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PERFORMANCES' ESTIMATION BY TESTS OF COMPOSITE MATERIAL STRUCTURES WITH RESPECT TO THE LAY-UP CONFIGURATION AND MIXING THE POSITION OF TAPE AND FABRIC LAMINAE

This paper presents an estimation of performances by tests on composite material structures. In order to evaluate the effects on the structural behavior, tests changing the percentage of orientation of the fiber at 0, 45 and 90 degrees and mixing the unidirectional plies with the fabric ones have been done. Fixed the lay-up configuration and so the stacking sequence, two typology of structures have been analyzed; the first one having only unidirectional plies while the second one having a fabric ply (plain weave 0/90) in place of the top and bottom unidirectional plies. The open-hole compressive strength and the filled-hole tensile strength and moduli have been characterized by test. A total of 72 specimens have been used in the test campaign. In order to well compare the test results a Performance Weight Index (PWI) has been introduced by authors in order to normalize the strength of each laminate with respect to its weight/unit of surface. Results and different laminate behaviors have been evaluated and discussed.

1. Introduction

A composite material is a macroscopic combination of two or more distinct materials, having a recognizable interface between them [1]. Generally, this combination brings in superior products. This practice started in the antiquity when, for example, mud bricks were reinforced with straw to build houses and it arrives to the modern age with the reinforced concrete. Modern composites owe much to glass fiber-polyester composites developed since the 1940s. In

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the early 1960s, the emergence of boron filaments gave birth to a new generation of composites. These composites, which employ high modulus continuous filaments, like boron and carbon (or graphite), are referred to as advanced composites. The term composites or advanced composite material is defined as a material consisting of small-diameter (around 6 to 10 microns), high--strength, high-modulus (stiffness) fibers embedded in an essentially homogeneous matrix [2]. The use of composite materials increases day-by-day and not only for their structural properties but also for electrical, thermal, tribological and environment applications. In aeronautical and aerospace industries, composite materials are largely used thanks to their high properties/weight ratio. Pointing towards this way, a pollutants reduction (in terms of CO_2) or alternatively greater range (endurance) or flight speed can be achieved.

The technological innovation of the past decade has positively impacted the manufacturing costs such to decrease them drastically. However, notwithstanding this manufacturing costs reduction, the application of the composite materials on primary aircraft structures is still waiting to take-off in a complete way. The main reason is the behavior of the composite to the failure that obligates the aeronautical industry to do a lot and expensive tests in order to certificate the structures and each of their components [3]. In fact, even if many studies have been performed [4], the behavior of the composite in proximity to the failure, or after that it has occurred, is still not so known. Despite the uncertainties in the failure behavior, progress have been reached in the aviation industry about the use of composite materials. In fact, the application of composites have increased from 2% for airplanes like MD-80, Boeing 757 up to 47% in Boeing 787 Dreamliner [5]. The participation of composites is even greater in lighter airships and sailplanes, and in the so-called light airplanes [6]. Additional studies have been started in order to increase the performances of the structures realized in composite materials without compromising the weight reduction. In that direction is focused this study. The presents research activity has the purpose to characterize the effect on the structural behavior, in terms of strength and moduli, of the unidirectional carbon ply replaced with the carbon fabric (Plane-Wave) one. Fixed the lay-up configurations and so the stacking sequences, two typology of structures have been analyzed; the first one having only unidirectional plies, while the second one having a fabric ply (plain weave 0/90) in place of the top and bottom unidirectional plies. The open-hole compressive strength and the filled-hole tensile strength and moduli have been carried out. A total of 72 specimens have been used in the test campaign. In order to well compare the test results a Performance Weight Index (PWI) has been introduced by the authors in order to normalize the strength of each laminate with respect to its weight/unit of surface.

The use of fabric as top and bottom plies in the laminate is mainly guided by a great technological advantage in the manufacturing process of the composite part. For example, in the drilling activity, the presence of fabric plies reduce the risk of delamination. Additional splitting of the specimens was done for the three analyzed layups as shown in Table 1.

Table 1.

