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Effect of impact speed and friction on the in-plane crashworthiness of composite plates

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Abstract

The effectiveness of composite materials in crashworthiness applications is well-known in the literature. In most cases, the Specific Energy Absorption (SEA) of composite structures is higher than that of metallic structures, but at present there is no standard available to characterize their crash behavior. A new fixture to test flat composite samples in in-plane impact conditions has been used to investigate the effect of the impact speed and of the friction on the SEA of carbon fiber/epoxy flat plates. Tests have been carried out in impact conditions. The effect of the friction has been studied varying the clamping force given by the fixture. The force-displacement curves have been acquired in all tests and used to calculate the SEA of the material. The tested specimens have shown a splaying failure mode and values of SEA that increase with the clamping force given by the testing fixture.

Keywords: *Crashworthiness; Specific energy absorption; Impact testing*

1. Introduction

It is well-known in the literature (e.g. Lukaszewicz (2013)) that composite materials are effective for crashworthiness applications thanks to their good energy absorption during crash combined with the low weight, that make them more efficient than metals in this field. Several studies have been carried out in the past decades to

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understand the behavior of composite materials during crash and to compare different materials. Even though at present a wide literature on crash mechanisms (Thornton (1979); Farley and Jones (1989); Hull (1991)) and design of energy-absorbing elements (Bisagni et al. (2005); Heimbs and Strobl (2009); Dalli et al. (2020); Obradovic, Boria, and Belingardi (2012); Lescheticky, Barnes, and Schrank (2013)) is available, comparing different studies is a hard task because of the absence of a standard for testing composite materials in crash conditions (Feraboli, Deleo, and Garattoni (2007)).

The idea of using tests that have been carried out on flat specimens as a standard for the evaluation of the crash behavior of different materials was first proposed by Lavoie and Morton (1993). A flat specimen is low cost and easy to manufacture but has some drawbacks: the testing equipment requires a fixture to avoid the buckling of the specimens and the results obtained by Lavoie and Morton showed a crash force rather higher than that obtained with other specimen shapes. This issue was addressed by several researchers that proposed different solutions and obtained better results, like Feraboli (2009), the company Engenuity (Lescheticky, Barnes, and Schrank (2013)) and others (Israr et al. (2014); Cauchi Savona and Hogg (2006)).

None of the cited testing fixtures is today recognized as a standard setup for testing the crashworthiness of composite materials, even if the achieved results are in some cases good. To further develop the idea of carrying out crash tests on flat coupons, a new fixture has been designed within a collaboration between Politecnico di Torino and the companies Instron and CRF (Babaei et al. (2020); Vigna et al. (2021)), and it is used to study the effect of two parameters on the energy absorption of composite materials: the friction between the specimen and the anti-buckling fixture and the crash velocity.

Nomenclature

CFRP	carbon fiber reinforced polymer
SEA	specific energy absorption (kJ/kg)
E	energy absorption during crash (J)
ρ	material density (kg/dm^3)
A	cross section of the specimen (mm^2)
δ	displacement of the impactor during crash (mm)
α	fracture angle (°)
k	slope of the regression line (kJ/(kg°))

2. Materials and methods

2.1. Specimen

The material chosen for this study is a carbon fiber reinforced polymer (CFRP) composite laminate. The laminate consists of four pre-impregnated layers of Microtex GG630 carbon fiber twill fabric coated with E3-150 high toughness epoxy resin (resin content is 37% in volume). The layup direction is 0°/90° for all the layers. The layup and autoclave cure of the material is performed by the company Carbon Mind srl according to the material specifications. The thickness of the cured plates is 2.6 mm. The plates are then cut by milling to obtain the rectangular plates, with dimensions 150x100 mm, having a saw-tooth on one of the edges to trigger the failure initiation (Fig. 1a).

