Experimental determination of compressive strength of an unidirectional composite lamina: indirect estimate by Using Back-out Factor (BF)

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ABSTRACT. In this paper, the determination of compressive strength of an unidirectional lamina (carbon/epoxy composite), using the Back-Out Factor correction of experimental data, is presented.

Since early ’70s, many methods were developed to deduce a compressive characterization of a composite material, each of which has been based on a different way of applying load to specimens.

After a detailed examination of these methods, the ASTM D 6641/D 6641M-09 Test Method has been chosen due to its advantages, i.e. load application to the sample (end load combined with shear load), measurement reproducibility and experimental equipment quite simplified. The experimental equipment (according to ASTM D 6641) used for compressive tests is the Wyoming Combined Loading Compression (CLC) Test Fixture.

Four different laminates were tested in compressive tests. They were realized by the same unidirectional pre-preg, but with different stacking sequences: two cross-ply $[0/90]_{ns}$ and two unidirectional laminates, $[0]_{ns}$ and $[90]_{ns}$. The last two laminates were used to evaluate the linear elastic properties of unidirectional lamina. The Back-Out Factors, that multiply the laminate measured compressive strength, were determined using the elastic properties previously measured.

This indirect analytic method, developed from the classical lamination theory, was used to find out the unidirectional 0° lamina compressive strength. At last, extrapolated data were compared with pre-preg manufacturer datasheet.

SOMMARIO. Nel presente lavoro viene determinata sperimentalmente la resistenza a compressione di una lamina di composito unidirezionale (UD) a matrice epossidica e rinforzo in fibra di carbonio, basandosi sul metodo di calcolo indiretto che fa uso del Back-out Factor (BF).

Fin dai primi anni ’70 sono stati sviluppati vari metodi per la caratterizzazione a compressione di materiali compositi rinforzati a fibre lunghe, ognuno dei quali contraddistinto da una specifica modalità di applicazione del carico al provino. Dopo una attenta analisi di questi metodi, si è scelto di utilizzare il Wyoming CLC Test Method (descritto nella normativa ASTM D 6641/D 6641M-09) che presenta molti vantaggi, legati principalmente alla modalità di applicazione del carico sul provino (combinazione di carico di taglio e di estremità) ed alla facilità di utilizzo del telaio Wyoming.

Attraverso tale metodo, sono stati testati a compressione quattro laminati, realizzati a partire da uno stesso prepreg unidirezionale: due cross-ply $[0/90]_{ns}$ ognuno con una diversa sequenza di laminazione, e due laminati ognuno dei quali con fibre solo a 0° od a 90°. Questi ultimi due laminati, sono stati utilizzati per determinare le proprietà elastiche della lamina UD. Il Back-out Factor, che moltiplica la resistenza a compressione misurata per i laminati cross-ply, viene determinato utilizzando queste proprietà elastiche.
Questo metodo analitico indiretto, sviluppato a partire dalla teoria classica della laminazione, è stato usato per determinare la resistenza a compressione di una lamina unidirezionale a 0°. Infine i dati estrapolati sono stati comparati con quelli contenuti nella scheda tecnica fornita dal produttore del prepreg.

KEYWORDS. Back-out Factor; Compressive strength; Unidirectional lamina; Cross-ply laminate.

INTRODUCTION

The compressive properties of advanced composite materials have been examined thoroughly only from the early'70s. Since then, many test methods have been developed. Depending on the way the load is applied, the characterization is performed by the following methods: Shear Loaded, End Loaded, Sandwich-Beam and Combined Loaded Specimen Test Methods [1].
In this paper, an unidirectional Carbon Fiber Reinforced Polymer is characterized using the Combined Loading Compression (CLC) Test Method [2]. The main advantages of this method are [1]:

- combined load allows to test untabbed straight-sided specimens avoiding high stress concentrations;
- simple test method allows repeatable results which can be compared to results obtained in other laboratories using the same method;
- small and little complex test fixture simplifies tests (especially not room-temperature ones).

