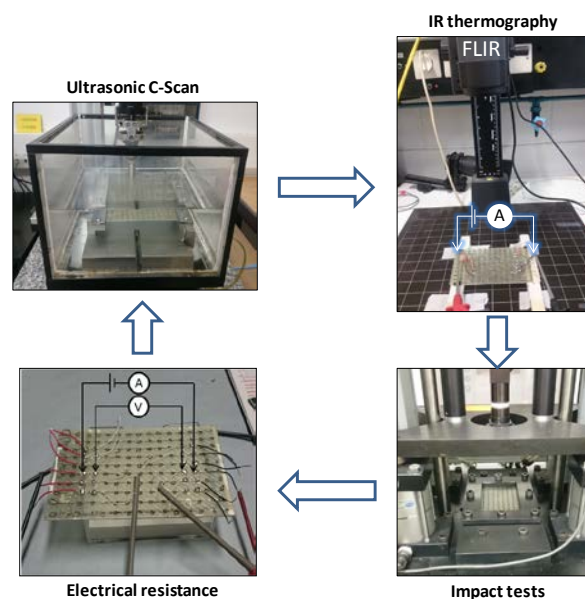


Figure 2. Experimental procedure employed to the investigation of the electrical resistance response before each impact loading

The pull-off tests were carried out at a constant cross-head displacement speed of 1 mm/min. Two fixed rolls (10 mm diameter) were placed 74.5 mm distant from the longitudinal center of the samples and in contact with the skin top surface. The single roll (20 mm diameter) equidistant from the fixed rolls was placed in the bottom surface of the stiffener for loading the structure. The tests were monitored by DIC to evaluate the strain fields in the critical zone of the omega stringer from both sides of the contact flange/skin throughout the loading history and correlated with the software VIC 2D[®]. The subset and step size employed in the image correlation were 21 and 3 respectively. The AE analysis was also performed for monitoring damage events from the acoustic signals. The signal acquisition was carried out with two wideband sensors (Micro80 - 200-900 kHz) longitudinally positioned on the bottom side of the skin from 80 mm to the center. Furthermore, two-wire measurement was employed to acquire the resistance from both sides of the omega structure by using digital electrometers. Figure 3 exhibits the test apparatus for investigating the omega stringers under pull-off loading and its schematic illustration (symmetrical to the longitudinal center of the sample).