2.2. Testing setup

The anti-buckling fixture used to perform the tests (Fig. 1b) was designed to carry out in-plane compression tests on flat composite samples under a falling weight load or a quasi-static compression load. The fixture consists of six vertical columns and a supporting structure. The specimen is clamped between the anti-buckling columns, with the saw-tooth edge positioned downward in contact with an horizontal steel plate. The upper edge of the specimen is left free to get in contact with the dropped weight or with the loading element in case of quasi-static test.

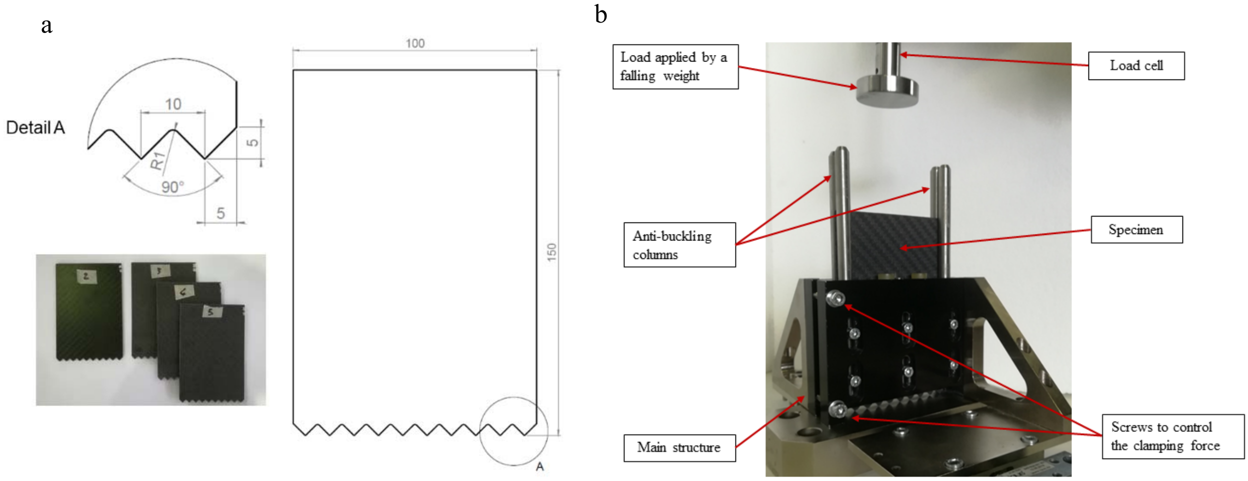

Fig. 1. a) Picture and drawing of the carbon fiber/epoxy specimens used for this research, with dimensions in mm. b) Fixture for impact compression crash testing on composite flat plates.

Four screws (two for each side) provide the force necessary to clamp the specimen and avoid buckling. The torque of the screws is controlled using a dynamometric wrench; in this way the friction force due to the sliding contact between the specimen and the anti-buckling columns can be regulated.

The tests are performed in an Instron 9450 drop tower testing system, that allows to test using different impact masses, velocities and energies up to 1800 J. The crash force is acquired using an instrumented tup with maximum load of 222 kN and sampled with an acquisition system at a frequency of 1 MHz. The test is recorded using a Photron FASTCAM Mini AX high speed camera to capture the failure process.

The force-time curve is acquired during the test. Force-displacement curves (Fig. 2a) are obtained by double integration of the force-time signal.

