Estimate of compressive strength of an unidirectional composite lamina using cross-ply and angle-ply laminates

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ABSTRACT. In this work has been estimated the compressive strength of a unidirectional lamina of a carbon/epoxy composite material, using the cross-ply and angle-ply laminates.
Over the years various methods have been developed to deduce compressive properties of composite materials reinforced with long fibres. Each of these methods is characterized by a specific way of applying load to the specimen.
The method chosen to perform the compression tests is the Wyoming Combined Loading Compression (CLC) Test Method, described in ASTM D 6641 / D 6641M-09. This method presents many advantages, especially: the load application on the specimen (end load combined with shear load), the reproducibility of measurements and the experimental equipment quite simplified.
Six different laminates were tested in compressive tests. They were realized by the same unidirectional prepreg, but with different stacking sequences: two cross-ply [0/90]ns, two angle-ply [0/90/±45]ns and two unidirectional laminates [0]ns and [90]ns.
The estimate of the compressive strength of the unidirectional laminates at 0°, was done by an indirect analytical method, developed from the classical lamination theory, and which uses a multiplicative parameter known as Back-out Factor (BF). The BF is determined by using the experimental values obtained from compression tests.

Finally, extrapolated data were compared with prepreg manufacturer datasheet.

SOMMARIO. In questo lavoro è stata stimata la resistenza a compressione di una lamina unidirezionale di un composito a fibre di carbonio e matrice epossidica, utilizzando dei laminati cross-ply ed angle-ply.
Negli anni 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. Il metodo scelto per eseguire le prove di compressione è il Wyoming Combined Loading Compression (CLC) Test Method, descritto nella normativa ASTM D 6641/D 6641M-09. Tale metodo presenta molti vantaggi, tra i quali: la modalità di applicazione del carico sul provino (combinazione di carico di taglio e di estremità), la riproducibilità delle misure e la facilità di utilizzo del telaio Wyoming.
Sono stati testati a compressione sei laminati, realizzati a partire da uno stesso prepreg unidirezionale: due cross-ply [0/90]ns ognuno con una diversa sequenza di laminazione, due angle-ply [0/90/±45]ns ognuno con una diversa sequenza di laminazione e due laminati con fibre solo a 0° od a 90°.
Il calcolo della resistenza a compressione della lamina unidirezionale a 0°, è stato fatto utilizzando un metodo analitico indiretto, sviluppato a partire dalla teoria classica della laminazione e che fa uso di un parametro moltiplicativo noto come Back-out Factor (BF). Il BF viene determinato utilizzando i valori sperimentali ricavati dalle prove di compressione.
Infine i valori di resistenza così ottenuti sono stati comparati con quelli presenti nella scheda tecnica fornita dal produttore del prepreg.

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

INTRODUCTION

Since the ’70s, many test methods have been developed to estimate the compressive properties of advanced composite materials. Depending on the way the load is applied, the mechanical characterization can be performed by the following methods: Shear Loaded, End Loaded, Sandwich-Beam and Combined Loaded Specimen Test Methods [1].
In this paper, a unidirectional Carbon Fiber Reinforced Polymer is characterized using the Combined Loading Compression (CLC) Test Method [2]. The main advantages of this method are [1]:
- the combined load allows to test untabbed straight-sided specimens avoiding high stress concentrations;
- the simple test method allows to obtain repeatable results;
- the test fixture is small and simple to use (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 and angle-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 follows:

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

where:
$\sigma_{x\max}^{0°}$ = 0°-ply maximum compressive strength;

L_{max} = maximum load applied to the specimen;
A = cross-sectional area of the specimen.
The BF values used in this paper are 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

In this study the cross-ply laminate is defined as a composite with plies oriented at 0° or 90° [5] and the angle-ply laminate is defined as a composite with plies oriented at 0°, ±45°, and 90°.
The BF for symmetric and cross-ply laminate is given by the following equation [6]:

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

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.

