IMPACT BEHAVIOUR OF COMPOSITE PANELS SUBJECTED TO IN-PLANE LOAD

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Abstract

This work investigates the effect that a biaxial preload causes on woven laminate panels of glass fibre and polyester matrix subjected to high-velocity transversal impact. For this, an existing analytic model based on energy considerations was used, this being modified to include the presence of a preload.

The results of the analytic model for the biaxial preload state were compared with the results found for the free state of preload. Minimal difference was found between the two results. Therefore, numerical simulations were made to order to study the effect of the preload in greater detail; furthermore, experimental tests were made, validating the analytic and numerical model.

In general, the two methods revealed minimal differences between the values of the ballistic limit and those of the residual velocity.

1 Introduction

The structural elements used in the transport industry can be subjected to impulsive loads during their lifetime of service or during operations of assembly and maintenance. The increasing use of glass/polyester composites in manufacturing components of vehicles and vessels make it necessary to determine their behaviour under these types of loads, given their greater sensitivity to impact damage than metal materials [1]. Two types of impact are usually considered, low- and high-velocity impact, and these cause different types of damage. The first type can produce internal defects in the form of delaminations that significantly reduce the residual strength and stiffness of the structure without resulting in catastrophic failure. High-velocity impact can perforate the structure, compromising its structural integrity. Several studies examine the behaviour of structural elements subjected to low-velocity impact [2, 3] and high velocity impact [4, 5].

Most studies on impact focus on load-free panels; however, in many cases the structural elements can be submitted to in-plane loads. A relatively small number of studies have considered the impact behaviour of uniaxially preloaded panels under tension [1, 4, 6, 7] and compression [8]. However, this preloading condition does not properly reproduce the complex stress-state that appears in practical structural problems. A few more realistic tests have been made in which the panel is statically biaxially preloaded, although most of the available bibliography concentrates on low-velocity impact [9, 10,11]. Also, most research has centered on carbon/epoxy laminates subjected to low-velocity impact, and much less information is available on woven laminate and glass/polyester material under high-velocity impact. Diverse results have been published on the behaviour of preloaded panels undergoing impact. Whittingham et al. [11] affirm that, in carbon-fibre laminated panels with biaxial preload, the penetration depth, peak load, and absorbed energy are independent of the preload at low-impact energy. Khalili et al. [12] also state that in uniaxilly reinforced graphite/epoxy composites the influence of the preload in the contact force is marginal; nevertheless, the deflection and contact duration are infuenced significantly by the preload. However, Nettles et al. [6] indicate that in IM7/8551-7 composites, when the tensile preload augments, the peak load also does, diminishing the compression after impact strength. Chiu et al. [7] observed that a tensile preload enlarges the damage area when the energy of the impact surpasses a certain value for T300/976 quasi-isotropic graphite/epoxy laminates.

A useful technique to study this behaviour is first to use an analytical model that provides approximate solutions and allows the understanding of the influence of different parameters that control the impact process. In the case of composite panels without preload, a great number of studies present analytic models to evaluate the behaviour of such materials under impact loads both at low velocity [13, 14, 15] as well as high [16, 17, 18, 19]. Many of the models for high-velocity impact are based on energy considerations, analysing the loss in kinetic energy of the projectile due to the energy consumed during the process of elastic deformation of the panel, energy absorbed in the failure process of the panel, and the energy spent in accelerating the panel after impact.

Naik and Shrirao [18] proposed an energy model based on that of Moyre et al. [17] to analyse the behaviour of two-dimensional woven-fabric composites that take into account different energy-absorption mechanisms that can appear in these types of materials: cone formation, tensile failure of primary yarns, deformation of secondary yarns, delamination, matrix cracking, shear plugging, and friction during penetration. With the use of this model, the ballistic limit, contact duration, and damage area are predicted. The main difference between the two models is the greater number of absorption mechanisms incorporated in the model of Naik and Shriano [18]. Lopez-Puente et al. [19] use an energy model in the study of carbon/epoxy tape and woven laminates subjected to a high-velocity impact, which also considers different contributions to the energy absorbed by the panel. It differs from the previous ones in using distance instead of time as an integration variable and in resolving the differential equation of the projectile velocity with perturbation techniques, enabling the analytic resolution of the equation and thereby providing a closed expression for the ballistic limit. Other models are based on considering the deformation that results in the panel due to the formation of a cone, such as that proposed by Vinson and Walter [16]. These authors studied a carbon-fibre weave AS4/3501-6 using a model based on conical-shell theory and geometric considerations to predict the deformation of the panel and the displacement of the cone formed. Their model requires two tests to be made at different velocities to determine the relationship between the strain, failure and the impact velocity. With this model, they were able to predict the ballistic limit and the residual velocity.