The direct experimental determination of compressive strength of a carbon/epoxy unidirectional lamina, through mechanical test of 0° composite laminates, leads to an underestimation due to fibre micro-buckling failure [3]. Then, in this paper, the indirect determination of the compressive strength by testing cross-ply laminates, is used.

METHODOLOGY

The indirect determination of the compressive strength of a 0° lamina is based on using a multiply factor, called Back-out Factor (BF) which is determined from the classical lamination theory, using the stiffness properties of the unidirectional material [4]. Therefore the unidirectional (UD) compressive strength is determined as follow:

$$\sigma_{x\max}^{0°} = BF\frac{L_{\max}}{A} \tag{1}$$

where:
$\sigma_{x\max}^{0°}$ = 0°-ply compressive strength;
$L_{\max}$ = maximum load applied to the specimen;
A = cross-sectional area of the specimen.
The BF used in this paper is given by the following equation [3]:

$$BF = \frac{t(\overline{Q_{11}^{0}}A_{22} - \overline{Q_{12}^{0}}A_{12})}{(A_{11}A_{22} - A_{12}^{2})} \tag{2}$$

where:

$\overline{Q_{ij}^{o}}$ is the ij element in the transformed plane stress stiffness matrix for a unidirectional lamina
A_{ij} is the ij element in the laminate extensional matrix
t is the total laminate thickness

The BF for any symmetric and cross-ply laminate is given by the following equation [5]:

$$BF = \frac{\left\{E_x\left[V_0 E_y + \left(1-V_0\right)E_x\right] - \left(\nu_{xy}E_y\right)^2\right\}}{\left\{\left[V_0 E_x + \left(1-V_0\right)E_y\right]\cdot\left[V_0 E_y + \left(1-V_0\right)E_x\right] - \left(\nu_{xy}E_y\right)^2\right\}} \tag{3}$$

where:
V_0 = fraction of 0° plies in the cross-ply laminate;
E_x = axial compressive stiffness of the 0° plies;
E_y = transverse compressive stiffness of the 0° plies;
ν_{xy} = Poisson's ratio of 0° plies.
In this study the cross-ply laminate is defined as a composite with all plies oriented at 0° or 90° [6].
In summary, the 0° lamina compressive strength is determined by Eq. (1) and (3), through the mechanical characterization of two UD laminates (0° and 90°) and a cross-ply laminate with a maximum of 50% of 0° plies [2].

EXPERIMENTAL

Four separate stacking sequences were used in the present experimental test campaign, as shown in Tab. 1.

Lay Up ID Code	Configuration
A	Cross-ply with 21.1 % of 0° plies
B	Cross-ply with 42.1 % of 0° plies
E	UD 0°
F	UD 90°

Table 1: Stacking sequences of test specimens.

Test specimens were produced according to ASTM [2, 7]. This procedure was simplified because untabbed specimens are permitted, as reported in ASTM D 6641/ D 6641 M: "The specimen may be untabbed (Procedure A) or tabbed (Procedure B), as required. (…) Untabbed specimens are usually suitable for use with materials of low orthotropy, for example (…) laminates with a maximum of 50% 0° plies" [2].
The experimental tests were conducted at ambient laboratory conditions, using an MTS electro-hydraulic universal testing machine, equipped with an MTS 100 kN load cell. The test procedure is in accordance with ASTM D 6641 / D6641 M [2] which is referred to "Combined Loading Compression (CLC) test fixture". All tests were performed at a constant displacement rate of 1.3 mm/min, while the data were acquired at a rate of 10 samples/s and processed in accordance with the same ASTM standard.
A Wheatstone bridge system in half-bridge configuration, was used for strain measurements. This system was composed by an active strain gauge and a "dummy" for temperature compensation. The acquisition unit and the strain gauges used are HBM products. The specimens were instrumented with two strain gauges applied in two alternative back-to-back configuration in the gage section, thus distinguished:
1) two unidirectional strain gauges;
2) an unidirectional strain gauge and a bidirectional strain gauge.