Test Plan

Specimen ID	Test type	Nr. plies	Percentage orientation [0/45/90]	Laminate Lay-up	Nominal specimen dimensions		
					L mm	W mm	th mm
AUD	OHC/FHT	22	18/18/64	[**90/0**/90/+45/90/ 90/0/90/90/–45/90]$_S$	305	28.96	4.092
BUD	OHC/FHT	20	30/40/30	[**90/0**/+45/0/–45/ 90/+45/0/ –45/90]$_s$	305	28.96	3.72
CUD	OHC/FHT	22	27/55/18	[**90/0**/+45/0/–45/90/+45/ –45/+45/–45/0]$_S$	305	28.96	4.092
AF	OHC/FHT	20	11/22/67	[**OF**/90/+45/90/ 90/0/90/90/–45/90]s	305	28.96	3.764
BF	OHC/FHT	18	25/50/25	[**0F**/+45/0/–45/ 90/ +45/0/ –45/90]$_S$	305	28.96	3.392
CF	OHC/FHT	20	22/67/11	[**0F**/+45/0/–45/90/+45/ –45/+45/–45/0/0/–45/+45/ –45/+45/90/45/0/+45]	305	28.96	3.764

2. Specimen, experimental set-up and facility

The open-hole compressive (OHC) and the filled-hole tensile (FHT) tests were performed in this work. The topology of tested structure was identified with the acronym "UD" and "F" that indicate the structure realized with Unidirectional Ply only or those having Fabric ply as top and bottom lamina. A test batch of six coupons for each configuration was manufactured and the samples were obtained by cut from a large sheet after the lamination process. A total of 72 specimens were used in the experimental campaign. As above mentioned, three lay-up configurations, for both structure topologies, were tested. In particular, laminates with orientation at [0°/45°/90°] having percentage equal to [18/18/64], [30/40/30] and [27/55/18] were analyzed. Those percentages become [11/22/67], [25/50/25] and [22/67/11] in the case of structure having plain weave fabric. It is evident that these are apparent percentages since obtained replacing the 90°/0° top and bottom plies with one plain weave fabric ply. The fabric ply is manufactured by two unidirectional fibers oriented at 0° and 90° weaved between them; this allows that mechanical properties of the fabric lamina are close to that of two unidirectional fiber oriented at 90/0, with the advantage to have less smaller thickness. Since the materials used are copyrighted, no further details were reported in this work like i.e. the type of manufacturing process used, the carbon fibers and resin used for the reinforcement and for the matrix or the curing process. The aim of this activity is to investigate if the use of one fabric ply instead of two unidirectional ones can positively affect the behavior of the structure in terms of strength and moduli. The hole diameter is equal for all the specimens and it is equal to 4.826 mm.

The experimental activity was performed in the laboratory of Industrial Engineering Department (Aerospace section) of the University on Naples Federico II. The mechanical tests were performed using the Lonos Test AMPTLT035 PMA60 Galdabini test machine (Fig. 1).

Fig. 1. Galdabini traction/compressive test machine

The test machine is composed of mobile upper part that, thanks to electrical actuators, can slide up and down with respect to the fixed base. The facility is equipped with load cell and displacement sensor able to perform Force Control Tests and Position Control Tests, both managed by a software installed on a control unit. The maximum allowed load in both tensile and compressive tests is 660 kN.

3. Tests results

3.1. Open Hole Compression Tests

The Open Hole Compression tests were performed in agreement with the ASTM D6484 [7]. The ASTM D6484 indicates the geometrical features of the testing specimens (width, thickness, transverse section area, hole's diameter) and additional details, to correctly perform the test. An anti-buckling fixture [7] was used to grip the coupon when was in the test machine. The fixture has two assembled grips closed by eight bolts having a closing torque of 7 Nm [7]. The fixture is placed into the test machine between upper and lower plates as suggested by ASTM. The control of displacement was used to perform the tests. The displacement control rate was set to 2 mm/min with 23 N as a preload [7]. The failure that occurred during the OHC test in the specimen ID = 001 is pictured in Fig. 2a. The obtained failure mode for this test is conformed to that reported in the ASTM-D6484. In particular, that specimen highlights the laminate compressive failure (LGM) laterally across the center of the hole (0° dominated ply kinking/buckling).

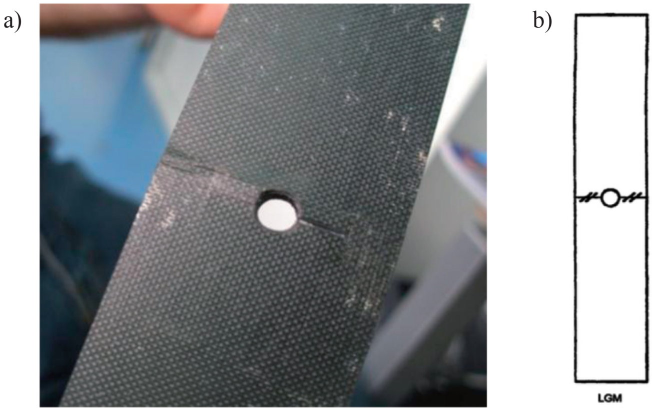

Fig. 2. Failure Mode that occurred at the specimen 001 (AUD) during the OHC test (a) and equivalent ASTM failure mode LGM (b)

An example of Force-Displacement curve measured during the test is reported in Fig. 3. The applied load is measured by the load cell while the displacement is measured by the upper plate of the test machine. Initially, since the handles have not reached the necessary grip, the force measured by the load cell is zero. Subsequently, when reaching the correct grip, the applied load has been correctly measured.

