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Experimental determination of thickness influence on compressive residual strength of impacted carbon/epoxy laminate

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Abstract

An experimental campaign was performed on 5.5 mm thick carbon/epoxy specimens and results were compared with data obtained in a previous work to understand thickness influence on material mechanical characteristics. In particular, this campaign consists of two different steps: impacts tests, performed by means of a modified Charpy pendulum, and Compression After Impact (CAI), using Wyoming Combined Loading Compression (CLC) test method. Impacts were performed on twenty cross-ply specimens with different energies and impact location. Other 5 specimens were tested only in compression. Non Destructive Inspections (NDI) by Ultrasonic Test (UT) were performed on impacted and pristine specimens, in order to understand damage size and correlate it with residual strength results. During CLC tests, compression strength and Young modulus values were acquired.

Keywords: CFRP; impacts; BVID; CLC; CAI; NDI; UT

Nomenclature

ASTM	American Society for Testing and Materials International
BVID	Barely Visible Impact Damage

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CAI	Compression After Impact
CI	Central Impact
CLC	Combined Loading Compression
NE	Near Edge
NDI	Non Destructive Inspection
PE	Pulse Echo
TT	True-Transmission
UD	Unidirectional
UT	Ultrasonic Tests

1. Introduction

In aeronautics, as well as in automotive, the most important aim of industries has always been making lighter and safer vehicles. This is the principal reason that sustained composites rise in these two fields. These materials have high strength-to-weight ratio but unfortunately their behaviour under operative conditions is still not completely known.

For automotive field, unknowns issues are not as delimitating as for aeronautical: applied safety factors are not as high as for aeronautical industry, where operative conditions are extreme. Moreover, all composite structures in aerospace vehicles have to satisfy the 'no-growth' principle [Composite Material Handbook (2012)]. This means that during static and dynamic tests (e.g. fatigue) a composite structure has not to show either damage initiation or growth of existing flaws.

Many factors could create damages in composite elements: hygro-thermal aging, lighting strikes, impacts, etc. Most of them are avoided by means of additional structure protections or prevention. On the other hand, impact occurrence is not predictable due to many possible causes: maintenance tools drop, debris, luggage loading, bird strikes, hail. It is, therefore, necessary to better understand composites response to impacts and their subsequent residual strength [Abrate (1994) & (1998)].

Hence, impact tests are performed at different level of airplane design, from coupon dimensions to panel or substructure. Tests are also conducted with different aims: at sample level they are usually done to understand material mechanical characteristics while, when they involve a real structure, principal aim is to check actual resistance, limit and ultimate load bearing capability.

Furthermore, depending on impact energy and velocity, resulting damages could be different. High specific energies conduct to evident defects that must be repaired; lower energies do not result in any clue on external surfaces but might create wide internal damages. The latter is the worst scenario: during inspections, first step is visual inspection; after this, if a damage is detected, more accurate NDI are used. Therefore, if surfaces do not show any external evidence of an internal damage, it would be possible to overlook something potentially dangerous. This kind of damages are known as BVID (Barely Visible Impact Damages).

In this contest, authors worked to better understanding carbon/epoxy laminate behaviour under BVID. First step results are reported in Falaschetti et al. (2015) where a thin carbon/epoxy laminate was tested under compression after low energies impacts to estimate their influence on mechanical strength. It was demonstrated that impacts quite badly influence the compressive strength. Moreover, impact position influences material strength over a certain energy level, defined as 'energy threshold' for that kind of geometry.

An experimental investigation, which could clarify material thickness effect on impact damages, has been performed.

2. Experimental

2.1. Specimens

Twenty-five specimens were cut from a carbon/epoxy laminate. This was made by means of hand-lay-up of 17 pre-preg unidirectional (UD) plies. Stacking sequence was chosen to obtain a symmetric balanced laminate: $[(90/0_2/$

$90)_2/\overline{0}]_s$. Specimens dimensions were chosen according to CLC (Combined Loading Compression) test fixture that was used to perform CAI (Compression After Impact) tests. Length is related to untabbed specimens and width to maximum dimension allowable in CLC fixture.

The average thickness is 5.5 mm, almost equal to double thickness of specimens tested in a previous experimental campaign (Falaschetti et al. (2015)). Hence, it was possible to compare results from both campaigns and understand thickness influence on composite impact resistance.

