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Analysis of the mechanical behavior of composite T-joints reinforced by one side stitching

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ABSTRACT

T-joints stiffeners made from carbon/epoxy composites have been increasingly applied in aeronautical structures, however as majority of the carbon fiber reinforced structures, they have faced with delamination problems. Through-the-thickness reinforcements for laminate composites have been studied as manner to increase transversal strength, especially reducing delamination. In the present work, carbon/epoxy T-joints reinforced transversally by one side stitching (OSS) and molded on Resin Transfer Molding (RTM) process have been performed as well as the reference (unstitched T-joints). The stitching position were designed after analysis of the unstitched T-joints by means of strain field on Digital Image Correlation (DIC) under pull-off test to better improve the areas submitted to large strain. Also, the stitched samples were mechanically tested in pull-off mode and were analyzed during tests by in situ microscopy and post-failure on Scanning Electron Microscopy .The energy release was better contained in the stitched structures especially in the critical region (delta-fillet), due to crack bridging that improved the delamination toughness. Otherwise, the stitch pattern generated by OSS process changed the strain fields asymmetrically when analyzed on DIC during tests. The stitched T-joints showed greater ultimate strength (25%) and load recovery post ultimate strength (19%) in comparison to the reference.

1. Introduction

T-shaped joints ("T-joints") made from carbon fiber reinforced polymers are widely used in load-bearing aircraft structures and others light-weight structural applications as stiffeners and connections for the thin-skin composite panels. In general, they are used to mainly transfer flexural, tensile and shear loads to the skin [1].The basic design of a composite T-joint is illustrated in Fig. 1, and it consists of a delta(Δ)-fillet, skin laminate, stiffener laminate, and radius bend region where the stiffener laminate is curved into a flange that bonds to the skin [2].

A long-standing problem with T-joints is the delamination cracking between the skin and the flange. It occurs due to the low strength and toughness of the interfacial region between these two components and the presence of a large geometric stress concentration [3]. This damage frequently initiates in the radius region as well as in the delta-fillet region, once they are subjected to high transverse shear and peeling stresses due to the high load transfer from the stiffener laminate to the flange [4,5].

In order to counteract this deficiency, different methods have been used to improve the mechanical properties of T-joint structure, as increasing the resistance in the delta-fillet region with the use of toughened resins [6,7], developing the geometry by redesigning the radius/delta-fillet region to minimize the geometric stress concentration factor [8,9] or with bio-inspired design [2,3,5], introducing through-the-thickness reinforcements as for example stiff carbon fiber rods on z-pinning process [10–13] or threads (glass, carbon or aramid) by stitching [14–16]. Unfortunately, most of these strengthening methods provide only an incremental (rather than large) improvement to the ultimate load of joints [17].

Experimental studies have shown that the transversal reinforcements in the composite joints by means of stitching is an effective method for improving the structural properties [17]. According to Greenhalgh & Hiley [6], the stitching process enhances transversally the structure, improving the energy of release at the damage boundaries. Some mechanisms by which the stitches improve interfacial strength involve steps such as deformation and failure of the stitching fibers, ploughing through the laminate, and delocalization of the crack-tip forces. Enhancements by up 15 times of stitched composites in the mode I [18]

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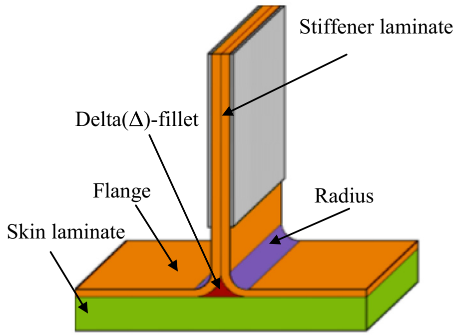

Fig. 1. Scheme of the T-joint structure and its nomenclature.

and ranging from 8% to 15 times in the mode II [19–21] in delamination toughness have been found in comparison with non-stitched composites. Both assembly and reinforcement of composites can be made with different types of stitching such as tufting [16], modified-lock stitch [22] and/or one side stitching (OSS) [23].

There are several works in the literature showing the post-mortem failures in the typical composites T-joints. The failures concentrate in the Δ-fillet region and propagates to the base and to the vertical stiffener, especially to the pull-off and bending tests [2–4,24]. However, there is a lack of the strain field analysis during mechanical tests of the reference T-joints structures (2D laminates) based on DIC method. May et al. [25] studied carbon fibers composite T-joints with three assembly configuration and also varying the resin type (neat and toughened resins). They performed quasi-static and dynamic tests in a classical 0° pull-off and a 30° pull-off/bending tests. The tests were submitted with DIC analysis and showed that in both type of tests the maximum strain initiates from the Δ-fillet to the vertical stiffeners and then propagates from the Δ-fillet to the base between the skin and flange. Cui et al.[26] studied the adhesive bonded composite T-joint structures behavior and its numerical simulation. For this purpose, pull-off tests were carried out aided by DIC. The results showed a strain concentration in the Δ-fillet and then propagates to the vertical stiffener where an important crack appears.