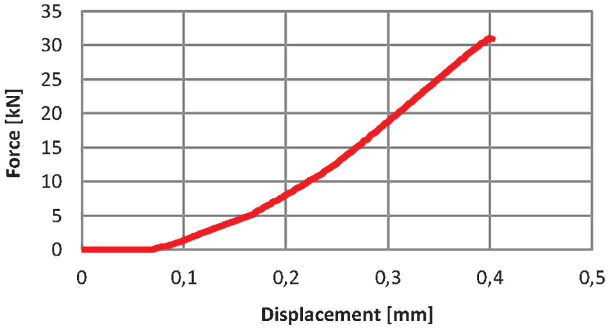

Fig. 3. Force-Displacement curve at specimen 031 (laminate CF_OHC)

In each tests, the maximum strength of the specimen has been evaluated considering the maximum applied load and the gross cross-sectional area, as reported in the following equation:

$$\sigma_{\max} = P_{\max}/A\,, \tag{1}$$

where:

$\sigma_{\max}$ is the ultimate open-hole compressive strength, MPa,
$P_{\max}$ is the maximum force prior to failure, N,
A is the gross cross-sectional area, mm^2.

To find the modulus, one fixed the tangent on the force displacement curve (Fig. 3), after reaching the correct grip, the modulus has been calculated as a function of the load at a point on the tangent, gross cross-sectional area, the elongation at a point on the tangent and the initial gage length, as follows:

$$\text{Modulus} = \frac{\dfrac{\text{(load at point on tangent)}}{\text{(gross cross-sectional area)}}}{\dfrac{\text{(elongation at point on tangent)}}{\text{(initial gage length)}}}\,. \tag{2}$$

The test results for every fabric batch with lay-up type A (Specimen ID = AF) are arranged in Table 2.

The same table results were realized for all the other batch coupons (BF, CF, AUD, BUD and CUD). The overall test results, in terms of maximum stress and modulus, for all the batch of coupons tested at Open Hole Compression, are reported in Table 3.

Table 2.

Test results (OHC) and characteristics of the AF batch coupons

Test number	Coupon ID	Width mm	Thickness mm	Hole diameter mm	Max Force kN	Cross Section Area mm^2	Sigma max MPa	Modulus GPa
9	19	29.06	3.65	4.70	22.34	106.1	210.67	224.67
10	21	29.14	3.93	4.86	24.27	114.5	211.93	217.77
19	20	28.96	4.00	4.71	22.34	115.8	192.85	218.65
20	22	29.09	4.02	4.45	21.93	116.9	187.53	212.33
28	23	29.05	3.83	4.61	22.63	111.3	203.39	224.22
35	24	28.99	3.82	4.64	22.19	110.7	200.38	218.10
Mean Values					22.62		201.12	

Table 3

Overall test results for all the batch of coupons tested at OHC

Specimen ID	Mean Cross Section Area mm^2	Sigma max MPa	Standard Deviation MPa	Modulus GPa	Standard Deviation GPa	% 0°,45°,90°
AUD	120.85	185.63	8.99	241.59	5.20	18/18/64
BUD	109.94	265.46	2.93	369.98	8.84	30/40/30
CUD	120.51	268.95	8.03	357.52	7.32	27/55/18
AF	112.56	201.12	9.65	219.29	4.60	11/22/67
BF	101.89	270.63	9.05	338.54	20.71	25/50/25
CF	111.10	278.02	5.60	335.28	8.01	22/67/11

A comparison must be done between the pairs of specimens AUD-AF, BUD-BF and CUD-CF since they have the same lay-up except the top and bottom laminae, as described in Section 1. The results highlight that, in all the compared pairs of specimens, the unidirectional (UD) have the modulus higher than the fabric (F) ones. Conversely for the ultimate tension, which in the unidirectional specimens was always lower than in the fabric ones.

3.2. Filled Hole Tension Tests

The Filled Hole Tension tests were performed in agreement with the ASTM D6742 [8]. The ASTM D6742 indicates the geometrical features of the testing specimens (width, thickness, transverse section area, hole's diameter, dimensions of the filler) and additional details to correctly perform the test. For the Filled Hole Tension test is mandatory the use the filler (pin) inserted into the hole during the execution of the test (Fig. 4).

