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Analytical Model for Energy Absorption Capabilities of Glass/polyester Panels Subjected to Ballistic Impact

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Abstract

This work examines the behaviour of glass/polyester panels under high-velocity impact. A theoretical analysis of the problem by an engineering model based on energy balance is validated by experimental impact tests. A gas gun was used for the tests, firing high-velocity projectiles against the panels. With the analytical model, the energy absorbed by the glass/polyester panels on impact (at velocities of 140 - 525 m/s) is calculated, and therefore the residual velocity of the projectile and the ballistic limit. Both these variables are very close to the results of the experimantal tests.

1. Introduction

Many vehicles are now equipped with components made of composite materials on account of their low density, good mechanical performance, chemical stability and low cost. During the operations of assembly or maintenance, and in the service life of these components, they may be subjected to low- or high-velocity impacts, so both static and dynamic loads should be considered in their design. One of the limitations to the use of composite materials in structural applications is that these loads may produce damage that modifies the behaviour of the elements [1], and this imposes the need to study the impact behaviour of the composite materials.

Low-velocity impacts are considered dangerous to composite materials because the damage they cause could not be visible to the naked eye [2]. The importance of studies of this occurrence is reflected in the large number of works on the subject [3–5]. The main form of damage observed in composites subjected to low-velocity impact is delamination, which reduces the compression strength of the material.

The danger of high-velocity impacts is that they can affect the structural integrity of the component. Various mechanisms of energy absorption are involved in high-velocity impact (tensile failure of fibres, elastic deformation of the composite, delamination, matrix cracking, shear plugging of the projectile into the target, and the inertia of the composite). The factors that control the absorption of energy are the tensile properties of the matrix, the arrangement of the fibres in the composite, and the inter-laminar strength [6]. A theoretical model is necessary to quantify the energy absorbed by the material during the impact, which is useful in the design of a structural component.

Several numerical methods can be used in the study of the impact behaviour of composite materials: the Finite Elements method [7] or the Difference Finite method [8]. Given the anisotropic nature of the composites, three-dimensional models can be required in design, which raises the complexity and the computational cost of the model, but simplified analystical models can provide a sufficiently accurate solution at lower cost. They are valuable in the preliminary design of the structures and at the stages of optimization since they reveal in a simple way the influence of the parameters of the problem in the response of the element.

The impact behaviour of woven laminates has been studied by several investigators [9-11] who offer empirical formulae to calculate the ballistic limit, for example that of Lyons [9] for nylon fabrics, or that of Van Gorp et al.[10] for polythene fibres in a polythene matrix. Moyre et al. [6] developed a model for woven laminates, validated for three composites of nylon, aramid and dyneema fibres. López-Puente [11] developed an analytical model based on energy approaches to determine the residual velocity of a projectile after the perforation of a composite panel, a model which he validated for carbon/epoxy laminates (woven and tapes) and which can also be used to calculate the ballistic limit.

In this work the model of López-Puente [11] was modified to take account different mechanisms of energy absorption in order to determine the residual velocity of the projectile after penetration. This model was validated by impact tests of a fiber glass-E/polyester woven laminate. Experimental impact tests were done with a gas gun at velocities of 140 to 525 m/s.

2. Modelization

The analytical model developed uses an energy balance in which the kinetic energy of the projectile, E_k, is absorbed by the laminate by three different mechanisms: laminate breakage due to crushing, E_c; linear momentum transferred from the projectile to the detached part of the laminate, E_m; and breakage by tensile fibre failure, E_f. Elastic energy absorptions are usually neglected in analytical models of the penetration process since their contribution is insignificant [3].

The energy balance constitutes an equation from which it is possible to determine the projectile velocity during penetration and hence the residual velocity.

$$-dE_k = dE_c + dE_m + dE_f \tag{1}$$

Analysing the energetic terms of this equation:

Kinetic energy of the projectile. The energy balance is formulated by a spatial integration. The variable x is used for the position of the projectile, being $x=0$ when the impactor contacts the laminate. Between x and $x+dx$, the projectile will lose an amount of energy given by:

$$-dE_k(x) = \frac{1}{2} m_p\, d(v^2(x)) \tag{2}$$

en which m_p is the projectile mass and v its velocity.

This kinetic energy loss is absorbed by the laminate by three different mechanisms as follows:

Energy absorbed by laminate crushing. When the projectile impacts the plate, it breaks the laminate ahead of it by compression. The force can be calculated from the product of the compressive strength of the laminate, σ_c, and the frontal projectile area, $A(x)$. The corresponding energetic term is written as:

$$dE_c(x) = \sigma_c\, A(x)\, dx \tag{3}$$

In a spherical projectile, $A(x)$ varies with the depth of penetration.