2.2. Impact tests

Twenty-five specimens were split in five groups characterised by different impact level and location, as described in the following Table 1:

Table 1. Impacts performed on specimens

Specimens' group	Impact Energy [J]	Location
Group A	No Impact	-
Group B	5	Near-Edge
Group C	7	Near-Edge
Group D	5	Central
Group E	7	Central

A modified Charpy pendulum was used to perform impacts: specimens position and impactor movement were studied to obtain a normal impact, comparable with Drop Weight impact tests [ASTM D7136].

Impactor is a steel cylinder with a hemispherical 7 mm diameter end.

Near-edge impacts were performed at 2.5 mm distance from specimens edge while central impact in the middle of their width, as shown in Figure 1. In both cases, impacts took place in the middle of length, for producing damages at the centre of CLC gauge section [ASTM D6641].

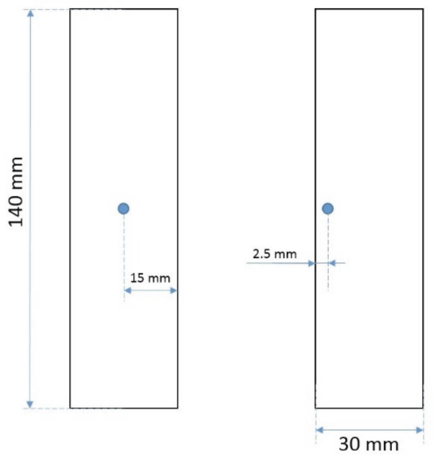


Fig. 1. impact locations: Central Impact on the left hand side, Near-Edge Impact on the right hand side.

Each impact test was filmed to be able to acquire actual mallet starting position and bounce angle, in order to evaluate real impact and residual energies.

Energies were calculated by means of (1):

$$E = mg(l - l\cos\alpha) \qquad (1)$$

where E is the energy, m is impactor mass, g is gravitational acceleration, l length of mass attachment and α angle (Figure 2).

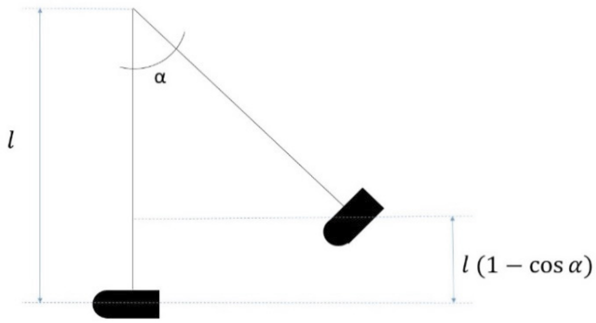


Fig. 2. Charpy pendulum scheme.

Each video was examined and energies were calculated (Table 2):

Table 2. Impacts energy values

Specimen	Actual Energy [J]	Residual Energy [J]	Absorbed Energy [J]
B1	5.3	2.2	3.1
B2	5.6	2.3	3.3
B3	5.3	2.2	3.1
B4	5.5	2.2	3.3
B5	5.7	2.2	3.5
C1	7.5	2.7	4.8
C2	7.5	2.8	4.7
C3	7.5	2.7	4.8
C4	7.3	2.7	4.6
C5	7.3	2.7	4.6
D1	5.4	1.2	4.2
D2	5.6	1.2	4.4
D3	5.6	1.1	4.5
D4	5.7	1.2	4.5
D5	5.7	1.3	4.4
E1	7.6	1.6	6.0
E2	7.6	1.6	6.0
E3	7.3	1.6	5.7
E4	7.5	1.6	5.9
E5	7.4	1.6	5.8

2.3. Non Destructive Inspections

Specimens were inspected visually and by means of NDI, in particular of UT (Ultrasonic Tests).

Visual inspection of impacted specimens was performed to check if impact energy values were enough to create a BVID. In fact, impact energies were chosen according to continue previous work on barely visible damages influence on composite compressive resistance (Falaschetti et al. (2015)). Preliminary impact tests were conducted to individuate energies that could result in a BVID. In facts, due to higher thickness it was not possible to assume the energy values of previous work (3 J and 5 J). Performing few tests, it was possible to indicate 5 J and 7 J as the lowest range of energy values that create damages on 5.5 mm thick specimens.

Ultrasonic tests, moreover, were conducted on impacted and pristine materials in order to individuate internal damages. Two different UT techniques were used: True-Transmission and Pulse-Echo.

True-transmission (TT) technique consists of two probes, one transmitting and the other one acquiring ultrasonic signals, while specimen is in the middle. If discontinuities are inside specimen, signal attenuation is measured.

