# AN EXPERIMENTAL INVESTIGATION OF LAMINATED FIBER-REINFORCED COMPOSITES UNDER SHEAR-AFTER-IMPACT CONDITIONS

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**Abstract.** *This work presents an experimental analysis of fiber-reinforced laminated composites under shear-after-impact loadings. Carbon-epoxy laminates are manufactured by hand lay-up process and material characterization of the specimens is performed. For the shear in-plane behavior, a rail test apparatus in accordance with the ASTM D4255 standard is used. Low-energy drop-weight face-on impact tests are performed in a drop-tower machine under the barely visible impact damage limit to introduce damage in the material. The shear-after-impact test is executed in the same rail apparatus for unidirectional stackings to evaluate essential characteristics of the phenomenon since scarce data of this approach is available in the literature.*

## 1. INTRODUCTION

Laminated composites usually do not possess significant transverse strength being susceptible to be severely damaged after an impact event [1]. For an aircraft, damage caused by this kind of loading can arise from numerous ways such as tool dropping during maintenance or manufacturing processes, flying debris from take-off and landing procedures, bird strike, collision with another vehicle, among others. The first example usually belongs to the category of low-velocity impacts (LVI). Although many authors classify LVI in such a manner it is important to highlight that this classification depends on several features besides its velocity, e.g., geometry of the impactor and constitution of the target. Thus, it is preferable and more accurate classifying it as low-energy impact (LEI) although it still lacks information about the phenomena. Generally, LEI causes minimal superficial damage in composite laminates. However, it can cause severe internal damage or even failure of the structure (which highly influences its residual strength) that cannot be detected by naked eye. The damage caused by this type of impact event is usually classified as barely visible impact damage (BVID) and because of the mentioned characteristics can remain undetectable being possibly harmful to the aircraft performance and even human life.

Several studies available in the literature appoints for quite reduction of compression strength of these structures on such events [2]. Furthermore, there are certain studies accounting for the flexural strength after impact [3] but only a few considering the shear-after impact (SAI) resistance of such laminates [4] under BVID conditions. In this context, it is important to study the SAI behavior of these structures since that once in operation, they are subjected to combined stress states which in many cases includes shear.

Thus, this work arises due to the lack of experimental studies in the subject aiming to perform initial investigations about the phenomenon. For shear characterization the ASTM D4255 standard [5] is used as basis for 3-rail tests. Adaptation of specimen dimensions is made so it can also be used for LEI experiments following the procedure presented by the ASTM D7136 standard [6] (also known as Boeing standard) for face-on impact tests. In this paper, carbon fiber-reinforced polymer (CFRP) coupons are tested for an initial understanding of its behavior under SAI loadings. A usual stacking sequence of $[0]_{16T}$ is used. All material characterization experiments for in-plane properties employs digital image correlation (DIC) technique to capture displacement of specimens during the tests. At the end of this paper, a novel experimental guideline for SAI testing based on the aforementioned standards is proposed.

## 2. MATERIALS AND METHODS

The laminated composite plates used in this work for material characterization, impact and post-impact tests were all manufactured from a pre-impregnated (with epoxy resin system) unidirectional (UD) carbon fiber fabric from Texiglass Industry and Textile Commerce with nominal areal weight of 208 g/m² and 0.29 mm of nominal thickness. Also, it was employed the hand-layup technique inside a vacuum bag with the aid of an oven for controlled heat input since it is a widely used method for composite manufacture being considered a relatively reliable and very cost benefit technique.

### 2.1. Fiber and matrix contents

Measurement of fiber $V_f$ and matrix $V_m$ volume fractions in three coupons is performed in accordance with the ASTM D3529 standard [7] (Procedure B). For these, the specimens are exposed to air at 500 ºC during a period of three hours inside an oven with 5 ºC/min of heating rate. The obtained results are depicted in Tab. 1.