Energy absorbed by linear momentum transfer. Once the differential laminate volume $A(x)\cdot dx$ is detached from the laminate, it is accelerated from rest to the projectile velocity. The associated energy may be calculated as:

$$dE_m(x) = \frac{1}{2}\, A(x)\, dx\, \rho_c\, v^2(x) \tag{4}$$

in which ρ_c is the composite density.

Energy absorbed by tensile fibre failure. Fibre failure due to tensile stress appears before laminate crushing. It can be calculated with the well-known equation for the specific energy needed for tensile failure:

$$\psi_f = \frac{1}{2} X_t\, \varepsilon_f \tag{5}$$

in which X_t is the laminate tensile strength and ε_f the failure tensile strain. It is estimated that the affected area is a square whose side is $2r$ (r being the projectile radius). The term is multiplied by 2 because of the biaxial shape of the tension field. The equation associated with this absorption mechanism is:

$$dE_f(x) = \psi\, dV \cdot 2 = \left[\frac{1}{2} X_t\, \varepsilon_f\, (2r)^2 dx\right] \cdot 2 \tag{6}$$

The four differential energy terms can then be grouped as follows:

$$-\frac{1}{2} m_p\, d(v^2(x)) = \sigma_c\, A(x)\, dx + \frac{1}{2}\, A(x)\, dx\, \rho_c\, v^2(x) + \left[\frac{1}{2} X_t\, \varepsilon_f\, (2r)^2 dx\right] \cdot 2 \tag{7}$$

Using the change of variable $w=v^2$ and making some simplifications, the previous equations is converted to a non linear first order differential equation which could be resolved with any well known numerical method such as Runge-Kutta:

$$\begin{cases} -\dfrac{dw}{dx} = \dfrac{2\sigma_c\, A(x)}{m_p} + \dfrac{A(x)\, \rho_c\, w}{m_p} + \dfrac{8 X_t\, \varepsilon_f\, r^2}{m_p} \\ w(0) = (v_i)^2 \end{cases} \tag{8}$$

3. Experimental procedure

To validate the results of the analytical model, impact tests were done with a fibre glass-E/polyester woven laminate, of five plain weave plies and 3.19 mm thickness. Rectangular specimens of 140 x 200 mm were used. The material properties required by the model were obtained easily by conventional tests in the laboratory, Table 1.

Table 1. Properties of the glass/polyester material

Property	ρ_c [kg/m^3]	X_t [MPa]	ε_f
Value	1980	367	0.036

The impact tests were done with a SABRE BALLISTIC gas gun with a spherical projectile of 7.5 mm diameter and 0.0017 kg mass, fired at between 140 m/s and 525 m/s. All the tests were recorded by a high-speed PHOTRON FASTCAM-ultima APXvideo camera that allowed measurement of the impact velocity and residual velocity.

4. Results

The values of the residual velocity versus impact velocity are shown in Figure 1. The model is seen to calculate accurately the impact behaviour of the glass-E/polyester woven laminate.

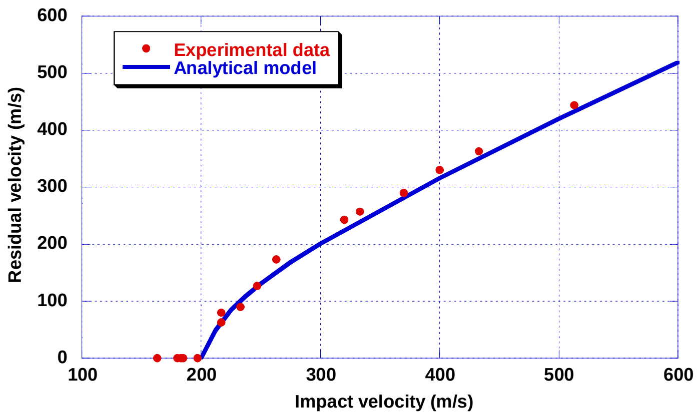

Figure 1. Residual velocity versus impact velocity

The experimental ballistic limit was calculated from a mathematical expression of the adjusted curve proposed by Zucas et al. [3] and then validated, experimentally and numerically, by Kasano [12]. A ballistic limit of 211 m/s was obtained, similar to the 200 m/s obtained in the analytical model

At velocities around the ballistic limit the main absorption mechanism is laminate crushing, while at higher velocities the linear momentum transfer plays the main role in the penetration process. Tensile fibre failure does not influence this decrease significantly.

5. Conclusions

The developed model reproduces accurately the residual velocity of the projectile after perforation, and the ballistic limit can be calculated with an error of 5%. This error is low enough to allow the use of this analytical model for parameter optimization purposes, in early stages of design. In addition, it is a very simple and fast way to analyze the influence of the material properties and specimen geometry in the energy absorbed by the laminate.

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7. References

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