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Damage in preloaded glass/vinylester composite panels subjected to high-velocity impacts

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Abstract
This paper examines the influence of in-plane preloading on the damage of thin composite panels under high-velocity impact loading. The composite was a tape laminate made with a glass-fibre and vinylester matrix. Impact on a preloaded laminate was analysed experimentally, comparing their behaviour with the condition in which the laminate was load-free. Two preload cases representative of actual structures were selected, uniaxial and biaxial load cases. An experimental device was developed to apply the load in two perpendicular directions. This device was combined with a gas gun to carry out impact tests in a broad range of impact velocities. The static preload altered the perforation-threshold velocity and the damage area in the laminate. Decrements of the both variables were detected in the preloaded specimens, both with uniaxial and biaxial loads. The reduction of the damage area was greater for impact velocities close to the perforation-threshold velocity in all the cases analysed.

Keywords: Biaxial pre-stress, uniaxial pre-stress, ballistic impact, composite, damage area, membrane preload

1. INTRODUCTION

Glass-fibre-reinforced composites are broadly used to manufacture structures subjected to internal pressure, such as pipes and pressure tanks, due to the good mechanical properties of these materials and low cost. In those applications, laminates are subjected to in-plane stress. In addition to the internal stresses, these structures can be subjected to high-velocity impacts of small fragments related, for example, to an explosion.

The high-impact velocity behaviour of fibre-reinforced composites has been intensively studied, as reflected in the reviews of Abrate [1], Reid and Zhou [2], and Bartus [3]. Nevertheless, major questions remain to be elucidated and investigation continues on this topic [4-7].

However, few studies on the impact behaviour of composite laminates under in-plane load are available in the literature despite that composite laminate structures usually undergo stress when subjected to an impact load. Therefore, the influence of an in-plane preload is not thoroughly understood. Most of the existing studies focus on low-velocity impacts [8-12]. Much less information is available concerning the influence of a preload in laminates subjected to high-velocity impact, mainly only for uniaxially preloaded laminates [13-15].

For laminate panels subjected to low-velocity impacts, the presence of a tensile preload could induce shorter contact duration, larger vibration frequencies, and greater loads [12]. Kelkar *et al*. [16] also observed that the greater the pre-stress level, the larger the maximum force and the greater the damage area. Also, a larger damage area has been reported for carbon/fibre composites subjected to a pre-stress of 20% of the strength of the material [8]. On the contrary, Mitrevki et al. [16] affirm that the maximum load, absorbed energy, and damage area are unaffected by the preload on GFRP laminates. These researchers tested specimens with a biaxial tension at several levels of stress. However, the performance of a structure subjected to high-velocity impact differs with respect to low velocity [1], so that the conclusions observed in low-velocity-impact tests should be verified in high-velocity impacts.

It has been reported that the application of a uniaxial tensile preload can change the perforation-threshold velocity in metal [18], ceramic [19], and composite [14] materials subjected to high-velocity impacts, and can even lead to catastrophic failure of the panel [18]. Nevertheless, a uniaxial tensile load does not properly reproduce the stress distribution of a real structure subjected to internal pressure. Therefore, this conclusion needs to be verified for the biaxial stress states, which are more representative of the stress state in a cylindrical or spherical pressure vessel.

To perform experimental impact tests on biaxially preloaded specimens, some authors use pipes subjected to internal pressure [20-21]. Nevertheless, many authors [22-25] suggest that for thin panels, specimens with cruciform-like geometry are more appropriate for studying the influence of the preload. This is because several load cases can be applied to the specimen and because it is simpler to grip the plate specimen than a tubular one for the test.

In a previous work the authors studied the high-velocity impact behaviour of woven laminates with membrane loads, focusing only on the perforation-threshold velocity and the energy absorbed by the panel [26-27]. However, the damage of a woven laminate and its evolution, especially the damage due to delamination, differ with respect to a tape laminate. Therefore, it is necessary also to consider this reinforcement type. No study on this topic is available in the literature.

In the present paper, the influence of the static tensile uniaxial and biaxial specimen preloading on the damage of composites panels made from a glass/vinylester tape laminate under high-velocity impact loading was studied with regard to the residual velocity, the perforation-threshold velocity, and the extent of damage area.

