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Analysis of the impact and compression after impact behavior of tufted laminated composites

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ABSTRACT

The effect of trough-the-thickness reinforcement by tufting on impact and after impact behavior of woven carbon fiber composites is investigated. The density and angle of the carbon fiber threads during tufting process were varied to achieve better results on damage tolerance. The samples were submitted to out-of-plane impact with two different energies to compare their response under loading. Then, they were analyzed by ultrasonic C-Scan technique in order to evaluate the damaged zone. Further, compression after impact (CAI) assisted by acoustic emission and Digital Image Correlation compared the compressive strength and materials response according to their tufting parameters. Also, compression before impact (CBI) were performed to evaluate the in-plane properties of the tufted composites. The transversal tufting reinforcement achieved the best results when compared to angular and non-tufted laminate composites. Moreover, when increasing the tufting density, the damaged area is decreased and the ultimate compressive strength improved. Tufting reinforcements were found to decrease the damage area up to 4 times (transversal tufting) when compared to non-tufted laminates. Additionally, the residual ratio (CAI/CBI) increased up to 30% and 28% for the transversal and angular reinforcements respectively in comparison to the reference.

1. Introduction

Carbon fiber reinforced composites has been increasingly applied to aircraft structures. The well known higher strength-to-weight as compared to metallic alloys helps the aircraft to reduce weight, consequently improving fuel efficiency. They also can offer the advantage to reduce parts counts and their longer life cycle can decrease the maintenance frequency [1]. However, despite great in-plane properties as strength and stiffness of the laminate composite materials, they can show weakness, particularly in the transversal direction when submitted to impact loading.

Laminated composite materials are liable to fatal damage under impact on service conditions, maintenance operations or even in part manufacturing [2–4].Therefore, when a foreign object impacts a laminate, several damage modes as delaminations, fiber breakage, and matrix cracks occur in the composite structure [5]. Particularly, delamination is one of the principal damage mechanisms on impact, especially in low-velocity under transversal loading. This failure mode reduces the impact strength due to the low interlaminar strength of the composites materials. In addition, this damage can seriously reduce the load bearing capacity of the laminate, especially under compressive loads, owing to local instability [6–8].

Hence, considerable improvements in damage tolerance and delamination growth resistance can be achieved using both the constituents of the composite as tougher resin or reinforcement in z-direction [9,10]. For instance, the composites can be toughened by incorporation of micro-phase dispersed rubbery or thermoplastic polymers, rigid particles or ‘hybrid-toughened’ epoxy polymers by combining both rubber toughening and silica nanoparticles. However, these methods have difficulties in the proper particles distribution (rubber or thermoplastic polymers) in the matrix. Moreover, to achieve significant toughness an important amount of particle is necessary which typically increases the resin viscosity, usually unacceptable for resin-infusion process [11]. Furthermore, the tougher resins provide only moderate improvements on impact damage resistance and the usage in large practical composite structures is still being studied [9,12].

The interleaving approach has also been used to improve the penetration resistance and damage tolerance of carbon/epoxy composites by increasing their fracture toughness [13–18]. This method involves the incorporation of thin layers of a high shear strength resin along the interface of the laminas. However, it is not practical to add an adhesive layer along every interface of the laminate. This may cause the laminate

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a great weight penalty and potentially decrease of glass transition (Tg) [14,16]. Moreover, because the toughened resin layers have relatively lower stiffness and strength, their application has to be limited in order not to alter the overall composite performance [19,20].

Interesting enhancements in the transversal mechanical properties of the laminate composites can be achieved using three-dimensional (3D) reinforcements. Three-dimensional textile composites contain a 3D network of planar and through-the-thickness reinforcement (TTR) fibers. There are several types of 3D textile composites, and they are classified according to the method by which the 3D fibers reinforcement are formed within the material [21]. The main methods are 3D weaving, stitching, tufting, z-anchoring and z-pinning which are well dependent on the applied material (ex. dry perform or pre-impregnated) and end application.

In the present work, the tufting process has been used. It is a one-sided stitching process in which the needle pushes high-strength yarn into the fabric and tufts are held in place when the needles are withdrawn by friction resistance imposed through the fabric [21]. The advantage of tufting is the low tension under which the thread is inserted. This results in a reduction of the stitching effect on the in-plane properties of polymer matrix composites [9]. TTR in the form of stitching has been shown to increase the fracture toughness under both mode I and II loading [22]. In general, for mode I, the interlaminar loading increases the delamination resistance by reducing the crack opening displacement, while in mode II, it increases the delamination resistance by resisting crack sliding displacement [23].

