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AN INVESTIGATION OF THE INSERTION MECHANISM INFLUENCE ON THE OVERALL BEHAVIOUR OF THE THREE-DIMENSIONAL AEROSPACE COMPONENTS

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ABSTRACT

In this paper the effect of stitches on the overall behaviour of reinforcement structure is investigated by using a finite-element (FE) approach. It is intended to provide an understanding of the basic mechanisms which control the reinforcement structures. These structures have been manufactured using a fully automated cell described in previous publications. Simple uniaxial FE models been developed using the material properties that determined experimentally.

Those models have been successfully validated against the experimental tests and used as a basis from which the main models were generated. These latter FE models were employed to conduct a series of analyses on typical I-beams with a variation of stitch patterns and loading conditions. Following a successful validation of the FEA modelling, a parametric study has been conducted on a typical I-beam section with and without stitches to investigate the influence of both stitch position and the loading condition. The investigation has shown that the stitches would reduce the strength of the beam by 8% atmost.

KEYWORDS

Aerospace, carbon fibre, robotics, stitching, resin transfer moulding (RTM), automation, finite element

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1. INTRODUCTION

Dry carbon fibre is currently being considered as an alternative to resin-impregnated 'pre-preg' materials in the aerospace industry for structural components, [1-6]. A relatively new form of dry carbon fibre is non-crimp fabric (NCF), which has the mechanical performance of unidirectional material and the handleability of a woven fabric, but without the design restrictions of either. NCF comprises a number of distinct layers. Each individual layer has fibres at a single orientation. A number of layers are laid up in sequence to form a fabric, usually with alternate layers of fibres oriented at 90˚ to each other, with *z* direction stitching fastening the individual layers together [7-8].
NCF material has been utilised in a fully automated cell designed and described in previous publication [9] to produce the reinforcement structures (I, C, T, J). The fully automated cell uses a newly developed technique so called robotic tacking device (RTD), to assemble the plies of the structures together. This is done performing number of stitches in *z* direction called '*blind stitch*'. Details of the RTD and its design were described elsewhere [9-10].

The aim of this paper is to develop analytical models for predicting the behaviour of the reinforcement structures (I, C, T, J) with different geometries and to study the effect of the stitching characteristics on the overall behaviour of the structural components.
The mechanical characteristics of the material modelling have been extracted from the experimental work performed on samples produced by the cell.

2. EXPERIMENTAL WORK

The construction of the non crimp fabric (NCF) specimens investigated in this work is shown in Figure 1. NCF laminates were produced with an untwisted fibre bundle in a triaxial lay-up, by Hexel Company, namely Hand A and B. The lay-up, which is knitted together by a polyester yarn, has a distribution of areal weight as follows: [±45^0 (230 g/sm) 0^0 (390 g/sm) [1,3]

The specimens consist of six plies, Figure 1. stitched together, three of them hand A and three of them hand B, allowing symmetric laminates to be produced. The Hexel 914 epoxy resin system was used in the resin transfer moulding (RTM) to fabricate the composite test specimens. The resin was infused into the preform under vacuum and pressure with minimum viscosity of 30 cps at a temperature of 160^0 C. The achieved volume fraction from this process was 58%.

All the specimens were routinely screened non-destructively by ultrasonic C-scanning after manufacturing to ascertain the quality of the product. Any defective specimen was rejected. Stitched and non stitched specimens have been cut from the consolidated panels for tests in tensile and compression with a diamond cutter, in both the 0^0 and 90^0 fibre orientations. All ends tabbing material was aluminium with square ends.

All basic mechanical tests have been conducted on instron 8501. Ten specimens have been tested for each material per orientation. Full stress- strain curves have been obtained by strain gauges samples on a single surface, this allowed to determine the moduli in tensile and compression, and by using cross gauges, the Poisson's ratios have been measured. All tests have been carried out at room temperature, 20^0 C.

2.1 Tensile Properties

The average tensilestrength for the stitched and non stitched specimens is shown in Figure 2. Test results are shown for 0^0 and 90^0 orientations. A significant difference was noted when the specimens were loaded in the 90^0 direction. The measured strength of the non stitched specimens, tested in 0^0 direction, reached the failure point on average 580 MPa, whereas it was 150 MPa for the 90^0 direction specimens. The absence of the fibre reinforcement in 90^0 direction reflects the drop of the mechanical properties for both stitched and non stitched specimens.

Thus, the tested results have shown that the tensile strength of the stitched samples was 12% lower than the non stitched samples in the same 0^0 orientation, and 18% lower in the case of 90^0 direction samples. These strength reductions may be caused by fibre misalignment; damage to the carbon fibre tows, local stress concentration due to resin pocket around the stitched area and/or delamination may occur during the deformation as shown in Figure 3.This clearly appeared in the fracture origin which initiated in the stitched area as shown in Figure 4.