2. EXPERIMENTAL PROCEDURE

The material used for this work was a seven-ply glass-fibre-reinforced vinylester resin composite in the form of panels. The stacking sequence was [0º, ±45º, 0º; ±45º, 90], and the laminate thickness was 2.2 mm.

Two specimen geometries were used depending on the type of static preload (non-loaded/uniaxial or biaxial preloads). For uniaxial preloaded and non-loaded panels rectangular-shaped specimens (140 x 200 mm) were used, whereas cross-shaped specimens were used for the case of biaxial preload; the grip-to-grip arm length was 200 mm and the arm width 140 mm. The clamping area in all panels was 140 mm x 27 mm (Fig. 1). The geometry of the specimen allowed an impact zone of 140x140 mm, approximately.

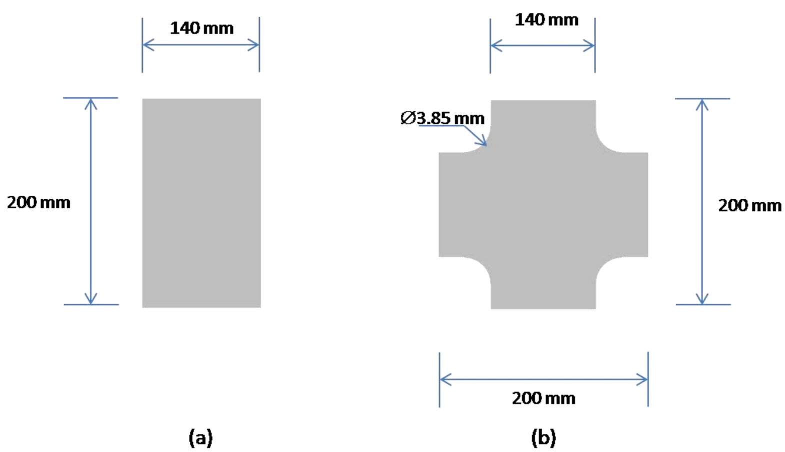


Fig. 1 Geometry of the specimens, a) unloaded and uniaxial preloaded panels and b) biaxial preloaded panels

Impact tests were made using a gas gun and a loading device used to apply the load onto the specimens. The loading device enabled different static loads to be applied in two mutually orthogonal directions. The device had two loading cylindrical actuators (one vertical and another horizontal) which could work together or independently. In this work a load of 51kN was applied in the uniaxially preloaded specimens, whereas, the panels subjected to biaxial a load of 37.5 kN was applied on each axis. No greater load could be applied, because of panel failure under static load.

The impact tests on the preloaded specimens were conducted with a high-pressure gas gun manufactured by SABRE BALLISTIC. A high-pressure gas (helium) provides the force to propel spherical steel projectiles of 12.5 mm in diameter and 8.33 g in mass.
The tests were recorded by a high-speed video camera (APX PHOTRON FASTCAM) with a data-acquisition system capable of taking up to 150,000 frames per sec. For better recording quality, a high-intensity light source, model ARRISUN 12 plus, was used. Data gathered from the images was used to estimate the impact and residual velocities of the projectile.
After the impact tests, the specimens were inspected by a C-Scan technique; the experimental equipment was manufactured by TECNITEST. The inspections were made with a SONATEST pulse-echo transducer of 1MHz. Fig. 2 shows the diagram of experimental set-up employed during the non-destructive inspection by C-Scan.

