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Analysis of high velocity impacts of steel cylinders on thin carbon/epoxy woven laminates

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ABSTRACT

In this work a numerical model was developed to predict the behavior of thin woven laminates under high velocity impacts. The material model, implemented in a user subroutine to be used with a commercial FE code, takes into account different failure mechanisms. The inter-lamina failure prediction is achieved by means of the use of cohesive elements. Finally, in order to validate the model, experimental tests were accomplished in a wide range of velocities from 100 to 400 m/s. Residual velocity of the projectile and damaged area of the laminates are compared with the numerical results. Once the model is validated, a further investigation has been made in order to analyze the influence of projectile slenderness on the laminate response.

1. Introduction

Aeronautic and aerospace industries play a very important role in the technical development of composite materials. These industries are continuously increasing the use of laminated composite structures, due to their high strength-to-weight and stiffness-to-weight ratios as well as their anisotropic behavior. Those special characteristics allow to optimize designs and fulfil the strict requirements of the mentioned industries. In addition the total mass of the structures is reduced and hence the fuel consumption diminished. Laminated carbon fiber in an epoxy matrix is the most used composite material in structural applications in these sectors because their good combination between mechanical properties, high resistance to corrosion and fatigue, and low density. The reduction of raw material costs, the development of automation of manufacturing processes and the growing experience in design technology have increased the CFRP applications in commercial aircraft, where the percentage of this kind of materials in last designs of aeronautical structures constitute more than the 50% (in terms of weight). Due to the use of these materials in primary structures, it is necessary to understand how composites behave during their service life when they are subjected to the different loads.

Vulnerability studies of CFRP aerospace structures are of great importance in the design of any aircraft. These structures may suffer high velocity loads due to bird strikes or hailstones, especially dangerous because of their high possibility of occurrence and their disastrous consequences. Moreover, a stone, small fragment or metallic piece located in the take off runaway, as well as any other kind of debris could impact a fuel tank causing hydrodynamic ram effects and the catastrophic failure of the aircraft [1–8]. The aeroengine turbine blade may also fail due to fatigue and may penetrate the wall of containment cell, damaging oil tanks and airframes [9]. Impact engineering is also of great interest in the field of spacecraft because of the probability of impact between some of the numerous space debris and a satellite or space shuttle structures. CFRPs are well known to be particularly vulnerable to foreign objects impacts, mainly due to the brittleness of the polymeric phase which cause a multiplicity of failure modes and leads to significant strength reduction in post-damage performance. Therefore understanding their response to a range of potential impact loadings and resulting damage mechanisms is essential for the successful use of these materials.

The response of CFRP panels is quite different depending on the velocity of impacts [10]. Numerous works that study the behavior of CFRPs subjected to low velocity impacts have been carried out by means of experimental tests methods such as pendulum impact or drop tower impact. However, the number of papers regarding the behavior of carbon fiber laminates impacted at hundred of meters per second is relatively small. Experimental results of CFRPs impacted by steel projectiles at high velocities can be found in the works of Cantwell and Morton [10], Sun and Potti [11], Larsson [12], Bland and Dear [13], López-Puente et al. [14–16], Will et al. [17], Tanabe et al. [18,19], Hammond et al. [20], Hosur et al. [21], Herzsberg and Weller [22], Caprino et al. [23], and Hazell et al. [24], among others.

The impact process of a projectile onto a composite plate can be described in different phases: initial contact and stress wave propagation, compression and local punch, plug formation under

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shear and compression, fiber breakage at the rear layers, and final perforation. During these phases, the initial energy of the projectile is totally or partially absorbed (depends if the projectile is arrested or not) by the laminate and transformed into kinetic energy, strain energy or irrecoverable energy associated to different damage mechanisms, namely matrix cracking, delamination, fiber shear or tensile fiber failure. To predict the behavior of composite laminates, influenced by parameters such as fiber and matrix types, stacking sequence [17], woven or tape architecture [14], stitching [12,21], service temperature [14], impact velocity and angle [10,16,25] and shape of impactor [26], quite complex numerical [27] or analytical [10,23,28,29] simulation models have been developed by different authors.

This work proposes a numerical methodology to predict the response of carbon/epoxy woven laminates under high velocity impacts. A material model which takes into account different intralaminar failure mechanisms, such as fiber failure in both fiber directions and in plane and out of plane matrix failure, was implemented through a user subroutine; in addition the use of cohesive elements allow to reproduce the inter-lamina failure. The finite element code ABAQUS/Explicit was used in the numerical simulations. In order to validate the numerical simulations, experimental tests were performed. A lightweight gas gun was used to carry out impacts of a steel cylindrical projectile onto carbon epoxy woven laminates at different velocities. The residual velocity of the projectile, in case of perforation, and the damaged area of the laminates were measured to validate the numerical results. In addition once the numerical model is validated, a further investigation has been made in order to analyze the influence of projectile slenderness on the laminate response.

