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## **Experimental study of woven-laminates structures subjected to high-velocity impact**

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### **Abstract**

This study was designed to evaluate the experimental behaviour of monolithic structures consisting of E-glass/polyester woven laminates subjected to high-velocity impact. A number of monolithic laminates with areal densities ranging from 5.94 kg/m<sup>2</sup> to 23.76 kg/m<sup>2</sup> were taken into account during the study. The principal objectives of this paper are to study the influence of the composite plate areal density on projectile residual velocity, the minimum energy and velocity of the projectile at the moment of perforation, the consequent energy absorbed by the laminate, the contact time between the plate and the projectile during the impact event and the extension of the damaged surface area on both faces of the laminate.

### **Keywords**

Woven laminate, Ballistic impact, Absorbed energy, Damaged area, Areal density, GFRP

### **1. - Introduction**

Due to their stiffness, strength, low manufacturing cost, reduced weight, and permeability to electromagnetic waves, woven laminates of glass fibres/polyester are commonly used in the aeronautic, maritime, and ground-transport industries as well as in civil infrastructures. While these laminate structures are usually designed to withstand common loads, in some cases they may be accidentally subjected to impact loads caused by foreign bodies, problems that may lead to structural failure due to the low transverse stiffness that composite structures show under impact loads. Bearing this in mind, the study of the high-velocity impact behaviour of glass-fibre laminates is a key aspect for consideration where structural design is concerned, and an understanding

of the influence parameters that control the perforation process in structures made of composite laminates is essential if their performance under service conditions is to be ensured [1].

While the high-impact velocity behaviour of fibre-reinforced composites has been studied in depth, a fact that is reflected in the reviews of Abrate [2], Reid and Zhou [3], and Bartus [4], major questions remain unanswered and investigation into the topic continues [5-9].

One of the main parameters affecting perforation is laminate thickness, which bears an intimate relationship with the areal density (composite mass per square metre) of the laminate. Numerous authors have studied the influence of these parameters on both projectile perforation velocity and the perforation-threshold energy of laminates with different fibres and resin matrices [10-16]. Examination of these relationships has produced contradictory results, and both linear and non-linear relationships between the minimum perforation velocity or minimum perforation energy and the thickness in composite plates have been observed. [11-14, 16-19].

In glass-fibre laminates, the behaviour of perforation velocity in relation to thickness has been seen to vary. Gellert et al. [12] tested glass-fibre woven laminates of various thicknesses (4.5-20.0 mm) struck with three nose shapes rounds. A bilinear relationship was found between perforation-threshold energy and plate thickness. By proposing a simple model to explain this relationship, these authors affirm that energy absorption in thin glass-reinforced laminates is largely independent of projectile-nose geometry. By studying the perforation of a number of thick laminates impacted with projectiles of different mass and geometry, Wen [13] demonstrated the influence of thickness on perforation velocity. Both linear and non-linear variations were found in this case. For example, for an E-glass/polyester struck by a flat-faced low-mass projectile, the researcher observed both linear and non-linear relationships when the mass and diameter of the projectile increased. Similar behaviour was observed for hemispherical-ended projectiles. Deka et al. [14] applied a numerical model to analyse the damage evolution on E-glass/polypropylene laminates of several thicknesses subjected to high-velocity impacts of cylindrical flat-nosed projectiles. These authors used a progressive-failure model based on Hashin failure criteria in order to estimate the energy absorbed by the laminate. A non-linear relationship was observed between perforation velocity and thickness. In addition, He et al. [18], using a theoretical model, proposed a non-linear relationship between perforation velocity and thickness for glass-fibre laminates

less than 7 mm thick. Naik et al. [19], however, found a linear variation for woven E-glass/epoxy laminates for a thickness range from 1.0 mm to 2.6 mm when these were impacted by flat projectiles. These researchers applied an analytical model based on energy considerations in order to predict the variation of perforation velocity as a function of thickness. Furthermore, by using an analytical model, García-Castillo et al. [16] found a linear variation for woven thin laminates of E-glass/polyester for thicknesses ranging from 3 mm to 6 mm when these were impacted by spherical projectiles.

The damage area is another important parameter taken in to consideration in studies of high-velocity impact phenomenon on laminates as it is directly related to the residual strength of the component after impact. It has been observed that, in ballistic impacts on glass-fibre composites, the damage generated is quite widespread, making this a critical parameter to be taken into consideration in structural design [20]. The ultrasonic C-Scan is a non-destructive technique that has the ability to detect and quantify damage extension in all thicknesses of composite laminates [21-22]. Gellert et al. [12] demonstrated that the damage extension depended on the laminate thickness. For thin plates the delamination (damage extension) is cone shaped and opens towards the exit side of the laminate plate. This cone increased in diameter and height with increasing target thickness until, with sufficiently thick plates, a delamination cone opening towards the impact side also appeared.