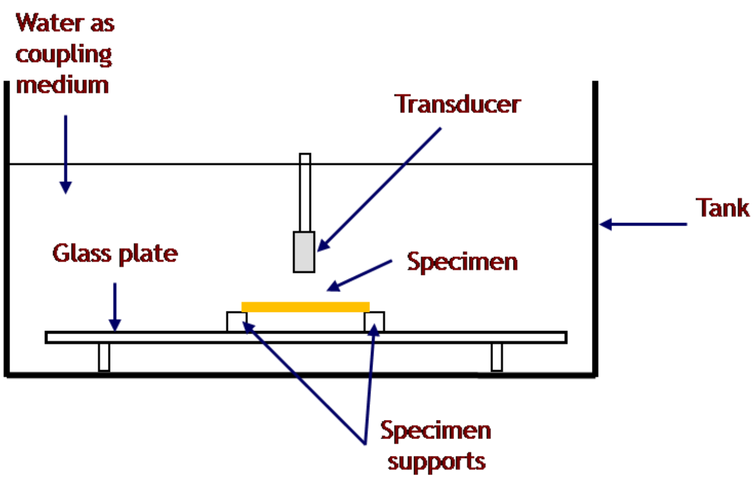


Fig. 2 Experimental set-up for the non-destructive testing of the impacted laminate panels

3. RESULTS AND DISCUSSION

3.1. Influence of the preload on the residual velocity

An evaluation was made of the influence of in-plane preloads on the residual velocity and the perforation-threshold velocity of glass-reinforced panels subjected to high-velocity impact. The impact and residual velocities were determined from the record of the impact tests made by a high-velocity video camera. Fig. 3 shows the relationship between the impact and residual velocities of the three cases analysed. In this work the experimental data were fit to the curves shown in the Fig. 3, by fitting the Lambert-Jonas equation (1) [29] using the least-squares method. This equation relates residual velocity to impact velocity. It has been validated by other authors using several materials and impact conditions [30-32].

$$v_r = \begin{cases} 0, \ 0 \le v_0 < v_{bl} \\ \alpha \cdot \left(v_0^p - v_{bl}^p\right)^p, \ v_0 \ge v_{bl} \end{cases} \qquad (1)$$

where v_0 is the impact velocity of the projectile, v_{bl} is the perforation-threshold velocity, v_r is the residual velocity of the projectile, and α and p are empirical parameters. After Eq. 1 was fitted to the experimental data, the best fit was achieved when these parameters were equal to 1 and 2, respectively. In all cases, the correlation coefficient of the curve fit was more than 0.9, and therefore the fit can be considered good. These values are consistent with results from the literature for impact tests on thin panels with non-deformable projectiles [33]. In thicker laminates or sandwich plates the empirical parameter can differ [32].