Second methodology, Pulse-Echo (PE), consists of only one probe transmitting and acquiring ultrasonic signal, which passes twice through coupon thickness. Both coupon and probe are put inside water that allows signal transmission. Discontinuities are detected due to electric signal amplitude changes. The resolution of both scans was 1mm.

Only 7 J near edge impact on specimen C1 was quite clear with TT technique (Figure 3) while all other damages were rather blended with porosity or boundary effects.

Instead, by means of the PE technique, internal damages were clearer in all impacted specimens, as shown in Figure 4.

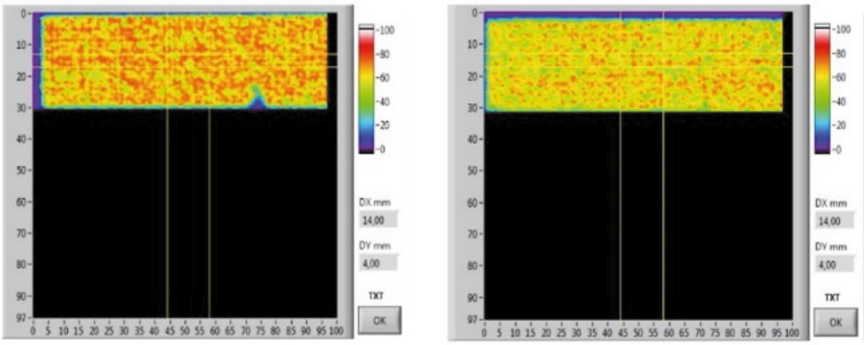


Fig. 3. C-scan specimen C1 (7 J NE) on the left, specimen B5 (5 J NE).

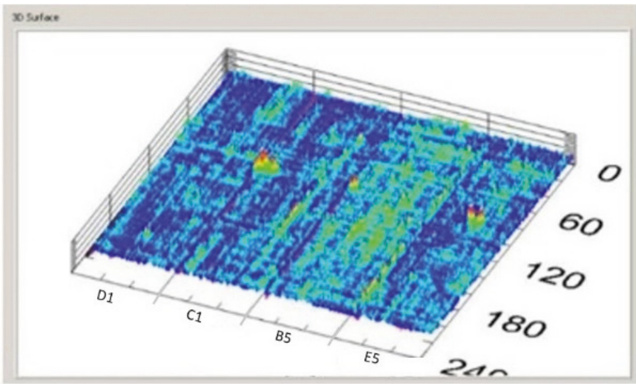


Fig. 4. 3D scan impacted specimens (from the left D1, C1, B5, E5).

Full A-Scan at 0.55 mm depth from the impacted surface is shown in Figure 5b: clear damages are noticed with wider damage for the near-edge impacted coupons. Central impacted specimens, on the contrary, show more localized effects.

This depth could be referred as an interlaminar interface and, therefore, the damage is more evident than at a different depth (e.g. 0.2 mm as shown in Figure 4a).

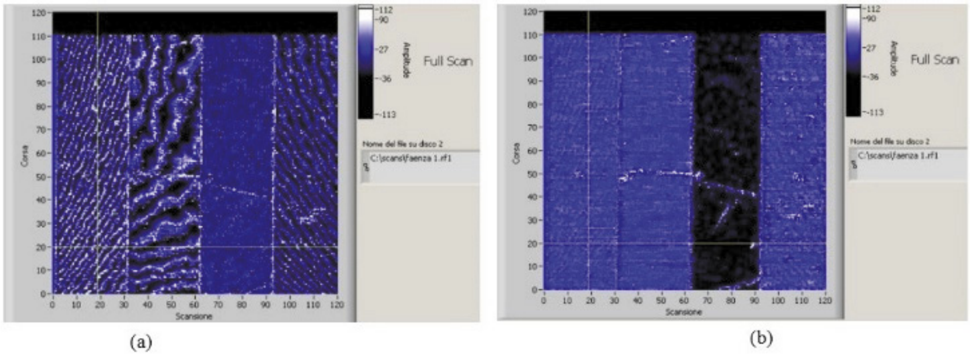


Fig. 5. Full Scan impacted specimen (from the left D1, C1, B5, E5) (a) at 0.2 mm and (b) at 0.55 mm depth

2.4. Compression After Impact tests

CAI tests were performed by means of a CLC test fixture, described in Falaschetti et al. (2015), Wegner et al. (2000), Scafé et al. (2013) & (2014).