Several authors have used analytical models to study preloaded panels subjected to impact, but only for the case of low-velocity impact. Sun and Chattopadhyay, [20] analysed the behaviour of cross-ply laminate composite plates under initial biaxial stress when submitted to an impulsive low-velocity load, using a nonlinear analytic model that combines the Hertz contact-force law with plate theory. These researchers developed formulas to estimate the deflection, the stress and the energy absorbed by the panel. A similar approach was used by Khalili et al. [12] to analyse the same type of impact of uniaxially reinforced graphite/epoxy panels subjected to uniaxial and biaxial tensile pre-stresses. These authors used Sveklo's contact law due to the orthotropic nature of the plate, analysing the influence of the impactor mass, velocity, and energy of the impact in the response of the plate. The modelling of the behaviour against high-velocity impact of the preloaded panels is a complex matter, for which no references involving analytical models were found in the literature.

Nevertheless, numerical simulations are needed to achieve more accurate results in order to minimize the number of experimental tests and hence to reduce design costs. These models have to be assessed through experimental tests. As in analytical models, the theoretic studies made on the preloaded panels subjected to impact concentrate on low-velocity impact. Kelkar et al. [1] analyse the behaviour against impact on AS4/3501 graphite-epoxy panels employing a model of finite elements using the criterion of Tsai-Wu to predict the failure of the panel. The above authors affirm that under low-velocity impact, the behaviour is equivalent to a quasi-static indentation, and thus use a static model. Zhang et al. [8] study T800/924 carbon/epoxy laminate panels subjected to in-plane compressive load followed by low-velocity impact using the FEM code in a sequential way. They first calculate the compressive stresses of the preloaded panel and afterwards consider this state as the beginning of the impact problem. They use the damage model of Chang and Chang [21] to predict the failure of the panel during impact.

In this study the influence of static tensile biaxial preload on the behaviour of panels under high-velocity impact load was examined. A plain woven laminate of a glass/polyester material is used. An analytical model was used to estimate the ballistic limit and residual velocity in preloaded panels, combining those proposed by Vinson and Walker [16], Moyre et al. [17] and Naik et al. [18], while adding the effect of the presence of preload. In addition, a numerical model has been used, using the criterion of Hou et al. [22] to predict the progressive failure of the panel. The results of the models were compared to those resulting from high-velocity impact tests on glass/polyester panels with a biaxial static preload, at velocities between 140 and 525 m/s.

2 Analytical Model

For the present study an analytical model was developed, based in the models of Moyre et al. [17], Naik et al. [18, 23, 24, 25] and Vinson et al. [6], while adding the effect of an in-plane preloading. This model allows an estimate of the residual velocity of the projectile (hence the ballistic limit) and the energy absorbed during the penetration of the laminated panel (E_T), Eq. 1.

$$E_T = E_{TF} + E_{ED} + E_{KE} + E_{DL} + E_{MC} \qquad (1)$$

For the calculation of E_T, Moyre et al. [17] proposed three energy-absorption mechanisms: tensile failure of the primary yarns (E_{TF}), elastic deformation of the secondary yarns (E_{ED}), and the kinetic energy of the moving cone formed on the back side of the panel (E_{KE}). In addition to these, two new terms were added to improve the model accuracy: delamination damage (E_{DL}) and matrix cracking (E_{MC}), which were proposed by Naik et al. [18, 23, 24, 25].

The following hypotheses were considered:

- The projectile is perfectly rigid and remains totally indeformable over impact.
- The energies absorbed by shear plugging and friction are considered negligible [18, 24].
- The energies absorbed by tensile failure of primary yarns and deformation of secondary yarn are treated independently (Fig.1).
- Longitudinal and transversal wave velocities are the same in all the layers.
- The velocity of projectile remains constant in each time interval.

The impact energy (E_i) for the projectile of mass (m) that moves at a velocity (V_0) is given by the following expression:

$$E_c = \frac{1}{2} \cdot m \cdot V_0^{\,2} \qquad (2)$$

The residual velocity and ballistic limit were calculated from the absorbed energy during the impact.

Preliminary considerations

In this study, the impact on composite laminates was processed for instants of time (Δt).