RESULTS AND DISCUSSION

Overall 36 tests were carried out, as follows: 24 tests for cross-ply laminates (material A and B with 10 instrumented and 14 not instrumented tests) and 12 tests for UD laminates (materials E and F, all instrumented tests). Normalized results are summarized, relative to an appropriate experimental value, in Tab. 2 to 5, where the symbols are:

- σ_{max} = compressive strength

- $E_{SG1chord}$ = axial compressive stiffness measured by strain gauge 1[1]
- $E_{SG2chord}$ = axial compressive stiffness measured by strain gauge 2
- ΔE % = variation between ESG1chord and ESG2chord referred to their average value
- ν = Poisson's ratio
- % Bending = percent bending of the specimen
- CV % = coefficient of variation

Material A	σ_{max}	**% Bending**	
		Midpoint	**Failure**
A1	37.9	4.9	-9.3
A2	35.0	8.3	30.0
A3	36.0	1.2	-17.1
A4	36.8	9.4	-8.7
A5	35.1	16.2	40.0
A6	42.1	-	-
A7	35.2	-	-
A8	36.9	-	-
A9	39.3	-	-
A10	40.0	-	-
A11	39.4	-	-
A12	39.2	-	-
Mean Value	37.7	-	-
Std. Deviation	2.3	-	-
CV %	6.0	-	-

Table 2: Compressive test results of A samples (normalized results).

Material A	σ_{max}	**% Bending**	
		Midpoint	**Failure**
B1	62.5	0.5	-2.9
B2	66.5	5.7	-17.4
B3	63.7	6.7	-29.8
B4	64.2	7.9	15.0
B5	64.6	19.6	1.8
B6	66.5	-	-
B7	67.3	-	-
B8	63.4	-	-
B9	65.3	-	-
B10	63.8	-	-
B11	62.6	-	-
B12	60.8	-	-
Mean Value	64.2	-	-
Std. Deviation	1.9	-	-
CV %	3.0	-	-

Table 3: Compressive test results of B samples (normalized results).

Material E	σ_{max}	$E_{SG1chord}$	$E_{SG2chord}$	**ΔE %**	ν	**% Bending**	
						Midpoint	**Failure**
E1	71.4	97.0	100.0	3.0	100.0	2.4	-8.1
E2	79.4	98.8	94.4	-4.6	91.1	5.3	1.2
E3	71.9	93.7	95.1	1.5	81.2	3.6	4.7
E4	77.1	99.8	99.5	-0.3	-	7.0	3.4
E5	75.8	95.2	92.5	-2.8	-	2.7	0.4
E6	100.0	-	-	-	-	-	-
Mean Value	79.3	96.9	96.3	-0.6	90.7	-	-
Std. Deviation	10.6	2.5	3.3	-	9.4	-	-
CV %	13.4	2.6	3.4	-	-	-	-

Table 4: Compressive test results of E samples (normalized results).

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[1] Strain gauge 1 is identified with the bidirectional strain gauge (if present), or with the strain gauge whose data are recorded first.

Material F	σ_{max}	$E_{SG1chord}$	$E_{SG2chord}$	**ΔE %**	**ν**	**% Bending**	
						Midpoint	**Failure**
F1	21.0	4.9	5.2	5.6	6.7	18.0	-
F2	19.9	5.2	4.9	-7.3	5.0	5.7	-
F3	20.5	5.0	5.0	-0.8	5.5	8.4	-
F4	20.8	4.7	5.3	11.9	-	9.4	-
F5	20.6	4.7	5.1	8.8	-	9.0	-
F6	21.2	-	-	-	-	-	-
Mean Value	20.7	4.9	5.1	3.6	5.7	-	-
Std. Deviation	0.5	0.2	0.2	-	0.8	-	-
CV %	2.2	4.8	3.2	-	-	-	-

Table 5: Compressive test results of F samples (normalized results).