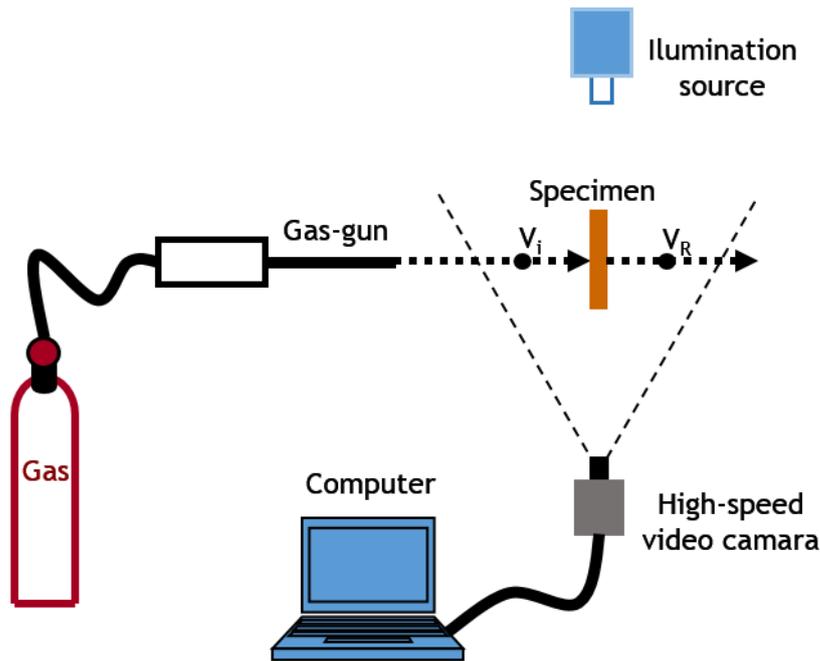
The principal objective of this work was to carry out an experimental analysis of the influence of areal density on minimum perforation velocity, contact time, and extension of the damage area (front and back sides of plates). Moreover, two analytical models previously developed and validated by the authors [23] were used to confirm the experimental results obtained.

## **2. Materials and experimental procedures**

For the purposes of this work an E-glass/polyester woven laminate of  $1980 \text{ kg/m}^3$  density was studied and four different areal densities were considered:  $5.94 \text{ kg/m}^2$ ,  $11.88 \text{ kg/m}^2$ ,  $17.82 \text{ kg/m}^2$  and,  $23.76 \text{ kg/m}^2$  - these corresponding to four different thicknesses (3, 6, 9 and 12 mm).

The impact tests carried out during the study were performed on laminates with an areal density of  $17.82 \text{ kg/m}^2$  (9 mm thickness). For the other areal densities to be considered the experimental data (same material and geometry) was taken from a previous study carried out by Buitrago et al. [24]. The dimensions of the specimens tested were of 150

mm x 150 mm, ensuring that the damage did not reach the edge of the specimen and, therefore, that boundary conditions did not influence the damage area [14]. The conditions of the impact tests were the same as those taken into consideration by Buitrago et al. [3] for the remaining areal densities (5.94, 11.88 and 23.96 kg/m<sup>2</sup>) The experimental impact tests were carried out using an A1G+ gas gun manufactured by Sabre Ballistics (Fig. 1). The specimens were impacted with spherical steel projectiles of 1.725 g mass and 7.5 mm diameter.



*Fig.1. Experimental devices employed for the impact test*

Impact tests were recorded using a high-speed video camera (APX PHOTRON FASTCAM) with a data-acquisition system capable of capturing up to 120k frames per second. For improved recording quality, a high-intensity light source, model ARRISUN 12 Plus, was used.

Impact and residual velocities were calculated by evaluating the distance travelled by the impactor in several consecutive frames. The number of frames was selected according to a previous study in order to ensure accurate estimation of the velocity [25]. From these velocities, the impact and absorbed energies were estimated.

Once the impact tests had been performed, non-destructive inspection (IND) was carried out on all impacted specimens of the four areal densities. While the composite laminate is translucent, the extension of damage area was not determined using optical techniques [26] as differences between the damage extension at the front and rear face of the 3 mm

thickness plates were not observed using this technique. Rather, the IND technique used to study the damage caused by the impact was C-Scan with water as coupling medium and, non-contact ultrasounds. This experimental equipment is manufactured by TECNITEST and comprises the following components: a computer, a Sonda USPC7100 LA, an automatic system to move the transducer for the inspections (Fig. 2). For the purposes of this study the transducer chosen had a frequency of 5 MHz and a diameter of 10 mm. The task of the transducer is to emit the ultrasonic pulse and receive the signal.

