Mechanical Characterization of Composite Layered Structures Used in Aviation Turbines

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Aeronautic industry is on the trend of development and more comforts are being incorporated in the aircrafts. On the other hand it is necessary to achieve stringent demand of fuel economy and high performance at low cost. To achieve high fuel economy the aeronautics manufacturers are induced to reduce weight in the possible fields. Light weight composite materials like carbon fiber for the impeller of aerodynamic compressors have been used to achieve the requirements of the aeronautics industry. The paper is focused on the FEM modeling and experimental determination of the two tests of the composite material characteristics used for the impeller of aerodynamic compressors.

Keywords: CFRPs materials, Mechanical tests, FEM modelling

The word of composite became more and larger in the last decade since every time the new performed materials can be created from two or more materials that are combined on a macroscopic scale. If is well designed, the new material usually exhibits the more qualities than the components and often some qualities that neither the constituent possesses ([1-4]).

Since the design information is finished, it needs to be shared across other design items and of course across contractual schemes to make sure that the project ideas are in progress. This process is not a linear sequence. The design information does not pass to the next stage until it is completed from the point of view of material type choosing. Efficient composite design practices request that the integration of the material type and structure lay-up has to be at the highest level and universal across the pieces applications in a certain industry.

Complex engineering problems in aeronautics which have to be solved by many different disciplines have an iterative feature. The original design is evolving through a process of change to achieve the target. The constant change of the lay-up and structure is necessary to be adopted and therefore the systems and processes need to be flexible and light so that to incorporate a practice without adding complexity or overhead.

Carbon fiber-reinforced polymer, carbon fiber-reinforced plastic or carbon fiber-reinforced thermoplastic (CFRP, CRP, CFRTP or often simply carbon fiber, or even carbon), is a very strong and light fiber-reinforced plastic that contains carbon fibers. Nowadays, CFRPs are expensive to produce but are used in industries that requires high strength-to-weight ratio and rigidity, such as aerospace, automotive, shipbuilding, civil engineering, sports goods etc.

In the last decade the aircraft designers and manufacturers have extensive used the CFRP throughout their design range. Due to its high strength to weight ratio, CFRP is widely used in micro air vehicles (MAVs). Light weight carbon fiber compressor impeller/blade manufacturing studies in [5] have been aimed to achieve TRL 4 and some steps towards TRL 5 and 6 for using light weight composite materials like carbon fiber for the impeller of aerodynamic compressors, taking it beyond the state-of-the-art.

The composite materials prepreg have been used to fabricate the parts in the studies in [5].

Different process velocity, different duration and environment parameters (temperature and humidity of the curing) could produce significant changes in the fabricated composite mechanical behavior and therefore the mechanical characteristics can be different from the theoretical values.

Therefore, the mechanical tests are however usually necessary for the prototypes and in case of implementation of a new product, so that to achieve the optimal design.

This paper presents FEM simulations of three mechanical tests for determining the material characteristics to achieve the ultimate value of the acting force.

Consequently, the success of numerical simulation for the composites will depend on simple methods for determining material characteristics.

Mechanical tests

Mechanical testing has been carried out to produce information to be used in impeller design ([5]). The mechanical property data can be obtained by applying the standard tests.

The layered composite based on prepreg have been used for specimen fabrication. The raw material, prepreg, is partially cured which means that it in this case the composite is in an advanced stage of fabrication. FEM models have been used for mechanical testing simulations to estimate data that may be used for impeller design purposes ([6]). The most important function may be that of providing design data since it is essential that the limiting values that the structure can withstand without failure are known.

The numerical test simulation is used to potentially reduce lead time, and thus reduce manufacturing cost. It offers the ability to apply virtual changes to the composite lay-up and components, in a more cost-effective manner than real process trials might be.

Tensile tests

The tensile test is used to provide data that will be used in design studies. Before to start the mechanical tests, FEM analysis has been performed in order to determine the ultimate force used for the tensile tests.