2.2 Compression Properties

The specimens have been loaded at right angle to the 0^0 orientation. The results indicate that the stitched plies exhibited a 14% lower strength than the non-stitched plies. This reduction may be attributed to fibre damageand/or gaps between the fibre tows.

The failure of the specimens was very complex and dependent upon a number of factors as the failure may occur through shear deformation, or buckling depending on the stiffness of the specimens i.e. if the laminate stiffness is low then failure may be due to buckling and if the laminate is stiff with a high shear modulus, then the failure will be attributed to shear deformation.

The average compression strengths of the stitched specimens compared with the strength of the non stitched specimens in both 0^0 and 90^0 orientations are shown in Figure 5. The results show that the average compression strength for the stitched specimens is about 11% lower than the strength for the non stitch specimens in the 0^0 orientation.
The measured compression strength of the specimens, tested in 0^0 direction, reached the failure point on average 520 MPa, whereas it was 200 MPa for the 90^0 direction specimens.

3. FEA MODELLING

3.1 Modeling and Analysis Procedure

The ANSYS finite element package has been used to investigate the problem. The ANSYS program is one of the most popular and most powerful Computer-Aided Engineering tools which specialises in producing finite element analysis solutions for Structural, Thermal, Vibration, Electro-Magnetic, Fluid Flow and Impact simulation problems.

It has been employed here to simulate the experiments [11-14] in order to obtain the material characteristics for the general models and to investigate the effect of the stitches on the behaviour of those models. Hence, the analytical study has been divided into two main parts:

I. Modelling of the samples specimens, simulation of the compression and tensile tests described earlier in the experimental section and predicting stitched and non stitched material data.
II. Modelling typical I-beam with and without stitches and analysing the effect of the stitches, their number and pattern on the behaviour and strength of the beams.

In both parts the FE procedure adopted consisted of the following steps:

- Setting the type of analysis to be used; i e, structural.
- Creating the geometrical models, the dimensions of which are according to those of the samples, used the tensile and compression tests for part(i) and those of a typical prototype I-beam for part (ii).
- Defining the element type used for modelling the specimens. Shell element 63 has been used in this study. it has bending and membrane capabilities and both in-plan and normal loads can be applied on it [15].
- Assigning material properties. These have been obtained from the experiments carried out on the simple rectangular compression and tensile specimens. The orthotropic feature of the material used has been taken into account by assigning appropriate value in the three different directions.
- Generating the FE meshes for the stitched and non stitched cases.
- Applying boundary conditions: fixed at one end and loaded at the other for case (i) and simply supported in the case of bending or one end fixed and the other free in case of torsion for case (ii).
- Applying loads: pure tensile and compression axial loads for case (i) and bending and torsional forces for case (ii). in all cases the load (or loads) increased by increments until the failure stress is reached at a location of the specimen.
- Solution: selecting the solver algorithm and executing the solution phase and obtaining the results.
- Post-processing the results and analysing the output data.

3.2 Compression and Tensile Tests Modeling

Figure 6a, b show typical FE models used for simulating the tensiletests. The same procedure has been followed to simulate the compression tests.

In order to check the accuracy of the material properties obtained by the FE analysis of the compression and tensile specimens, the models have been validated by comparing the FE results with the corresponding experimental data. Both the FE elastic modulii and the stress failure results were compared to those obtained by the experiments.

Figure 7 and 8 show the axial stress distribution at failure level for both the tensile and compression tests in the 90^o and 0^o material directions respectively. In the case of non stitched specimens, the stress distribution was uniform and has not been, therefore, presented.
As can be seen for both cases, the specimens experienced higher concentration of stress at locations adjacent to the stitched areas.

3.3 Parametric Study

After successful validation of the FEA compression and tensile test models against the experimental data, a parametric study has been conducted. The aim of the parametric study is to investigate the influence of stitches, as important manufacturing parameter, and their number and pattern on the overall behaviour of the reinforcement structures and its failure level.

The study has been conducted on a typical I- beam section with and without stitched with following main parameters being varied:

a. Stitched position: the automated cell has been designed and implemented with considerations to be very flexible and to allow any component of the cell to do its task without any collision with the rest of the cell. In the robot program can easily modify the stitched positions. Three patterns of the stitches as shown Figures 9 a,b,c have been considered.
b. Loading conditions: three different types of loads have been applied on a simply supported I-beam model: a vertical bending uniform load applied along the top flange of the I-beam, Figure 10, two concentrated loads on the top flange of the I-beam applied over the stitched position as shown in Figure 10b and a torsional load applied at one end of the I-beam, the other end being fixed, Figure10 c.

FE models of the I-beam have been developed by adopting the same procedures that has been described in section 3.1.