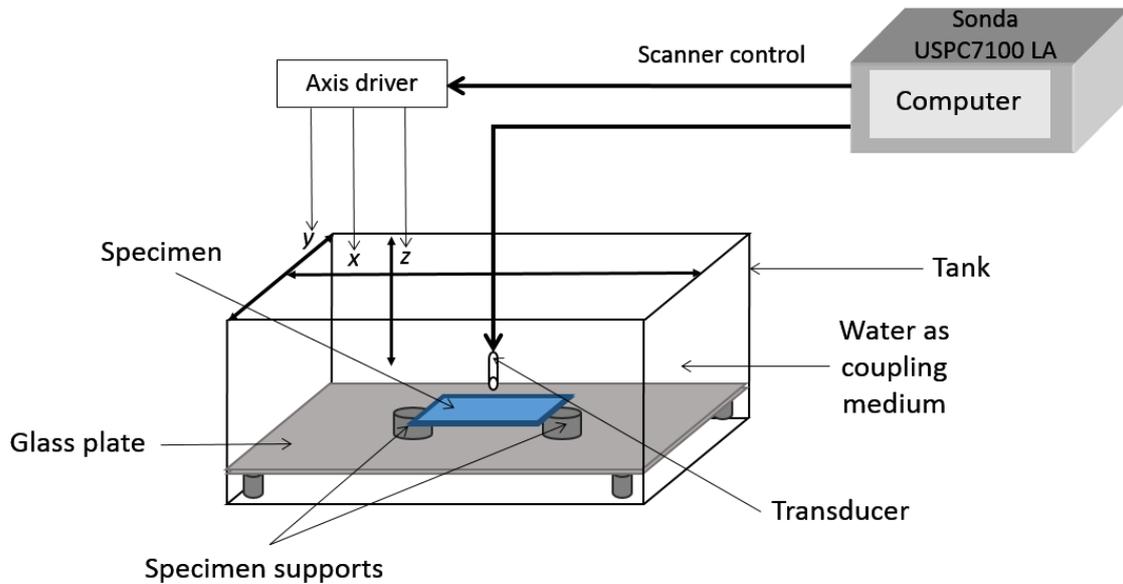


Fig. 2. Experimental set-up for C-Scan inspection of impacted monolithic plates

### 3. Results

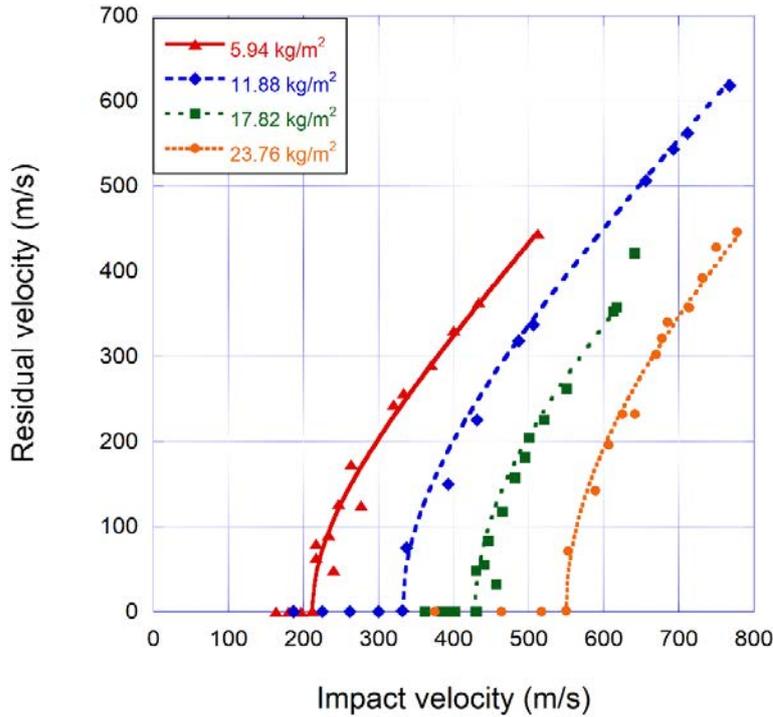
The results of residual velocity versus impact velocity for the E-glass/polyester woven ply laminates with various areal densities ( $5.94 \text{ kg/m}^2$ ,  $11.88 \text{ kg/m}^2$ ,  $17.82 \text{ kg/m}^2$  and  $23.76 \text{ kg/m}^2$ ) are shown in Fig. 3. The results of residual velocities for laminate plates of areal density  $5.94 \text{ kg/m}^2$ ,  $11.88 \text{ kg/m}^2$ , and  $23.76 \text{ kg/m}^2$  were taken from previous experiments carried out by the authors for the same projectile and impact conditions [24].

In the study it was not possible to calculate the minimum perforation velocity in a determinist manner as an impact-velocity interval exists in which the structure may or may not be entirely perforated. In addition, the residual velocity of the projectile from the gas gun cannot be fully controlled. The fitting curve for the laminate of  $17.82 \text{ kg/m}^2$  shown in Fig. 3 was calculated using the Lambert–Jonas model [27], in the same way it was calculated for the other laminates.

The Lambert–Jonas model [27] relates residual velocity to impact velocity by means of the following equation: (1)

$$v_r = A \cdot (v_i^p - v_{bl}^p)^{1/p}$$

where  $v_i$  is the impact velocity of the projectile,  $v_{bl}$  is the minimum velocity of perforation or ballistic limit,  $v_r$  is the residual velocity of the projectile and  $A$  and  $p$  are empirical parameters.



*Fig. 3. Residual velocity versus impact velocity for woven laminate E-glass/polyester with different areal densities*

The minimum velocity of perforation for the considered projectile and target (areal density of  $17.82 \text{ kg/m}^2$ ) is  $428.4 \pm 1.7 \text{ m/s}$ .

Once the minimum perforation velocity has been determined for the four areal densities of the laminates studied, these can be plotted against the areal density and the minimum perforation energy versus the areal density can be represented, as can be seen in Fig. 4.

The results of the experiment showed a linear dependence between the minimum velocity of perforation and the laminate areal density (from  $5.94 \text{ kg/m}^2$  to  $23.76 \text{ kg/m}^2$ ).

