Mechanical behaviour of composite materials made by resin film infusion

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Abstract. Tensile and compression tests are a part of the qualification process for composite parts in aircraft structures. With each new material, a new set of tests is required. To reduce costs, it is advantageous to develop analysis tools for the prediction of damages and failure in such tests, so that the amount of testing can be reduced and predictions about material behavior can be made early in the design process. In this paper, an experimental and numerical study is presented on the tensile and compression strength of composite material developed by Alenia Aeronautica for aerospace applications and produced by means of the resin film infusion (RFI) and stitching process. Tensile and compression tests have been performed on specimens with three different lay-ups: 33/33/33, 40/40/20 and 100/0/0. They refer to the percentage of oriented fibres for each layer along three directions (0°/±45°/90°). The data observed are being used to develop a method for predicting the tensile and compression strength, and the numerical results are compared with the experimental ones.

1 Introduction

Experience with composite structures for aerospace applications has indicated a high level of complexity in design, due to the almost unlimited combinations of composite materials and fibre patterns and the fact that composites fail at loads that are not predicted by either perfectly elastic or perfectly plastic assumptions [1]. Thus, experimental tests remain a significant part of the qualification process for new composite parts.

Aircraft structural design follows a pyramidal structure of testing, ranging from specimen tests to full-scale structure tests.

The present work forms a part of a project that intends to look at several different type of load, lay-ups and geometries. An extensive experimental program is being carried out in parallel with the

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numerical work. Presented in the current paper are initial results on the tensile and compression tests of a carbon/epoxy composite with 33/33/33, 40/40/20 and 100/0/0 lay-ups. The results are compared with numerical results.

2 Experimental methods

The tests are carried out in accordance with ASTM official standard [2,3], and with some specific requirements suggested by the manufacturer.

The material under study is a new fibre reinforced composite material produced by means of resin film infusion (RFI) technique, in order to realize complex 3D components, and by means of stitching technique, in order to improve the material strength in the direction normal to the fibres and in order to reduce delaminations.

The composite is manufactured in finite tiles, balanced in different ways, and consists of epoxy matrix and carbon fibres.

Fourteen different kinds of composite material configurations are tested, each of them is manufactured in a tile of specific sizes (Table1).

Tab. 1 Data of tested materials

Tile	Fibres Orientation %	No. Ply	Lay-up	Specimen Size [mm]	Ply thickness [mm]	Resin %
M1	33/33/33	12	$(0,45,90,-45,0,90)_s$	250x25	0.21	35.8
M2	33/33/33	12	$(0,45,90,-45,0,90)_s$	250x25	0.21	35.9
M3	33/33/33	12	$(0,45,90,-45,0,90)_s$	250x25	0.21	35.2
M4	33/33/33	12	$(0,45,90,-45,0,90)_s$	155x25	0.21	35.0
M5	33/33/33	12	$(0,45,90,-45,0,90)_s$	155x25	0.21	36.3
M14	33/33/33	12	$(0,45,90,-45,0,90)_s$	250x25	0.21	38.0
M18	40/40/20	10	$(0,45,90,-45,0)_s$	250x25	0.21	39.0
M19	40/40/20	10	$(0,45,90,-45,0)_s$	250x25	0.21	37.9
M22	40/40/20	20	$((0,45,90,-45,0)x2)_s$	155x25	0.21	33.0
M23	40/40/20	20	$((0,45,90,-45,0)x2)_s$	155x25	0.21	33.0
M24	100/0/0	4	(0,0,0,0)	250x15	0.20	40.0
M25	100/0/0	4	(0,0,0,0)	250x15	0.20	32.0
M26	100/0/0	14	14 times 0	155x10	0.21	34.0
M27	100/0/0	14	14 times 0	155x10	0.21	34.0

Three classes of tiles are defined and tested. They refer to the percentage of oriented fibres for each layer, along three directions (0°/±45°/90°): 33/33/33, 40/40/20 and 100/0/0.

Specimens are obtained by cutting tiles in three different directions: 0°, 45° and 90° referring to zero lamina, which is the fibers’ direction of the surface layer (Figure1).

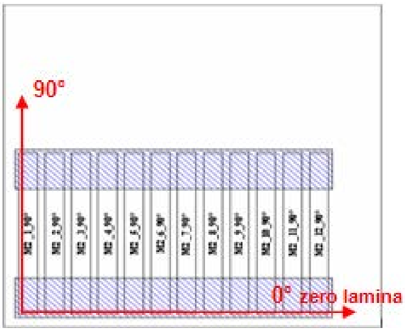

Fig. 1 Cutting of specimens

A code is assigned to specimens during the cutting process. It consists of:

1. "M" letter followed by the tile's progressive number (M1, M2, etc.);
2. Specimen's progressive number (M1_1, M1_2, etc.);
3. Cutting angle, i.e. the specimen axis orientation referred to the zero lamina (M1_1_0°, M2_1_90°, etc.).

