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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.

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 (2005), Reid and Zhou (2000), and Bartus (2007). Nevertheless, major questions remain to be elucidated and investigation continues on this topic (Xin and Wen, 2012; Carrillo et al., 2012; Garcia-Castillo et al., 2012; Laurenzi et al., 2013).

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 (Chiu et al., 1997; Whittingham et al., 2004; Pickett et al., 2009; Choi et al., 2010; Ghelli and Minak, 2010). Much less information is available concerning the influence of a preload in laminates subjected to high-velocity impact, mainly only for uniaxially preloaded laminates (Tweed et al., 1996; Wiedenman and Dharan, 2006; Mikkor et al., 2006).

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 (Ghelli and Minak, 2010). Kelkar et al. (1998) also observed that the greater the prestress 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 (Chiu et al., 1997). On the contrary, Kelkar et al. (1998) 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 (Abrate, 2005), 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 (Garcia-Castillo et al., 2011a), ceramic (Holmquist and Johnson, 2005), and composite (Wiedenman and Dharan, 2006) materials subjected to high-velocity impacts, and can even lead to catastrophic failure of the panel (Garcia-Castillo et al., 2011a). 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

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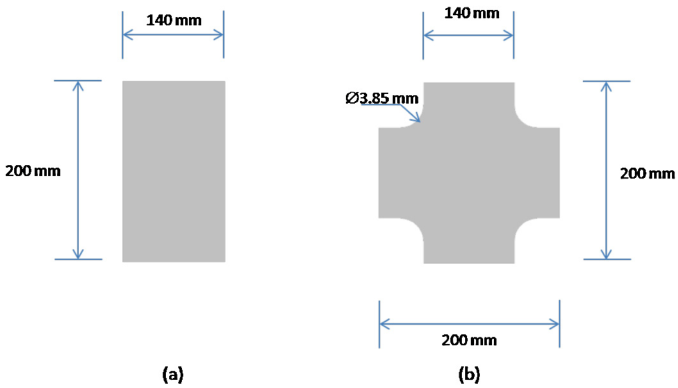

Fig. 1. Geometry of the specimens: (a) unloaded and uniaxial preloaded panels and (b) biaxial preloaded panels.

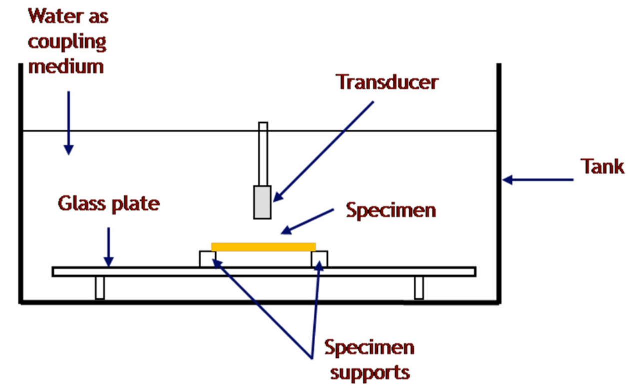

Fig. 2. Experimental set-up for the non-destructive testing of the impacted laminate panels.

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 (Daniel, 1986; Soden et al., 2002). Nevertheless, many authors (Jonston et al., 2002; Ohtake et al., 1999; Welsh and Adams, 2002; Smits et al., 2006) 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 (Garcia-Castillo et al., 2006, 2009). 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 [0°, ±45°, 0°; ±45°, 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 mm × 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 × 27 mm (Fig. 1). The geometry of the specimen allowed an impact zone of 140 mm × 140 mm, approximately.

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 51 kN 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 1 MHz. Fig. 2 shows the diagram of experimental set-up employed during the non-destructive inspection by C-Scan.

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 Fig. 3, by fitting the Lambert–Jonas equation (1) (Lambert and Jonas, 1976) 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 (Kasano, 1999; Sanchez-Saez et al., 2011; Garcia-Castillo et al., 2011b).

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

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 (Zukas et al., 1992). In thicker laminates or