Table 1 – Fiber and matrix volume fractions results.

| Property | Unit | Value | Procedure |
|---|---|---|---|
| Mean matrix volume fraction | n/a | 0.359 | ASTM D3529 |
| Mean fiber volume fraction | —"— | 0.641 | —"— |
| Reinforcement density | g/cc | 1.9 | Manufacturer data |
| Matrix density | —"— | 1.3 | —"— |

### 2.2. Monotonic quasi-static material characterization tests

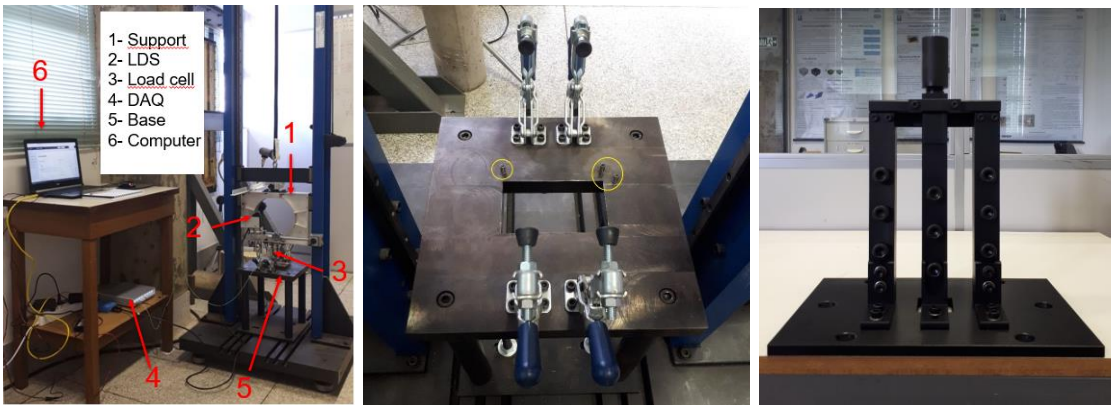
A test campaign for material characterization is performed following the adequate standards [8,9] and the DIC technique that can replace other displacement/strain data acquiring methods [10]. In this context, tensile tests for longitudinal, transverse and shear properties of the CFRP are performed in specimens with $[0°]_{8T}$, $[90°]_{8T}$ and $[\pm 45°]_{8s}$ stacking sequences, respectively. The obtained results are listed in Tab. 2.

Table 2 – Carbon fiber composite in-plane mechanical properties.

| Elastic properties [GPa] | | Strength values [MPa] | |
|---|---|---|---|
| $E_{11}$ | 122.33 | $X_T$ | 1404.08 |
| $E_{22}$ | 6.78 | $Y_T$ | 21.55 |
| $G_{12}$ | 3.47 | $S_{12}$ | 37.71 |
| $\nu_{12}$* | 0.287 | $S_{13}$ | —"— |

### 2.3. Drop-weight apparatus and specimen adaptation for SAI

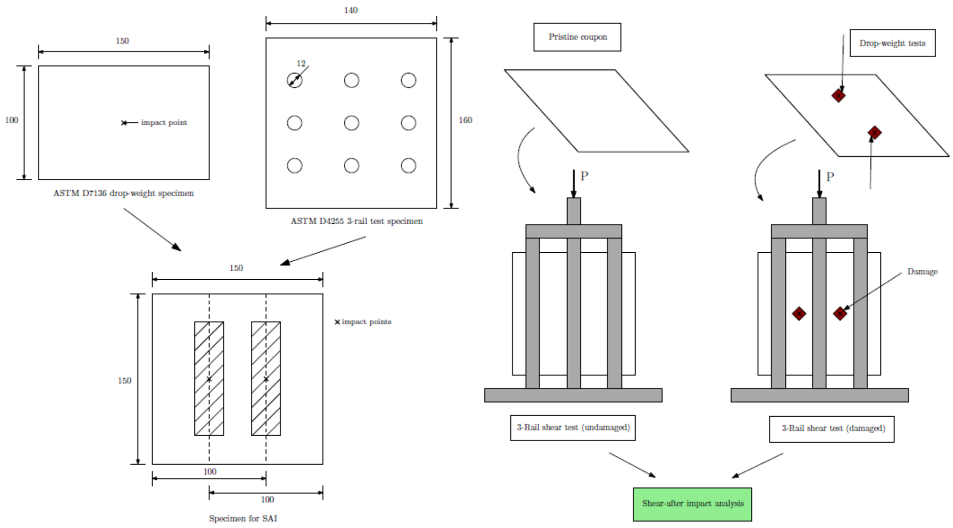
The ASTM D7136 standard specifies a rectangular specimen to be impacted by a hemispherical aluminum indenter, the prior being fixed by four toggle clamps attached to an inertial base. The complete drop-weight system or, simply, drop-tower and the rail test apparatus are shown in Fig. 1.