The transverse impacts on composite laminates generate in these longitudinal and traverse waves.

$$V_t = \sqrt{\frac{G_{23}}{\rho}} \qquad (3)$$

$$V_l = \sqrt{\frac{\sigma}{\rho}} \qquad (4)$$

where V_t is the velocity of the transversal wave, G_{23} is the transverse shear modulus, ρ is the density of composite, V_l is the velocity of the longitudinal waves, and σ is the failure stress of the composite.

The radius of the cone (R_c) formed on the back side of the plate and the distance covered by longitudinal waves (R_l) for each instant of time were calculated by the following equations:

$$R_{c_i} = V_t \cdot \Delta t \qquad (5)$$

$$R_{l_i} = V_l \cdot \Delta t \qquad (6)$$

The velocity of projectile for each instant of time (V_i) was determined by

$$V_i = \sqrt{\frac{\frac{1}{2} \cdot m \cdot V_0^{\,2} - E_{T(i-1)}}{\frac{1}{2} \cdot (m + M_{C_i})}} \qquad (7)$$

where E_{i-1} is the absorbed energy in the previous instant and M_{Ci} is the mass of cone for each instant of time.

$$E_{T(i-1)} = E_{TF(i-1)} + E_{ED\,(i-1)} + E_{KE\,(i-1)} + E_{DL\,(i-1)} + E_{MC\,(i-1)} \qquad (8)$$

The mass of the cone formed was defined by

$$M_{C_i} = \pi \cdot R_{C_i}^2 \cdot e \cdot \rho \qquad (9)$$

where e is the thickness of the target.

If the projectile velocity is known in each instant of time, then the deceleration of projectile for the interval time (a_i) can be calculated as

$$a_i = \frac{V_{i-1} - V_i}{\Delta t} \qquad (10)$$

Also, the distance travelled by the projectile (Z_i) or the depth of the cone can be calculated with the following equation:

$$Z_i = \sum_{i=0}^{i=n} \left(V_{i-1} \cdot \Delta t - \frac{1}{2} \cdot a_i \cdot (\Delta t)^2 \right) \qquad (11)$$

And the deformation in the primary yarns (Fig.1) was calculated with this equation [16]:

$$\varepsilon_i = \frac{Z_i \cdot \sin(\theta_i) \cdot \cos(\theta_i)}{R_{p_i} \cdot \ln\left(\frac{R_{c_i} + R_{l_i}}{R_{l_i}} \right)} \qquad (12)$$

where R_{pi} for this analytical model was assumed equal to radius of the projectile and

$$\theta_i = \tan^{-1}\left(\frac{R_{c_i}}{Z_i} \right) \qquad (13)$$

Energy absorbed due to tensile failure of primary yarns

Fibres that undergo direct impact from the projectile are know by the name of primary yarns (Fig.1), which failed in tension on reaching the failure strain.

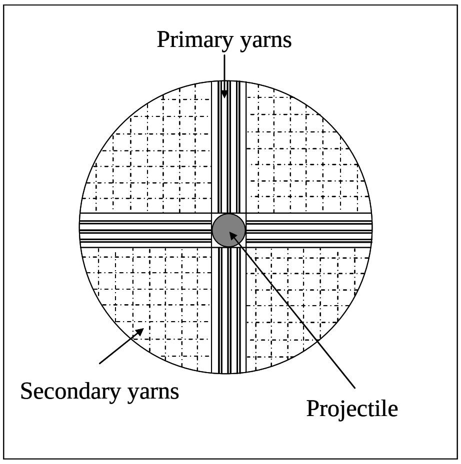


Fig 1. Location of the primary and secundary yarns in a composite plate.

The energy absorbed by tensile failure of primary yarns is

$$E_{TF\,i} = c \cdot e \cdot \int_0^{R_{li}} \left(\int_{\varepsilon_{in}}^{\varepsilon_r \cdot b^{(x/c)}} \sigma(\varepsilon) \cdot d\varepsilon \right) \cdot dx \qquad (14)$$

where c is the yarn width, $\sigma(\varepsilon)$ is stress in function of the strain, ε_{in} is initial strain (zero in the non preload case), ε_r is the failure strain of the composite, and b is the stress wave transmission factor.

Energy absorbed due to deformation of secondary yarns

The energy absorbed by elastic deformation of secondary yarns (Fig. 1) in the composite laminate was calculated from area under stress-strain curve of material, which in this case presents linear behaviour.