Fig. 4. Lateral view of the coupon with pin in the Test Machine, FHT

The tolerance between the hole and the pin of +75/–0 μm was granted, as suggested by the ASTM D6742. As in the OHC, even in these tests the control of displacement was used. The displacement control rate was set to 2 mm/min without preload [8].

The failure occurred during the FHT test in the specimens having ID 42-56 as pictured in Fig. 5a-b. The obtained failure modes for that tests are conformed to that reported in the ASTM-D6742. In particular, both specimens (unidirectional (42) and Fabric (56)) highlight MGM failure mode reported in the ASTM. For that failure mode, the laminate fails in tension at the hole and exhibits multiple modes of failure in various sublaminates. Extensive splitting and delamination were present.

a)

b)

Fig. 5. Failure Modes occurring at the specimen 42 (AUD) (a) and at the specimen 56 (AF) during the FHT tests

Analogous to what has been done for the OHC, even for the FHT the maximum stress was evaluated by Equation 1. This way the $\sigma_{\max}$ represent the ultimate filled hole tensile strength. The overall test results, in terms of maximum stress and modulus, for all the batch of coupons tested at Filled Hole Tension, are reported in Table 4.

Table 4.

Overall test results for all the batch of coupons tested at FHT

Specimen ID	Mean Cross Section Area mm^2	Sigma max MPa	Standard Deviation MPa	Modulus GPa	Standard Deviation GPa	% 0°,45°,90°
AUD	118.50	357.27	13.20	20.34	0.87	18/18/64
BUD	107.73	546.10	11.05	23.04	1.03	30/40/30
CUD	121.05	525.09	13.64	19.72	1.19	27/55/18
AF	109.01	291.90	19.98	18.63	1.51	11/22/67
BF	98.23	509.98	16.10	29.62	1.45	25/50/25
CF	111.38	470.69	13.46	26.42	0.82	22/67/11

Even in that case, as for the OHC tests, a comparison between the pairs of specimens AUD-AF, BUD-BF and CUD-CF is mandatory, since they have the same lay-up except the top and bottom laminae, as described in Section 1. Conversely to what happened for the specimens tested at OHC, the same specimens tested at FHT highlight that the ultimate tension of the unidirectional coupons were always higher than the fabric ones.

About the modulus, the behavior is strictly connected with the lay-up. In particular, the laminates having lower percentage of fiber oriented at 0° (AUD, AF) highlight a maximum modulus for the unidirectional coupons (AUD), while laminates having higher percentage of fiber oriented at 0° (BUD, CUD, BF, CF) have a maximum modulus for the fabric coupons (BF, CF). In order to bring out the effectiveness of the fabric plies in terms of ultimate strength and modulus, further considerations about the weight reduction are needed. In the manufacturing point of view, the laminates having outer plies in fabric present technological advantages. For example, in the manufacturing process of composite parts where drilling activities are required, the laminates having fabric plies are preferred since they reduce the risk of delamination. Another advantage is the better compressive strength of the specimens having fabric than the unidirectional one, as reported in the last sections. About the tensile strength, instead, the laminates with unidirectional plies are more performant than those having fabric ones. A crucial aspect in aeronautical and aerospace field is the weight. Any structural component is chosen as compromise between the performance and weight. Since the tested batches AF, BF, CF were respectively thinner than the AUD, BUD and CUD with a resulting weight reduction, the Performance/Weight Index (PWI) was introduced in order to estimate contemporarily the performances and the lightness of the structure.

The Performance/Weight index was defined as the ratio between the mean value of ultimate strength in a single batch and its weight per unit of surface.

$$\mathrm{PWI} = \sigma_{\max}/\mathrm{Thickness}\,. \tag{2}$$

The results reported in Fig. 6 show that in compressive tests, the PWI in each couple of laminates for the fabric material is always higher than the respective unidirectional one. The PWI increment is about the 12-17%.

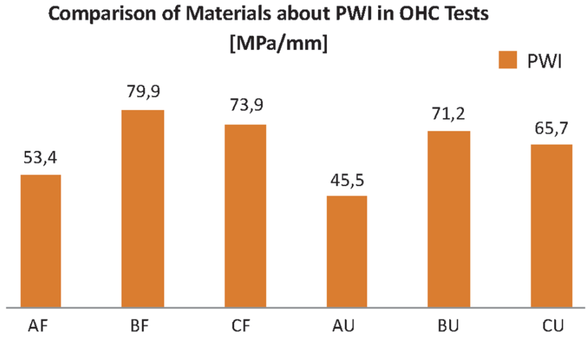

Fig. 6. PWI for every material in OHC Tests

Such a behavior, not affected by the thickness of the materials analyzed, shows the potential advantage of using a hybrid laminates with respect to unidirectional ones for improving compressive strength.