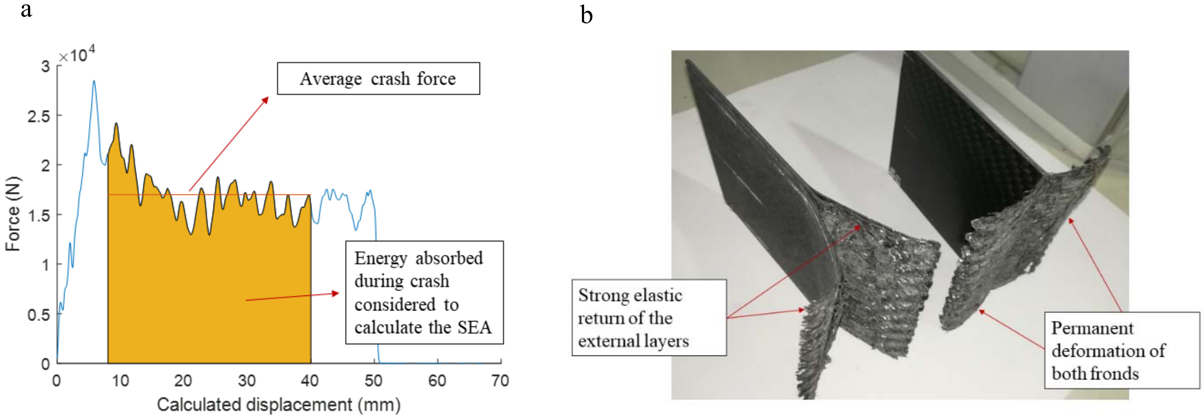

Fig. 2. a) Force-displacement curve acquired during a test and visual representation of the absorbed energy calculation in the range between 8 mm and 40 mm, used to calculate the SEA. b) failure modes after crush test: more elastic behavior in the specimen on the left, higher permanent deformation in the specimen on the right.

The energy absorption can be calculated as the integral of the force-displacement curve. The specific energy absorption is then calculated as:

$$SEA = \frac{E}{\rho A\delta} = \frac{\int F dx}{\rho A\delta}, \tag{1}$$

where E is the energy absorbed during the crash of the specimen, ρ is the density of the specimen, A is the cross section of the specimen, δ is the displacement of the impactor, that corresponds to the crashed length of the specimen, and F is the force signal acquired. The extremes of integration are 8 mm, since the force-displacement curve is influenced by the saw-tooth trigger up to this value, and 40 mm to have the same integration span in all tests.

The goal of the present work is to study the effect of the impact velocity and of the friction between the specimen and the supporting columns on the SEA of the material. A full factorial design of experiment with a center point is implemented as described in Table 1.

Table 1. Experimental plan

Treatment	Clamping force (kN)	Velocity (m/s)	Mass (kg)
A	0.8	4.8	69.4
B	0.8	9.9	16.4
C	8	4.8	69.4
D	8	9.9	16.4
E	4	7	32.9

To get comparable data, the same impact energy of 800 J is used in all the tests; to change the impact velocity, the impact mass is also changed to keep the kinetic energy constant. The impact velocities are chosen to avoid too low impact masses, that cause a force signal with strong oscillations. The clamping force levels are limited to 8 kN to avoid the overestimation of the SEA caused by excessive friction, while the lower value corresponds to the lowest torque that can be exerted with the dynamometric wrench.

3. Results

At a first analysis, due to the large experimental scatter, results do not show any significant effect of the impact velocity or of the clamping force as showed in Fig. 3.

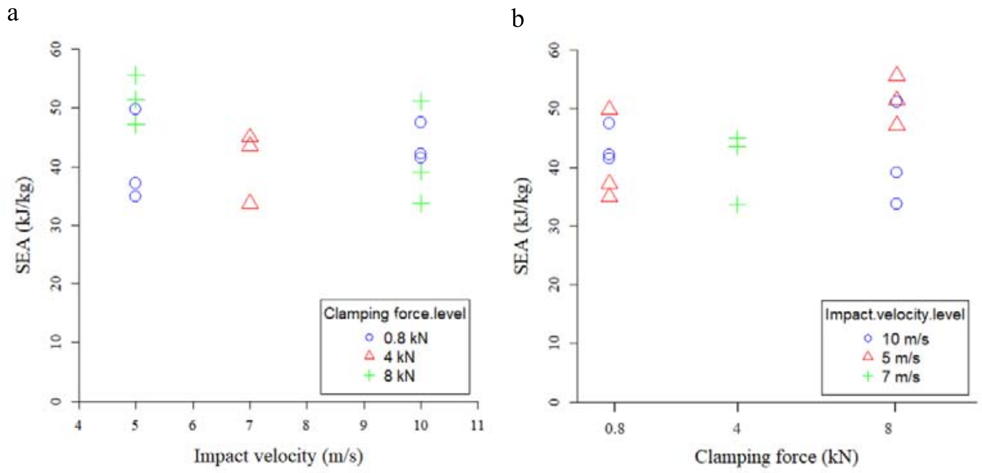

Fig. 3. a) SEA measured during experiments as a function of the impact velocity, that does not appear to be influent on the results. b) SEA measured during experiments as a function of the clamping force, that does not appear to be influent on the results.