The calculation of the energy absorbed by elastic deformation of secondary yarns was made using the following equation:

$$E_{ED_i} = 4 \cdot E \cdot \varepsilon_r^2 \cdot e \cdot \pi \cdot \int_{D/2}^{R_{ci}} \left(\frac{R_{c_i} - r}{2 \cdot R_{c_i} - D} + \varepsilon_{in} \right)^2 \cdot r \cdot dr \qquad (15)$$

where E is the tensile modulus of the composite, D is the diameter of projectile and r is the distance from the impact point, being $\varepsilon = \varepsilon_r$ at $r = D/2$ and $\varepsilon = 0$ at $r = R_{c_i}$.

Kinetic energy of the moving cone formed on the back side of the plate

The kinetic energy of the moving cone is defined by the following equation:

$$E_{KE_i} = \frac{1}{2} \cdot M_{c_i} \cdot V_{c_i}^{\,2} \qquad (16)$$

where V_{ci} is the velocity of the cone formed, which is equal to the velocity of projectile (V_i) for each instant of time.

Energy absorbed due to delamination and matrix cracking

The formation of the cone on the back side of the plate produces two more damage mechanisms that contribute to the process of energy absorption. These damage mechanisms are called damage by delamination, and matrix cracking.

The damaged area that contributes to the energy-absorption process during the impact is confined to the cone radius, and thus for this analytic development, it was assumed that the area that contributes to the absorption mechanism by delamination and matrix cracking is given by the cone radius at each instant in time. Furthermore, the damaged area is estimated as a circular surface.

The energy absorbed due delamination was calculated with the following equation:

$$E_{DL_i} = A \cdot R_{c_i}^{\ 2} \cdot G_{IIC} \qquad (17)$$

where A is the quasi-lemniscate reduction area and G_{IIC} is the critical dynamic-strain energy-release rate in mode II.

The energy absorbed due matrix cracking was calculated with the following equation:

$$E_{MC_i} = A \cdot R_{c_i}^{\ 2} \cdot E_{MT} \cdot e \qquad (18)$$

where E_{MT} is the energy absorbed by matrix cracking per unit volume.

3 Analytical Results

Particularizing the model for a fibreglass/polyester laminate, for which the properties are shown in Table 1, the contribution of each energy-absorption mechanism was calculated from the energy absorbed due to each mechanism for non-preloaded and biaxial preloaded panels.

Composite laminate properties were easily determined by conventional tests in the laboratory and by consulting the literature.

Table 1. Properties of the glass/polyester laminate

Property	Value
ρ	1980 kg/m^3
E	10.13 GPa
G_{23}	3.4 GPa
G_{IIC}	2800J/m^2
σ_r	367.39 MPa
ε_r	0.03568
ε_{in}	0 in non-preloaded panel 1.127% in preloaded panels
b	0.9
A	1
E_{MT}	0.9 MJ/m^3

Figs. 2, 3, and 4 present the relationship of the normalised energy of each mechanism as a function of the time in the non-preloaded panels. The normalised energy is defined as the ratio between the energy absorbed by each mechanism and the total energy absorbed by the laminate.

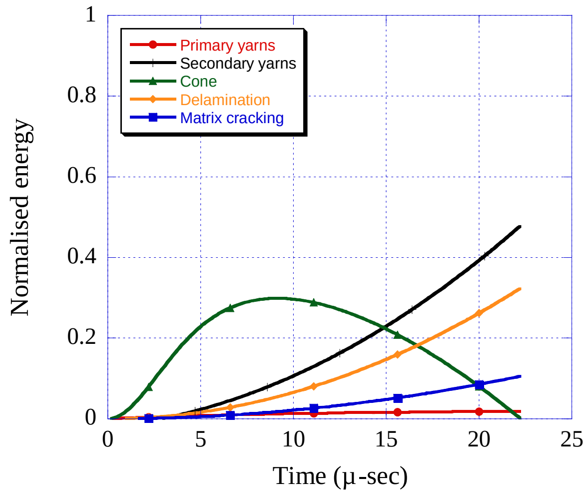


Fig. 2. Normalised energy versus time for non-preloaded panels at an impact velocity of 163 m/s.