Karuppannan et al. [9] compared unidirectional and quasi-isotropic tufted carbon fabric composites and showed that in-plane properties of quasi-isotropic and notched composites are not well affected with transversal tufting reinforcement. Also, the mode I fracture toughness obtained values more than 16 times greater compared with non-tufted composites. Deconinck et al. [24] studied the high-velocity impact-induced behavior on tufted carbon fiber composites laminates. They found that delamination area was decreased by 24% when the tufting density was increased compared with specimens without tufting. Colin de Verdiere et al. [25] studied the tufting effect on mode II fracture toughness of the carbon non crimp fabric composites. It showed about 2 times higher than the non-tufted samples. Dell'Anno et al. [26] investigated the Compression After Impact (CAI) strength on carbon fiber composites laminates reinforced by tufting with carbon and glass threads. The authors reported an increase of CAI strength by 25% and 27% for carbon and glass threads respectively. They also reported 10% of the decrease in static tensile modulus and strength for the glass tufted laminate. The improvements on CAI strength were also reported by Scarponi et al. [27], when compared to non-tufted composites, employing tufted aramid fibers reinforcements. They studied the techniques of low and high tensioned lock stitch, tufting and z-pinning to reinforce trough-the-thickness carbon fiber preforms. The tufted laminates showed CAI strength superior to the others techniques and especially 16% higher than the non-tufted laminates.

Also, the improvements on out-of-plane properties were reported for sandwich structures reinforced by stitching. Lascoup et al. [28] obtained improvements under 4-point bending tests in the bending module (278%) and maximum stress (9 times greater) when compared with the non-tufted specimens. Moreover, great values on transversal flatwise compression tests were achieved with intrinsic modulus growing by a coefficient 14 and the ultimate stress by a factor 8. The impact resistance was also enhanced and reported by different authors [29–32].In general, the stitched sandwich composites were capable of bearing greater the impact load, absorb more the impact energy, reduce damaged area and penetration depth.

This introduction reviews, in a non-exhaustive manner, various works about the through-the-thickness reinforcements. In general, these reinforcements provide out-of-plane improvements and in-plane reduction of the mechanical properties. Consequently, it is important to well understand this subject in order to better control the tufting technique which contributes along with other techniques [9–20] to improve the delamination behavior of composite structures.

The research works based on tufted composites have not been expressively presented in the literature, especially concerning to increase the mode II fracture toughness. This case is very important to the out-of-plane impact loading because the delamination cracks resulting to the impact are driven especially by mode II shear [33]. Therefore, this research investigates the behavior of inclined tufting reinforcements in order to increase the damage tolerance of the carbon fiber laminate composites under impact and evaluating their CAI strength.

Moreover, in the majority of works presented on impact resistance and compression after impact, there is a lack of studies which deal with the detection of the first major damage. Indeed, it is this load level that must be taken into account in a design project, while the maximum stress reached, although interesting to evaluate, is not important in a project. Therefore, it has seemed interesting to focus on the detection of this first level of damage. Nevertheless, it is quite difficult to visualize this event using the stress curve alone. In this study, two techniques were used to accurately detect the major damage initiation point: the acoustic emission (AE) technique by means of clustering analysis associated with digital image correlation (DIC). It contributes to estimating the effect of tufting parameters (density and angle) in the initiation of the first major damage on compression after impact. Moreover, it is possible to identify a class of acoustic signals related to this point which will cause the failure on CAI.

2. Materials and methods

2.1. Materials

Woven carbon fabric/epoxy composites were manufactured using a 5HS woven fabric from 6K with an areal density of 364 g/m^2. For the tufting process, 2K Tenax-J HTA 40 carbon thread wrapped by two PBO yarns was employed to reinforce the carbon fabric preform. Two laminates with the layup $[0]_{12}$ were processed according to the angle of the reinforcement insertion. The transversal and angular tufting threads were inserted parallel and at ± 30° to the normal plane (Fig. 1) of the preform respectively. The insertion at ± 30° was chosen as the maximum angle possible due to the machine limits. Also, the preforms had different tufting densities divided by zones for the reference (non-tufted), 5 × 5 and 10 × 10 mm tufted square patterns.

The tufting reinforcements were performed by KUKA 6-axis robot arm (KR 100-2 HA 2000). Pressure foot to compact the dry preforms during the process was develop and manufacture by a 3D printer. It was made with a flat surface in order to avoid misalignments on fabric tows, homogenizing the force applied. The process used polyurethane foam as well as a nylon film placed under dry preform to hold the tuft loops.

The composite plates were molded by VARTM with EPOLAM 5015 epoxy resin system. During infusion process, the vacuum pressure was about −1 bar at room temperature. The cure cycle was performed at room temperature for 24 h and post cured at 80 °C for 16 h. The final thickness was about 5 mm. Then, samples with 100 × 150 mm dimensions were prepared for the impact and CAI tests. The specimens were designated according to the tufting density and angle as REF for non-tufted, T10 and T5 for 10 × 10 and 5 × 5 mm transversal square patterns respectively. A10 and A5 were designated to angular tufting (± 30°) with 10 × 10 and 5 × 5 mm square patterns respectively.

2.2. Compression before impact

Compression Before Impact (CBI) was performed to three samples of the REF, A5 and T5 configuration. They were tested according to the standard test method ASTM D6641/D6641M-01 [34].