Tests were performed at room temperature and humidity, using 70 and 500 kN MTS electro-hydraulic testing machines, equipped respectively with MTS 100 and 500 kN load cells. All experimental tests were conducted in displacement control with a constant rate of 1.3 mm/min and data were acquired at 10 sample/s rate.

Residual compressive strength was calculated considering specimen cross section and ultimate load (Table 3-7).

Due to not satisfactory failure mode, some specimens test results were not taken into account; therefore, due to their unreliability, those data are not presented.

Table 3. Compression results for non-impacted specimens

Specimen	Cross sectional area [mm^2]	Maximum load [N]	σ_{max} [MPa]
A1	162.5	70708	435.14
A2	168.5	81107	481.34
A3	164.7	80815	490.66
A4	164.5	76958	467.71
		σ_{mean}[MPa]	468.71
		Sd. Dev [MPa]	24.29
		CV [%]	5

Table 4. Compression results for 5J near-edge impacted specimens

Specimen	Cross sectional area [mm^2]	Maximum load [N]	σ_{max} [MPa]
B1	168.0	73429	437.08
B2	168.9	71656	424.14
B3	168.8	75856	449.43
B4	166.0	78094	470.49
B5	168.7	75753	449.16
		σ_{mean}[MPa]	446.06
		Sd. Dev [MPa]	17.17
		CV [%]	4

Table 5. Compression results for 7J near-edge impacted specimens

Specimen	Cross sectional area [mm^2]	Maximum load [N]	σ_{max} [MPa]
C1	167.9	73032.82	435.00
C3	169.4	74375.72	439.11
C4	167.9	79110.28	471.15
C5	168.3	81623.90	484.93
		σ_{mean}[MPa]	457.55
		Sd. Dev [MPa]	24.38
		CV [%]	5

Table 6. Compression results for 5J central impacted specimens

Specimen	Cross sectional area [mm^2]	Maximum load [N]	σ_{max} [MPa]
D4	167.1	85308	510.63
		σ_{mean}[MPa]	510.63
		Sd. Dev [MPa]	-
		CV [%]	-

Table 7. Compression results for 7J central impacted specimens

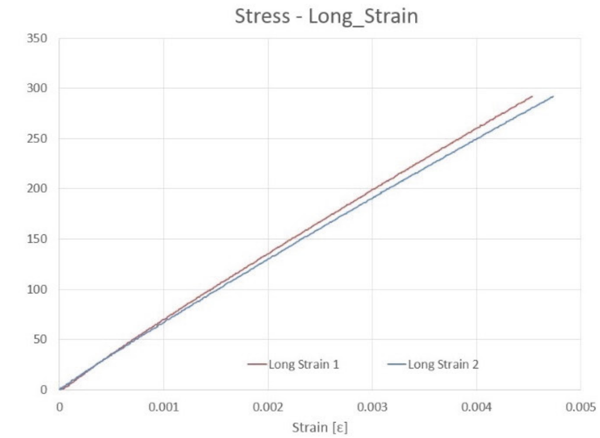
Specimen	Cross sectional area [mm^2]	Maximum load [N]	σ_{max} [MPa]
E1	164.3	80677	490.93
E2	164.6	85997	522.47
E5	162.7	79473	482.29
		σ_{mean}[MPa]	498.57
		Sd. Dev [MPa]	21.15
		CV [%]	4

Two specimens per group were instrumented with strain gauges: one coupon with two longitudinal strain gauges, the other with a longitudinal and a bidirectional strain gauges (D and E specimens were instrumented with only one strain gauge, one longitudinal and one bidirectional, due to impact indentation presence in the middle of gauge section). The latter were in back-to-back configuration in order to check specimen buckling occurrence. A Wheatstone bridge with a half-bridge configuration was used for strain measurements.

Results are shown in the following table: Young and Poisson moduli were obtained by means of Chord method, as required in [ASTM D6641]. Figure 6 shows a typical trend for specimens deformation, acquired during this experimental campaign.