The main failure mechanism is delamination with formation of two fronds (Fig. 2b) and some powders due to matrix fragmentation. Different failure modes are found after the test, as shown in Fig. 2b: some specimens show higher permanent deformation causing a wider opening angle of the two fronds, whereas other specimens show a stronger elastic return of the external layers that causes a narrower opening angle of the fronds.

The presence of different failure modes could be the reason for the scatter in the experimental results. To assess the influence of the failure mode on the SEA, the opening angle of the specimen fronds (‘fracture angle’ in Fig. 4a) has been measured and considered in the analysis of the experimental data. The SEA measured in each test is then plotted as a function of the fracture angle (Fig. 4b). A good correlation between SEA and fracture angle is found, probably due to the higher level of deformation of the material, that causes a higher energy absorption.

Considering the failure mode as a new parameter in the analysis, it is then possible to correct the results to hide the effect of the failure mode and reveal the effect of the investigated factors (i.e., impact velocity and clamping force).

If the values of SEA are modified to get to an ideal situation where the failure angles are the same for all the specimens (an average angle of 120° in this case), this corresponds to the translation of all the experimental points in Fig. 4b parallel to the regression line in Fig. 4b that interpolates them according to the following formula:

$$SEA_{corr} = SEA + k(120° - \alpha), \tag{2}$$

where $k = 0.131$ kJ/(kg°) is the slope of the regression line in Fig. 4b, SEA is the experimental SEA value and α is the fracture angle.

With this correction, results change as shown in Fig. 5; the scatter is reduced and, even though no effect of the impact velocity is visible in Fig. 5a, the increase of the corrected SEA with the clamping force is clearly visible in Fig. 5b. The friction due to the sliding contact between the specimen and the supporting columns is then influent and must be controlled carefully to avoid an overestimation of the measured SEA. For this material, an increase of 1 kJ/(kg·kN) is found.

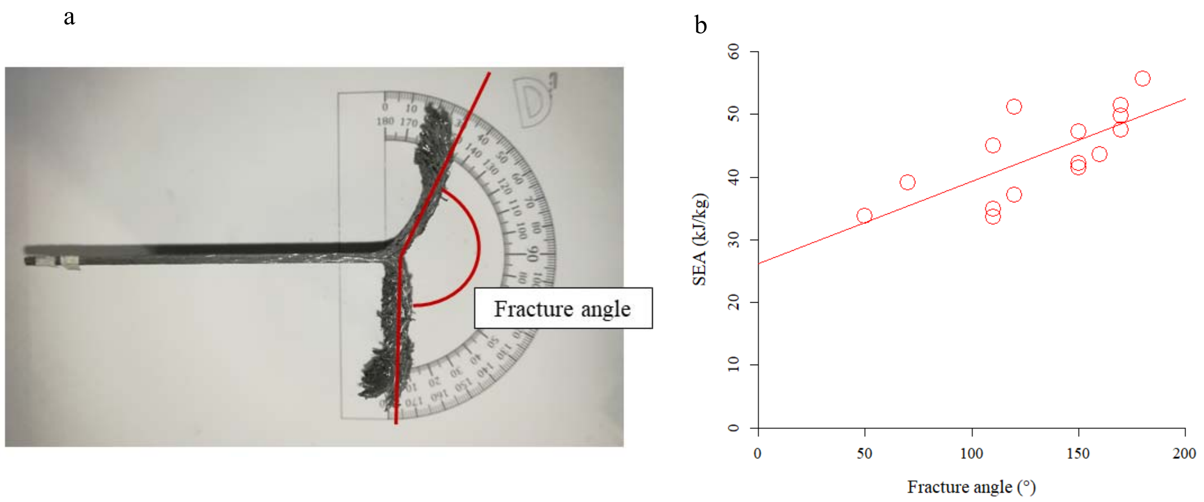

Fig. 4. a) Measurement of the fracture angle of a crashed specimen. b) SEA as a function of the fracture angle.