Indeed, one can note from this work that the DIC can be used as a very interesting and effective tool to analyze the strain fields during loading tests and consequently to identify the strain concentration zones. Also, it is possible to identify the main direction of the strains. Consequently, the data obtained from the DIC analysis enables a better understanding of the damage process. This technique has been used in the present work to analyze the behavior of the unstitched T-joint. It allows us to indentify the weakness zones and therefore optimize the local reinforcement. Moreover, there was not evidenced in the literature about the use of DIC for the analysis of stitched T-joint structures. Finally, a discussion is conducted in this paper comparing the local strain fields between the unstitched and stitched T-joint structures.

The main goal of the present study is to manufacture stitched carbon fiber reinforced polymers T-joints by OSS process. Carbon fiber threads were employed in the process as manner to improve mechanical properties, especially rigidity and strength of the joints comparing with unstitched T-joints on pull-off tests. Then, Digital Image Correlation (DIC) was applied during pull-off tests to analyze the critical strain zones in the unstitched T-joints. Additionally, SEM and in-situ microscopy images were obtained to compare the failure mechanisms and improvements related to stitching reinforcement.

2. Manufacturing techniques and materials

The OSS method offers new technique of interlocking thread that makes the tooling on the underside of the preform not necessary. This method is a type of stitching process which uses two different needles (Fig. 2a). The needle with the reinforcement thread (sewing needle) crosses the dry perform at 45° while a needle-catcher crosses the plies at 90° to pick up the sewing needle thread and then, it returns to the initial position where a loop is made with an auxiliary catcher tool for the next step. The implementation of the 45° stitching angle enables the optimum position of the stitching thread as a reinforcement element in the structure [27]. Based in the insertion thread at 45°, the OSS method offers the possibility to access the core of the T-joint preform as manner to reinforce the Δ-fillet region which is resin predominated in the 2D laminates. Also, in comparison with the tufting, other technique used to reinforce trough-the-thickness from only one side, the OSS method locks the fabrics of the preform, which enable its easily manipulation. Additionally, this method imposes a higher force during process in comparison with tufting, compacting more the fabrics and consequently reduces the resin pockets.

A commercial OSS head (KSL RS 530) was installed on KUKA 6-axis robot arm (KR 100-2 HA 2000) which allows stitching complex shapes accurately. The Fig. 2b shows the machine system in operation, while Fig. 2c the pattern of the OSS technique on the top and bottom surface side of the preform respectively.

The parts were manufactured with 5-harness satin carbon fibers woven (5HS) with areal weight of 500 g/m^2. The T-joints were manufactured as the follow layups: $[0/45/0/45/0]_S$ for each L side of the stiffener laminate with a nominal thickness of 2.25 mm and $[(0/45)_5]_S$ for the skin laminate with 9.75 mm of nominal thickness. The thread carbon/PBO (2 K Tenax-J HTA 40

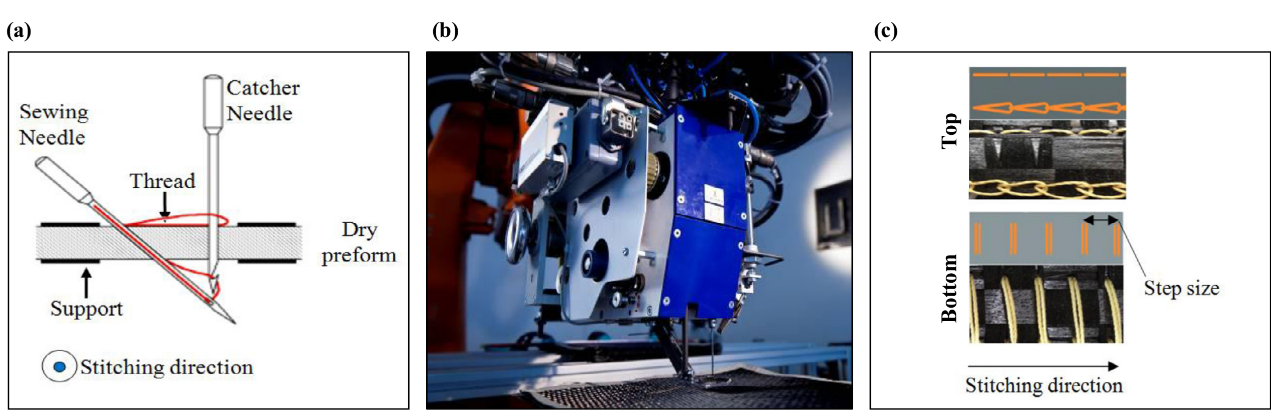

Fig. 2. (a) Illustration of the manufacturing process OSS. (b) OSS head in process with Kuka Robot. (c) Stitching thread pattern on the top and bottom surface side of the fabric.