The strain gauge configuration allows the determination of sample bending during the test time, by means of the following factor:

$$Bending[\%] = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \cdot 100 \qquad (4)$$

where ε_1 and ε_2 are the longitudinal strains measured by the two strain gauges [2].

The percent bending, as calculated in eq. (4), provides a reasonable indication of Euler buckling [2]. Failure and midpoint bending are reported in Tab. from 2 to 4 as requested by ASTM D 6641 [2]. The latter is determined at the midpoint of the strain range used for chord modulus calculations [2].

Tab. 6 shows the compressive strength of UD material calculated by means of classical lamination theory. The two cross-ply laminate back-out factors, determined through Eq. (2), are:

- BF cross-ply A = 3.98
- BF cross-ply B = 2.22

The compressive stiffness (E_x and E_y) for BF determination were obtained averaging the mean values listed in Tab. 4 and 5. In Tab. 6, 0° lamina compressive strength values obtained by Eq. (1) can be found.

Sample ID Number	σ_{max} **UD (A)**	σ_{max} **UD (B)**
1	151.1	138.6
2	139.4	147.6
3	143.3	141.3
4	146.5	142.4
5	139.9	143.3
6	167.8	147.6
7	140.4	149.3
8	146.8	140.7
9	156.6	144.8
10	159.5	141.6
11	156.9	138.8
12	156.1	134.9
Mean Value	150.4	142.6
Std. Deviation	9.1	4.2
CV %	6.0	3.0

Table 6: UD lamina compressive strengths obtained through Back out Factor (normalized results).

Finally, in Tab. 7 the results of the mechanical characterization, in terms of mean values of compressive strengths with their standard deviation, are summarized. These values are in agreement with data reported in the datasheet of the pre-preg material used for lamination.

	Experimental characterization results
0° Compressive Strength	150.4 ± 9.1 (A) 142.6 ± 4.2 (B)
0° Compressive Modulus	96.6 ± 4.1
90° Compressive Strength	20.7 ± 0.5
90° Compressive Modulus	5.0 ± 0.3

Table 7: Results summary: mean values and standard deviation (normalized results).

As examples, in the following Fig. 1 and 2 the plots obtained from 0° UD compressive tests are shown. They represent the typical mechanical behaviour of these composite materials. As expected, Fig. 1 shows that the behaviour is of elastic type up to failure and Fig. 2 shows that the % bending of the sample is limited up to failure.

In the following pictures (from Fig. 3 to Fig. 6) some microscope photographs of the samples failure are shown. The microscope photographs were taken by a WILD HEERBRUGG optical microscope. The Fig. 3 and 4 show a cross-ply laminate failure (overview and detail). The failure mode (brooming) of this specimen (B4) is in agreement with the acceptable failure modes reported in ASTM D6641 [2]-. The brooming failure was frequently observed in our cross-ply specimens. Welsh and Adams indicated that this failure mode is probably a post-failure phenomenon and that a true compressive failure was achieved prior to the brooming effect [3].

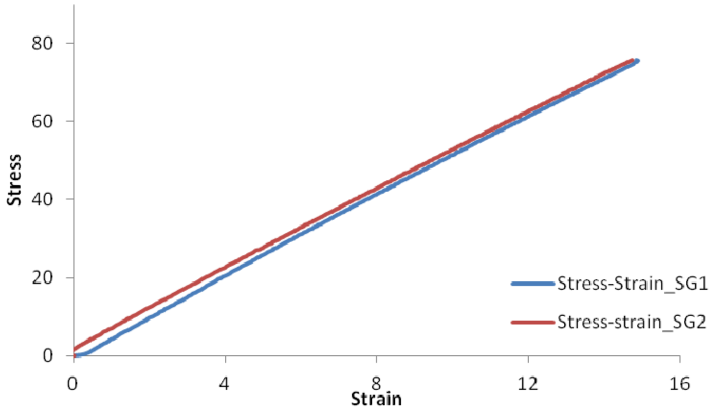

Figure 1: Stress-Strain curves of sample E5 (normalized results).