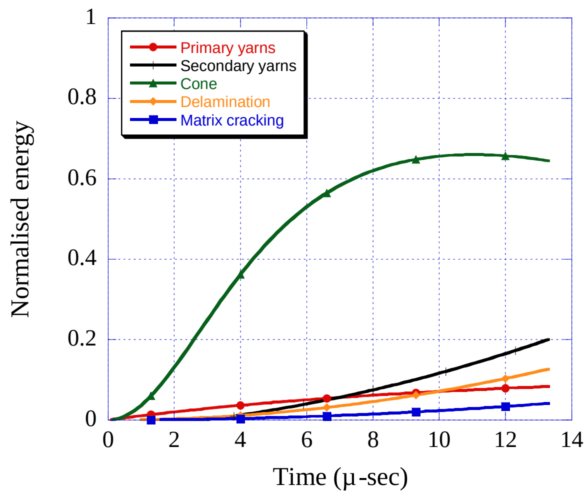


Fig. 3. Normalised energy versus time for non-preloaded panels at an impact velocity of 216 m/s.

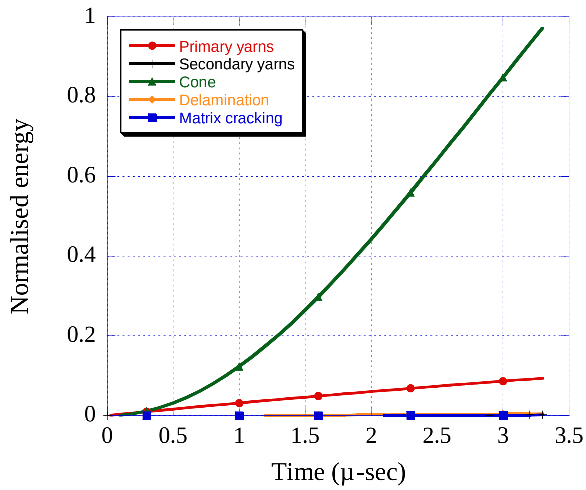


Fig. 4. Normalised energy versus time for non-preloaded panels at an impact velocity of 512 m/s.

For impact velocities lower than the ballistic limit (Fig. 2), the greatest contribution to the decrease in kinetic energy of the projectile corresponds to the energy absorbed due to deformation of secondary yarns and due to delamination. On the other hand, when the velocity of the impact increases, that corresponding to the kinetic of a moving cone formed on the back side of the panel becomes more important, as can be seen in Fig. 3 for a slightly higher velocity and Fig. 4 for a higher velocity than ballistic limit. It has been observed that neither the energy absorbed due to tensile failure of primary yarns nor matrix cracking contributes significantly to the energy absorbed by the panel.

The behaviour described above is not affected by the existence of an initial deformation of 1.13% that corresponds to a preload of 51 kN, as can be seen in Figs. 5, 6, and 7.

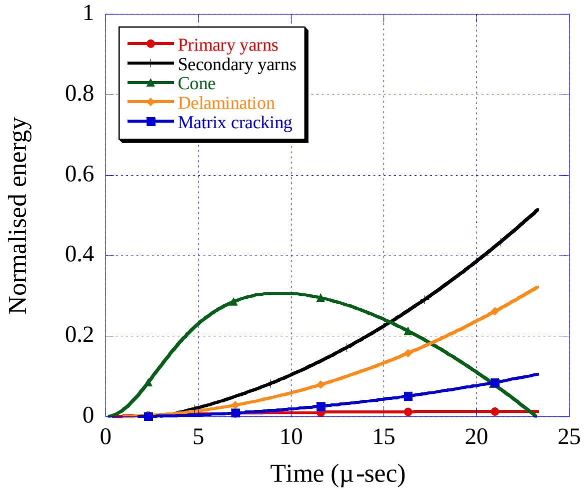


Fig. 5. Normalised energy versus time for biaxial preloaded panels at an impact velocity of 171 m/s.

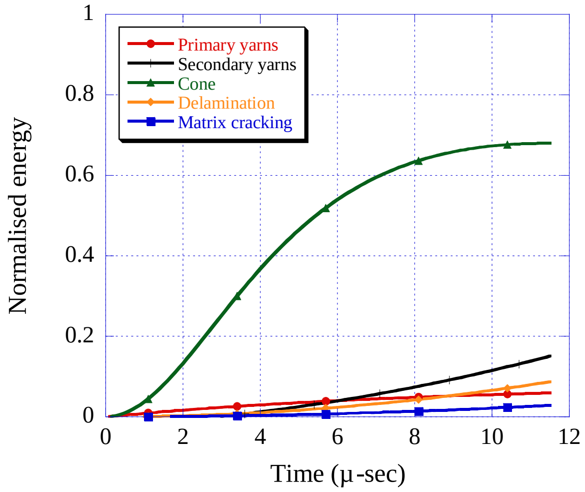


Fig. 6. Normalised energy versus time for biaxial preloaded panels at an impact velocity of 227 m/s.