Specimen's progressive number is always assigned numbering from left to right or from up to down, looking at the front surface of the tile. This code allows going back to the positions of each specimen into the tile, in order to individuate possible edge's effect and the relation of the measured characteristics with the position.

Table 2 and 3 summarize the experimental plan.

Tab. 2 Experimental plan for 0° and 90° specimens orientation

	0 deg		**90 deg**		
Type of test	**Tile**	**Quantity**	**Tile**	**Quantity**	**Tot.**
T	**M1**	3	**M2**	6	9
T	**M24**	6	**M25**	5	11
T	**M18**	4	**M19**	6	10
C	**M4**	6	**M5**	6	12
C	**M26**	3	**M27**	6	9
C	**M22**	3	**M23**	6	9

Tab. 3 Experimental plan for 45° specimens orientation

	45 deg		
Type of test	**Tile**	**Quantity**	**Tot.**
T	**M4**	3	3

The experimental campaign involves 63 specimens, with the aim of defining tensile and compression characteristics of this new composite material. At least three specimens are investigated for each lay-up.

For each test, load versus stroke of the test machine is recorded. The tests are carried out in control of position on a servo-hydraulic Instron testing machine with 100kN capacity. In addition, a pair of extensometers or electrical strain gages are attached to the mid-section of the specimen to enable an accurate recording of deflections, for a direct comparison with finite-element models. The readings from the two extensometers or electrical strain gages are averaged for each test. The experimental data are recorded by means of System 5000 (Micro Measurements, USA) with an acquisition frequency of 100 Hz.

The longitudinal modulus of elasticity and the ultimate strength σ_u of specimens are evaluated. The ultimate strength has been calculated as the ratio between the ultimate load and the resistant section, that is the gross cross-sectional area. The longitudinal elasticity modulus E is calculated from the stress-strain curve using equation $E = \Delta\sigma/\Delta\varepsilon$ (i. e. the slope of the elastic trend of the stress-strain curve far from fracture zone). The mode and location of failure of each specimen are analyzed at the end of each test and classified as suggested in [2,3].

Figure 2 represents respectively (a) the set up for tensile and for compression tests and (b) a typical fracture for tension and compression.

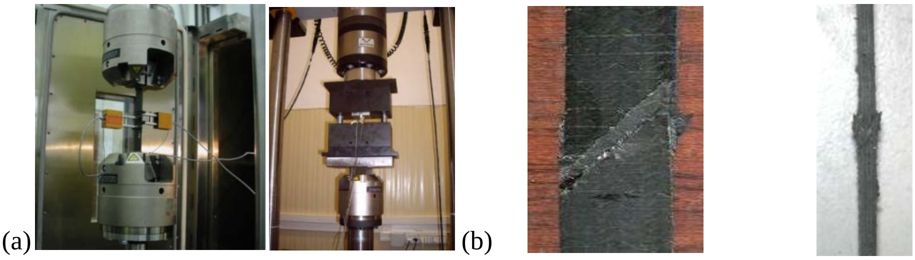

Fig. 2 Cutting of specimens

Table 4 reports mean values for ultimate tensile strength and longitudinal modulus obtained from tensile tests.

Tab. 4 Experimental results for tensile tests (T)

Tile	**Ultimate strength [MPa]**	**Modulus of elasticity [MPa]**
M1_0°	540	52300
M2_90°	538	54217
M18_0°	830	71125
M19_90°	555	43567
M24_0°	773	89225
M25_90°	43	5640

Figure 3 summarizes tensile tests results obtained for different fibers' percentages: M1 and M2, 33/33/33 class, show the same behavior both for 0° and 90° specimens; M24 and M25, 100/0/0 class, show respectively the highest and lowest slope; M18 and M19, 40/40/20 class, show an intermediate trend.