(a) (b) (c)

Figure 1 – Drop-tower complete system (a); inertial base detail (b);
3-rail apparatus for shear/SAI testing (c).

In Fig. 1(a) the support is used to attach the impactor with the piezoelectric load cell from Kistler and to set the test height. The transducer is capable to measure compression forces at the z-direction under the dynamic conditions of an impact test. Displacement measurement is carried out by a Laser Distance Sensor (LDS) from MEL Intelligent Sensors & Measuring Systems that is capable of capturing length variation with high precision in impact events during short amounts of time. Both the load cell and LDS are connected to a charge amplifier/data acquisition unit (DAQ - LabAmp 5156A) from Kistler that in its turn is connected to a personal computer. It can be noted in Fig. 1(b) that the base contains three guiding pins that are positioned to restrict the specimen movement in the x-y plane during tests. On the other hand, these pins tie the specimen size, since the impact needs to be performed at the center of the coupon. Moreover, since rail tests are going to be further performed using the apparatus in Fig. 1(c), a new specimen satisfying both impact and rail tests dimensions is proposed as depicted in Fig. 2.




(a) (b)

Figure 2 – Proposed specimen for SAI (a); summary for SAI analysis (b).

As presented, the SAI coupon is a square plate that can be impacted in two points. In Fig. 2(a), the dashed lines represent the limits of two overlapping impact specimens and as can be noticed, the impact points of the SAI coupon coincide with the ones of the two impact specimens. Also, the hatched regions are the free areas where the DIC technique is carried out for strain field assessment. As usual, the new specimen is fixed by the toggle clamps in the drop-tower basis and a drop test is conducted.

After it, the laminate plate is turned upside-down and is rotated so that another drop test is made. Thus, two identical impacts are done in the same plate introducing damage. Then, rail tests in pristine and damaged coupons are carried out for comparison as shown in the scheme in Fig. 2(b).

## 3. EXPERIMENTAL TESTS RESULTS

Two CFRP plates with $[0°]_{16T}$ layups are chosen to be subjected under the SAI procedure. The plates possess 150x150x3.0 mm dimensions drilled with nine 10.0 mm diameter holes weighting 95.8g.

### 3.1. Drop-weight tests

The drop-weight characteristics and parameters selected for the impact tests are listed in Tab. 3 while Fig. 3 shows the results compendium of the two drop tests embodying the force, displacement and energy histories and the force-displacement curves of the events.

Table 3 – Drop test parameters for the $[\mathbf{0}]_{\mathbf{16}}$ laminates.

| **Impactor mass [kg]** | **Test height [m]** | **Initial velocity [m/s]** | **Total impact energy [J]** | **Impactor radius [mm]** |
|---|---|---|---|---|
| 4.826 | 0.117 | 1.51 | 5.53 | 8.0 |
| **Impactor material** | | | | Aluminum |
| **Plate thickness [mm]** | | | | 3.0 |