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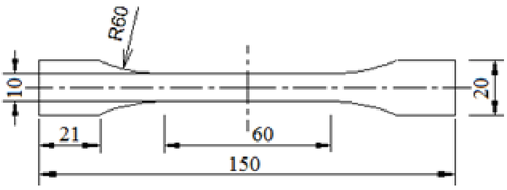


Fig. 1 Geometry of the tensile specimen type A

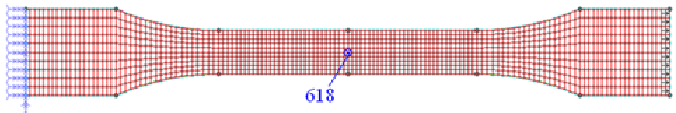


Fig. 2 FEM model of the specimen

Table 1
STRESS VALUES FOR TENSILE SPECIMENS

Specimen type	Number of layers	Thickness [mm]	Lay-up	Max. stress [MPa]	Needed ultimate force [kN]
Specimen_7_set2_2	7	2.45	0/90/45/0/45/90/0	0.0478	56
Specimen_15_set2_2	15	5.25	$0_3/90_2/45_2/0/45_2/90_2/0_3$	0.02202	122

Table 2
STRESSES IN LAYERS FOR SPECIMEN_7_SET2_2

Layer	Fibers angle	Stress [MPa]	
		top	bottom
1	0°	0.0478	0.0478
2	90°	0.0478	0.0478
3	45°	0.02336	0.02336
4	0°	0.0478	0.0478
5	45°	0.02336	0.02336
6	90°	0.0478	0.0478
7	0°	0.0478	0.0478

Table 3
STRESSES IN LAYERS FOR SPECIMEN_15_SET2_2

Macro-layer	Number of layers	Fibers angle	Stress [MPa]	
			top	bottom
1	2	0	0.02202	0.02202
2	2	90	0.02202	0.02202
3	2	45	0.01087	0.01087
4	1	0	0.02202	0.02202
5	2	45	0.01087	0.01087
6	2	90	0.02202	0.02202
7	2	0	0.02202	0.02202

Specimen characteristics

The geometry of the specimens for tensile tests is illustrated in figure 1, according to [7]. The reference mechanical characteristics are according to the reference material [8, 9], (Fabric prepreg laminates, version CC 204 ER450 42%), $E_x = E_y = 77.4$GPa; $G_{xy} = 3.93$GPa; $\mu_{xy} = 0.06$; $R_x = 1172$MPa; $R_{xy} = 106$MPa.

FEM modeling of tensile test

The FEM model of the tensile specimen used SHELL4L (layered) element. The mesh concerns 1400 elements (fig. 2). The loading of the specimen is an axial pressure acting on the end sections (grips), having a unitary resultant force F=1N.

The various lay-up composites, with 7 and 15 layers, have been used in tensile test analysis. In all cases, the fiber directions have been imposed to be 0, 45 and 90° and the criterion was to obtain the smallest value of the stress. The optimum specimen obtained in each set is illustrated in table 1. The normal stress distributions obtained in each layer in the median section (node 618 in fig. 2) are presented in tables 2 and 3.

Experimental tensile test

According to the FEM tests, the optimum lay-up has been selected to fabricate the specimens. The two specimen types geometries have been used (type A-rounded shape and type B-rectangular shape) (fig. 3).Equipment used for tensile tests is concerning stretching machine of 500kN, extensometer and strain gauges system (fig. 4). The tensile tests have been carried out according to the standard SR EN ISO 527-4:2009, presented in [7].

In figure 5 the stress-strain curve obtained for specimen 3 from figure 3 is illustrated. According to this curve the values obtained for material characteristics are: $E_x = 66$GPa; $E_y = 66$GPa; Poisson's ratio =0.28; Tensile strength is $R_x = 487.77$MPa.

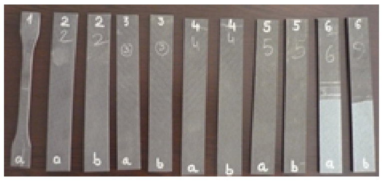


Fig. 3 Specimens prepared for tensile tests

Fig. 4 Rig used for tensile tests

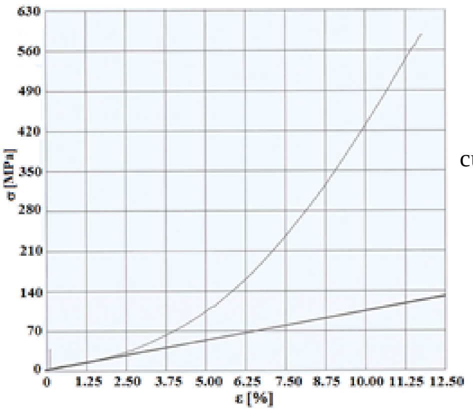


Fig. 5 Material curve stress-strain

ShearHEAR TEST

Shear testing is used to determine the shear strength characteristics of the material. The numerical modeling of the shear test is performed to estimate the ultimate force that will be used during the shear test in laboratory. This test is different from tensile test because the forces act parallel to the upper and lower faces of the specimen loaded in testing, so that in the middle area of the specimen pure shearing (only shearing forces and no any bending moment) occurs. Normally, the both characteristics (strength and stiffness) can be determined within the same test.