This PWI index suggests that the presence of fabric plies gives a real and strong contribute to the improvement of the laminate' strength for compressive loads.

The results reported in Fig. 7 show that, in tension tests, the PWI in each couple of laminates for the fabric material is always lower than the respective unidirectional one. The PWI decrement is about the 15-25%.

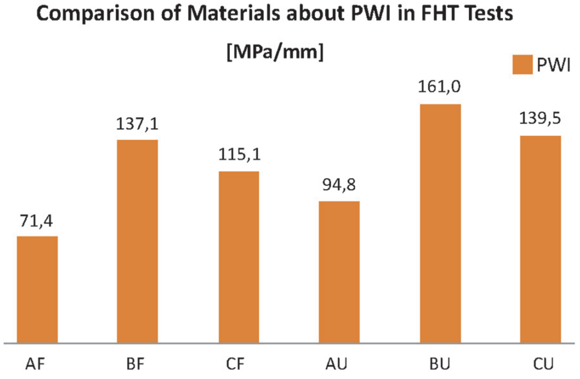

Fig. 7. PWI for every material in FHT Tests

As expected, taking into account the couples of laminates (i.e. AUD and AF), the higher tensile strength values of unidirectional laminates with the respect to the corresponding hybrid ones, are justified by their higher fibers percentage distribution oriented in 0 degree direction.

This PWI index suggests that unidirectional plies give a real and strong contribute to the improvement of the laminate' strength for tensile loads in comparison to the fabric ones.

4. Conclusion and future developments

The work has presented the experimental procedure, followed in order to compare the performances of composite laminates, totally constituted by unidirectional tape plies, and identical laminates with the two more external unidirectional plies on each side, substituted by a single fabric ply. It is reported a complete description of Open Hole Compression Test and Filled Hole Tension Tests. The experimental results in terms of mechanical strength, evaluated as the maximum value of sigma max, and the elastic modulus have been presented. One proposed a Performance Weight Index PWI, which makes it possible to normalize the performance of each laminate in relation to its weight. In conclusion, for compressive loads the activity shows that laminates with external plies in fabric have always better performance of strength as compared to the laminates composed only by unidirectional tape, and that this improvement is more evident when a normalization on the weight is introduced, considering the PWI evaluation. For the components subjected only to compressive loads, the use of materials with external plies in fabric is strongly favorable for the major strength for weight/unit of surface (higher PWI) and for the technological advantage in the manufacturing process of the composite piece. On the contrary, for components subjected to the tension loads the activity shows that laminates with external plies in fabric have always poor performance of strength (lower PWI) compared to the respective laminates, composed only by unidirectional. Future developments of the activity are the extension of the experimental campaign to other type of test, i.e. bearing tests and the evaluation of the strength, through statistical instruments as A- B-Basis Allowable [9] that is an useful information in the design phase. Besides A- B-Basis Allowable, gained by experimental results, will be compared with those obtained by a virtual testing procedure as affirmed in [10].

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Estymacja właściwości użytkowych struktur z materiałów kompozytowych na podstawie testów z uwzględnieniem konfiguracji prelaminatu i przy zamianie pozycji warstwy jednokierunkowej i warstwy tkaniny

Streszczenie

W artykule przedstawiono estymację, na podstawie testów, właściwości użytkowych struktur z materiałów kompozytowych. W celu oceny różnych wpływów na zachowanie się struktury wykonano testy przy zmiennej procentowej zawartości włókien o orientacji 0, 45 i 90° i przy zamianie pozycji warstwy jednokierunkowej i warstwy tkaniny. Przy ustalonej konfiguracji prelaminatu i takiej samej sekwencji ułożenia warstw, analizowano dwie topologie struktury, z których pierwsza miała tylko warstwy jednokierunkowe, a w drugiej była warstwa z tkaniny (splot płócienny 0/90) w miejscu warstw jednokierunkowych, górnej i dolnej. Na podstawie testu wyznaczono wytrzymałość na ściskanie próbki z otwartym otworem i wytrzymałość na rozciąganie oraz moduły przy wypełnionym otworze. W ramach badań doświadczalnych testowano ogółem 72 próbki. By prawidłowo porównać wyniki testów wprowadzono wagowy indeks osiągów (Performance Weight Index, PWI), pozwalający normalizować wytrzymałość każdego laminatu względem jego wagi na jednostkę powierzchni. Przedyskutowano i oceniono wyniki badań i zachowanie się różnych laminatów.