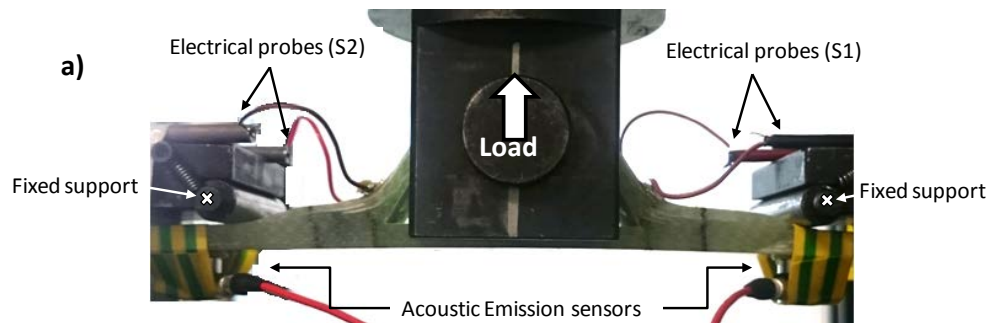


Figure 3. Pull-off test setup showing the electrical probes and AE sensors

3. Results

Figure 4 presents the results of electric resistance obtained before every impact tests to the 6 central tuft rows in the laminated plates. It is remarkable the significant increase of the row 3 and 4 are especially due to their proximity to the impacted zone. The line 4 was exhibited a important increase from the first impact test of 5J energy while line 3 increase gradually its electric resistance. The other rows also responds to impact damages generated during loading even if their response are weaker in comparison to the aforementioned tufts. Furthermore, they present a gradual increase of electric resistance from outside (row 1 and row 6) to inside rows (row 3 and 4), which is related to damage development in impact tests. A comparison between the analysis by C-Scan and infrared thermography (IRT) acquired before and after step III and IV impact tests is shown in Figure 5. The rise on amplitude of C-Scan images is mainly seen from the step III and IV (Figure 5a) and consists of significant damages created in the plate by impact loadings. The events are also reported by spots (rows 3 and 4) in IRT images (Figure 5b) concerning the heat concentration as a consequence of the damages generated during impact in the tufts. These damages difficult the current flow and therefore increase the heating in the specific region. This approach enables monitoring the health of tufts. Once that tufted threads are essential to the out-of-plane properties of laminated composites, monitoring their health may also be important for analyzing the state of health of the tufted structures.

The electrical method as employed in this investigation can also validate the manufacturing process by evaluating the electrical resistance of the tufts. A tuft which presents a significant deviation from the mean value of resistance may have had issues during tufting process, as incomplete insertion of the tuft, unloosening, or significant damage on the thread.

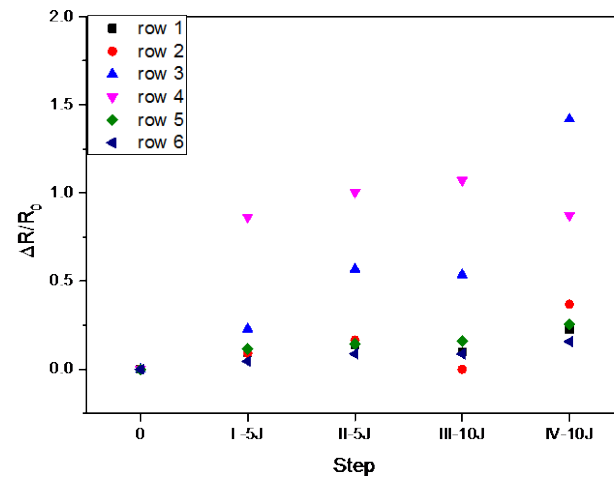


Figure 4. Electrical resistance measurements through different tuft rows before every impact test on the composite plate.

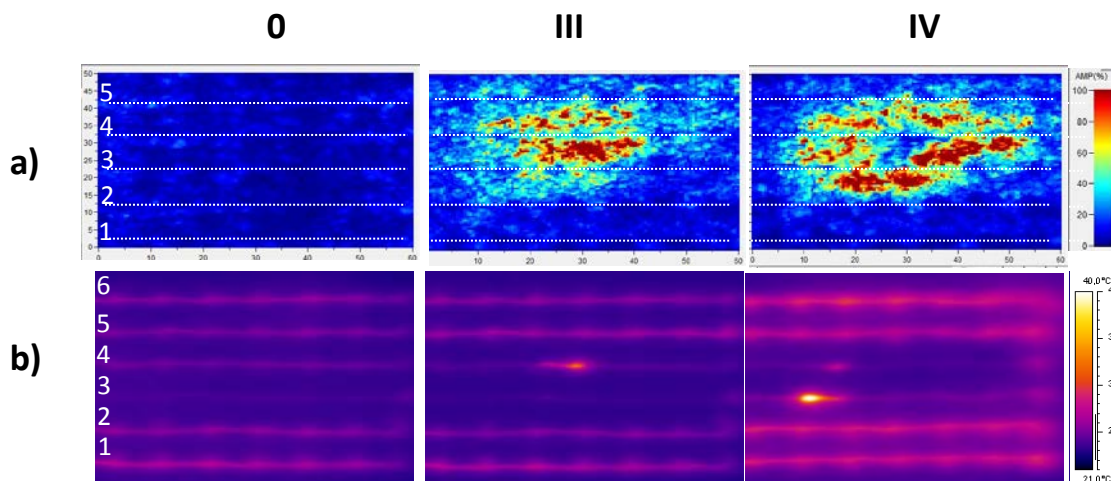


Figure 5. Images acquired before the test and, after step III and IV impact loadings, by a) ultrasonic C-Scan and, b) Infrared thermography.

