Composite Structures 94 (2012) 423–430

Contents lists available at SciVerse ScienceDirect

Composite Structures

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

Lightweight design and crash analysis of composite frontal impact energy absorbing structures

Jovan Obradovic [a], Simonetta Boria [b,*], Giovanni Belingardi [a]

[a] Department of Mechanics (DIMEC), Politecnico di Torino, Duca degli Abruzzi, 24, 10129 Torino, Italy
[b] School of Science and Technology, University of Camerino, Madonna delle Carceri, 9, 62032 Camerino, Italy

ARTICLE INFO

Article history:
Available online 2 September 2011

Keywords:
Lightweight design
CFRP tubes
Impact attenuator
Crashworthiness

ABSTRACT

Carbon fibre composites have shown to be able to perform extremely well in the case of a crash and are being used to manufacture dedicated energy-absorbing components, both in the motor sport world and in constructions of aerospace engineering. While in metallic structures the energy absorption is achieved by plastic deformation, in composite ones it relies on the material diffuse fracture. The design of composite parts should provide stable, regular and controlled dissipation of kinetic energy in order to keep the deceleration level as least as possible. That is possible only after detailed analytical, experimental and numerical analysis of the structural crashworthiness.

This paper is presenting the steps to follow in order to design specific lightweight impact attenuators. Only after having characterised the composite material to use, it is possible to model and realise simple CFRP tubular structures through mathematical formulation and explicit FE code LS-DYNA. Also, experimental dynamic tests are performed by use of a drop weight test machine.

Achieving a good agreement of the results in previously mentioned analyses, follows to the design of impact attenuator with a more complex geometry, as a composite nose cone of the Formula SAE racing car. In particular, the quasi-static test is performed and reported together with numerical simulation of dynamic stroke. In order to initialize the collapse in a stable way, the design of the composite impact attenuator has been completed with a trigger which is consisted of a very simple smoothing (progressive reduction) of the wall thickness. Initial requirements were set in accordance with the 2008 Formula SAE rules and they were satisfied with the final configuration both in experimental and numerical crash analysis.

1. Introduction

In order to ensure the driver's safety in case of high-speed crashes, special impact structures are designed to absorb the race car's kinetic energy and limit the deceleration acting on the human body. In current automotive development, in order to improve their crashworthiness and increase stiffness to weight ratio, composite material is introduced with the scope of optimisation of car body components. In fact, composites have a greater capacity to absorb energy compared to metals, mainly due to the different modes of failure that govern energy absorption.

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 bars, of circular or rectangular cross section, of prismatic or tapered shape, submitted to axial impact [1–7]. Also, a couple of analytical models have been proposed to predict the energy absorption characteristics of thin-walled tubular structures [11–14]. Furthermore, some studies can be found in the literature concerning composite crash-boxes for automotive applications, but they are still few and do not cover all aspects of composite structure modelling [8–10,16–19].

An important aspect of crashworthiness research is the validation of analytical and numerical models for accurate simulation of structural response to crash impacts. 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, not economically feasible with full scale crash testing.

This study covers the steps to follow during the design of a specific impact attenuator. After the mechanical characterisation of the CFRP material, it is possible to calibrate the numerical material model, to properly design and to perform experimental tests on thin-walled tubular structures. The good correlation between

* Corresponding author.
E-mail addresses: jovan.obradovic@polito.it (J. Obradovic), simonetta.boria@unicam.it (S. Boria), giovanni.belingardi@polito.it (G. Belingardi).
URLs: http://www.dimec.polito.it (J. Obradovic), http://www.sst.unicam.it (S. Boria), http://www.dimec.polito.it (G. Belingardi).