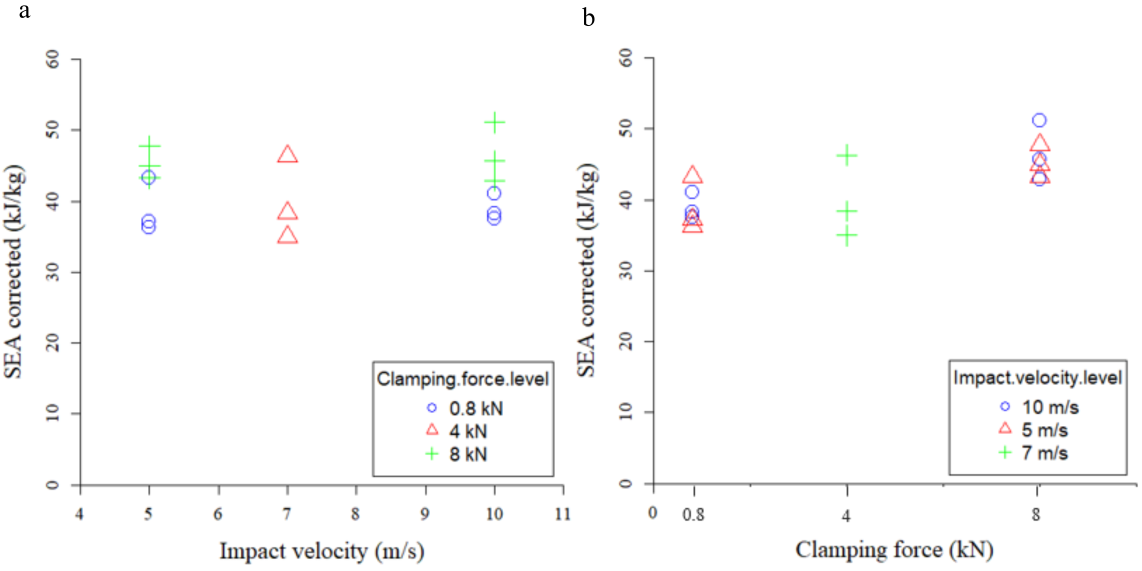

Fig. 5. a) SEA after correction as a function of the impact velocity, that does not appear to be influent on the results. b) SEA after correction as a function of the clamping force; higher values of clamping force cause higher level of SEA because of the higher level of friction force.

4. Conclusions

An innovative testing fixture to perform in-plane compression tests in impact conditions was used to measure the influence of impact velocity and friction on the SEA of CFRP composite plates. The delamination was the most evident failure mechanism, but some specimens showed a higher level of deformation of the two fronds that caused higher energy absorption. Considering these differences in the analysis and applying a correction to the measured SEA, the final results showed that the impact velocity does not significantly influence the SEA (at least, in the investigated velocity range); whereas a higher clamping force causes an increase of the SEA due to the increase of energy absorbed by the friction between the anti-buckling columns and the specimen. The results of this study pointed out some issues that need to be taken in account in future works:

- The scatter of results and the different failure modes are due to the internal variability of the material properties even in the same material batch.
- The effect of the friction due to the sliding between the specimen and the anti-buckling columns should be controlled and reduced as much as possible since it affects the SEA estimation.
- To have a complete characterization of the material, the testing fixture should be modified to reproduce not only delamination but also the other typical failure modes of composites during crash (tearing, fragmentation and local buckling).

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