Iosipescu Shear Test Fixture

Iosipescu shear test is based on the published paper that describes the shear behavior of metals, performed by Nicolai Iosipescu in 1967 ([10]). The name of the test (Iosipescu) has been internationally adopted by specialists and became the standard ASTM D 5379/1993 ([11]).

The first Iosipescu shear test fixture has been developed for composite materials testing in 1970 at the University of

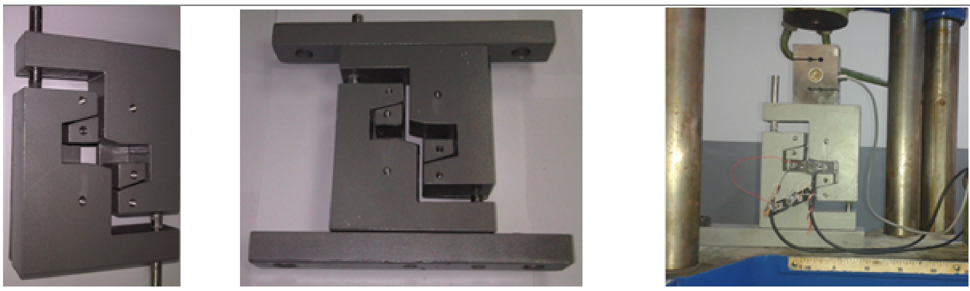


Fig. 6. Iosipescu Shear Test Fixture: a) System for the compression area of the stretching machine; b) System for the tension area of the stretching machine; c) System during shear testing

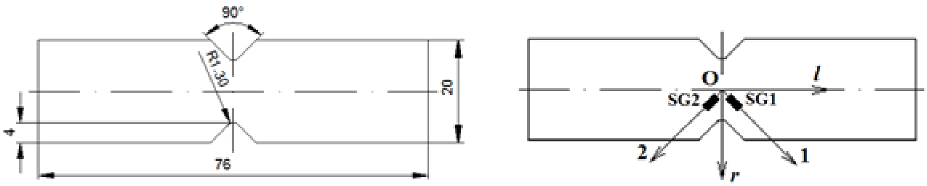


Fig. 7. Shear test specimen with notches: a) Geometry; b) Strain gauges positions

Wyoming, USA ([12]). Many fixtures have been developed around the world and the test method is now in a broad-based use.

The Iosipescu fixture is made out of steel. In figure 6 the Iosipescu fixture from Laboratory of composite strength tests from University Dunarea de Jos of Galati is illustrated.

The loading approach, done by the fixture, produces a theoretical loading state in the specimen test area with shear efforts [13], named in plane shear state.

The specimens geometry used for shear tests, made according to [11], are illustrated in figure 7.a.

Due to the loading approach, *F*, performed by test fixture, a theoretical loading state leads to the only shear efforts in the specimen section with notches ([12]). The specimen's analysis shows a uniform shearing state occurring in the centre of the section with notches although not just in the vicinity of the notches tips.

Additionally, the normal stresses are small in this area ([14]). By orienting of the longitudinal axes of the specimen along any of the orthotropic axes of the material, any of the six shear stress components can be determinate (in fact there are only three independent shear stresses).

To determine the shear modulus G_{lr} it is necessary to estimate the shear strains. The shear strains are measured with two strain gauges (bonded along directions 1 and 2, at $\pm 45^o$ towards longitudinal axis of the specimen), placed so that the measured point to be in the median point of the specimen (point O in fig. 7b).

According to figure 7b, the shear strain g_{lr} can be determined with the equation ([15])

$$\frac{1}{2}\gamma_{lr} = \varepsilon_1 l_l l_r + \varepsilon_2 m_l m_r + \frac{1}{2}\gamma_{12}\left(l_l m_r + m_l l_r\right) \quad (1)$$

where the director cosines are

$l_l = \cos(l,1) = \cos(45^o)$; $m_l = \cos(l,2) = \cos(-45^o)$; $l_r = \cos(r,1) = \cos(45^o)$; $m_r = \cos(r,2) = \cos(45^o)$.