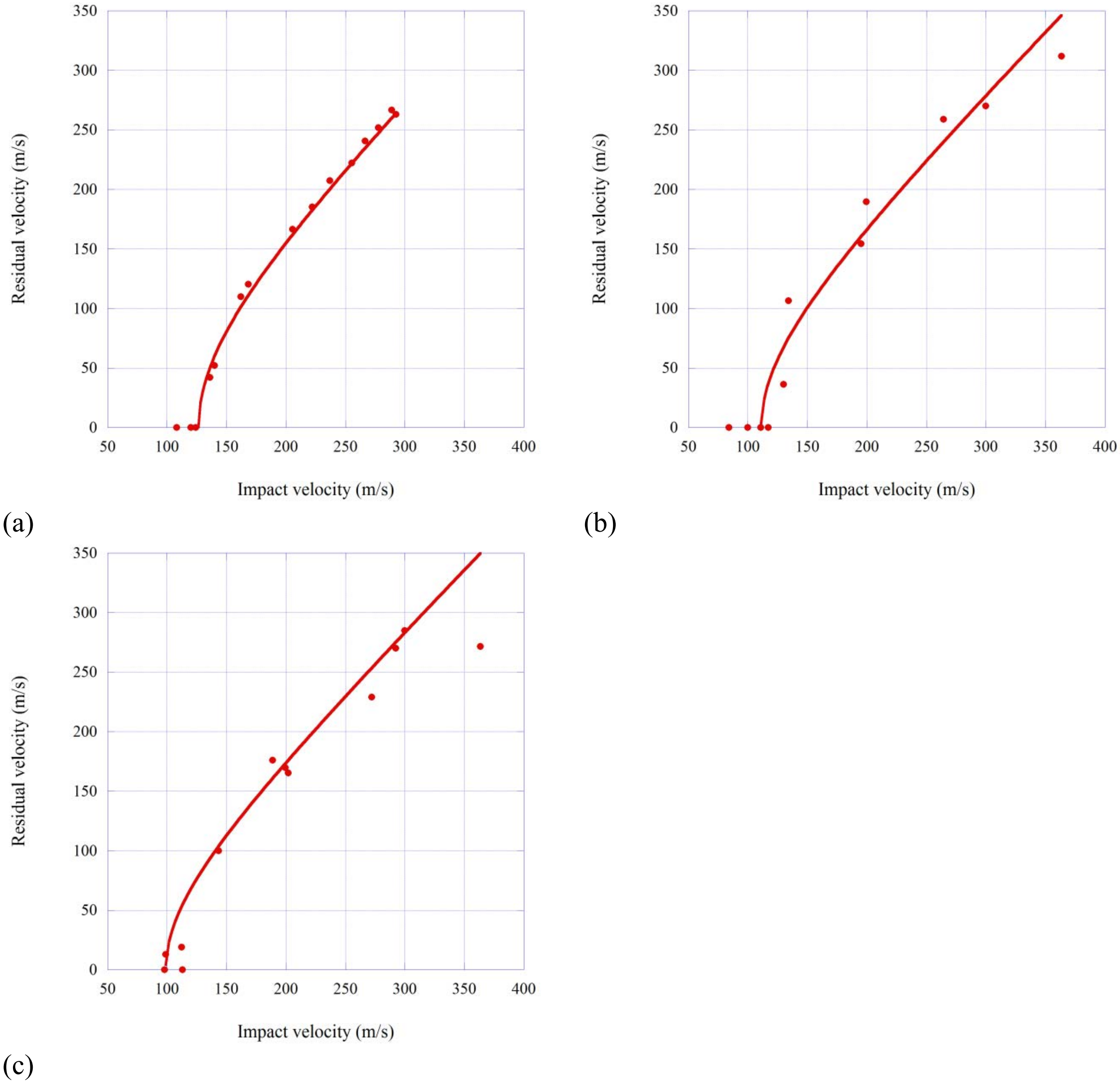


Fig. 3 Residual velocity vs. impact velocity for a glass/vinylester quasi-isotropic laminate. a) non-loaded, b) uniaxial preload, and c) biaxial preload

In some tests, the projectile was stopped. The highest impact velocity which did not result in the perforation of laminate was found in the non-loaded case (Table 1). On the contrary, the lowest impact velocity was found in the biaxial preload case.

In this study, the perforation-threshold velocity could not be calculated in a deterministic way, as there was an impact-velocity interval in which the structure might or might not be entirely perforated; in addition, the impact velocity of the projectile from the gas gun could not be totally controlled. Moreover, the objective of this work was to study a wide interval of impact velocities, from 90 m/s to 360 m/s, not focusing only on the threshold impact velocity. Therefore, in this study, the perforation-threshold velocity (Table 2) was estimated using Eq. 1 to fit the experimental data by a least-square method.

Load case	Velocities (m/s)

	Minimum perforation velocity	Maximum non-perforation velocity
Non-load	124	136
Uniaxial	117	130
Biaxial	113	99

Table 1. Minimum velocity that resulted in perforation, and maximum velocity that did not result in perforation

Load case	Perforation-threshold velocity (m/s)	Difference (%)
Non-load	126	------
Uniaxial	111	-12
Biaxial	99	-22

Table 2. Perforation-threshold velocity estimated from Eq.1

In Table 2, the perforation-threshold velocity was shown for the cases studied. For the non-loaded case, the highest perforation-threshold velocity was detected. On the contrary, the lowest perforation-threshold velocity occurred in the biaxial preload case. Furthermore, the perforation-threshold velocity decreased in the in-plane loading cases about 12% and 22% with respect to the non-loaded case.

The reduction of the perforation-threshold velocity of in-plane loading laminates could be due to the elastic energy of each panel, which was higher in the preloaded cases. Therefore, the perforation of the laminates required less impact energy and hence the perforation-threshold velocity decreased.

3.2. Influence of the preload in the damage area

The glass-reinforced composites are translucent materials; therefore many authors [1, 34] apply the visual examination as the first technique of non-destructive inspection to evaluate the extent of the damage area. In the present work, this technique was applied to determine the shape of the damage area.