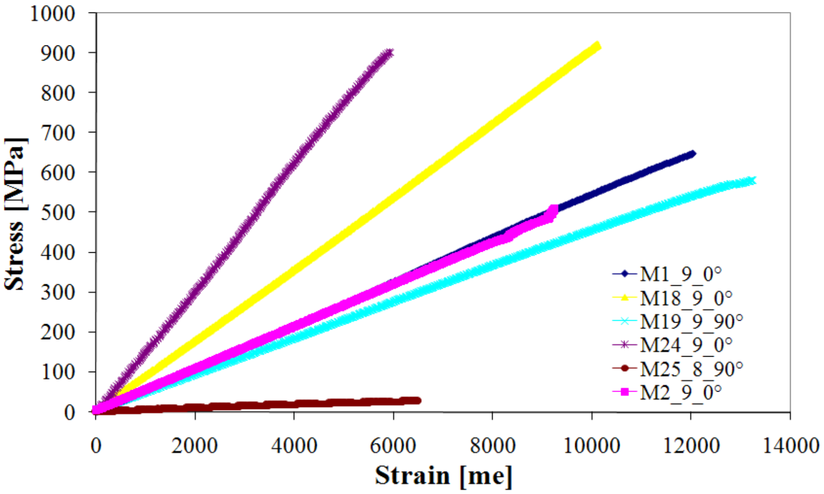

Fig. 3 Tensile tests results obtained at HT for different lay-up of tiles

Figure 4 reports experimental results for 33/33/33 tiles whose specimens are cut in different orientations: it can be observed that 0° and 90° specimens have an identical mechanical response, that is better than the other ones, thanks to the lay-up which comprises two times these fibers orientations.

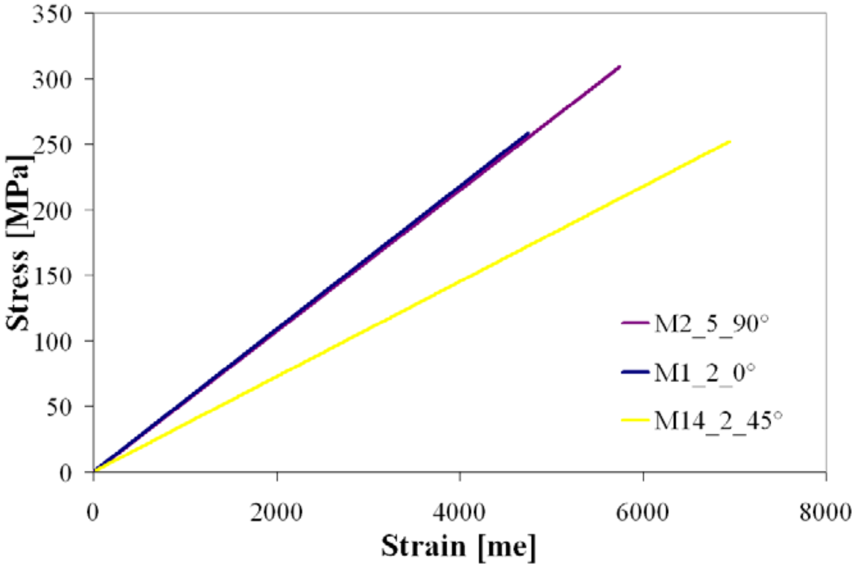

Fig. 4 Tensile tests results obtained for specimens cut in different orientations

Compressive test showed fragile ruptures; elastic strain has been recorded in all cases till final fracture.

Table 5 lists mean values for ultimate compressive strength and longitudinal modulus obtained from C tests. In this case, it can be observed that compression longitudinal modulus are mostly similar to those at tensile longitudinal modulus. The ultimate strength decreases at compression.

Tab. 5 Experimental results for compressive tests (C)

Tile	Ultimate strength [MPa]	Modulus of elasticity [MPa]
M4_0°	-311	45717
M5_90°	-198	55250
M22_0°	-305	58533
M23_90°	-257	40617
M26_0°	-504	115200
M27_90°	-110	7000

3 Finite-Element Model

A finite element model was developed in order to simulate tensile and compressive tests. The specimens have been modelled using the commercial software ANSYS 10.0 [4]. A multi-layered shell elements was used (SHELL 91). It includes 8 nodes each of which has 6 degrees of freedom, the translations in the coordinate directions X, Y and Z and the rotations about the nodal X, Y, and Z-axes.

Each specimen was modeled with respect to the geometry, dimensions, number of layers, percentage of fibers orientation and lay-ups. The elastic properties for this material were evaluated experimentally. They are:

- $E_x = 89.225\ GPa$. It corresponds to the elastic modulus of specimen with 100% of fibers along the load direction.
- $E_y = 5.640\ GPa$. It corresponds to the elastic modulus of specimen with 0% of fibers along the load direction.
- $G_{xy} = 2\ GPa$. It is evaluated testing unidirectional specimens cut at 45° respect to the fibers' direction and recording the strains along the fibers ($\varepsilon_{45°}$) and perpendicularly to the fibers ($\varepsilon^*_{45°}$).

$$G_{xy} = \frac{\tau_{xy}}{\gamma_{xy}} \tag{1}$$

where

$$\tau_{xy} = \frac{P}{2ab} \tag{2}$$

and

$$\gamma_{xy} = \varepsilon_{45°} - \varepsilon^*_{45°} \tag{3}$$

P is the load applied and ab is the specimen's cross section.