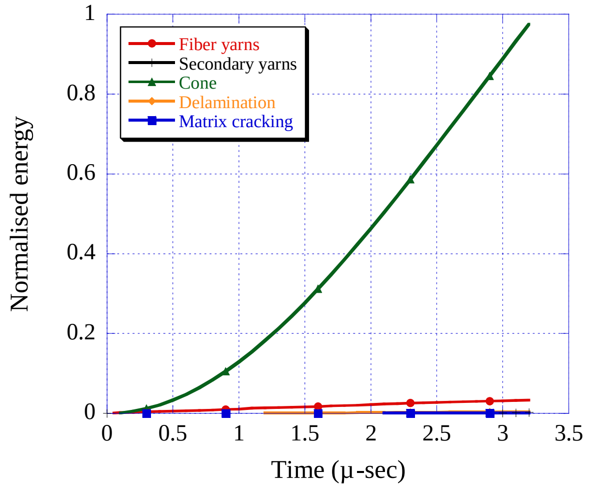


Fig. 7. Normalised energy versus time for biaxial preloaded panels at an impact velocity of 521 m/s.

4 Numerical Model

The analytical model shows little influence of the in-plane load on the ballistic limit. In order to establish whether this influence is a true tendency, decreasing the residual velocity after impact, a numerical simulation with the finite-element method was made. In addition, the possibility of arranging a validated numerical code in order to simulate with accuracy the behaviour of composite laminates under ballistic impact is of great interest. For the numerical simulations, the finite-element commercial code ABAQUS was used; this software allows the creation of material models through user subroutines.

The material model used to describe the behaviour of woven glass fibre/polyester laminates under ballistic impact derives from the Hou et al. model [22], which was developed for carbon-fibre epoxy-tape laminates. Some modifications were required mainly due to the different reinforcement architecture. Only two of the four failure criteria were used:

- Fibre Failure; which describe both tensile and compression breakage; fibres run in two directions, hence two different equations are used: Eq. (2) for fibres at 0º, and Eq. (3) for fibres at 90º.

$$d_{f1} = \left(\frac{\sigma_1}{X_T} \right)^2 + \left(\frac{\tau_{12}^2 + \tau_{13}^2}{S_f^2} \right)^2 \qquad (19)$$

$$d_{f2} = \left(\frac{\sigma_2}{Y_T}\right)^2 + \left(\frac{\tau_{12}^2 + \tau_{23}^2}{S_f^2}\right)^2 \qquad (20)$$

where X_T and Y_T are the fibre strength properties, in the 1 and 2 directions respectively, and S_f is through thickness shear strength.

- Delamination; the damage variable follows the equation

$$d_d = \left(\frac{\sigma_3}{Z_r}\right)^2 + \left(\frac{\tau_{23}}{S_f}\right)^2 + \left(\frac{\tau_{13}}{S_f}\right)^2 \qquad (21)$$

This criteria applies only to out-of-plane tension ($\sigma_{33} > 0$); Z_r represents the interlaminar strength, while S_f corresponds to the through thickness shear strength.

When the damage variable reaches the value of 1, the material point is considered to have failed completely and hence for the rest of the simulation the stress components participating in the criterion are set to zero. For a smooth transition when the stress is set to zero, the following equation is used to correct the stress components:

$$\sigma_{ij}^{cor} = \sigma_{ij}\left(1 - \frac{2 - e^{s(d_i - 1/2)}}{2 - e^{s/2}}\right) \qquad (22)$$

Where s indicates the smoothness and d_i is the damage parameter. An element erosion criterion was adopted in order to simulate the penetration of the laminate. This criterion eliminates the element reached.

The material model used for the projectile was linear elastic, because in the experimental test no plastic deformation was found in the tempered steel spheres after penetration.

Fig. 8 represents the undeformed configuration of the mesh. Eight-node hexahedral elements were used for the composite plate, whereas four-node tetrahedral elements were chosen for the steel sphere projectile.