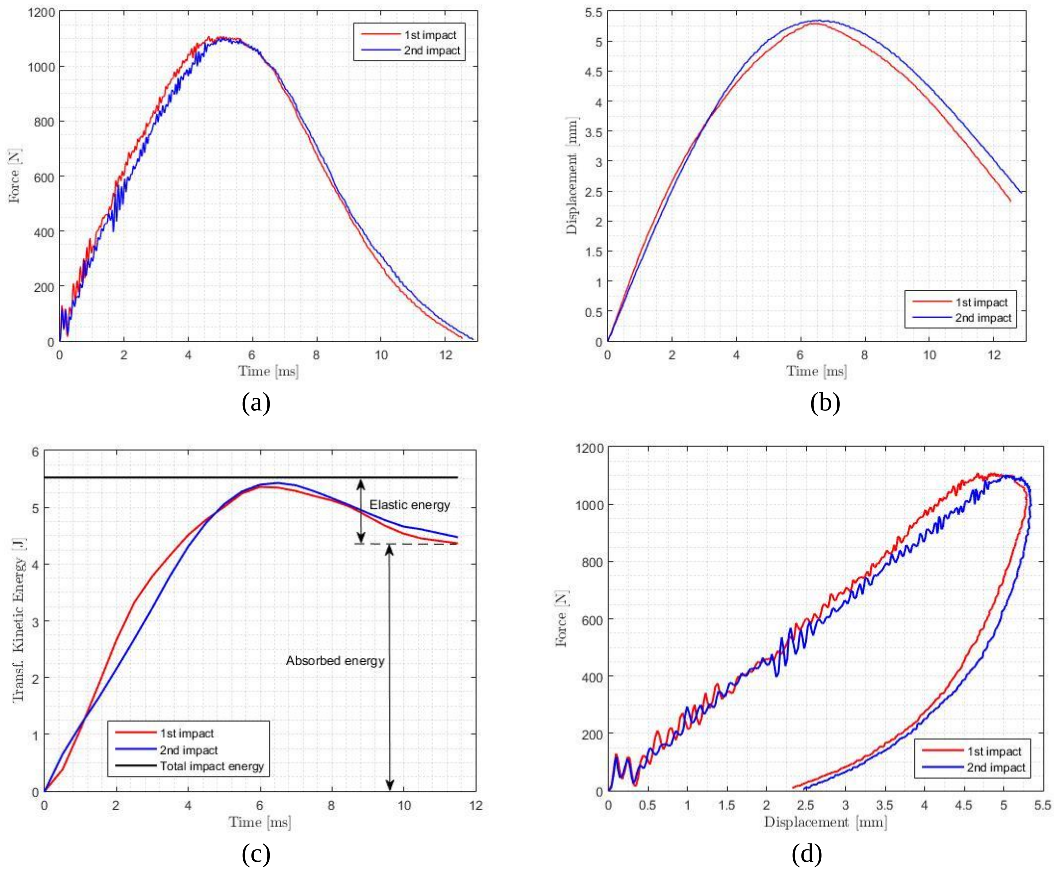



Figure 3 – Impact force (a), displacement (b) and energy (c) histories; force-displacement curves (d).

It can be noticed some high-frequency oscillations at the initial part of both curves in Fig. 3(a) up to approximately 1 ms due to the accommodation of the impactor with the target. The further oscillations observed in the first part of both curves occurs due to the introduction of damage by the impact event. Also, as expected, the damage from the second impact is slightly greater than the one from the first impact. This behavior is observed in Figs. 3(b) and (c) as well since the maximum displacement of the impactor is also slightly greater in the second impact regarding with the first one. The introduction of damage also implies in a greater impact duration (second event) since the plate will need to dissipate more of the transferred kinetic energy. Still, the dissipation phenomenon is also verified by the positive shift in every curve (from the second impact with relation to the first one) all after the introduction of damage in the second impact event that occurs mainly between 1.5~2.2 ms and further oscillations are due to crack propagation through the plate. Lastly, permanent indentation is accused analyzing Fig. 3(c) but since the displacement is measured with respect to the impactor and not to the plate directly these residual displacements are only approximations of the real values. Nevertheless, it is noticed a greater value for permanent indentation in the second impact which was expected to occur. Table 4 sums up the obtained results of the two impact events.