The BF for symmetric and angle-ply laminate is given by the following equation:

$$BF = N\frac{\left(E_x \cdot B - E_y \cdot \nu_{xy} \cdot C\right)}{\left(A \cdot B - C^2\right)} \tag{4}$$

with:

$$A = \left\{nE_x + pE_y + \frac{q+k}{4}\cdot\left[E_x + E_y + 2E_y\nu_{xy} + 2G_{xy}\cdot\left(1 - \nu^2{}_{xy}\frac{E_y}{E_x}\right)\right]\right\} \tag{5}$$

$$B = \left\{nE_y + pE_x + \frac{q+k}{4}\cdot\left[E_x + E_y + 2E_y\nu_{xy} + 2G_{xy}\cdot\left(1 - \nu^2{}_{xy}\frac{E_y}{E_x}\right)\right]\right\} \tag{6}$$

$$C = \left\{\left(n + p\right)\cdot E_y\nu_{xy} + \frac{q+k}{4}\cdot\left[E_x + E_y + 2E_y\nu_{xy} - 2G_{xy}\left(1 - \nu^2{}_{xy}\frac{E_y}{E_x}\right)\right]\right\} \tag{7}$$

where:
E_x, E_y, and ν_{xy} have the same meaning of Eq. (3);
G_{xy} = in plain shear modulus of elasticity;
N = total number of plies;
n = total number of 0° plies;
p = total number of 90° plies;
q = total number of +45° plies;
k = total number of – 45° plies;

In summary, the 0° lamina compressive strength is determined by equations:
- (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];
- (1) and (4), through the mechanical characterization of two UD laminates (0° and 90°) and an angle-ply laminate with a maximum of 50% of 0° plies.

EXPERIMENTAL

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

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

Table 1: Stacking sequences of test specimens.

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 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 gauge section, thus distinguished:
1) two unidirectional strain gauges;
2) an unidirectional strain gauge and a bidirectional strain gauge.

RESULTS AND DISCUSSION

Overall 60 tests were carried out, as follows: 24 tests for cross-ply laminates (materials A and B with 10 instrumented and 14 not instrumented tests), 24 tests for angle-ply laminates (materials C and D with 12 instrumented and 12 not instrumented tests) and 12 tests for UD laminates (materials E and F, with 10 instrumented and 2 not instrumented tests). Normalized results are summarized, relative to an appropriate experimental value, in tables from 2 to 7, 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

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

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 %	6.1	-	-

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

Material B	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	64.3	-	-
Std. Deviation	1.9	-	-
CV %	3.0	-	-

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

Material C	σ_{max}	% Bending	
		Midpoint	Failure
C1	41.0	1.7	-2.7
C2	40.8	3.3	9.1
C3	40.7	4.4	-12.3
C4	39.7	18.6	4.0
C5	44.2	7.9	5.0
C6	36.9	10.1	-20.9
C7	42.9	7.9	-15.1
C8	39.8	-	-
C9	40.1	-	-
C10	40.2	-	-
C11	39.5	-	-
C12	41.4	-	-
Mean Value	40.6	-	-
Std. Deviation	1.8	-	-
CV %	4.4	-	-

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

Material D	σ_{max}	% Bending	
		Midpoint	Failure
D1	61.9	-15.3	24.6
D2	64.1	-8.7	-23.1
D3	68.8	-7.9	-1.3
D4	64.8	-16.3	18.9
D5	64.4	-13.1	-5.9
D6	68.1	-	-
D7	65.3	-	-
D8	67.8	-	-
D9	69.6	-	-
D10	71.2	-	-
D11	70.0	-	-
D12	64.1	-	-
Mean Value	66.7	-	-
Std. Deviation	2.9	-	-
CV %	4.3	-	-

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

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

$$Bending[\%] = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \cdot 100 \tag{8}$$

where ε_1 and ε_2 are the longitudinal strains measured respectively by strain gauge 1 and 2 [2].
The percent bending, as calculated in eq. (8), provides a reasonable indication of Euler buckling. Failure and midpoint bending are reported in tables from 2 to 7 as requested by ASTM D 6641. The latter is determined at the midpoint of the strain range used for chord modulus calculations [2].

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	90.8	-	-
Std. Deviation	10.6	2.5	3.3	-	9.4	-	-
CV %	13.4	2.6	3.4	-	-	-	-

Table 6: Compressive test results of E samples (normalized results).

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	-	0.9	-	-
CV %	2.4	4.1	3.9	-	-	-	-

Table 7: Compressive test results of F samples (normalized results).

