Composites Part B 85 (2016) 1–7

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Effect of fibre volume fraction on energy absorption capabilities of E-glass/polyester automotive crash structures

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A R T I C L E I N F O

Article history:
Received 28 April 2015
Received in revised form
22 July 2015
Accepted 9 September 2015
Available online 26 September 2015

Keywords:
A. Glass fibres
B. Delamination
C. Damage mechanics
D. Mechanical testing
Fibre volume fraction

A B S T R A C T

Semi-hexagonal glass/polyester composite structures with different fibre volume fractions have been studied for automotive crash applications. Interlaminar shear strength and specific energy absorption capability of the material have been characterised in order to analyse the effect of the fibre content. Samples with different fibre content among 40% and 60% have shown similar interlaminar shear strength values, around 35–40 MPa. It has been found that by increasing the fibre percentage from 40% to 47% the specific energy absorption values of the material increased to 56 kJ/kg. For specimens with fibre volume fraction above 47%, the total amount of energy dissipated is similar. Increasing fibre content increases the linear density of the material and in fact, the same value of dissipated energy quantities with a higher linear density implies a decrease in the specific energy absorption values.

1. Introduction

Over the last number of decades, the automotive industry is making efforts to reduce CO_2 emissions due to environmental concerns. Lightweighting has become an important issue in order to reduce CO_2 emissions in fuel engine cars and improving range in electric cars. Hence, lightweight materials such as aluminium, magnesium or composite materials are being widely studied for automotive applications [1]. The safety of passengers must be ensured or improved in crash situations, so materials with higher impact energy absorption capabilities are in demand to fulfil safety and lightweight requirements.

Many authors have demonstrated that composite made impact structures show high specific energy absorption (*SEA*) capability [2–7]. Metallic structures are designed to absorb energy by plastic deformation, progressively buckling as the column walls collapse, while the fibre reinforced plastic (FRP) composite structures energy absorption mechanism is based on progressive material collapse in a brittle manner [8]. Many researchers have demonstrated that *SEA* values of FRP composites made impact structures are above 30 kJ/kg, depending on the geometry and materials used [2,9–11]. The most widely used geometry in real applications is a square sectioned tubular crash structure due to assembly and element integration feasibility. In addition, numerous authors have verified that circular sectioned tubular impact structures exhibited higher *SEA* values compared with square tubes [7,12]. Moreover, Palanivelu et al. [13–16] showed that constant circular tubes have the highest *SEA* values within tubes with constant section, axially corrugated impact structures and conical impact structures.

However, FRP composite impact structures exhibited higher *SEA* values when the collapse is stable and progressive, but not when the collapse is catastrophic [17]. In order to achieve and ensure a stable and progressive crushing process, trigger called collapse initiators are used [18,19]. Triggering is a geometric gradient feature in the top or upper zone of the component which acts as a stress concentration to ensure the collapse initiation. Although there are different kinds of triggers, chamfer and tulip type triggers are the most studied. The importance of a trigger mechanism in the progressive crushing, and therefore absorbed energy, of FRP composite structures has been demonstrated [19,20].

Furthermore, Mamalis et al. [21,22] concluded that the progressive crushing mechanism is based on two main collapse modes: Mode I and Mode II. Mode I collapse type is associated with large amounts of energy absorbing capability (axial crack propagation and axial splitting between fronds) while Mode II collapse type is associated with low energy absorption capability (delamination between plies and flexural damage of individual plies).

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http://dx.doi.org/10.1016/j.compositesb.2015.09.007
1359-8368/

The progressive crushing process also involves material properties such as mechanical properties of the fibre and resin, laminate stacking sequence, fibre orientation or fibre and resin volume fractions [8]. In this sense, the effect of fibre volume fraction (V_f) on the energy absorption capability of composite structures has not been extensively studied. Some authors concluded that there is a decrease in *SEA* values increasing fibre volume fraction [23–25], while other authors reported that there is an increase of *SEA* values increasing fibre percentage [26–29]. As fibre volume fraction increases, the volume of matrix between the fibres decreases increasing the material density. This further leads to a decrease in the interlaminar strength of the composite which makes interlaminar cracks form at lower loads, resulting in a reduction in the energy absorption capability of the material [23]. Farley [24] also concluded that there is a decrease in *SEA* values increasing fibre volume fraction from 40% to 70% and the author attributed this phenomenon to the decrease in interlaminar shear strength of the composite with increasing fibre content. On the contrary, Ramakrishna [26,27] found that the specific energy absorption capability increased with fibre content. One possible explanation for this is that a higher tube loading is associated with the generation of larger surfaces due to fibre/matrix debonding which results in increased energy absorption capability. At the same time, Thornton et al. [29] reported an increase in specific energy with an increase in fibre content from 10% to 50%.

