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Optimization of the semi-hexagonal geometry of a composite crush structure by finite element analysis

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In the present paper a numerical model for predicting the crushing behaviour of semi-hexagonal E-glass/polyester composite structures has been developed. Qualitative and quantitative analysis have shown that the results of the simulation are accurately predicted comparing with the experimental data. The peak force has been predicted with 7.5% of error while the mean force of the crushing process, the total amount of absorbed energy and the specific energy absorption capability have been simulated within 1% of error. Moreover the effect of the wall angle of the semi-hexagonal section and the effect of the overall size of the semi-hexagonal section have been numerically analyzed. The crushing process becomes stable when the wall angle is higher than 50° and the highest specific energy absorption values are obtained using the wall angle of 60° and wall length of 10 mm. Higher wall angles and wall lengths increases the stress concentration in the edges of the semi-hexagonal section and in consequence, the load carrying capability of the structure decreases dissipating less energy.

1. Introduction

The automotive industry is working in order to manufacture more environmental friendly vehicles and to reduce the CO_2 emissions. One of the strategies to achieve this objective is based on lightweighting, which is based on building cars using materials that are less heavy as a way to achieve better fuel efficiency and reduce emissions. Materials such as aluminium, magnesium or composite materials are being widely investigated for structural and non-structural automotive applications [1]. Nevertheless, the use of these new materials must ensure the correct performance of the vehicles and they must have same or higher safety levels for the passengers comparing with the current steel made cars.

Front rail structures or crash boxes are some of the components to be designed using structural lightweight materials to fulfil the crashworthiness requirements and reduce the weight of the components. Composite structures have shown great capability of weight reduction and high energy absorption levels during crash situations [2–4] with higher specific energy absorption (*SEA*) values than metallic crash absorbers [3,5,6]. The energy absorption mechanism of the composite structures is based on progressive material collapse in a brittle manner [7], while metallic structures are designed to absorb energy by plastic deformation.

Progressive collapse and energy absorption of the composite material are the contribution of several mechanisms such as axial crack propagation, axial splitting between fronds, delamination, matrix cracking, friction or trigger mechanisms [2,3,7–10]. Although these investigations have demonstrated that stable and progressive collapse of composite structures with high energy absorption levels is feasible, there are some factors that are delaying their use in commercial vehicles: (a) high material and manufacturing costs, and (b) lack of numerical models capable of accurately predicting their response [11].

Due to the high cost of experimental testing, most of the crashworthiness studies of vehicles are developed with finite element modelling and only final validation tests are experimentally carried out. For this purpose, it is essential the development of accurate numerical models for composite materials. Simulation of the crushing process of a composite structure requires predicting several deformation mechanisms in order to correlate with the load-displacement curves observed and measured experimentally. Due to these deformation mechanisms, an explicit finite element solver to describe the initiation and progression of a crushing mode failure is usually employed [12]. Although composite structures can

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be modelled using either solid or shell elements, multi-layer shell elements are more widely used [11–17]. Multi-layer shell elements allow simulating more accurately the formation of fronds and delamination among fibre layers, which is not possible with single-layer shell elements. Furthermore, multi-layer shell elements are more accurate option to model chamfer type trigger comparing with single-layer shell elements [12]. Using multi-layer continuum shell elements, the model has the geometry of a three-dimensional solid element but similar kinematic and constitutive behaviours of the conventional shell elements [17]. The most used strategies for simulating delamination between fibre layers are the use of cohesive elements or tiebreak contacts between shell layers [16,18–20]. The cohesive interface behaviour depends on the elastic energy stored by the crack in mode I and mode II propagation. The interface is damaged and failed when the prescribed interface fracture energy is reached [18]. On the contrary, traction-separation law or tiebreak contacts are usually based on the stress or strain criterion. In these cases, the damage initiates when the stresses or the strains on the interface satisfy the prescribed failure criterion [13,17].

Many authors have demonstrated experimentally the importance of the geometry of a composite structure in energy absorption applications [21–23]. The most used geometry in real applications is square sectioned tubular crash structure due to assembly and element integration feasibility. However, Palanivelu et al. [22] have verified that circular sectioned tubular impact structures have higher *SEA* values comparing with square tubes, while the energy absorption capability of the hexagonal structures is between the circular and square tubes. On the other hand, Joosten et al. [12] showed the high energy capabilities of the open sectioned semi-hexagonal structures. In this way, the assembling of semi-hexagonal profiles (honeycomb concept) allows designing and manufacturing composite crash structures for vehicles which have different energy absorption requirements in crash situations. The same semi-hexagonal profile can be used as a modular geometry to fulfil the crashworthiness requirements.