Tab. 8 shows the compressive strength of UD material calculated by means of classical lamination theory. The four back-out factors (2 for cross-ply and 2 for angle-ply), determined through Eq. (3) and (4), are:
- BF cross-ply A = 3.98
- BF cross-ply B = 2.22
- BF angle-ply C = 3.41
- BF angle-ply D = 2.04

The compressive stiffness (E_x and E_y) for BF determination were obtained averaging the mean values listed in Tab. 6 and 7. The 0° lamina compressive strength values obtained by Eq. (1) are reported in Tab. 8.

Sample ID Number	σ_{max} UD (A)	σ_{max} UD (B)	σ_{max} UD (C)	σ_{max} UD (D)
1	151.1	138.6	139.8	126.3
2	139.4	147.6	139.1	130.8
3	143.3	141.3	138.8	140.4
4	146.5	142.4	135.4	132.2
5	139.9	143.3	150.7	131.4
6	167.8	147.6	125.8	138.9
7	140.4	149.3	146.3	133.2
8	146.8	140.7	135.7	138.3
9	156.6	144.8	136.7	142.0
10	159.5	141.6	137.1	145.2
11	156.9	138.8	134.7	142.8
12	156.1	134.9	141.2	130.8
Mean Value	149.8	143.3	138.2	136.5
Std. Deviation	9.3	3.6	6.4	6.0
CV %	6.2	2.5	4.6	4.4

Table 8: UD lamina compressive strengths obtained through Back out Factor (normalized results)

Finally, the results of the mechanical characterization, in terms of mean values of compressive strength with their standard deviation, are summarized in Tab. 9. These values are in agreement with data reported in the datasheet of the prepreg material used for lamination.

Parameters	Experimental characterization results
0° Compressive Strength (cross-ply A)	149.8 ± 9.3
0° Compressive Strength (cross-ply B)	143.3 ± 3.6
0° Compressive Strength (angle-ply C)	138.2 ± 6.4
0° Compressive Strength (angle-ply D)	136.5 ± 6.0
0° Compressive Modulus	96.6 ± 4.1
90° Compressive Strength	20.7 ± 0.5
90° Compressive Modulus	5.0 ± 0.3

Table 9: Results summary: mean values and standard deviations of Compressive Strength and Modulus (normalized results).

The data reported in Tab. 9 show that the compressive strength of the 0° lamina is greater if the estimate is done by cross-ply specimens. The maximum difference between angle-ply and cross-ply is of about 10%.
In addition, the resistance values that agree better with those reported in the data sheet of prepreg, are those relating to cross-ply specimens.
Finally, the cross-ply lamination is simpler than that of the angle-ply and the expression of the BF is considerably simplified in the first case than in the second.
Then, the estimate of the 0° lamina strength, it's better by use of cross-ply specimens $[0°/90°]_{ns}$.
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. Fig. 1 shows, as expected, 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.

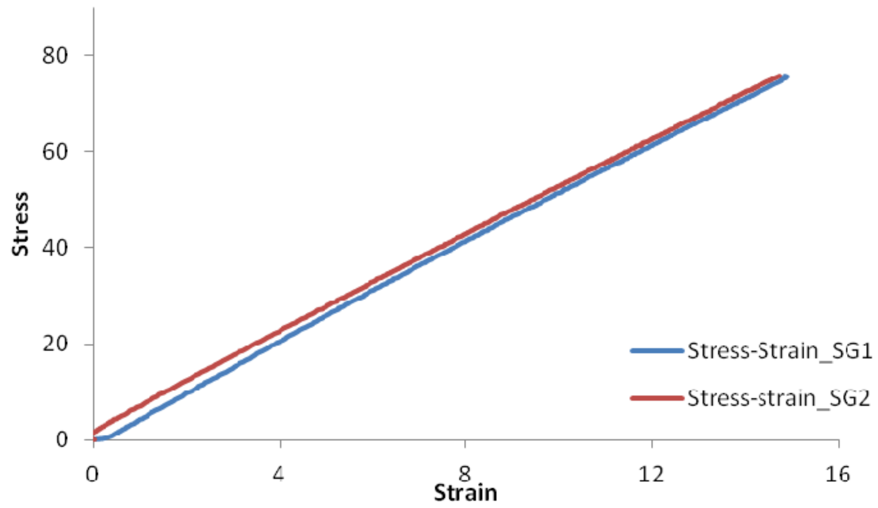

Figure 1: Stress-Strain curves of sample E5 (normalized results).