Fig. 4 shows the orientation and shape of damage area at 112 m/s in a glass/vinylester quasi-isotropic laminate subjected to biaxial preload and high-velocity impact.

This image has light and dark areas, the light areas corresponding to the zone not affected by the impact, and the dark area to the zone affected by the impact. The delaminations were visible due to the debonding between adjacent laminas with different fibre orientations. The delaminated area had an oblong or "peanut" shape, with its long axis in the direction of the fibres in the lower ply at the interface and concentric to the impact point. This was detected on all the membrane load states studied and for all impact velocities. This damage shape has previously been described for quasi-isotropic laminates without membrane loads subjected to low-velocity impact by Abrate [1] and Ishikawa et al. [36], and for high-velocity impact by Will et al. [35.

The greatest delamination appeared between the plies at -45º and 90º, oriented at 90º. A slightly smaller delaminated area was observed between the plies at +45º and -45º, which were located at the back of the panels. The damage area was greatest behind the impact point because the damage in a ballistic impact follows a conical profile from the point of impact [1]. The orientation of the delamination is equal to the orientation of the lower ply, in this case 90º and -45º.

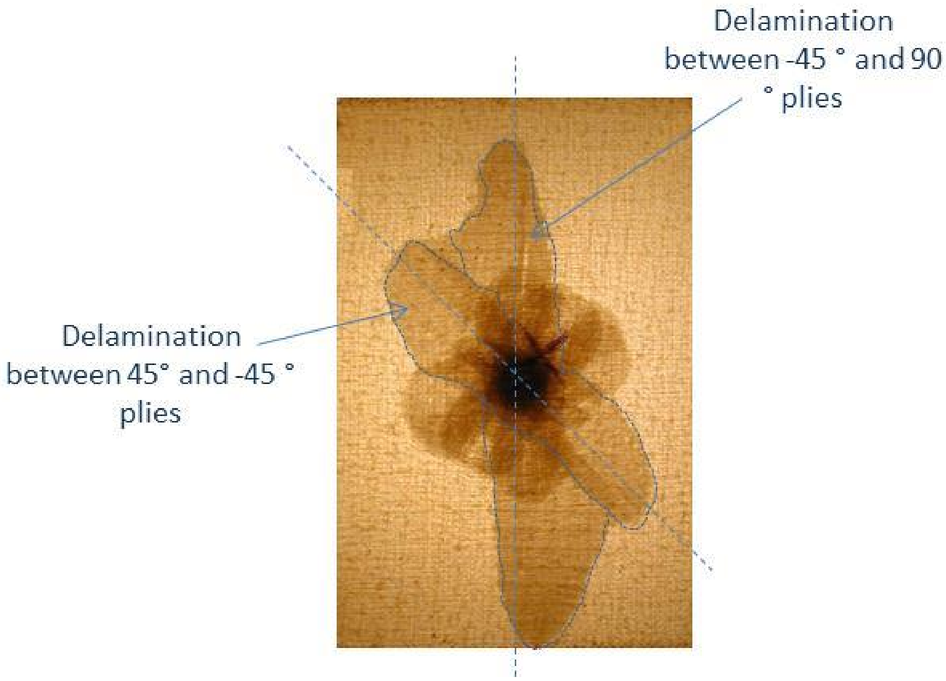


Fig. 4 Detail of the orientation and shape of damage area in a glass/vinylester quasi-isotropic laminate subjected to biaxial preload and high-velocity impact at 112 m/s

All panels were inspected by C-Scan technique to evaluate and determine the extent of damage area. Fig. 5, 6, and 7 show the images of the C-Scan inspection for the three cases studied, and for three impact velocities: one close to the perforation-threshold velocity (Fig 5b, 6b, and 7b), one below this velocity (Fig. 5a, 6a, and 7a), and another above it (Fig. 5c, 6c, and 7c). All images show that the damage area was localized in the centre of the panel. At the edge of some images a circular area was visible, corresponding to the specimen support (Fig. 5c, 6a, 6b, 6c, 7a, 7b and 7c), and a pink spot could be seen corresponding to the identification sticker.