Table 4 – CFRP drop tests summary.

| **Physical quantity** | **1st impact** | **2nd impact** |
|---|---|---|
| Impact duration [ms] | 12.54 | 12.88 |
| Peak force [N] | 1108.32 | 1102.06 |
| Maximum displacement [mm] | 5.29 | 5.35 |
| Indentation [mm] | 2.32 | 2.46 |
| Elastic energy [J] | 1.16 | 1.05 |
| Absorbed energy [J] | 4.37 | 4.48 |

## 3.2. Rail and shear-after-impact tests

Both pristine and damaged plates were subjected to a 3-rail shear test following the ASTM D4255 standard procedure where the applied load in the central rail by the INSTRON universal testing machine was of compression with a constant head displacement of 2.0 mm/min. Figure 4 shows the shear stress-strain obtained curves for both plates, compared with the experimental average curve of the $[\pm 45°]_{8s}$ coupons used to raise the shear properties data.

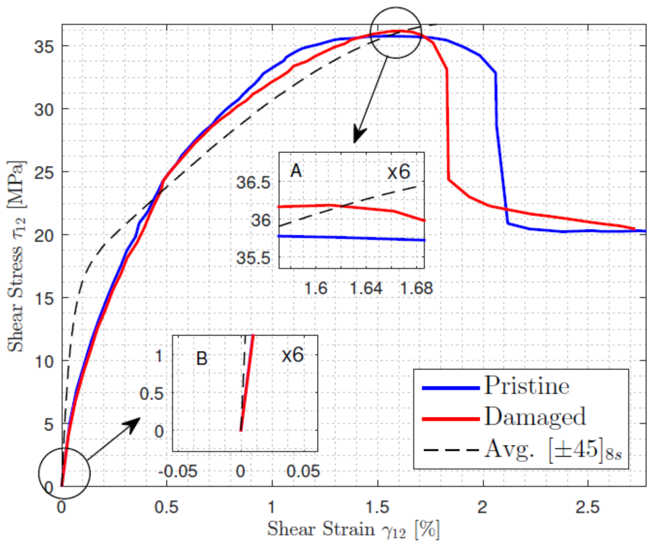



Figure 4 – Shear stress-strain curves: pristine/damaged rail test and $\pm 45°$ angle-ply coupons.

It can be noticed from Fig. 4 that the damaged laminate possesses no significant reduction in stiffness then the pristine one. This is a consequence of the employed impact energy level considering both the laminates' geometrical and physical characteristics. Since the impact occurs on unidirectional thin laminates, it is observed that the bending stresses in the bottom of the plate introduce matrix cracks firstly at the non-impacted side of the coupon, which is in accordance with the expected [1]. Moreover, the unique noticeable difference between both pristine and damaged coupons is that the last presents a premature failure regarding to the ultimate shear strain, which is 1.66% while for the prior is 1.83% at approximately the same level of shear stress. Then, both coupons are capable of supporting further load application with the pristine one presenting a broader interval before fracture. Also, it is worth to mention that both curves for rail tests have similar characteristics with the one for the $[\pm 45°]_{8s}$ coupons. Since only one rail test for each was performed, there is no significant statistical volume of data for definitive conclusions. Yet, it is notable that the rail tests resulted in a more non-linear behavior of the material compared with the bi-linear tendency of the angle-ply one. Also, as observed in Fig. 4, maybe tensile testing in 45º angle-ply laminates can provide similar levels of ultimate shear strain as UD laminates with BVID under rail test for similar ultimate shear stress levels as well.

Regarding to qualitatively results, Figure 5 shows up both pristine and impacted coupons after the rail tests.