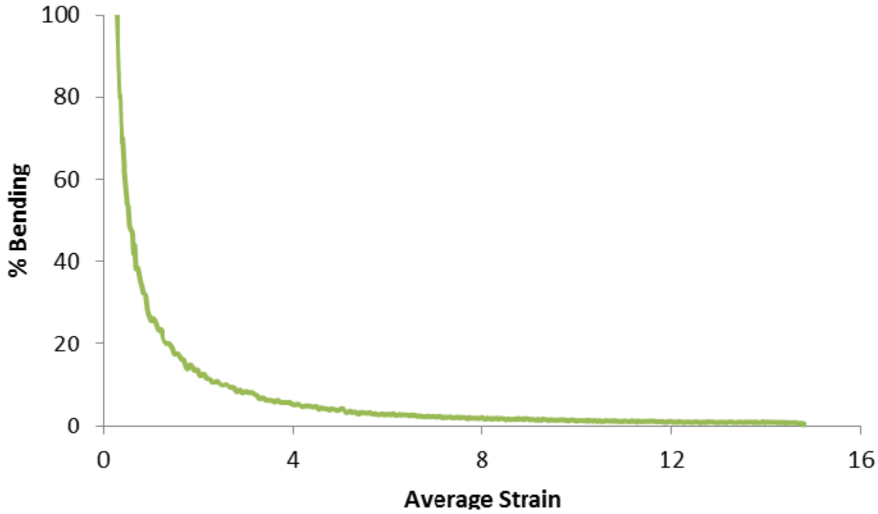

Figure 2: %Bending - Average Strain curve of sample E5 (normalized results).

The following Fig. 3 - 6 show some optical microscope photographs of the samples failure. Images 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 and angle-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].

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 – fig. 7 of [8]).

Low magnification Scanning Electron Microscope (SEM) images of the samples failure are shown in the Fig. 7 – 10. Images were taken by a SEM LEO 438-VP.

Fig. 7 and 8 clearly show the failure of a specimen taken from 0° UD laminate produced by micro-buckling of individual carbon fibres. In fact, Fig. 7 shows the kink-band reported in Fig. 5 - 6, while Fig. 8 details some bundles of fibres broken in buckling within the same kink-band of Fig. 7.

In Fig. 9 a cross-ply sample was photographed (lateral view of brooming failure); it is observable a 0° ply between two 90° plies. The effect of the presence of the 90° plies, which limits locally the buckling of the fibres in a sample subjected to compression, is highlighted by the absence of kink-bands throughout the sample. In Fig. 10 is visible a detail of compression failure of some 0° fibres bundles, within the same sample of Fig. 9.

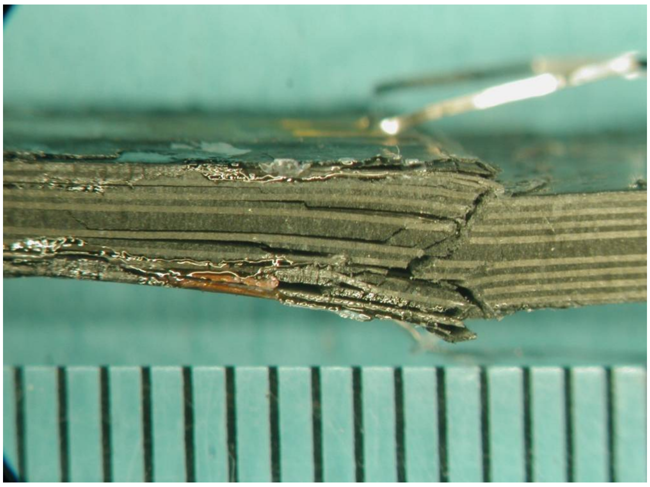

Figure 3: Optical microscope image of B4 sample gage section (lateral view).