While similar behaviour of perforation velocity versus areal density have been described by other researchers for Kevlar-fibre laminates [28] and for thin laminates of E-glass/polyester [16], this result contradicts those of other authors who propose a non-linear relationship between perforation velocity and areal density [12].

In addition, the minimum perforation energy can also be calculated and is proportional to the square of the velocity, meaning that perforation energy has a quadratic dependence on areal density (Fig. 4). In the areal density range  $5.94 \text{ kg/m}^2$  to  $23.76 \text{ kg/m}^2$  the experimental results would appear to contradict other studies such as those undertaken by Gellert et al. [12], which demonstrated a bilinear relationship between perforation energy and thickness, and therefore also with areal density.

With the aim of supporting the experimental results obtained in this work, the analytical models developed by Alonso et al. [23] were used to predict the minimum perforation velocity and energy. Both models consider that the kinetic energy of the projectile impact is absorbed during the perforation process by means of a number of energy-absorption mechanisms. In the case of thin laminates, these energy-absorption mechanisms include the tensile failure of fibres, the elastic deformation of fibres, acceleration of the laminate on the back side of the plate, delamination, and matrix cracking. For thick laminates, on the other hand, the energy-absorption mechanisms considered are compression, tensile failure of fibres, delamination, matrix cracking, shear plugging and friction.

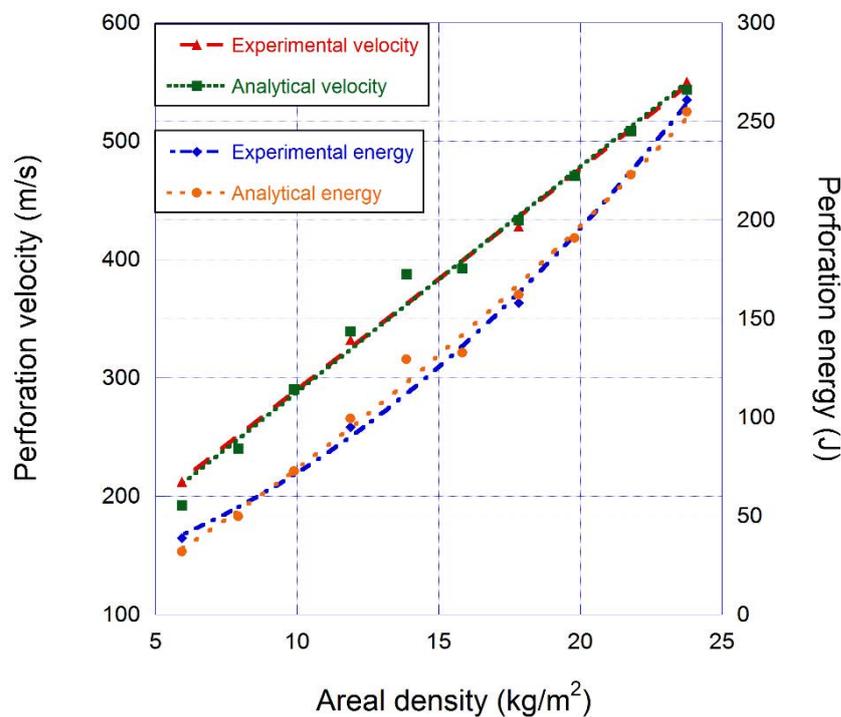


Fig. 4. Perforation velocity and energy versus areal density of woven laminate E-glass/polyester plates.

In the same Fig. 4 the high level of concurrence between the analytical model

predictions and the experimental results for the perforation velocity and energy of the target and its areal density may be observed. The estimated results from analytical models show similar curves to the experimental results for both parameters, namely perforation velocity and energy.

Fig. 5 shows the ratio of the absorbed energy/thickness versus the impact energy for all experimental tests available. The absorbed energy is divided by the thickness of the specimen in order to avoid inertial effects that may be due to the mass of the laminate. In addition, the minimum perforation energy ( $E_{bl}$ ), which is represented by a vertical line for each areal density, can be observed.

The graph shows that, for higher impact energies of 100-150 J, a roughly linear relationship exists between the absorbed energy per unit of mass and the impact energy and that this result is independent of areal density. These impact energies coincide with the minimum perforation energies for laminates with areal densities of 11.88 kg/m<sup>2</sup> (6 mm thickness) and 17.82 kg/m<sup>2</sup> (9 mm thickness), respectively, as can be seen in Fig. 4.