Figure 6 shows a typical behavior of the electrical resistance from both sides of the omega stiffened composite, named as Resistance S1 and S2, under pull-off test. Acoustic emission activities were also acquired during the test and presented as cumulative energy in the graph. The load drop events exhibited in the curve are also evidenced by AE cumulative energy as a rise in its value, as well as by the electrical resistance on both sides. The mentioned events are significant damages which occur during the tests. Delamination is responsible to the first load drop (steps I-II) and evokes a sharp fall of the electrical resistance, which is better verified in the measurements from the side S1, once the failure occurs on the same side (Figure 7a). This behavior is probably a combination of two simultaneous phenomena: the unloading post damage seen as a sharp drop in the load-time curve that unloads the tuft yarns and therefore enlarges the thread section area, and to the delamination which debonds the resin from the yarns and as consequence diminishes the electric resistance. The reduction of thread cross-section area yarns also leads to an increase in the length (L) when they are submitted to a longitudinal strain. It conducts to the fibers straightening and consequently increases the electrical resistance (R) as described

in Eq. (1). Besides, this straightening can induce changes in the contact network by reducing the number of the contact between fibers and also increases the resistance.

$$R = \rho \frac{L}{A} \quad (1)$$

where L is the length of the conductor (m), A is the cross-sectional area of the conductor (m^2), and ρ is the electrical resistivity of the material ($\Omega \cdot \text{m}$). During delamination, the right side is unloaded, which results in an electrical resistance decrease (Resistance S1), while the left side is slightly loaded and exhibits an increase in its electric resistance (Resistance S2). From the event II, the strain is progressively raised in the left side which amplifies the resistance until the complete rupture of the threads, described as a significant augmentation of the electrical resistance (event III). The events between III and IV characterized by measurements of resistance in the left side (S2) were mainly owing to the delamination generated on the right side (S1) from the analysis performed by DIC. The sharp increase in the electrical resistance seen on the event IV is characterized as delamination on the same side of the S2 (Figure 7b). The increase of the electric resistance was unexpected to a delamination event, which is explained by a continued increase in the opening strain (ϵ_{yy}) even that delamination was supposed to unload the structure. It is due to a quick sequence of the events, from delamination (event IV) to tuft rupture (event V), and consequently did not let enough time to unload the structure.

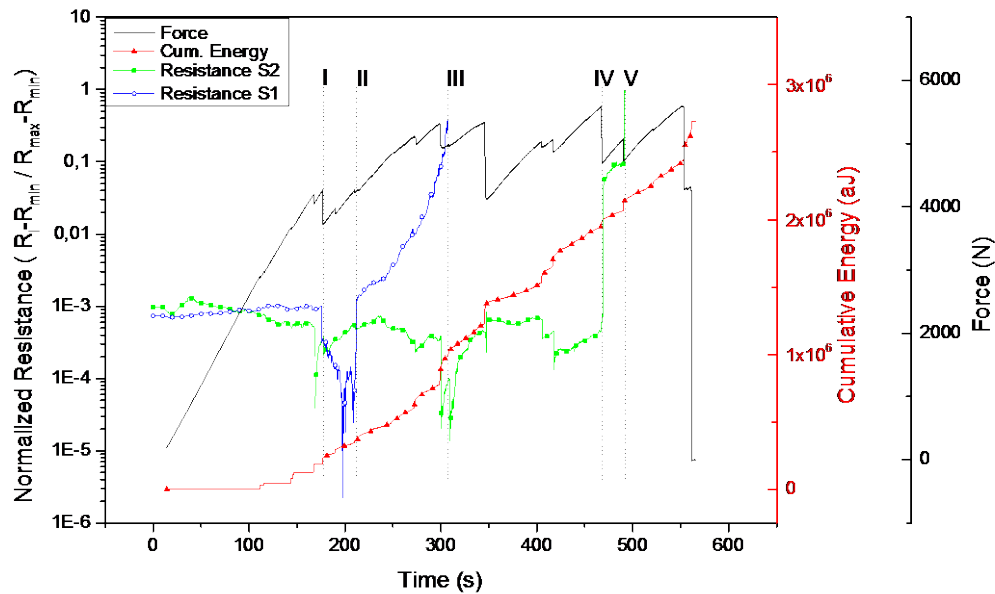


Figure 6. Omega stiffened panel response to pull-off loading assisted by electrical resistance measurements (S2-left side and S1-right side) and AE technique.