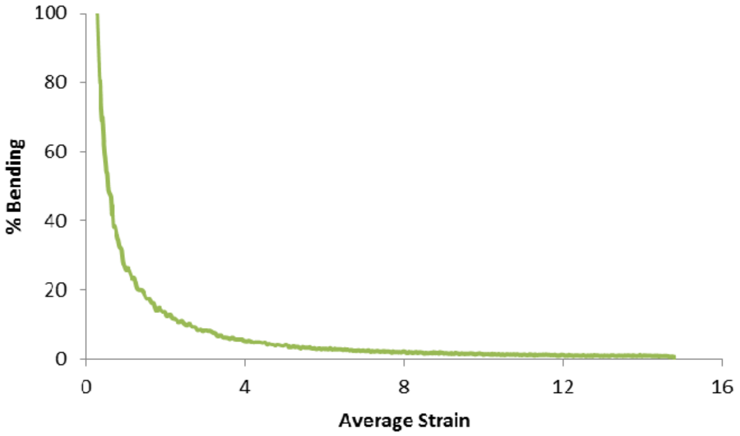

Figure 2: % Bending - Average Strain curve of sample E5 (normalized results).

The conventional 0° unidirectional composite specimens, typically fail in a fibre micro-buckling mode before the compressive strength of individual fibres is achieved. Fig. 5 and 6 show a 0° UD laminate failure (overview and detail), where a specimen premature failure caused by fibre micro-buckling can be observed (typical kink band).

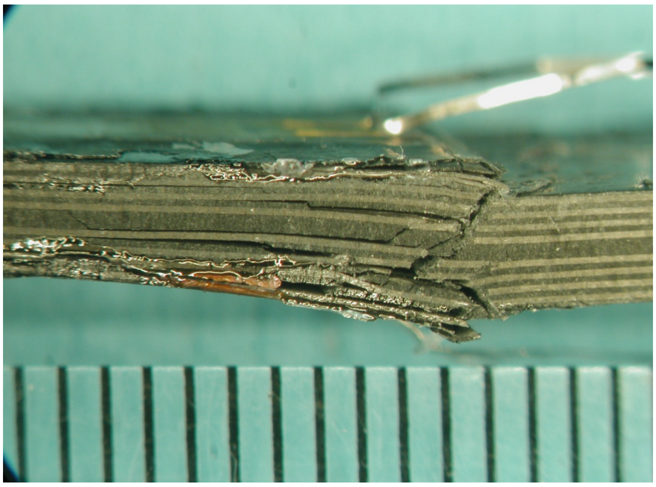

Figure 3: Microscope photograph of B4 sample gage section (lateral view).

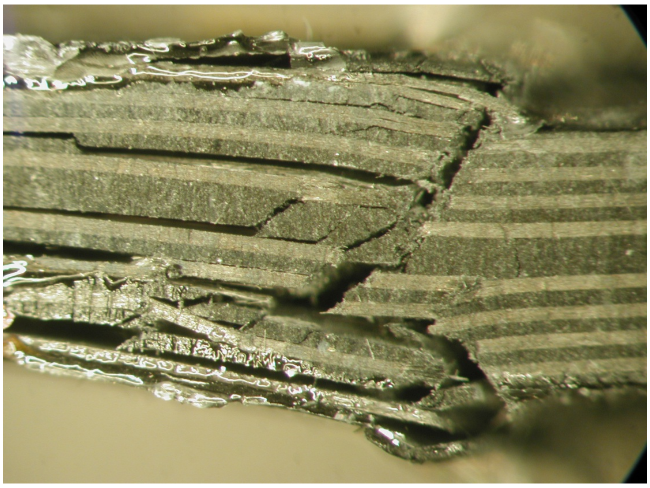

Figure 4: Microscope photograph (detail) of B4 sample gage section (lateral view).