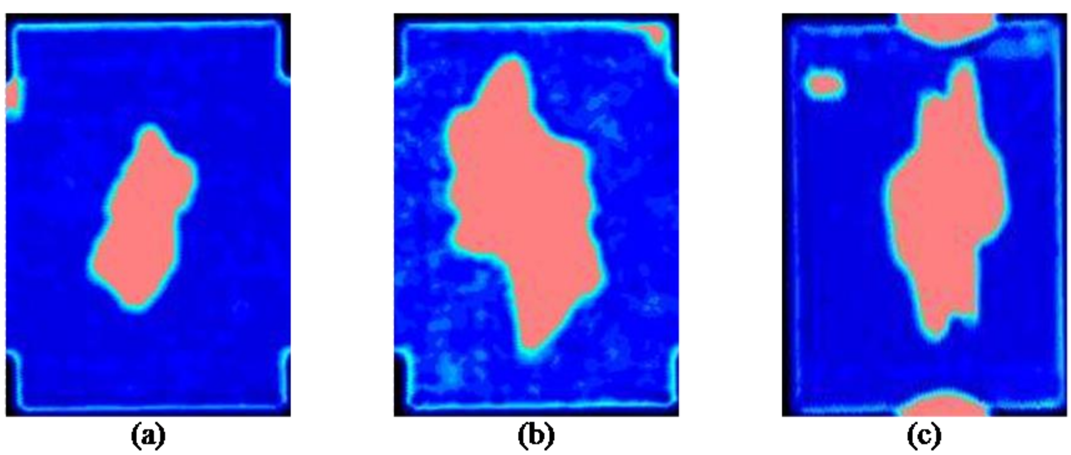


Fig. 5. Damage area for the glass/vinylester quasi-isotropic laminate without membrane load: a) 108 m/s, b) 136 m/s y c) 289 m/s

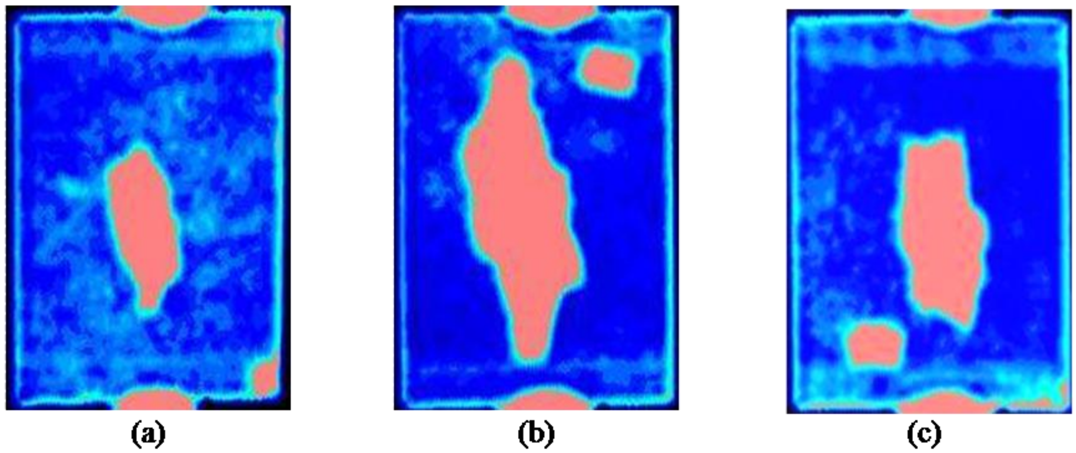


Fig. 6 Damage area for the glass/vinylester quasi-isotropic laminate with uniaxial preload: a) 100 m/s, b) 130 m/s y c) 364 m/s