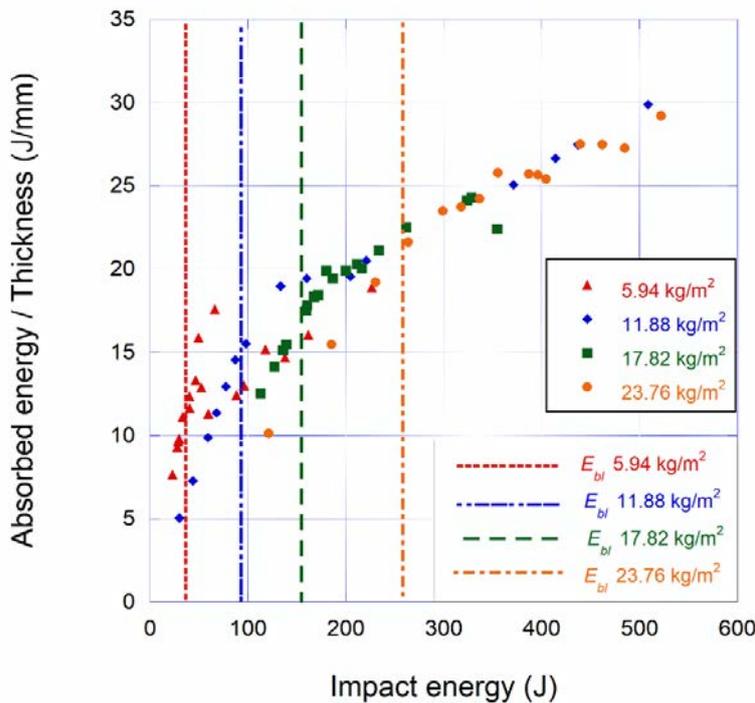


Fig. 5. Absorbed energy/thickness versus impact energy for woven laminate E-glass/polyester with different areal densities

These experimental areal densities of 11.88 kg/m<sup>2</sup> and 17.82 kg/m<sup>2</sup> correspond to the next ratios  $\frac{\phi_p}{e}$  of 1.25 and 0.83, respectively, where  $\phi_p$  is the diameter of projectile and

$e$  is the thickness of the specimen for a woven laminate of E-Glass/polyester. Both ratios are close to 1. In previous works by the authors [23] it has been demonstrated that the umbral thickness between thin and thick laminate plates of E-glass/polyester is around  $\frac{\phi_p}{e} = 1$  (approximately). Moreover, Rosenberg et al. [28] previously described this behaviour for metal plates.

In this work the contact time between the projectile and the target is also considered and defined. This parameter, defined as the time needed to perforate the laminate, may be calculated using high-speed video in tests in which the perforation of the laminate takes place (Fig. 6). Fig. 6a shows the contact time versus the impact energy and Fig. 6b the first magnitude versus the impact energy divided by the thickness of the specimen. In both figures, the minimum energy of perforation is represented by means a line for each areal density.

For all laminates studied, the maximum contact time is reached when perforation energy is close to the minimum and diminishes with the inverse of impact energy (Fig 6a).

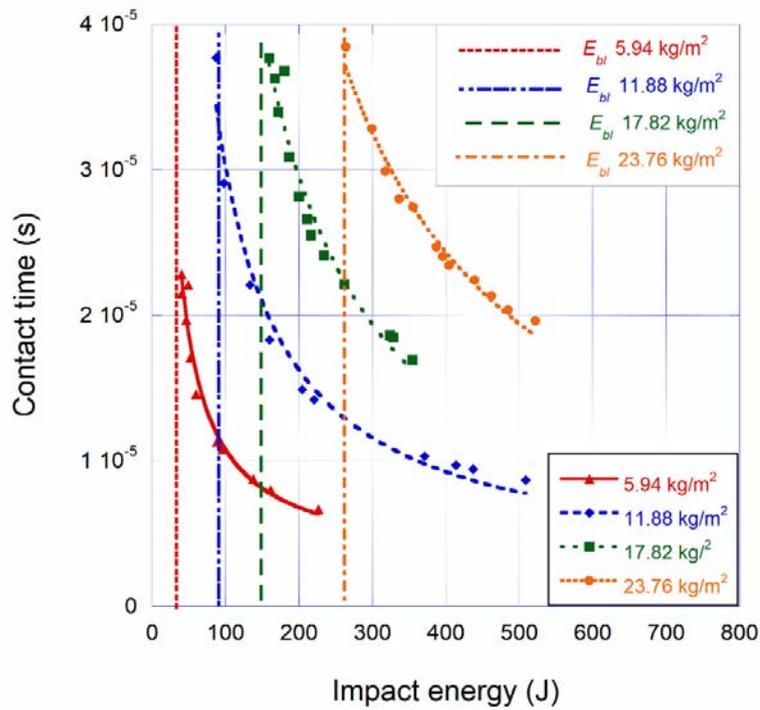
Moreover, in order to evaluate the influence of specimen thickness, the variation of the contact time was analysed as a function of impact-energy divided by thickness.

The tendency of the curves in Fig 6a is the same as in Fig 6b. Despite the fact that the impact energy has been divided by thickness (Fig. 6b) the contact time curve is not the same for all thicknesses, meaning that for the same impact energy per unit of mass, the greater the thickness, the greater the contact time, so contact time increases with thickness, subtracting the mass effect.