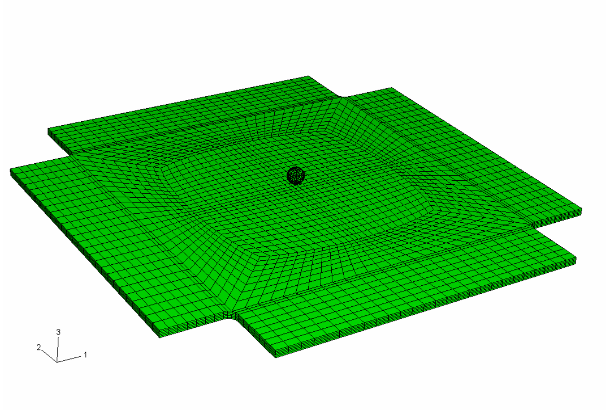


Fig. 8. Mesh used in the simulation

In the Fig. 9 the perforation of the plate could be shown; the projectile does no deforms after penetration.

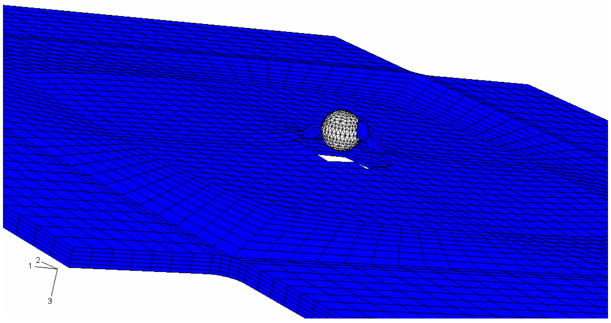


Fig. 9. Perforated plate impacted at 300 m/s, with in-plane load.

5 Experimental tests

For experimental validation of the results of the analytical and numerical models, impact tests were made with a gas gun under in-plane tensile preloaded panels. The panels were made by 5 plies of E-glass fibre and polyester resin plain weave and a thickness of 3.19 mm.

To keep the specimens pre-loaded during the impact test, a special experimental device was designed and manufactured (Fig. 10), and then it was coupled to a gas-cannon set-up. The device allows holding different static loads in two mutually orthogonal directions by two actuators, vertical and horizontal. These actuators may work together or independently. The set-up has a hydraulic device that applies and controls the loads applied to the specimen.

Fig.10. Biaxial preload device

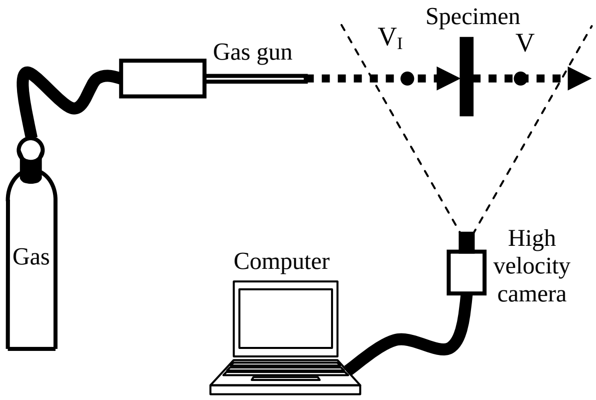
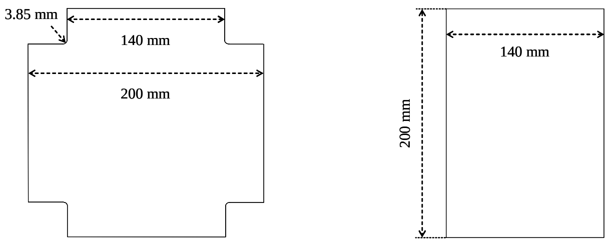


Fig.12. High-velocity impact-test set-up

The tests made on panels with a static biaxial preload (51 kN load applied on each axis), were compared with those made with non-preloaded panels. Cross-shape specimens (200mm x 200mm) were used for the biaxial tests, while rectangular specimens (140mm x 200mm) were used for the non-preload tests (Fig. 11). The geometry and the shape of the first specimens were selected, after a full-numerical simulation of the problem, in order to reach a uniform stress state in the impacted zone.



(a) (b)

Fig.11. Geometry of the specimens used in the impact tests, (a) biaxial preloaded and b) non-preloaded

The impact tests were made using a one-stage gas cannon manufactured by SABRE BALLISTIC. The specimens were impacted by steel spherical projectiles 7.5 mm in diameter, launched at velocities ranging from 140 m/s to 525 m/s. During the impact tests, both the projectile striking velocity and the residual velocity were measured by a high-speed video camera PHOTRON FASTCAM-ultima APX (Fig. 12).