- $\nu_{xy} = 0.0427$. It is calculated testing unidirectional specimens cut at 90° respect to the zero lamina and recording the strains in the longitudinal (ε_y) and transverse (ε_{yx}) directions:

$$\nu_{yx} = \frac{\varepsilon_{yx}}{\varepsilon_y} \tag{4}$$

Kinematic constraints were imposed in order to reproduce correctly the mechanism that transfers the load to the specimen. The lower edge was completely locked. The upper edge of the specimen was locked for all of the degrees of freedom except for the y-translation. It represents the load's direction.

The load applied was characteristic of each specimen and is evaluated in correspondence of a strain of 3000 με.

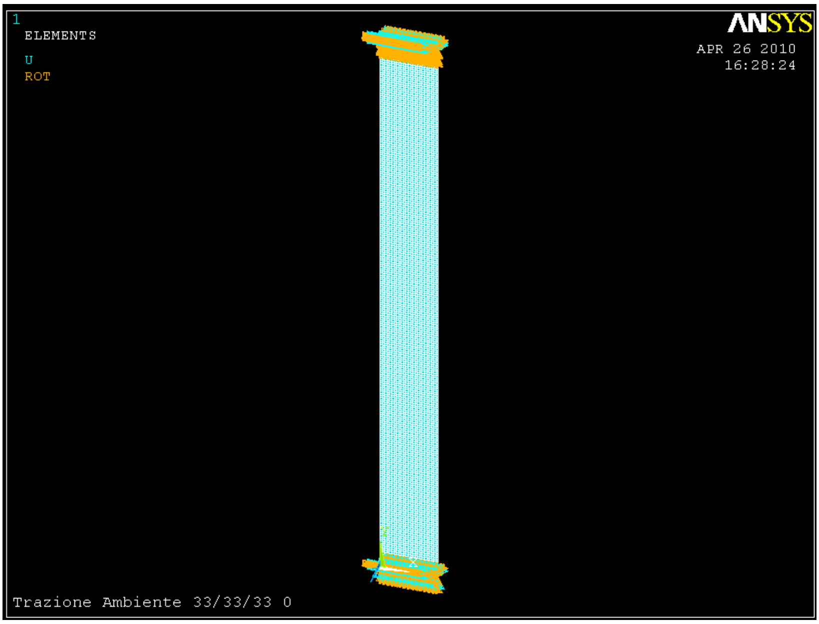

Fig. 5 Finite element model of the tensile test simulated numerically

The specimen material was modeled assuming each layer as an orthotropic material. This modeling choice was justified by the fact that each ply has the fibers in only one direction. This analysis was carried out in order to define a numerical model that good represents the experimental one, in order to reduce the numbers of tests.

The mesh included 6250 elements and 19301 nodes. All finite element analyses were run on a standard PC equipped by an Intel® Pentium Dual-Core processor and 3GB RAM memory. The structural analysis was completed in about 5 minutes.

4 Results

A serious problem with traditional fiber reinforced polymer (FRP) laminates is their relatively poor interlaminar fracture toughness and low impacted damage tolerance which makes them susceptible to delamination when subjected to interlaminar loading. Stitching as a cost-effective method has received recognition for the remarkable improvement in the through-the-thickness mechanical properties. The introduction of the through-the-thickness reinforcement can substantially improve the interlaminar properties of laminates. In the stitching process, a needle is used to perforate the laminate with the stitch yarn remaining in the laminate, which makes the local damages occur at the locations where the sewing needle and yarn penetrate the material. The forms of the damage are fiber distortion, fiber breakage and resin-rich pocket. These damages may affect the in-plane mechanical properties, which usually restrict the application to certain structural components where the requirement for in-plane mechanical properties is high.

It has been reported that the broken fibers due to stitching in a carbon fabric/epoxy laminate account for no more than 0.5% of all fibers. The fiber breakage is not believed to be the primary factor that affects the in-plane mechanical properties of stitched laminates although this needs more experiments to validate. The importance of fiber spreading has been assessed by the large number of studies who have examined the influence of fiber orientation on the tensile and compressive properties of FRP laminates. These studies show that misalignment of fibers by only a few degrees from the direction of loading causes a large reduction in the strength of unidirectional composites. A severe variance of the misalignment exists between different types of through the-thickness reinforcement laminates. The comprehensive investigation on the changes of the microstructure due to stitching is urgently needed for understanding the mechanical properties and failure mechanism of stitched composites [5].