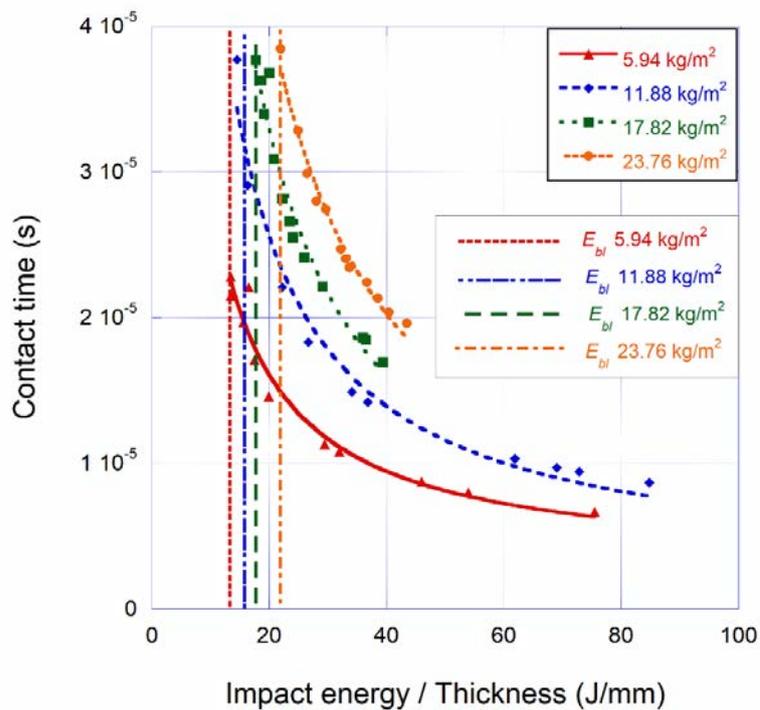
Another subject of interest in this study is the damaged area in the tested specimens.

Following impact tests of the laminates with areal density of  $17.82 \text{ kg/m}^2$ , all specimens were examined using C-Scan technique, including those with different areal densities.

Both the front and rear faces of the specimens were examined.



(a)



(b)

Fig. 6 Contact time versus: a) impact energy for woven laminate E-glass/polyester with different areal densities and, b) impact-energy divided by thickness of woven laminate E-glass/polyester with different areal densities

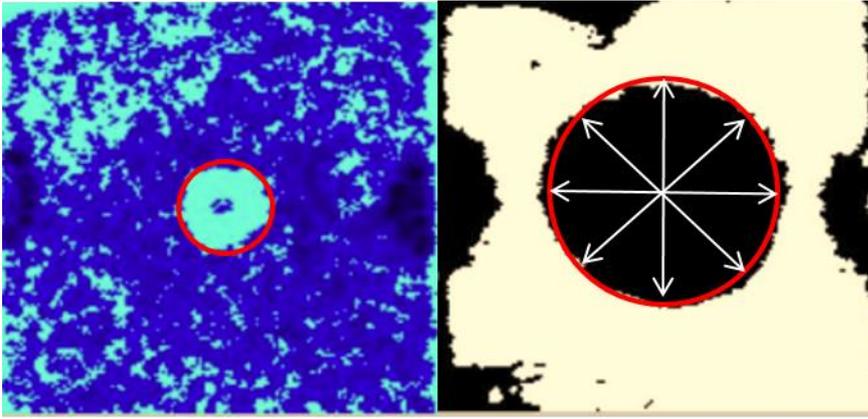
Fig. 7 shows the damaged areas on both sides of the specimens with an areal density of

17.82 kg/m<sup>2</sup> for three different cases, namely below, around and above the minimum energy of perforation. It may be observed that the damaged area has a circular shape in all cases. Measurements were taken of four different diameters (in different directions) for both faces in each specimen and the maximum deviation of the diameters on the front and rear faces was seen to be 12 % and 14 % respectively. Therefore, it would appear that, in terms of the problem in question, it is reasonable to consider the damaged area as being approximately circular. Bearing this in mind, the results shown below are presented as a function of the diameter of the damaged area, rather than of the damaged area itself. In Fig. 7, two stains can be seen in the lateral areas of the specimen. However, these stains correspond to the effect of the supports used to hold the specimen during the inspection and as such are not considered damaged areas. In Fig. 7, the maximum damaged area is reached around the ballistic limit, a result that would appear logical, as the maximum contact time also occurs around the ballistic limit (Fig. 6).

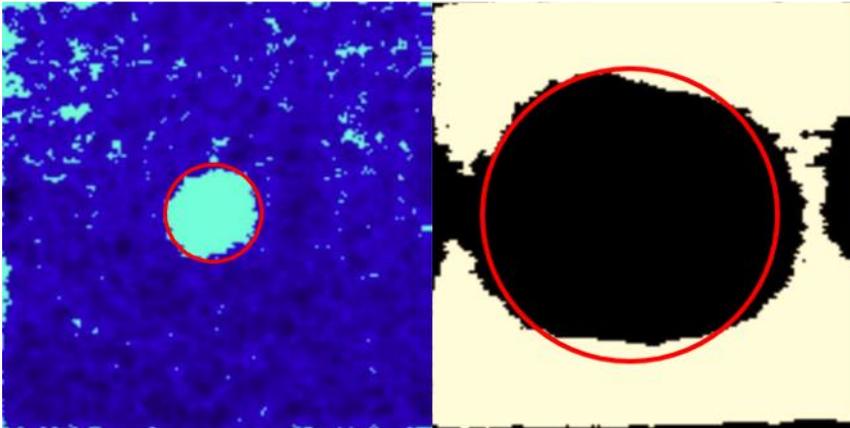
In Fig. 8 represents the diameters of the damaged areas as function of diameter versus the impact energy. By comparing both figures, it can be observed that, for all impact energies, the maximum diameter of damaged area is reached on the rear face of the plates.