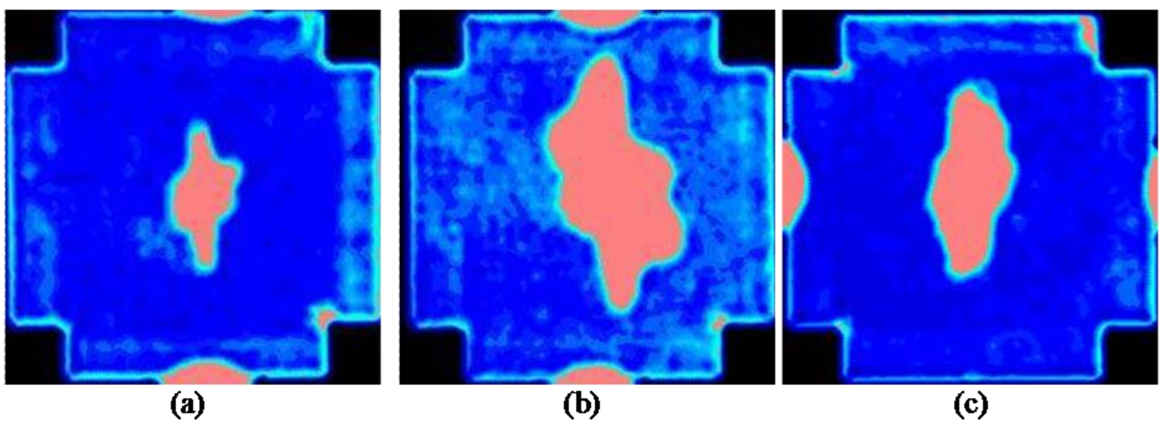
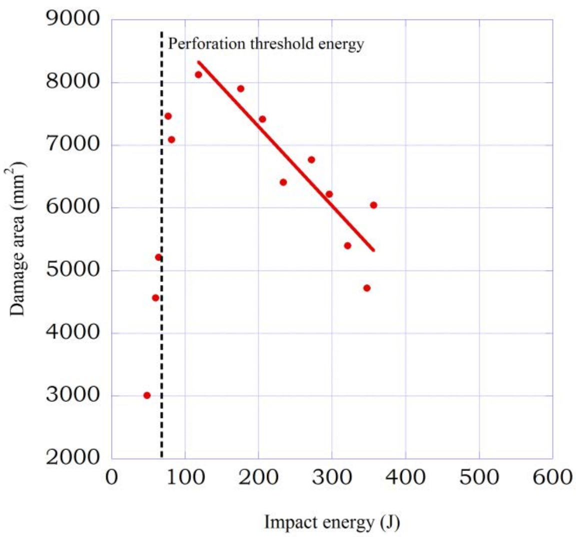


Fig. 7 Damage area for the glass/vinylester quasi-isotropic laminate with biaxial preload: a) 98 m/s, b) 112 m/s y c) 364 m/s

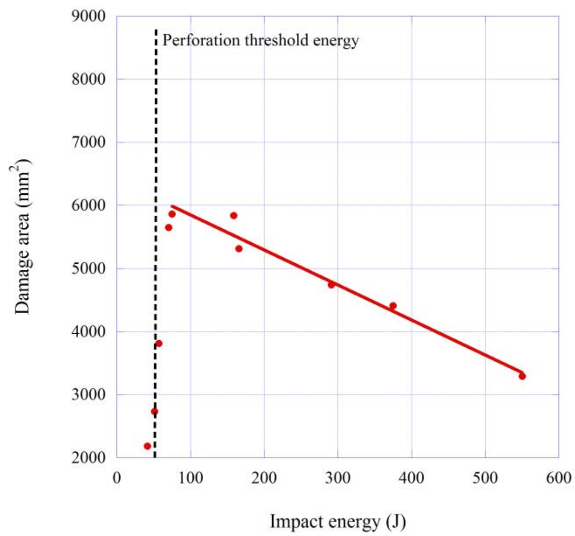
A qualitative study of these figures reveals that the damage area was larger for impact velocities close to the perforation-threshold velocity, as can be seen in the Fig. 5b, 6b, and 7b. Meanwhile, for impact velocities below (Fig. 5a, 6a, and 7a) and above (Fig. 5c, 6c, and 7c) the perforation-threshold velocity, the damage extent was less.