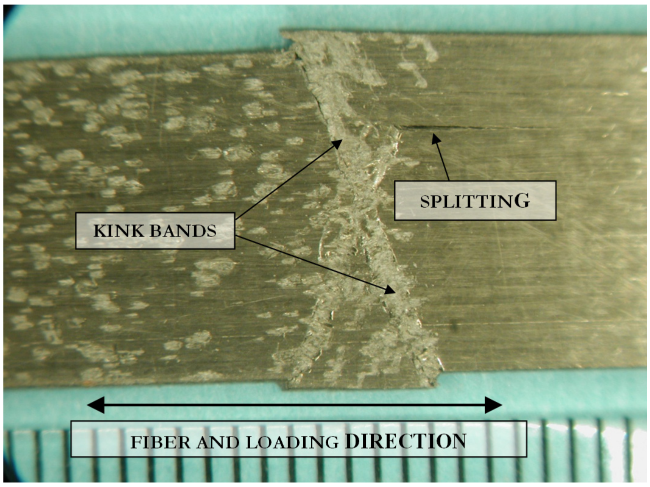

Figure 5: Microscope photograph of E13 sample gage section (front view).

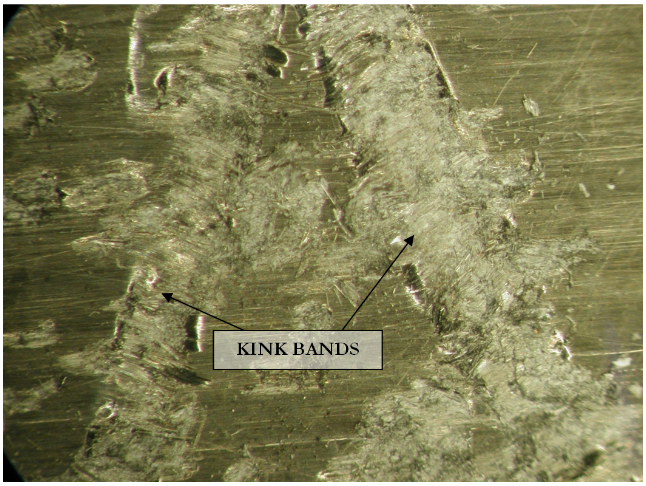

Figure 6: Microscope photograph (detail) of E13 sample gage section (front view).

CONCLUSIONS

In the present paper the use of two cross-ply $[0/90]_{ns}$ specimen configurations was examined, with the aim of determining the unidirectional lamina compressive strength of a carbon/epoxy material. The Combined Loading Compression Test Fixture (ASTM D 6641) was employed to execute the tests.

The experimental results showed that failure strengths determined by using cross-ply specimens and Back-out Factors are about twice to those obtained for 0° unidirectional specimens. This is due to the phenomenon of fibre micro-buckling in the UD samples at 0°, which is instead restricted in the cross-ply. Furthermore the values of strengths, determined by linear lamination theory, are in agreement with that reported in the datasheet of the pre-preg used to achieve our composite materials. In particular the maximum compressive strength was obtained by cross-ply with the minimum percentage of 0° plies (21.1 %), while the expected value (from datasheet) is intermediate between those obtained with the two cross-ply. The strength coefficients of variation (CV%) associated with the materials A and B were about 6% and 3% respectively. Considering the type of material examined, these are low levels of data scatter.

Finally this indirect analytical method, developed according to the classical lamination theory, and applied to a 0° unidirectional lamina, produced an high compressive strength associated with a low data scatter, two attractive characteristics for this kind of composite materials.

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