In general, as seen in Fig. 7 the maximum diameter of the damaged area occurs around the perforation energy for both faces of the specimen for the various areal densities considered.

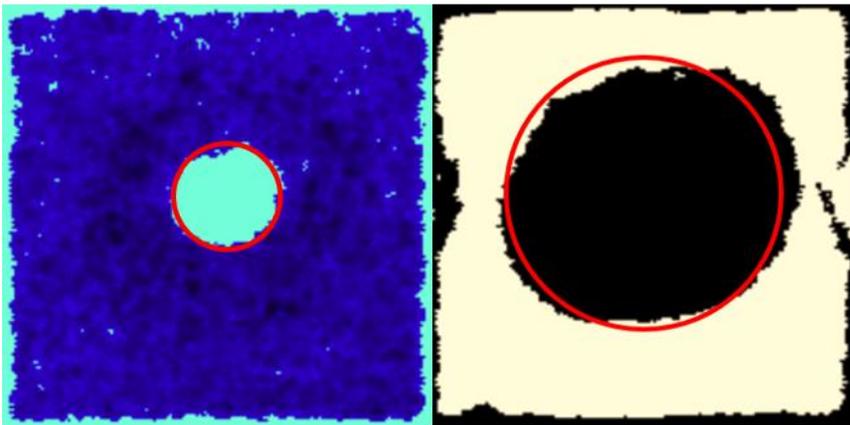
For low areal densities (5.94 kg/m<sup>2</sup> and 11.88 kg/m<sup>2</sup>) it can be observed (Fig. 8b) that the diameter of the damaged area grows rapidly until such point as the ballistic energy limit is reached. For impact energies greater than that of the energy corresponding to the ballistic limit, the diameter of the damaged area decreases slowly. However, for higher areal densities (17.82 kg/m<sup>2</sup> and 23.76 kg/m<sup>2</sup>), while the diameter of the damaged area increases up to the point where the ballistic energy limit is reached, a significant decrease below this energy value cannot be appreciated. This may be due to the fact few experiments relating to impact energies above the ballistic limit for specimens with these areal densities have been carried out. If they were to be carried out, the diameter of the damaged area would be expected to decrease.



(a)

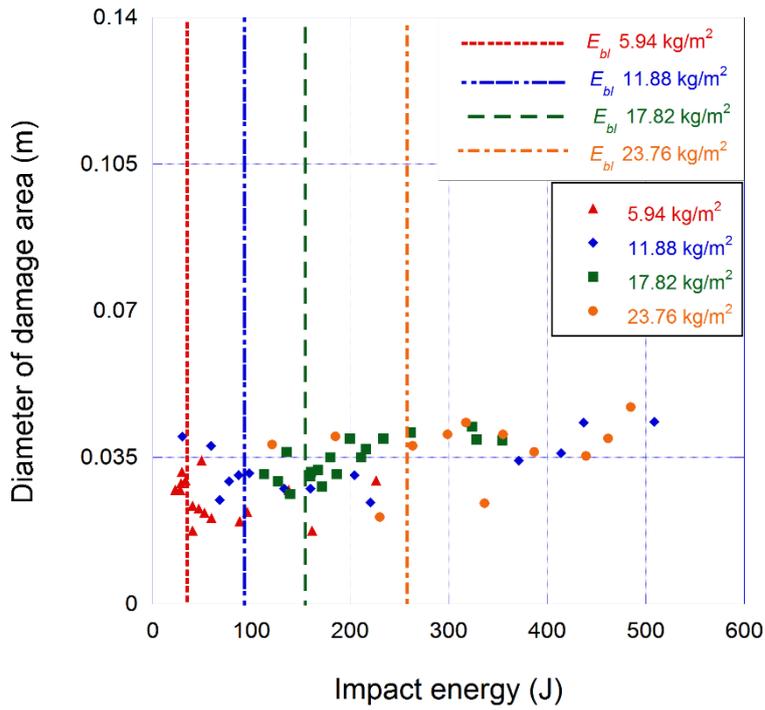


(b)