Although the conclusions of different authors are mismatched, it should be considered that the effect of fibre volume fraction in specific energy absorption capability may be different for different materials and different fibre volume ranges analysed. For that reason, the present study analyses the effect of the fibre volume fraction in energy absorption capabilities for glass/polyester impact structures. Furthermore, since *SEA* variations with V_f are attributed to the interlaminar strength of the material [23,24], the effect of V_f in the interlaminar shear strength (*ILSS*) of the material is also analysed.

2. Experimental procedure

2.1. Materials

The material employed in the present study is a glass/polyester composite. The reinforcement consists of a quasi-unidirectional E-glass ribbon with a weight of 300 g/m^2, with 91% of fibres oriented at 0° and 9% of fibres oriented at 90° to ensure cohesion and correct manipulation of unidirectional fibres. These transversal fibres are evenly spaced every 5 mm. The thermal curable resin is a non-accelerated and unsaturated polyester resin, called Crystic 3642.3 with a catalyst called Butanox M50.

2.2. Specimen geometry

The specimens used in this study are open sectioned semi-hexagonal samples (Fig. 1a). The overall length is 60 mm and the thickness of the specimen is 2 mm. Detailed dimensions of the section are shown in Fig. 1b. In order to ensure a stable and progressive crushing of the structure, a 45° chamfer type trigger is machined on the upper side of each specimen. A combination of semi-hexagonal profiles such as honeycomb concept, allows for the designing and manufacturing of different impact structures which are optimised for each type of vehicle, depending on the characteristics and energy to be dissipated in each case. For this reason, semi-hexagonal profiles are chosen to be manufactured and tested.

2.3. Manufacturing

Manufacturing of semi-hexagonal profiles has been carried out using the hand lay-up technique. Fig. 2a shows the mould and countermould used for manufacturing composite energy absorbing specimens. 6, 7, 8, 9 and 10 E-glass fibre layers have been manually impregnated and placed on the mould in order to obtain samples with different fibre volume fractions. 2 mm thick metallic plates have been placed between the mould and the countermould to control the thickness of the specimens. Finally, the semi-hexagonal profile is cured at 60 °C for 8 h (Fig. 2b).

2.4. Physical and mechanical characterisation

2.4.1. Fibre volume fraction

Fibre, matrix and void content of semi-hexagonal profiles manufactured with different numbers of fibre layers are measured following the procedure described in ASTM D3171-09. Three specimens of each configuration are used to determine the fibre volume fraction. The ASTM D3171-09 standard is based on the principle of Archimedes. FRP composite samples are weighed in an electronic precision balance, first in dry conditions and then immersed in bidistilled water. The next step consists in burning the polyester matrix using a high temperature furnace at 535 °C. Once the matrix has been burned, the fibres are weighed in the electronic balance in order to calculate the fibre, matrix and void content of the FRP composite following the equations described in the ASTM D3171-09 standard.

2.4.2. Interlaminar shear strength

Interlaminar shear strength of the material is measured in order to study the relation between *ILSS* and the energy absorption capability of the material. The EN ISO14130 standard test method for short-beam strength has been used. According to this method, the following specimen geometries were chosen (see Fig. 3): the specimen length, *l*; should be ten times the thickness, *e*; the specimen width, *b*; should be five times of *e*. Finally, the span length, L; should be five times of *e*. All tests were performed at a displacement rate of 1 mm/min and using a 5 kN load cell. The short-beam strength is calculated using equation (1).

$$F^{sbs} = 0.75\frac{P_m}{b\cdot e} \tag{1}$$

where F^{sbs} is the short-beam strength (MPa) and P_m is the maximum load observed during the test (N).

Finally, the samples used in *ILSS* tests are examined using a NOVA NANOSEM 450 scanning electron microscope (SEM) in order to ensure that the fracture of the specimen is by interlaminar shear.

2.4.3. Quasi-static compression tests

Quasi-static compression tests are carried out at 10 mm/min of compression speed. The tests are performed until 50 mm of collapse distance. This collapse distance is higher than the 80% of the overall length of the specimen and it is supposed to be enough to analyse the crushing behaviour of the structure. The equipment used is a universal test machine, Instron4206, equipped with 100 kN load cell. 3 specimens of each fibre volume fraction are tested in order to ensure the repeatability of the tests. From the force–displacement curve, the following crashworthiness characteristics are calculated:

Absorbed energy, A_e (kJ): the area under the force–displacement curve, equation (2).

$$A_e = \int_0^{l_{max}} P(l)\mathrm{d}l \tag{2}$$