6 Results

Figs. 13 and 14 present the residual velocity as a function of the impact velocity for the analytic and numerical model and their validation with the experimental results. Both offer a good approximation to the experimental results. The differences between the models and the experimental results are somewhat higher in the case of the preloaded panels.

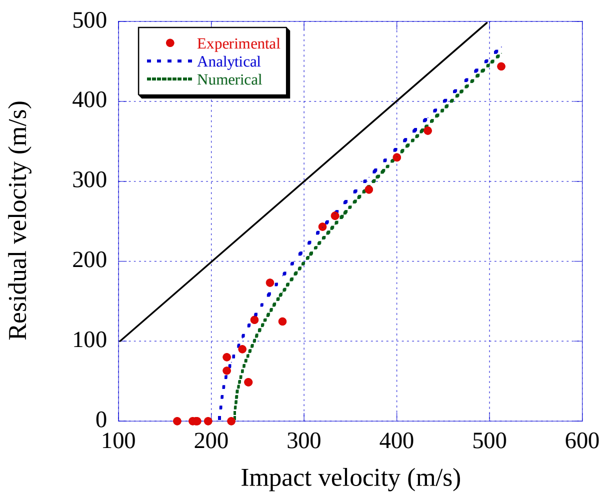


Fig.13. Residual velocity vs. impact velocity in non-preloaded panels

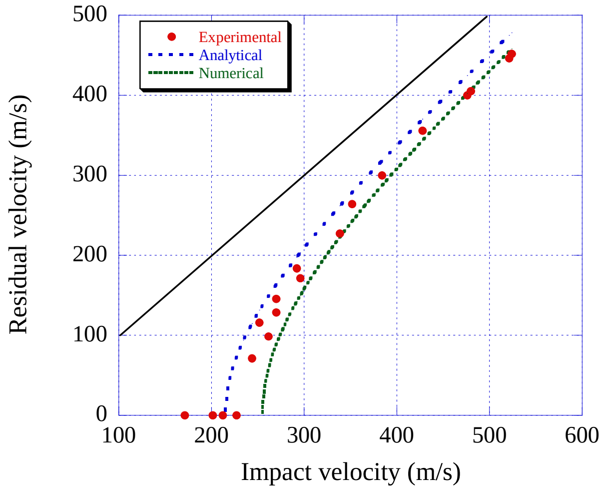


Fig.14. Residual velocity vs. impact velocity in biaxial preloaded panels

The differences between the residual-velocity curves for the non-preloaded and preloaded panels are not very high, given that the preload applied (51 kN) corresponds to a tension state of less than 30% of the one that caused failure.

Also, the ballistic limit was determined from result of the analytic and numerical models (Table 2). The experimental ballistic limit was determined by the following Eq. [26, 27]:

$$V_r = \begin{cases} 0 & ,0 < V_o \leq V_L \\ B \cdot (V_o{}^p - V_L{}^p)^{1/p} & ,V_o > V_L \end{cases} \qquad (23)$$

where V_r is the residual velocity, V_o the impact velocity, V_L the ballistic limit, and p and B are two empirical adjusting parameters.

Table 2. Ballistic limit

Ballistic limit (m/s)	Load case	
	Non preload	**Biaxial preload**
Experimental	211	234
Analytical	209	215
Numerical	225	255

It was observed that the preloading of the composite panels increased the ballistic limit. A good correlation was found between experimental, analytical and numerical results (Table 2), which demonstrate that the models used in this study faithfully reproduce the material behaviour.

7 Conclusions

The influence of the preload conditions (biaxial) on the behaviour of plates made of woven glass/polyester composite laminate materials under impact loading has been studied to determine the residual velocity and the ballistic limit.

In the biaxially preloaded panels, the ballistic limit for the projectile used proved approximately 11% higher. Both the analytic model and the numerical one reproduce this behaviour and can predict the ballistic limit for the non-preloaded panels with a precision of 2% and with 8% in the case of the preloaded panels.

For velocities lower than the ballistic limit, the contribution of the total energy of failure of the secondary fibres was the greatest, while, for velocities far above the ballistic limit the greatest contribution was the formation of the cone. The existence of preload did not affect the contributions of each energy term.

The energy absorbed due to tensile failure of primary yarns and due to matrix cracking did not contribute significantly to the reduction of the kinetic energy of the projectile.

Acknowledgements

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