However, the experimental development of these structures is expensive. Therefore, using an accurate numerical model that is capable to predict the behaviour of a composite structure during crushing process, experimental costs can be overcome. Furthermore, a detailed optimization of these structures would not be possible without high time and cost. For these reasons, in the present study a numerical simulation of the crushing behaviour of a semi-hexagonal composite structure made of E-glass/polyester is presented using Abaqus/Explicit finite element solver. Multi-layer continuum shell elements are used in order to capture the different deformation mechanisms and quantify the absorbed energies; intralaminar energy, interlaminar energy and energy dissipated by friction. Load-displacement curves and *SEA* values obtained numerically are compared with the experimental data. Finally, a numerical optimization of the semi-hexagonal geometry of the composite structure is presented in order to maximize the *SEA* values. The effect of the wall angle and the overall size of the semi-hexagonal structure are analyzed numerically.

2. Material and experimental details

The composite profiles are manufactured by vacuum assisted infusion method [8]. A semi-hexagonal mould has been used to manufacture the semi-hexagonal composite structures. Peel ply and vacuum bag are placed over the fibre layers and the resin is injected at 1 bar vacuum pressure. The reinforcement consists in a quasi-unidirectional E-glass ribbon with 300 g/m^2 weight supplied by Mel Composites. 91% of fibres are 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 resin is a non-accelerated and unsaturated polyester resin, Crystic 3642.3 with a Butanox M50 catalyst, supplied by Hegardt S.L.

The specimens are open sectioned semi-hexagonal samples. Detailed dimensions of the section are showed in Fig. 1. The overall length is 60 mm (distance between compression plates) and the thickness of the specimen is 2 mm. The composite lay-up consists in 8 layers of quasi-unidirectional E-glass ribbon. All the fibres layers are oriented with the longitudinal axis of the semi-hexagonal profile. A 45° chamfer type trigger is machined in the upper side of each specimen in order to control the collapse initiation that will ensure a progressive collapse of the specimen during the compression test, maximizing the energy absorption capability of the composite structure.

Quasi-static compression tests are carried out at 10 mm/min of compression speed during 50 mm of collapse distance using a universal test machine, Instron 4206, equipped with 100 kN load cell. 3 specimens of the profile manufactured by each process are tested in order to ensure the repeatability of the tests. Force-displacement curves of the crushing stage are acquired and dissipated energy and *SEA* values are calculated:

Absorbed energy, A_e (kJ): the area under the force-displacement curve, equation (1).

$$A_e = \int_0^{l_{\max}} P(l)dl \qquad (1)$$

Specific Energy Absorption, *SEA* (kJ/kg): the absorbed energy per unit of crushed specimen mass (m_t in kg), equation (2).

$$SEA = \frac{\int_0^{l_{\max}} P(l)dl}{m_t} \qquad (2)$$

3. Finite element model

The constitutive model used for fibre reinforced composites simulation has been ABQ_PLY_FABRIC VUMAT user subroutine which is implemented in Abaqus/Explicit. The fabric-reinforced ply is modelled as a homogeneous orthotropic elastic material with the potential to sustain progressive stiffness degradation due to fibre/matrix cracking and plastic deformation under shear loading. The shear response of the material is defined by the user following the procedure explained in detail in Ref. [24].

3.1. Elements and boundary conditions

Eight continuum shells have been individually meshed using an 8-node, quadrilateral, first-order interpolation, stress/displacement continuum shell elements with reduced integration (SC8R

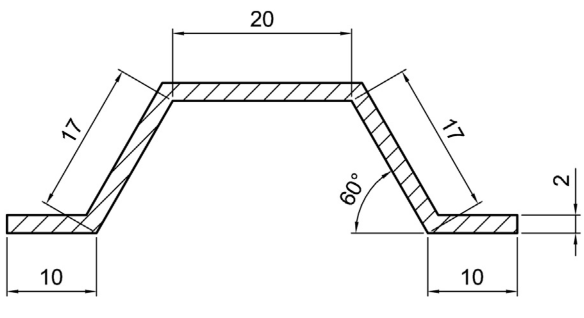

Fig. 1. Dimensions (in mm) of the section of the specimen.