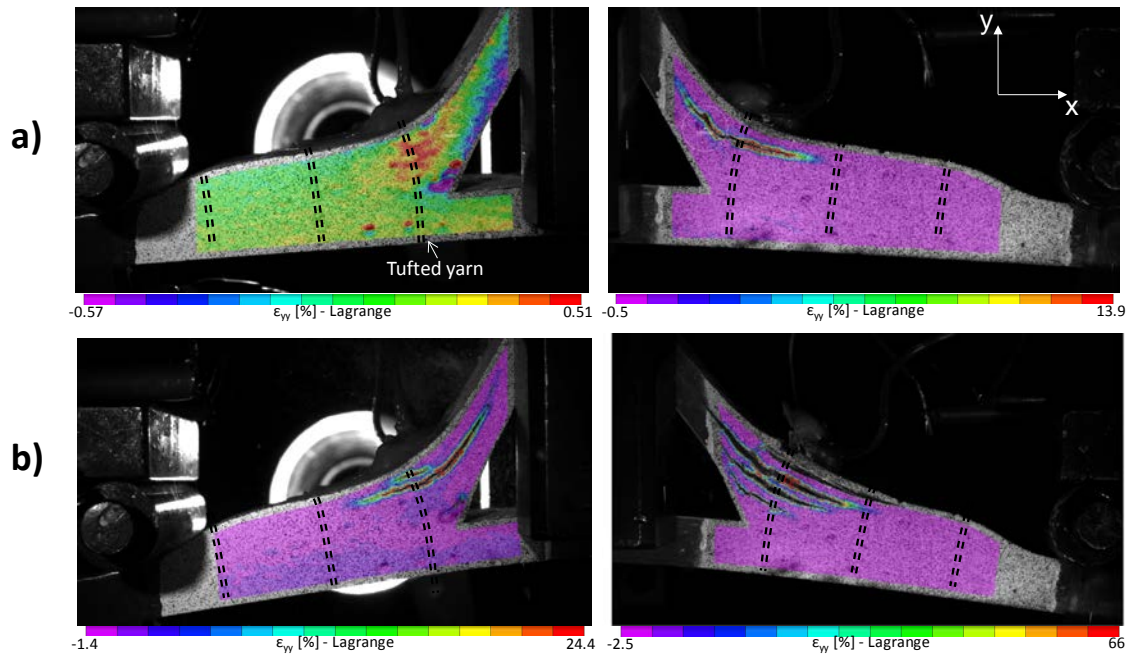


Figure 7. Longitudinal Strain fields (ϵ_{yy}) measured by DIC at a) Step I and, b) Step IV.

4. Conclusion

The carbon tufted threads employed for reinforcing the GFRP laminate plates were effective to monitor progressive damage by multiple impact tests. An increase in the electrical resistance of the tufts is reported when the laminate composite is subjected to impact loading. This behavior is progressive with the number of impact tests, which consequently increase the damage extent in the composites. It is important to note that despite the monitoring is made through the tuft threads, their structural role in the laminated composites lead to a considerable information of the state of health of the composite from that of the tufts. Future work may explore the electrical resistance response as a method to qualify the state of health of the composite by investigating the relation of residual strength with electrical resistance. It should be employed as a threshold to validate the structure in service. Moreover, IRT technique was able to localize damage in tufts by imposing an electrical current in the tufted threads and consequently acquiring the temperature gradient by Joule's effect. This approach may be employed as a complementary technique to C-Scan imaging.

Since the investigation on the laminate composite plates reinforced by tufting presented a good response of electrical resistance of the tuft threads to damages generated during impact, the following analysis of this work studied the strain-sensing and damage monitoring of GFRP omega stiffened composites reinforced with carbon tuft threads. The tufts were able to respond to physical phenomena, such as delamination as well as strain-sensing, with electrical resistance variation when loading the specimens under pull-off tests. The results exhibited are promising in order to apply tuft threads as strain sensors of composite structures, however, more studies have to be performed so as to validate this approach.

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