2. Experimental tests

In order to have experimental data to validate the numerical model that will be proposed, impact tests were performed. Carbon/epoxy laminated plates with 10 plies, $([0])_{10}$), a total thickness of 2.0 mm and a size of 80×80 mm^2 were impacted with a steel projectile. Afterwards the mentioned specimens were inspected by means of a non-destructive technique to measure the damaged area.

2.1. Impact tests

The projectile consisted on a tempered steel cylinder with a diameter of 5.5 mm and a mass of 1.1 g. The tempered steel is hard enough to ensure that no plastic deformation occurs during penetration, simplifying the analysis because all the energy associated to the projectile is kinetic. The wide range of impact velocities performed (100 – 400 m/s) allows to obtain the minimum velocity at which the projectile perforates the laminate plate, known as ballistic limit.

The set-up employed in the impact tests consists on a one-stage light gas gun which uses helium at a pressure of up to 200 bar to impel the projectile up to 500 m/s against the plate. The projectile travels through a gallery in which two photoelectric cells detect the passing of the projectile, obtaining the impact velocity. At the end of the gallery, the projectile reaches an armored chamber ($1 \times 1 \times 1$ m^3), inside of which the specimen is placed. The appropriate position of the plate is ensured by means of a support that avoids the movement of the edges of the specimen. The windows included on the armor chamber, one in a lateral side and another on the top, allow to light inside the chamber and to capture the video sequence of the impact. Fig. 1 shows a sketch of the experimental device used for impact tests.

A Photron Ultima APX digital high-speed camera was employed to measure the residual velocity when the projectile perforates the plate. The selected frame rate (15,000 frames per second), resolution (1024×128 pixels) and the shutter time (11 μs) were chosen based on early testing and represent an optimal trade off between available lighting and the minimization of blur in the images. The camera was placed on the top of the chamber allowing the perfect capture of the entry the exit of the projectile trough the laminate. A sequence recorded by the high speed camera is shown in Fig. 2. It is easy to determine the residual velocity using an image treatment software, because the Δt between the two instants is pre-configured in the camera, and the distance traveled by the projectile is scaled using the length of the projectile or even the millimeter paper.

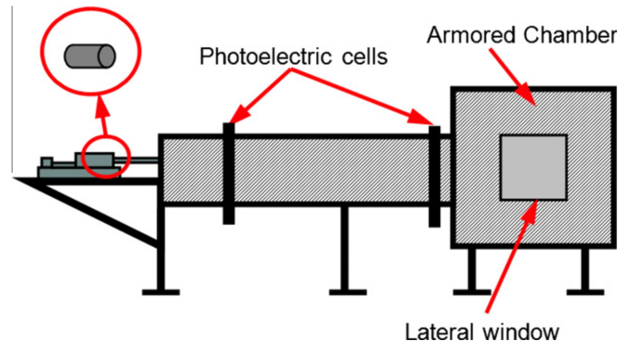

Fig. 1. Sketch of the experimental device.

2.2. Damage inspection tests

Once the specimen is impacted, it is analyzed in order to know the extension of the damage. To achieve this, the specimens are inspected using the C-scan ultrasonic method, Fig. 3. The ultrasonic techniques are based on the elastic waves attenuation passing through discontinuities of a continuum media, as delaminations or another kind of damage. A computer processes the ultrasonic

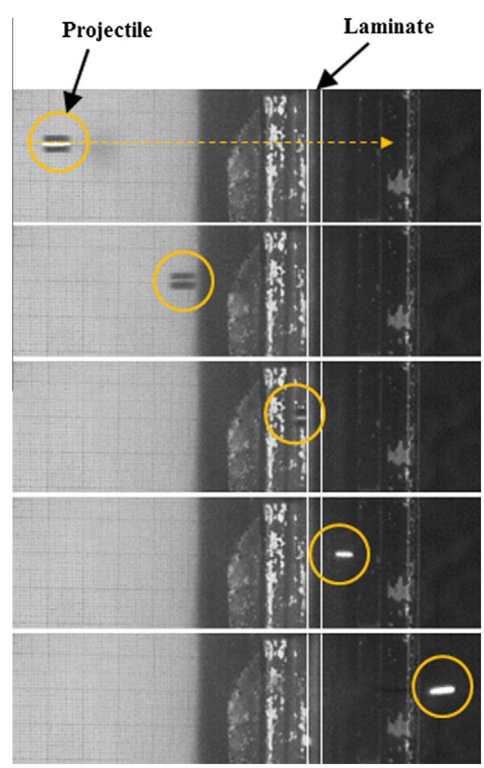

Fig. 2. Sequence of impact process.