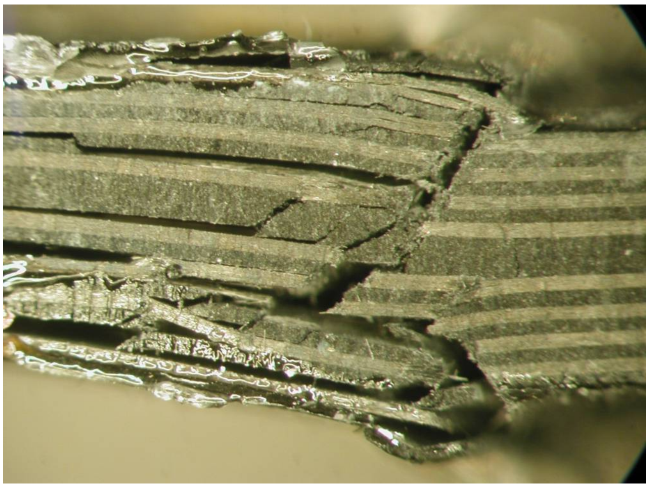

Figure 4: Optical microscope image (detail) of B4 sample gage section (lateral view)

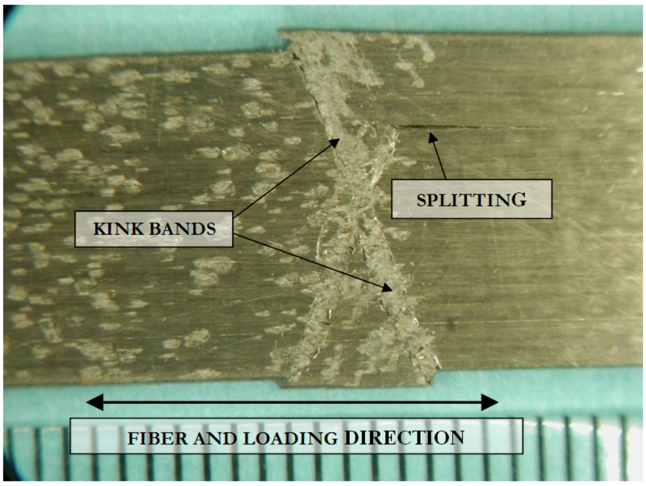

Figure 5: Optical microscope image of E13 sample gage section (front view).

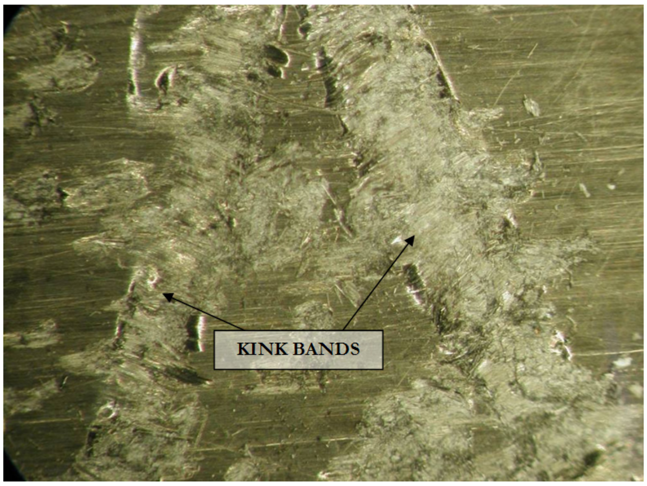

Figure 6: Optical microscope image (detail) of E13 sample gage section (front view).

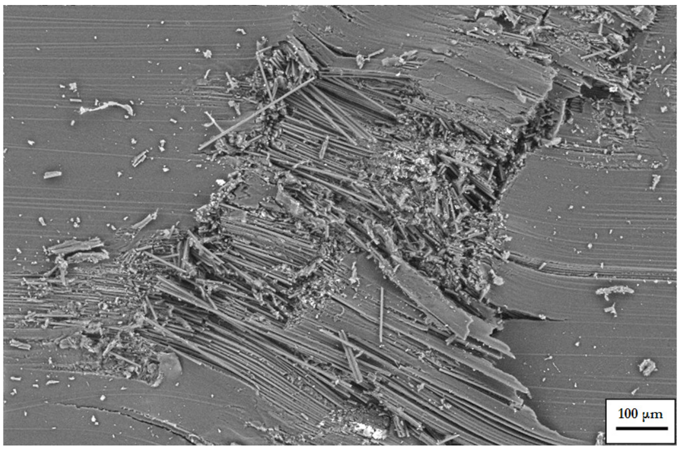

Figure 7: SEM image of E13 sample kink-band (front view).

