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Evaluation of stitched fabric composite processed by RTM in quasi-static test

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Abstract

Stitched fabrics have been widely studied for potential application in aircraft structures since stitch yarns offer improvements in the out-of-plane mechanical properties and also can save time in the lay up process. The down side of stitch yarns came up in the manufacturing process of fabric in which defects introduced by the needle movement creating fiber-free-zones, fiber breakage and misalignment of fibers. The dry stitched carbon fabric preform has mainly been used in the Resin Transfer Molding (RTM) process which high fiber content is aimed, those defects influence negatively the injection behavior reducing the mechanical properties of final material. The purpose of this research work focused on testing in quasi-static mechanical mode (in-plane tension) of a monocomponent resin CYCOM® 890 RTM/carbon fiber anti-symmetric quadriaxial fabric stitched by PE 80Dtex yarn processed by RTM. The evaluation consisted in comparing the scatter of the quasi-static test with the attenuation of ultrasonic maps, which show the path of the resin and possible dry spots considering that interference of yarn in resin flow is detectable in ultrasonic measurement. Microscopic analysis was also considered for further evaluation in case of premature failure.

Keywords: Carbon/epoxy composites; resin transfer molding (RTM); flexural test; ultrasonic test

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1. Introduction

RTM process has been widely employed in the aeronautical field mainly for producing structural components which demand for high fiber volume percentage usually greater than 40% [1]. The injection process can be made using multiple inlet and outlet ports requiring strategic positions to avoid voids and entrapped air, common defects in the process. The low viscosity resin (<500 mPa.s) flows through the dry preform within a closed rigid mold, the procedure time depends on the fiber volume percentage, which also determines the mechanical performance [2,3].

Laying up unidirectional fibers in different directions to produce a multidirectional laminate is time consuming and can introduce errors when fibers are stacked in different angles. In order to improve the stacked fiber position as well as save time in laying up process, a stitched fabric has been introduced in the RTM manufacturing process. This type of fabric is known as non-crimp fabric (NCF), in addition of the mentioned up sides of the fabric the out-of-plane properties can also be improved. Despite of advantages some down sides of the fabric has been reported like defects introduced during the fabric manufacturing process, e.g. distortion caused by the needle movement, insertion of the yarn, breakage of the fiber tows and splitted yarn [4,5].

With regard to in-plane properties stitched fabrics have shown inconclusive results, literatures have reported reductions between 10 to 20% in tensile, compression and bending properties [6]. Those limited assessment is due to the heterogeneous nature of the structure composed by the yarns that change the location of matrix areas and fiber tows which make the failure analysis complex [7,8].

In compression tests experimental work shown that kinking of the 0° ply causes shear instability and consequently failures occur. Regarding this approach, tow crimp in weave fabric affects the laminate performance in compression [8].

Combining the process technique with the relatively new concept of non-crimp fabric, this research work aimed the evaluation of the composite behavior in three point-bending test by comparing the ultrasonic C-scan map.

Nomenclature

A	radius of
B	position of
C	further nomenclature continues down the page inside the text box

2. Materials and Methods

2.1. Processing parameters and laminate architecture

The laminate was processed with a stacking sequence of 5 multidirectional non-crimp fabric (NCF) stitched in the following sequence: [90°/-45°/0°/45°]. Fiber bundles were stitched with a PE 80DTex polyester yarn in the chain pattern. Those plies were assembled to form a quasi-isotropic laminate that provide approximately a 54% in fiber volume fraction. The summary of fiber properties used in the fabric is shown in Tab. 1.

Accordingly to the macromechanical approach the laminate architecture was assembled in the way to maximize the flexural strength in which 0° plies were placed far from the middle plane for this purpose, the flexural strength can be calculated based on Eq. 1.

$$[D] = \sum_{K=1}^{n} \frac{h_k^3 - h_{k-1}^3}{3} [\overline{Q}]_k \qquad (1)$$

Table 1. Fabric properties

Fabric	Fiber type	Weight (g/m^2)	Fiber tow (x1000)
[90°/-45°/0°/45°]	IMS	580	24

One line inlet gate combined with one vacuum gate at the end of a rectangular rigid mold was used to produce the laminate. The low viscosity resin CYCOM 890®, provided by CYTEC, was injected at 100 °C, which heat transfer was avoided by using heated line as well as heated mold, in order to keep the viscosity at 75 mPa.s.

A constant pressure of 3 bar and a variable flow rate was applied in the laminate. In the end of the injection process, the resin run through the outlet vacuum pipe for some time to assure that the remaining bubbles were removed. Afterwards the cure cycle took place at 180 °C during 120 minutes.

2.2. Ultrasonic test

The ultrasonic inspection was performed by an equipment from MATEC model PSS-600 that works in a pulse-echo mode. The water bath is used as a coupling medium and the specific probe for a thin laminate ranges between 5 to 10MHz, for this quasi-isotropic laminate the 10 MHz flat probe worked out to detect all features that influences the mechanical performance of a composite, e.g. dry spots, race-tracking, fiber misalignment.

Without a standard reference defect to calibrate the ultrasonic C-scan map the following procedure was conducted: firstly the A-scan graphic aided in calibrating the patterns of a typical structural composite peaks (reference); then captured all the peaks, in gates 1 and 2, that work as acquisition data. The resulting difference between the pattern peaks (without defects) and defect peaks are shown in a gray scale C-scan map in which was attributed a color scale for better evaluation. The analysis of the background echo, resulting from Gate 2, is sufficient to provide an accurate assessment of the laminate health.