After the creation of the models for the stitched and non stitched prototype I-beams as shown in Figure 10 a, b, c using shell 63, material properties obtained experimentally have been assigned to the corresponding stitched and non stitched parts of the I-beams. Then, appropriate boundary conditions and loads are applied on the models, the solution phase is executed and the results are obtained and analysed.

It should be noted here that a linear static analysis has been used in which the load is increased until the beam reaches the failure level of the material (stitched and non stitched) at its weakest location. In each stitched I-beam case, the failure level and position is recorded and compared with the corresponding case of the non stitched I-beam.

4. RESULTS & DISCUSSION

The compression and tensile tests described earlier showed that the material used behaves almost linearly until sudden failure. This justifies the use of a linear analysis in the numerical investigation. It is believed; therefore that such an analysis would predict the failure level of the beam models with a reasonable accuracy.

This is good enough for the present analysis qualitative parametric study. Furthermore, the I-beam has been selected for the study as it represents fairly good other typical structures (T,C,J). the range of loading conditions adopted here also comprises all types of loads that such structures would be subjected to in practice (mainly bending -uniform distributed , concentrated or torsion).

The failure level used in the analysis of the three-dimensional(3D) I-beams were the same corresponding levels obtained from the uniaxial compression and tensile tests. This is perfectly justified by the stress histories presented in this section which show that under the loads considered here, the beam web and flanges behave virtually in a uniaxial manner (the stresses are always very close to the von Mises stresses, i.e. the transverse stresses are closed to zero.

Figures 11 to 13 show the equivalent von Mises stress distribution for the non stitched beam cases at the failure level under a bending line load, two concentrated bending loads and a torsional load respectively. The failure area for each case is as shown in the corresponding Figure. The most highly stressed element is picked up from that area, its stress history is plotted and its failure load is determined based on the failure stress level.

Figures 14 to 16 show the equivalent von Mises, transverse and longitudinal stress histories of the most stressed elements for the non stitched beam under uniformly distributed load, concentrated load and torsional load respectively. These are used to extract the failure loads as shown in Figure 14 a.

The stitched I-beam models (stitches patterns a, b, c) have been subjected to the same loading cases as the non stitched beam. The stress distribution plots for these cases are shown in Figures 17 to 25 and the failure load for each case is determined in the same way as described for the non stitched beam cases.

The typical results presented in these Figures indicate that in the case of the line load and concentrated load cases for all the three stitches patterns, the maximum stress moved to stitched area positions. In the case of the torsional load, there was no difference from the behaviour observed with the non stitched beam.

The results of the parametric study for all the cases considered have been recorded. These show the stitches positions and the type of load applied and give the failure load obtained by the analysis for selected elements within the failure area of the beam. Table 9.6 lists the absolute maximum failure loads for both the non stitched {NS} beams and the stitched {S} beams. This correspond the (zig-zag) stitched pattern C. Comparison between the {NS} and the {S} cases show that stitches reduce the failure load by 4.8% under the uniform bending and by 7.7% under concentrated loads bending. the stitches ,however, do not have any effect under torsional loading.

Element No	Load type	Element type	Critical element position	Failure Load N	percentage difference%
NS-B-1726	Uniform	NS	Top Flange	177	7.5
S-B-3-4332		S	Top Flange	164	
NS-B-611	Uniform	NS	Bottom Flange	207	6.7
S-B-3-4002		S	Bottom Flange	192	
NS-PL-1966	concentrated	NS	Top Flange	122	4.8
S-PL-3-4402		S	Top Flange	116	
NS-PL-301	concentrated	NS	Bottom Flange	196	7.7
S-PL-3-4042		S	Bottom Flange	181	
NS-T-1000	Torsion	NS	Bottom Flange	32.40	0
S-T-3-1000	Torsion	S	Bottom Flange	32.40	

Table 1. Summary: comparison of Max failure loads between stitched(S) and Non stitched (NS) beam cases

5. CONCLUSION

A Finite Element Analysis has been conducted to investigate the stitches and their patterns on the strength of typical I-beam model of the reinforcement structures.

In order to determine the properties of the material used simple compression and tensile tests have been carried out. For that, simple stitched and non stitched specimens have been cut from the consolidated panels using a diamond cutter and tested in both the 0^{o} and 90^{o} fibre orientations. Ten specimens have been loaded for each material per orientation and the average material properties (elastic modulus, Poisson's ratio and failure stress) determined for each case.

Simple uniaxial FE models have then been developed using the material properties that were determined experimentally. Those models were successfully validated against the test data and used as a basis from which the main models were generated.

These latter FE models were employed to conduct a series of analyses on typical I-beams with a variation of stitch patterns and loading conditions. the investigation has shown that the stitches would reduce the strength of the beam by 8% at the most.

Hence, it can be concluded that the stitching operation adopted in the proposed manufacturing process has almost no effect on the load capacity or behaviour of structural beams made of a dry carbon fibre.

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