Therefore, in the point O the shear strain is

$$\gamma_{lr} = \varepsilon_1 - \varepsilon_2 \quad (2)$$

If the linear deformation in the strain gauge 1(ε_1) is negative (compression) and the deformation in strain gauge 2 (ε_2) is positive (tension) a negative shear is obtained.

The shear stress can be determined according to the equation

$$\tau_{med} = F / S \quad (3)$$

where *F* is applied load and *S* is the specimen's sectional area between the notches.

The shear modulus G_{lr} is determined with the equation

$$G_{lr} = \tau_{med} / \gamma_{lr} \quad (4)$$

FEM modeling

A 2D finite element model was performed, to simulate the loading conditions of the Iosipescu fixture, by assuming the plane stress approach.

The shear test with Iosipescu Shear Test Fixture has been modeled by using SHELL3L layered elements for the specimen (material: composite) and SHELL3T elements for the fixture (material: steel). The mesh concerns 9477 elements (fig. 8a). The system was loaded with a unitary force F=1N. In figure 8b the shear stress map occurred in the Specimen_7_set3 is illustrated.

Table 4
OPTIMUM REPRESENTATIVE SPECIMENS

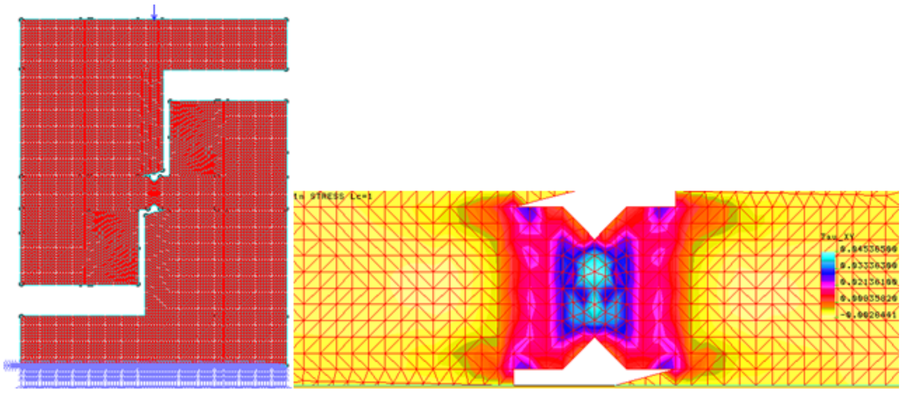
Specimen type	Number of layers	Thickness [mm]	Lay-up	Maximum stress [MPa]	Ultimate force [kN]
Specimen_7_set3	7	2.45	0/0/0/**0**/0/0/0	0.04053	2.62
Specimen_15_set3	15	5.25	$0_3/0_2/0_2/\mathbf{0}/0_2/0_2/0_3$	0.01893	5.60

Table 5
SPECIMENS WITH THICKNESS OF 2.45 mm (7 LAYERS)

Specimen type	Lay-up	τ_{xy} in node 7 top [MPa]	Ultimate force [kN]
Specimen_7_set1	0/45/90/**45**/90/45/0	0.03821	2.78
Specimen_7_set2	0/45/90/**0**/90/45/0	0.03644	2.21
Specimen_7_set3	0/0/0/0/0/0/0	0.04053	2.62

Table 6
SPECIMENS WITH THICKNESS OF 5.25 mm (15 LAYERS)

Specimen type	Lay-up	τ_{xy} in node 7 top [MPa]	Ultimate force [kN]
Specimen_15_set1	$0_3/45_2/90_2/\mathbf{45}/90_2/45_2/0_3$	0.01720	6.2
Specimen_15_set2	$0_3/45_2/90_2/\mathbf{0}/90_2/45_2/0_3$	0.01698	6.3
Specimen_15_set3	$0_3/0_2/0_2/\mathbf{0}/0_2/0_2/0_3$	0.01893	5.6



a) FEM model: the Iosipescu Shear Test Fixture and the specimen

b) Zoom of the specimen with shear stress map [Pa]