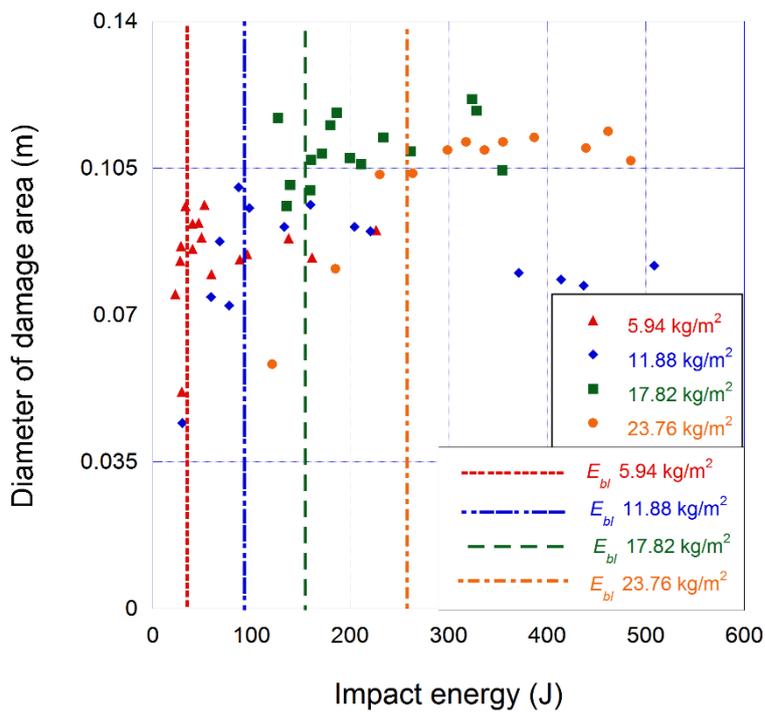


(c)

*Fig. 7 Damage area of the front (left) and back (right) face in 9 mm-thick specimens for impact velocities: a) below the minimum energy of perforation, b) around the minimum energy of perforation, c) above the minimum energy of perforation*



(a)



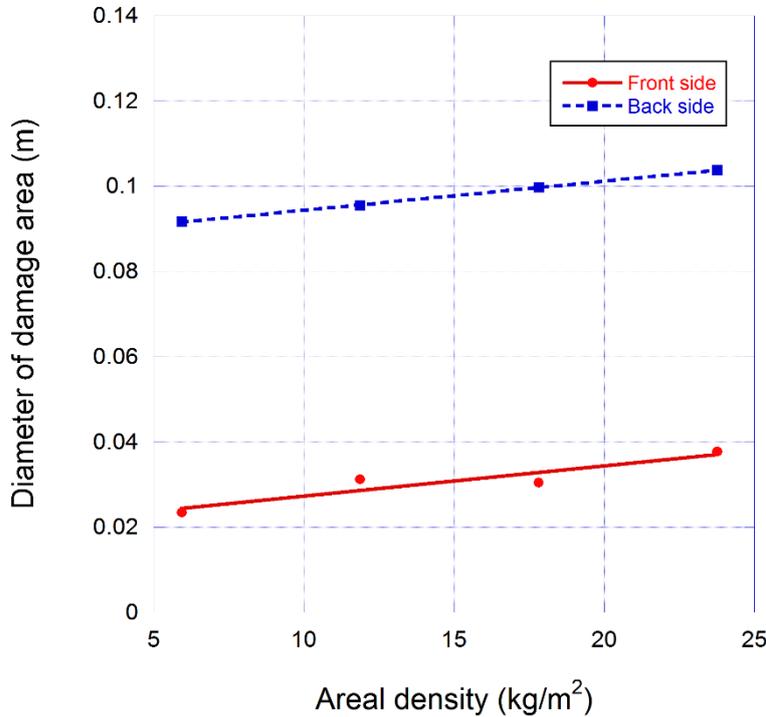
(b)

Fig. 8 Diameter of the damaged area of the a) front b) rear face versus impact energy for a variety of areal density composites

Moreover, the diameter of the damaged area in the specimens precisely at the ballistic limit is of interest here, as it has been demonstrated that the maximum extensions of

damaged areas are found at minimum perforation velocity when composite laminates are subjected to high-velocity impact

Fig. 9 represents the diameter in both the front and rear faces versus the areal density of the specimen for the minimum perforation energy.



*Fig 9. Diameter of damage area vs. areal density at an impact velocity close to the minimum perforation velocity*

A linear relationship was observed between the damaged area diameters on the front and rear faces for the range of areal densities considered in this work.

The diameter of the damaged area increases with areal density for velocities close to the ballistic limit. Furthermore, Fig. 9 shows that both lines have practically the same gradient, with a difference of about 3.8 %, implying that a certain relationship exists between the damaged area on the front and rear faces for velocities close to the ballistic limit. In this case, the diameter of the damaged area on the rear side of the specimen is equal to the diameter of the damaged area on the front side plus 0.063 m.

## **5. - Conclusions**

In this study the behaviour of monolithic structures of woven laminae of E glass/polyester subjected to high velocity impacts was evaluated. A number of aspects of interest, such as the energy absorbed, the minimum perforation energy, the contact time and the

extension of the damaged area, were evaluated for areal densities ranging from 5.94 kg/m<sup>2</sup> to 23.76 kg/m<sup>2</sup>.

The following conclusions were obtained:

- The perforation velocity, the corresponding perforation energy and the size of the damaged area increase according to the thickness of the composite, and therefore with its areal density.
- The minimum perforation energy shows a quadratic dependence on areal density. This has been demonstrated using an analytical model developed by the authors in a previous paper.
- A linear relationship between the absorbed energy per unit of mass and the impact energy was observed for greater areal densities than 12.5 kg/m<sup>2</sup>.
- Maximum contact time and maximum damaged area are reached at approximately the point of minimum perforation energy.
- Contact time decreases for impact energies above the minimum perforation energy and increases with areal density for the same impact energy per unit of mass.
- The damaged area on the rear face is always larger than the damaged area on the front face.
- Damaged area diameters increase linearly with areal density for the minimum perforation energy and show the same gradient on both faces.

### **Acknowledgements**

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