Composites Part B 79 (2015) 20–27

Contents lists available at ScienceDirect

Composites Part B

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

Experimental and numerical investigations of the impact behaviour of composite frontal crash structures

S. Boria [b,*], J. Obradovic [a], G. Belingardi [a]

[a] Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Torino, Italy
[b] School of Science and Technology, University of Camerino, Camerino, Italy

A R T I C L E I N F O

Article history:
Received 27 May 2014
Received in revised form
6 March 2015
Accepted 11 April 2015
Available online 18 April 2015

Keywords:
A. Carbon fibre
A. Layered structures
B. Impact behaviour
FEA
A. Prepreg

A B S T R A C T

The present paper deals with the lightweight design and the crashworthiness analysis of a composite impact attenuator for a Formula SAE racing car, in order to pass homologation requirements. The analysed impact attenuator is manufactured by lamination of prepreg sheets in carbon fibres and epoxy matrix, particularly used for sporting applications, and has a very similar geometry to a square frusta, so as to obtain a progressive and controlled deformation. During the design, attention was focused on the material distribution and gradual smoothing, but also on the lamination process, which can heavily affect the energy absorption capability. To reduce the development and testing costs of a new safety design, computational crash simulations for early evaluation of safety behaviour under vehicle impact test were carried out. The dynamic analysis was therefore conducted both numerically, using an explicit finite element code such as LS-DYNA, and experimentally, by means of an appropriately instrumented drop weight test machine, in order to validate the model in terms of deceleration values during crushing. To assess the quality of the simulation results, a comparative analysis was initially developed on simple CFRP composite tubes subjected to dynamic axial loading. The numerical analysis was conducted using both shell and solid elements, in order to reproduce not only the brittleness of the composite structure but also the effective delamination phenomenon. Both the analyses show a good capacity to reproduce the crushing process; this is confirmed by the fact that model estimated displacements and accelerations are in close agreement with observed values for these variables. This confirms the quality of the methodology and approach used for the design of a racing car impact attenuator.

1. Introduction

Composites are increasingly used in cars because their lightweight, high strength, corrosion resistance and easy manufacturing offer significant advantages [1]. Recently, carbon fiber reinforced plastic (CFRP) has gained growing popularity in numerous advanced and high performance applications for crashworthiness thanks to its superior impact resistance, with regard to metals or other composite materials, despite the material costs. One of the challenging points in impact design is the great difficulty in modelling material behaviour due to its fully orthotropic and multiple failure modes [2]. As regards racing cars, the regulations have become stringent and restrictive over time and cover different safety related aspects. As a consequence, new structures for energy absorption have become indispensable parts to be taken into account during design.

Crash investigations on composite structures reported in the literature are mainly based on experimental test analysis of small plates submitted to bending impact and on simple tubes, of circular or rectangular cross section, of prismatic or tapered shape, submitted to axial impact [3–7]. In addition, the behaviour of composite laminate plates subjected to low velocity impact loading were examined. This was done by subjecting a number of plates made of glass fiber epoxy matrix layers both with unidirectional and woven reinforcement and with three different staking sequence to the standard drop dart test [8]. The results indicate that the glass fiber epoxy matrix has no sensitivity to its mechanical characteristic to the strain rate effect. Furthermore, some studies can be found concerning composite crash-boxes for automotive applications, but they are still a limited in number and do not cover all aspects of composite structure modelling [9–14].

* Corresponding author.
E-mail address: simonetta.boria@unicam.it (S. Boria).

http://dx.doi.org/10.1016/j.compositesb.2015.04.016
1359-8368/

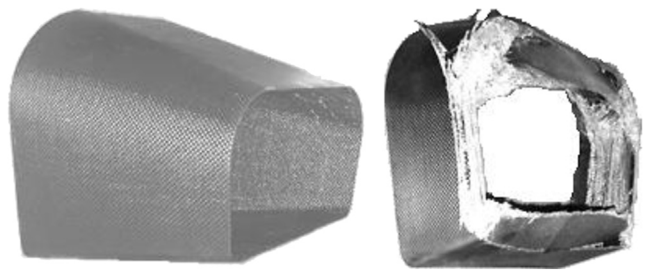

Fig. 1. Impact attenuator before and after impact.

The present paper deals with the lightweight design and the crashworthiness analysis of a composite impact attenuator for a Formula SAE racing car (Fig. 1).