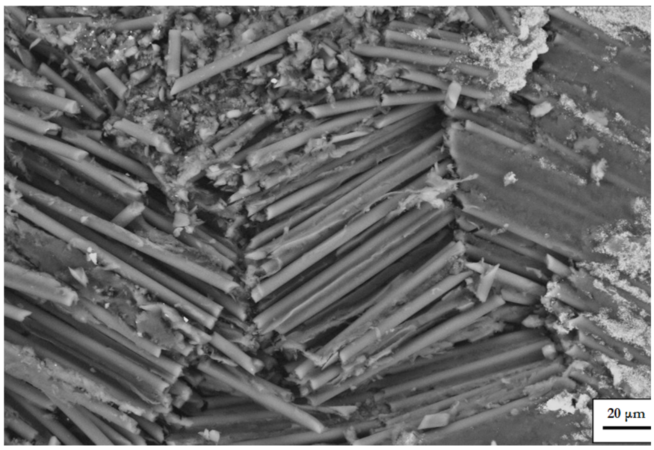

Figure 8: SEM image (detail) of E13 sample kink-band (front view).

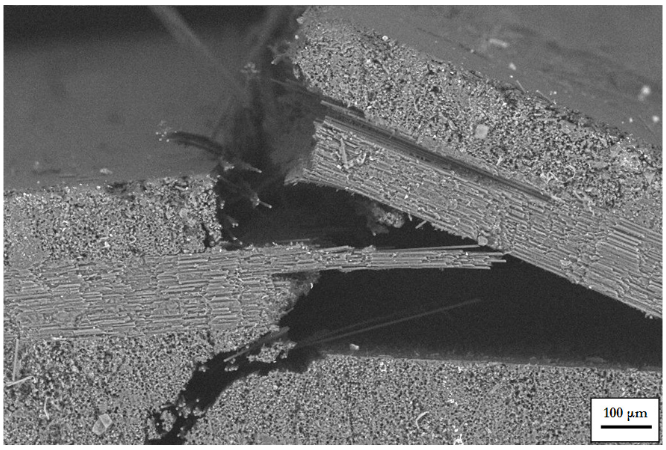

Figure 9: SEM image of A6 sample brooming failure (lateral view).

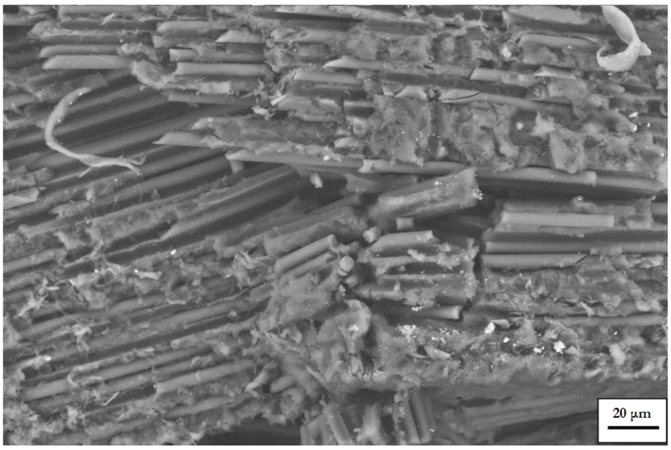

Figure 10: SEM image (detail) of A6 sample brooming failure (0° ply).

Conclusions

The present paper is aimed to study the unidirectional lamina compressive strength of a carbon/epoxy composite lamina by using two cross-ply and two angle-ply composite materials. The Combined Loading Compression Test Fixture (ASTM D 6641) was employed to execute the experimental tests.

The results showed that failure strengths determined by using cross-ply and angle-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 limited in the cross-ply and angle-ply samples. Furthermore the values of strengths, determined by linear lamination theory, are in agreement with those reported in the data sheet of the prepreg used to make our composite materials. In particular the maximum compressive strength was obtained for cross-ply composite with the minimum percentage of 0° plies 21.1 %, while the value specified in the data sheet is between those obtained for the two cross-ply samples. The strength coefficients of variation (CV%), associated with the materials A, B, C and D, were between 3% (B composite) and 6% (A composite). Considering the type of material examined, these are low levels of data scatter.

As previously mentioned, the compressive strength values obtained for the cross-ply composites agree better with those reported in the data sheet, compared to those obtained for the angle-ply composites. Also the cross-ply lamination is simpler than the angle-ply lamination and the BF equation is considerably simplified in the first case than in the second. Then, the estimate of the 0° lamina strength obtained by linear lamination theory, seems to be better for cross-ply specimens respect to angle-ply ones.

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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