At least three experimental tests were performed with each lay-up. Each test was performed at a quasi-static rate in position control. Figure 2b shows the post-failure state of each lay-up. All specimens failed in accordance with the acceptable failure modes set out in ASTM Standard [2,3]. The ultimate failure occurred in all specimens almost instantaneously, with little warning given of the onset of failure, except for some audible “pings”, characteristic of fiber failure, and harsh tearing sounds, characteristic of large catastrophic laminate delamination, heard seconds before the ultimate failure.

The tables below show a summary of the different tiles tested and modeled. They underline the percentage error evaluated as

$$E = \frac{\varepsilon_{simulated-} \varepsilon_{experimental}}{\varepsilon_{experimental}} * 100. \tag{5}$$

The percentage errors are all positive, because the numerical results are bigger than the experimental ones. This demonstrates that in the model it is difficult to represent correctly the stitched points that affect the composite behavior. It can be noted, also, that the error relative to the compressive tests are larger than the tensile ones, because the effects of the stitching are more influent in this type of test.

Another interesting observation is that the errors for 40/40/20 tiles are higher than the other ones. Finally it can be observed that the errors relative to the 0° specimens are lower than 90° ones, while 45° specimens show an intermediate trend.

Tab. 6 Tensile percentage errors between numerical and experimental results.

Tile	**Deg**	**Fibres Orientation %**	**No. Ply**	**Lay-up**	**Error %**
M1	0°	33/33/33	12	(0,45,90,-45,0,90)s	+ 10,63
M2	90°	33/33/33	12	(0,45,90,-45,0,90)s	+ 35,95
M14	45°	33/33/33	12	(0,45,90,-45,0,90)s	+ 18,21
M18	0°	40/40/20	10	(0,45,90,-45,0)s	+ 47,62
M19	90°	40/40/20	10	(0,45,90,-45,0)s	+ 50,74
M24	0°	100/0/0	4	(0,0,0,0)	+ 9,74
M25	90°	100/0/0	4	(0,0,0,0)	+ 33,08

Tab. 7 Compressive percentage errors between numerical and experimental results.

Tile	**Deg**	**Fibres Orientation %**	**No. Ply**	**Lay-up**	**Error %**
M4	0	33/33/33	12	$(0,45,90,-45,0,90)_s$	+ 19,41
M5	90	33/33/33	12	$(0,45,90,-45,0,90)_s$	+ 40,12
M22	0	40/40/20	20	$(0,45,90,-45,0)_s$	+ 45,93
M23	90	40/40/20	20	$(0,45,90,-45,0)_s$	+ 47,78
M26	0	100/0/0	14	14 times 0	+ 45,96
M27	90	100/0/0	14	14 times 0	+ 20,54

5 Conclusions

An experimental and numerical study of tensile and compression specimens made from a high-strength carbon/epoxy composite has been performed. Three significantly different lay-ups have been tested and modelled.

The deformations predicted from the FEM analysis has been shown to be bigger than the experimental ones because the composite behavior is sensitive to the stitching procedure and the stitched points are difficult to represent correctly in the model. In addition, the compression numerical results indicate that stitching has a beneficial effect especially on the compression strength. Through-thickness stitching followed by resin film infusion (RFI) process is one of the most promising and cost-effective methods of manufacturing composite structures with higher delamination resistance [6].

The future work will involve different type of load, lay-ups and geometries.

References

1. N. K. Kucher, M.P. Zemtsov, M.N. Zarazovskii, *Deformation Behavior and Strength of Unidirectional Carbon Fiber Laminates*, Mechanics of Composite Materials, **42**, No. 5, (2006)
2. ASTM D 3039/D 3039M, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Material*, (Luglio 2000)
3. ASTM D 3410/D 3410M, *Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading*, (Agosto 2003)
4. Swanson Analysis System Inc., *The ANSYS 10.0 Users' Manual*, (2005)
5. Yuqing Wei, Junqian Zhang, Composite Part A, *Characterization of microstructure in stitched unidirectional composiet laminates*, **39**, 815-824, (2008)
6. N.L. Hana, S.S. Suha, J.-M. Yanga, H.T. Hahnb, Composite Part A, *Resin film infusion of stitched stiffened composite panels*, **34**, 227-236, (2003)