Table 8. Compressive Young and Poisson moduli

Specimens Group	E_{mean} [GPa]	υ
A	63.40	0.05
B	62.12	0.05
C	62.51	0.07
D	63.11	0.03
E	65.45	0.04



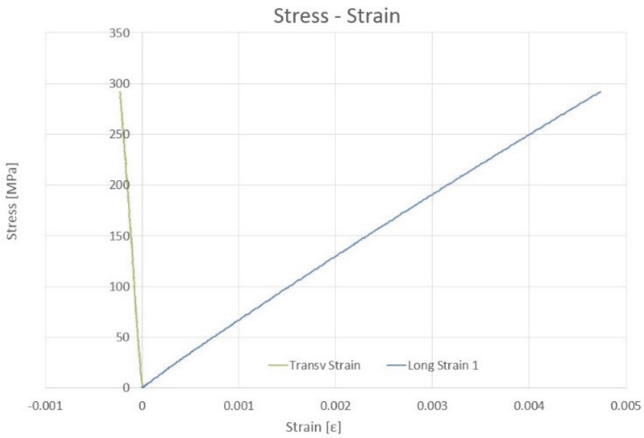


Fig. 6. Strain-gauges acquired data example: on the left longitudinal strains acquired from both surfaces of specimen A5; on the right A5 longitudinal and transversal deformation acquired from bidirectional strain-gauge.

2.5. Results and discussion

Looking at compression tests mean values for 5.5 mm thick specimens (Table 9), there is not a clear evidence of impact energy and location influence on residual strength. The compressive strength for centrally impacted specimens is higher than pristine coupons, while a lower compressive strength has been obtain for near-edge impacted coupons.

Table 9. Compression mean values

Specimen	Impact kind	σ_{mean} [MPa]	Sd. Dev [MPa]
A	No Impact	468.71	24.29
B	5 J near-edge	446.06	17.17
C	7 J near-edge	457.55	24.38
D	5 J central	510.63	-
E	7 J central	498.57	21.15

This decrease is quite small but still can be evaluated as an impact effect, as shown by the analysis of failure modes. During compression tests, almost all near-edged impacted specimen resulted in an acceptable failure mode (at gauge sections), while pristine and central impacted specimen groups had more unreliable failures (edge failure or between grip surfaces). This shows that a near-edge impact creates a low resistance area that acts as a trigger for failure.

Data scatter does not permit a correlation between impact damage dimensions (acquired by NDI) and compressive strength, but it is possible to underline that, in case of 5.5 mm thick specimens, damages coming from low energy (5 and 7 J) impacts are not as dangerous as for thinner structures (see [4]). This is clear comparing 5 J near-edge impact results of the two experimental campaigns (Table 10): in the present study, for 5.5 mm thick specimens, a 5J near-edge impact resulted in a 4.8% reduction of compressive residual strength, while for 2.6 mm thick specimens, it produced a 31.2% drop. This value is quite high and shows an objective influence of the low energy level of impact on residual strength for the 2.6 mm thick laminate.

Table 10: 5 J near-edge impact test results: comparison with [4]

Specimens mean thickness	σ_{mean} [MPa] No impact material	σ_{mean} [MPa] 5 J NE impact material	$\Delta\sigma_{mean}$ [%]
2.6 mm	386.3	265.4	31.2
5.5 mm	468.7	446.1	4.8

Conclusions

An experimental campaign regarding low energy impacts on CFRP has been conducted: 5 J and 7 J near-edge and central impacts were performed on 5.5 mm thick specimens, obtaining Barely Visible Impact Damages (BVID). Pristine and impacted specimens were, then, tested by compression to measure compression after impact strength.

BVID represents one of the most dangerous damage that an aeronautic structure could face and, therefore, it needs a detailed study. In a previous experimental campaign [Falaschetti et al. (2015)], 2.6 mm thick specimens were tested to prove impact location influence on laminate compressive residual strength.

Comparing results of the current campaign with the previous [Falaschetti et al. (2015)], it was seen that, while for thin specimens impact location and energy are really affective on residual compressive strength, thick specimen tests did not show clearly this effect. A small drop in residual strength appears only for near-edge impacted specimens groups while central impacted ones do not show any decrease.

Strength reductions obtained in the present experimental campaign (2.4% for 7 J NE and 4.8% for 5 J NE impacts) could be, therefore, ascribed to secondary factors, as: manual lay-up process, curing process, cutting process, etc. Hence, while for thin laminate impact energies used were clearly over a threshold that creates an influencing damage, 5 J and 7 J impacts were not enough to create a damage that could overwhelm usual composite data scatter, showing a clear influence on residual compressive strength.

Summarising, low energy impact location does not affect compressive residual strength of thick specimens (5.5 mm), as certainly as for thinner specimens (2.6 mm); but it was undoubtedly demonstrated that a low energy near-edge impact can result in a trigger for damage growth, even for thick specimens, creating a weak spot in the structure and, therefore, a stress concentration point.

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