In the images obtained by the C-Scan inspection, the typical damage shape generated by impacts on quasi-isotropic laminates could not be seen, previously displayed in Fig. 4. The C-Scan inspection gave the projection of the area and, therefore, the lamination between adjacent plies could not be observed. From the C-scan images, the extent of the damaged area was determined. Fig. 8 shows the damaged area vs. the impact energy. In these images, two zones can be distinguished, separated by a straight line (discontinuous line) corresponding to the perforation-threshold energy.

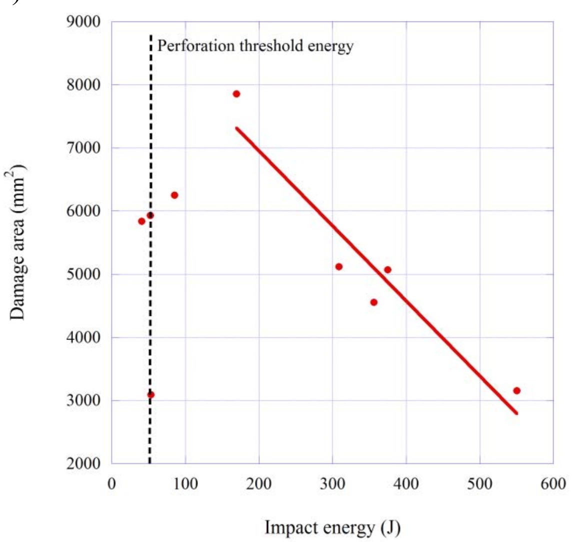
In all the cases, the maximum damage areas were reached for impact energies close to the perforation-threshold energy. For energies below the perforation energy the damage area increased with energy. While for energies greater than the perforation energy, the damage area diminished with greater energy. Similar tendencies have been reported by the authors for woven laminates with similar load states [27], although the size and shape differed. In the woven laminate the damage shape can be approximately circular and the damage area is larger. Furthermore, this quantitative study is consistent with the qualitative study (Fig. 5, 6, and 7), which has previously been described.



(a)



(b)



(c)

Fig. 8. Extent of the damage area vs. the impact energy for the glass/vinylester quasi-isotropic laminate. a) non-loaded, b) uniaxial preload y c) biaxial preload

Table 3 shows the maximum damage area for the more similar impact energies in the three cases studied. This result reveals that the damage area was greater in the non-preload specimens than in the uniaxially and biaxially preloaded specimens. The percentage difference regarding the non-loaded state was 17% for uniaxial preload state and 22% for the biaxial. This difference could be due to the increment of effective stiffness in panels subjected to membrane loads, which decreases the displacement of the panels, and accordingly reduces the damage area. This phenomenon is more significant at the perforation-threshold energy, where the bending of the panels is the greatest.

Load case	Impact energy (J)	Damage area (mm^2)
Non-load	59.97	4563
Uniaxial	57.08	3809
Biaxial	53.22	3091

Table 3. Extent of damage area for the glass/vinylester quasi-isotropic laminate, at similar impact energies

4. CONCLUSIONS

In this work, the influence of in-plane loadings (uniaxial and biaxial) on the behaviour of panels made of quasi-isotropic glass/ vinylester composite laminate materials under impact load was investigated. The residual velocity, the perforation-threshold velocity and the damage extension was determined. From the analysis of the experimental tests the following conclusions were drawn:

- In-plane loadings states, both in uniaxial as biaxial conditions, the perforation-threshold velocity decreases with respect to the non-loaded case.
- The damaged area follows the same trends in the preloaded specimens as in the non-preloaded cases.
- The damaged area grows with increased impact energy until the perforation-threshold energy is reached, beyond which the damaged area decreases. These tendencies are similar to those described for woven laminates, with similar membrane loads.
- For similar impact energies, the extent of damage area was greater in the non-loaded case.

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Figure captions

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Fig. 5 Damage area for the glass/vinylester quasi-isotropic laminate without membrane load: a) 108 m/s, b) 136 m/s y c) 289 m/s
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Table 2. Table 2. Perforation-threshold velocity estimated from Eq. 1
Table 3. Extent of damage area for the glass/vinylester quasi-isotropic laminate, at similar impact energies