Fig. 1 represents the color scale of attenuation signal that is employed along the analysis of the C-scan maps. Where 0% represents low attenuation or region of low material density, which is proportional to the acoustic impedance, and 100% all the sound returned, which means there is a region without void or high material density.

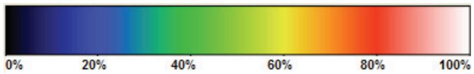

Fig. 1. Color scale for C-scan maps

2.3. Flexural tests

A 3-point bending tests were performed in a universal test machine INSTRON 8801 according to standard ASTM-D790 [9]. The flexural modulus and strength were calculated for 8 specimens obtained from the different location as shown in Fig. 2 (a).

This test can well evaluate the properties that the injection process might contribute to change the laminate performance in tensile stress at the outer part of the beam and in compression at the inner part of the beam [10]. Moreover the specimen test is easily obtainable due to the simple rectangular geometry, the test avoids the interference of pressure grips as used in tensile tests that might induce premature failure and save time compared to compression test that demand for rigorous alignment of the test machine to avoid macrobuckling.

It was employed 48 mm of the support span in the way to comply with the 16:1 ratio between the length and thickness (3mm) of the specimen [9].

3. Results and Discussions

3.1. Ultrasonic test

In blue color, Fig 2 (b), is shown the characteristic attenuation (around 70%) of the inter town impregnation and in green to red color the characteristic attenuation (20% to 50%) of the intra town impregnation.

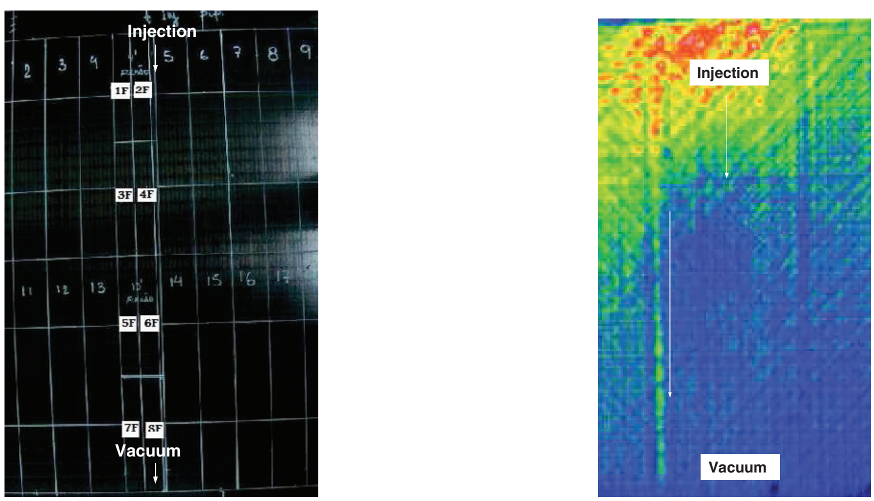

Fig. 2. NCF laminate: (a) location of the specimens in the laminate; (b) ultrasonic C-scan map

The laminate showed no voids from entrapped air as this is in the range of 90% to 100% of attenuated sound. The arrow in Fig.2 (b) points a path of the resin followed at a flaw created by the stitching process.

In the C-scan map major heterogeneous follow front, green color attenuation, may be related to the intra tow permeability, which is proportional to the applied pressure and inversely proportional to the fabric porosity. Therefore the yarns did not interfere greatly on the flow front at the inter tow medium. Small deviations at the preform compaction may also change the mentioned permeability features.

3.2. Flexural test

Dispersive results in flexural strength were observed in the laminate as reported in Table 2. Such low results as in specimen 3F, 4F, 5F, 6F and 8F may be attributed to macrobuckling in the first 0° ply. Despite the lack of weave in this type of fabric, misalignment of fibers may be considered at the inner surface. Specimens with high flexural strength were loaded until fail in shear mode, induced by the small specimen length.

In flexural modulus property, specimens showed homogeneous elastic behavior, which demonstrated same proportion of composites constituents: fiber and matrix.

Comparing specimens locations at the C-scan map with the flexural strength, no correlations were found. The observation indicates that flow features through the yarns did not interfere in the flexural behavior.

Hypothesis of the combination: buckling and kink failure is not discarded due to highly instability of 0° fibers during the injection and preform compaction at the mold closing procedure, this may create a fiber misalignment.

Delamination was observed after reaching the flexural strength; therefore this failure did not take into account for the analyzed properties. However that is a useful information to verify a strong interface and consequently the compatibility of the matrix and fiber therefore delamination could be another form of diminishing the flexural strength properties.

Table 2. Laminate flexural properties

Specimen	Flexural Strength (MPa)	Flexural Modulus (GPa)
1F	883	30.7
2F	922	31.9
3F	711	27.0
4F	670	28.1
5F	717	26.0
6F	761	26.8
7F	835	27.3
8F	799	34.0
Average	787	28.9
Standard Deviation	89	2.9

4. Conclusion

So far yarns have not played major role in detrimental properties on flexural test. Particularly for RTM process the fabric parameter did not create resin-rich region that have more influent degradation effect on flexural strength property.

The major concern was the interference on the inter tow flow front by the yarn which could create dry spots and change the alignment of fiber beams. However it was observed weave formation of the 0° fiber at the surface, which caused the premature failure and consequently lowered the flexural strength.

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