This structure has a very similar geometry to a square frusta in order to obtain a progressive deformation confined at impact wall while maintaining a nearly constant strength during the axial crushing [9,10,15]. During the design of this type of impact attenuators it is important to pay attention not only to the material distribution and the gradual smoothing in various zones, thereby avoiding sudden failure and high peaks of deceleration, but also to the lamination process, which can heavily affect the energy absorption capability. The analysed impact attenuator is manufactured by lamination of prepreg sheets in carbon fibres and epoxy matrix, particularly used for sporting applications. To reduce the development and testing costs of a new safety component design, computational crash simulations for early evaluation of safety behaviour under vehicle impact test were carried out. The validation of numerical models for accurate simulation of structural response to crash impacts is an important aspect of crashworthiness research. Indeed, they constitute the necessary tools for the designer to study the response of the specific structures to dynamic crash loads, to predict global response to impact, to estimate probability of injury and to evaluate numerous crash scenarios. This amount of analysis is not economically feasible with full scale crash testing [16,17]. The dynamic analysis was therefore conducted both numerically, using the explicit finite element code LS-DYNA, and experimentally, by means of an appropriately instrumented drop weight test machine, in order to validate the model in terms of deceleration values during crushing. In order to assess the quality of the simulation results, a wide comparative analysis was initially developed on simple CFRP composite tubes subjected to dynamic axial impact loading starting from the material characterization. Only after having obtained a good correspondence between numerical and experimental results on these simple geometries, it was possible to conduct the dynamic analysis on the impact attenuator which presents a more complex geometry. The structures were numerically analysed using both shell and solid elements in order to reproduce the laminate. In particular the solid modelling was done using cohesive elements between the layers, even if this leads to an increase in computation time. Both the analyses show a good capacity to reproduce the crushing process; this is confirmed by the fact that model estimated displacements and accelerations are in close agreement with experimentally observed values for these variables. The obtained results confirm the quality of the simulation approach and of the design methodology used for racing car impact attenuator.

2. Material and geometry definitions

As regards the material, the decision was taken to use plain weave composite prepreg with carbon fibres and epoxy resin [12]. Mechanical testing for material characterization was carried out on an electromechanical Zwick Z100 machine at Politecnico di Torino laboratory. Tensile, interlaminar and relevant fracture mechanic characteristics were evaluated using industry standard techniques. In particular, for interlaminar fracture mechanic characteristics, the Double Cantilever Beam (DCB) and the Four Point End Notched Flexure (4ENF) procedures were utilised.

After the characterization of the material and before the production of a frontal impact attenuator for a Formula SAE car, it is necessary to reproduce as closely as possible the brittle deformation of simple geometries, such as 200 mm long cylindrical tubes with different wall thickness and radius values, made of the same material. Only after having properly set the material model properties, can a more complex geometry be modelled. The impact attenuator analysed has a very similar geometry to a square frusta (Fig. 2), in order to produce as closely as possible a Mode-I failure mechanism which is characterised by a nearly constant strength throughout the crushing process and to obtain the highest energy absorption ability, compared to the other deformation modes. Moreover, a truncated pyramid was chosen in order to fit into the existing envelope dictated by aerodynamic and mechanical constraints and fulfil the technical regulations [18]. The sections are almost rectangular with rounded edges to avoid stress concentrations during crushing. The design of the thin-walled structure was completed with a simple, properly conceived trigger which consists in a progressive reduction of the wall thickness, from the back to the front, to reduce the resisting section locally. The trigger is intended to reduce force peaks and to ensure a stable collapse. In particular, three different wall thickness zones were implemented along the longitudinal axis: 1.68, 2.16 and 2.4 mm respectively, as shown in Fig. 2.

The manufacture of the cylindrical tubes and of the impact attenuator was obtained by hand lay up of pre-impregnated composite layers and autoclave curing at 135 °C and 7 bar applied pressure. The manufacturing process of the impact attenuator

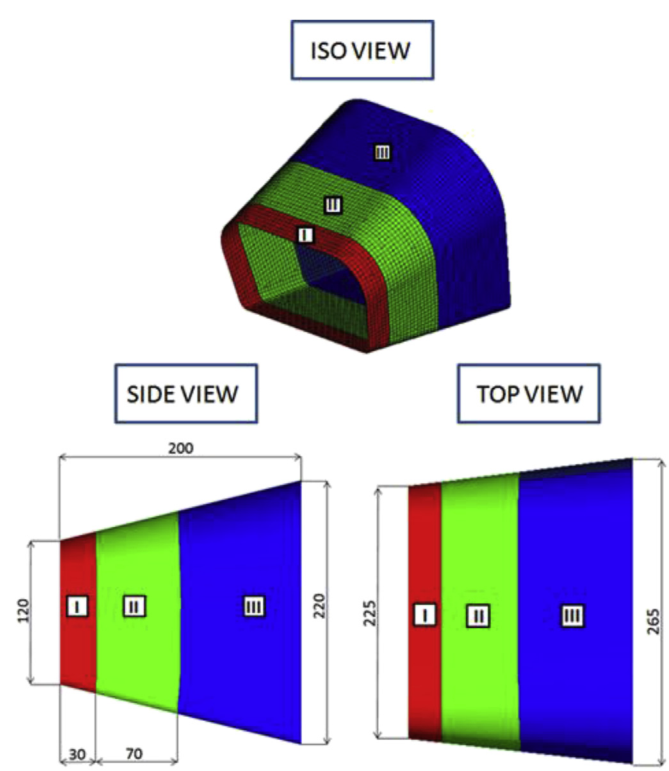

Fig. 2. Geometrical configuration of the impact attenuator.