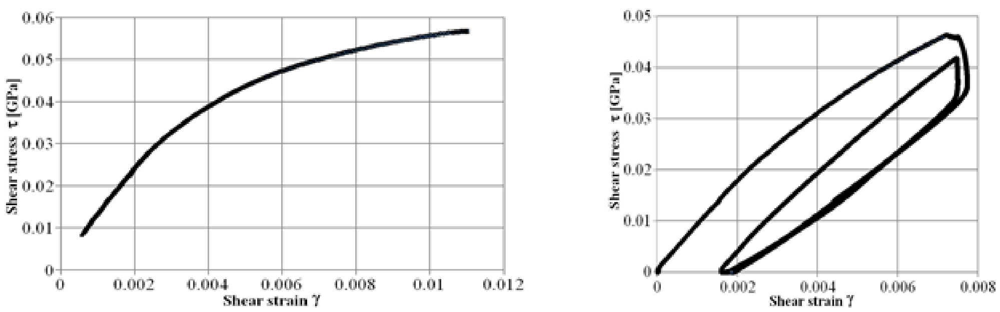
Fig. 8 Shear test modeling with FEM

Table 7
RESULTS FOR SHEAR STRENGTH

Specimen No.	F_{ultim} [N]	th [mm]	h [mm]	Area [mm^2]	Shear strength [MPa]
1b	10163	2.9	12.2	35.4	287.25
1c	8511	2.8	12.2	34.2	249.15
5a	17500	3.7	12.1	44.8	367.65
5b	10000	4.0	11.9	47.6	223.02
5d	9500	3.8	11.8	44.8	185.66
6c	5850	4.3	11.9	51.2	123.94
6d	8300	4.0	11.8	47.2	174.37
6e	8700	4.0	11.9	47.6	182.77

Table 8
EXAMPLES OF SPECIMENS WITH IN PLANE SHEAR MODULUS, OBTAINED IN EXPERIMENTAL TESTS

Specimen No.	F_{ultim} [kN]	t_h [mm]	h [mm]	Area [mm^2]	G_{xy} [GPa]
5c	1.2	3.98	11.4	45.38	**9.38**
6a	1.2	4.1	11.2	45.95	**8.95**



a) Charging

b) Sequential charging-discharging

Fig. 9 Shear stress-strain curves

Various lay-up composites, with 7 and 15 layers, have been used for the shear test analysis. In all cases, the fiber directions have been imposed to be 0, 45 and 90° and the criterion was to obtain the smallest value of the stress. The optimum specimens obtained in each set are presented in table 4.

For the both specimen types the values of the shear stresses (in central node, as it is seen in figure 7b) and corresponding ultimate force are illustrated in tables 5 and 6.

Experimental shear tests

The shear tests have been carried out with the Iosipescu Shear Test Fixture (fig. 6) according to the American standard ASTM 2344-00 ([16]). Based on the record performed during the shear tests, the shear strength values are presented in table 7. In figure 9a the shear stress versus shear strain curve for charging of the specimen is illustrated. In figure 9b the shear stress versus shear strain curve for charging-discharging of the specimen is illustrated. The phenomenon of re-positioning of the material structure is observed, since the curve for charging period and also for discharging period has other trajectories after the first two cycles.

Starting with the third cycle the material behavior is stabilized, the trajectories are fixed and finally a constant hysteresis is performed.

The shear characteristics of two CFRP specimens tested with Iosipescu method are illustrated in table 8. As it is seen, the values of the shear modulus are different due to the differences in the geometry and fabrication for each specimen.

Conclusions

FEM modeling of the tensile tests requires that the all mechanical properties of the specimen material must be known. Based on elastic characteristics the advantage with this method is that only the moduli, E_x and E_y, of the material must be known. Sufficient values of needed ultimate strength have been to offer a database for the experimental tests.

The FEM modeling of the Iosipescu shear test has been performed to determine shear characteristics of the CFRP used for the impeller of aerodynamic compressors, so that an appropriate finite-element model has been used so that to determine the stresses and strains at failure in the vicinity of the notches roots.

The shear test has several imperfections depending on the fixture characteristics and material imperfections. The inconvenient issues of the test performed according to this standard are: inhomogeneous stress and strain state in the middle area of the specimen, possibility of the specimen twisting in the fixture, producing differences in strain measuring among front and back, crushing occurred in loading points, failure modes occurring, differences in specimen fabrication and also influence of material manufacturing [17, 18].

The specimen geometrical imperfections have an important role that may affect the test results. To avoid this situation, previously the FE-analysis has been performed, so that to show how important is the influence of these imperfections and how to minimize the effect of the stresses in the test region.

One important issue related to shear testing is gripping of the specimens in place of fixture. The imperfections in correct gripping may cause additional and unwanted stress states, which may affect the test performance. Such imperfections may involve crushing and splitting in the gripping area. After the testing, besides the shear characteristics determination, the examination of the specimen concluded sometimes three critical phenomena that have been observed: very big contact stresses at the inner loading areas, partially loss of contact on the opposite face of these area, and high tensile stresses in the areas where the contact is lost.

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