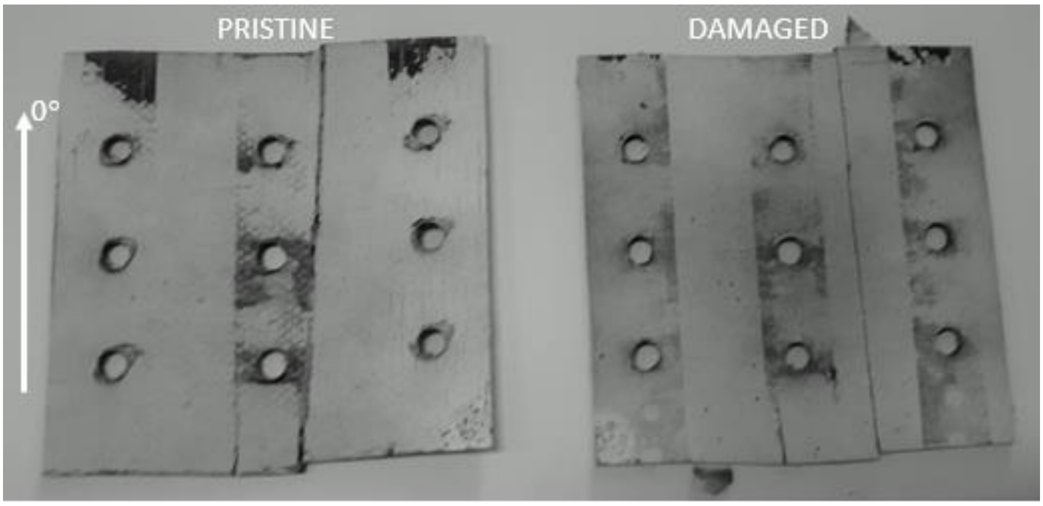



Figure 5 – Pristine (left) and impacted (right) plates after 3-rail testing.

It can be observed that the both coupons failed with cracks growing at the fibers' direction, parallel to load application. Also, crack onset occurs nearby the moving rail for the intact specimen while for the impacted one it is observed the growth of the already existing cracks from impact damage. In time, it is worthy to mention that the performed impacts are large mass ones, as classified by Olsson [11], which for our purposes fulfills the LEI requirements. Moreover, no noticeable undesirable effects like screw bearing, laminate local/global buckling and stress concentration at the holes were observed during both tests and a simple shear state is noted during DIC data treatment, as desired.

## 4. CONCLUSIONS

In this study, the impact and post-impact behavior of carbon-fiber reinforced composite plates with $[0]_{16T}$ layup under the barely visible impact damage limit or, simply, low-energy impact, was experimentally assessed considering for the post-impact event a simple shear state. For this, a new specimen that fits both drop-weight and 3-rail tests is proposed and the experiments follows a straightforward procedure of analysis. Some key aspects are noticed during the impact events that introduce damage in the coupon, that are: 1) the time duration of the 2nd impact increases as a consequence of the necessity of dissipate more of the transferred kinetic energy culminating in a positive shift in all force/displacement curves; 2) damage introduction due to the 2nd impact event is slightly more severe; 3) permanent indentation grows for the 2nd impact even though the obtained experimental value is only an approximation of the real one. Regarding to the shear-after-impact analysis, more experiments need to be made. Since only one set of two plates are used for comparison using the proposed methodology for SAI, some tendencies should be observed but this can only be used as a basis for further testing. Nevertheless, both the pristine and impacted coupons show remarkable similarity in their stress-strain curves, with the second presenting approximately the same ultimate shear stress and strain values as compared with the 45° angle-ply specimens which can imply that the last ones can underestimate these values. Also, a highly non-linear behavior is noticed for the rail test results compared with the bi-linear trending of the angle-ply laminates. As expected, failure occurs at the already existing crack due to its growth in the fiber direction for the damaged plate, in which two low-energy impacts in the BVID range are performed as for the pristine one, crack onset and propagation occur at the neighborhood of the central rail. Lastly, the DIC technique was fully capable of capturing the desired simple shear state, indicating that the rail apparatus and the analysis procedure are promising in being used as tools for residual shear strength assessment.

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