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doi:10.1016/j.compstruct.2011.08.005

Nomenclature

η_c	crash load efficiency (defined as the ratio between average and peak load)
$F_{average}$	average load
F_{max}	peak load
$\sigma_{average}$	axial average strength
SEA	specific energy absorption
t	wall thickness
σ_0	ultimate stress in uni-axial tension
σ_m	matrix shear strength
R_B	mean radius in B
H	axial length of tube
t_1	thickness of the plies bending outside the shell radius
t_2	thickness of the plies bending inside the shell radius
L_C	length of central crack
l_{s1}	side length of the wedge inscribed to the external bent frond
l_{s2}	side length of the wedge inscribed to the internal bent frond
ϕ	cone angle
α_1	angle formed by the height and the external side of the wedge
α_2	angle formed by the height and the internal side of the wedge
μ_1	coefficient of friction between frond and platen
μ_2	coefficient of friction between wedge and fronds
W_b	energy due to bending
W_h	energy due to hoop strain
W_m	energy required for propagation of the central crack
W_f	frictional energy
W_T	total energy
s	total displacement

experimental and numerical test represents efficient modelling of composite laminates. Also, the numerical simulation has been coupled with a simplified analytical model, able to predict the energy absorption of thin-walled composite structures with circular cross section. The thin-walled tubular structures made of composite material, are used as frontal impact attenuator, applied for urban vehicle's body-in-white. Instead, in the case of racing cars, it is usually used the conical absorbing structure [20].

Therefore, it is also presented the development, quasi static testing and numerical simulation of impact event for the lightweight frontal safety structure of Formula SAE vehicle, designed by the Politecnico di Torino team (Fig. 1). The production strategy of this car consists in a concurrent analytical and experimental development, from the initial conceptual design and coupon testing, through the stages of element and subcomponent engineering, to final component manufacturing.

2. Material characterisation tests

The used carbon fibre type material to manufacture thin-walled cylindrical specimens and the impact attenuator is plain weave prepreg GG203PIMP530R-42. The matrix type is resin epoxy and it is developed for automotive sector, in particular for sport application. It is characterised by good impact resistance properties and quality surface finish and is adapted for high speed cold stamping. The resin content is 42 ± 3%.

To obtain appropriate input data for the simulation of the composite components and for the validation of the numerical material model, standard coupon tests were performed at Politecnico di Torino laboratory. The material characterisation tests were performed in tension, according to ASTM Standard D3039, with the warp direction aligned with the test direction (0° tests) and also according to ASTM Standard D3518 with fibres aligned at 45° to the test direction. Coupon tests were performed up to material failure; Young's modulus, Poisson's ratio, yield stress and strain in the warp direction were obtained from the 0° tests, while the shear properties were extracted from the 45° tests. The flat specimens, used to measure these properties, were made from one ply of prepreg sheet, 200×10 mm^2, and composite end tabs were bonded at each end. Tensile tests were conducted with an electromechanical Zwick Z100 machine at a crosshead speed of 0.05 mm/s. Two strain gages were bonded onto one side of the specimen, in order to acquire longitudinal and transversal strains, respectively.

After the careful analysis, it is noticed that the obtained material characteristics are similar to properties of CFS003/LTM25 carbon-epoxy prepreg. In order to model numerically the appropriate material card with all necessary properties that are significantly influencing structural response, the obtained experimental test data are completed with material compression parameters of CFS003/LTM25 carbon-epoxy prepreg that are available in the literature. Although this material is twill weave, in numerical simulation is modelled as plain weave. The mechanical properties, for considered material, are reported in Table 1.

Fig. 1. The racing car of Polytechnic of Turin – season 2008.

3. Definition of energy absorbing structures

After the characterisation of the material, it is possible to constitute three complementary phases: the first one is the definition of a simplified analytical model that reproduces, as faithfully as

Table 1
Material properties for used prepreg.

Property	Composite CFS003/LTM25 carbon-epoxy fabric prepreg
Density	1.45×10^{-3} g/mm^3
Young modulus in fibre longitudinal direction	53.6 GPa
Young modulus in transverse direction	55.2 GPa
Poisson's ratio	0.042
Shear modulus$_{12}$	2.85 GPa
Shear modulus$_{23}$	1.425 GPa
Shear modulus$_{31}$	2.85 GPa
Longitudinal tensile strength	0.618 GPa
Transverse tensile strength	0.652 GPa
Longitudinal compressive strength	0.642 GPa
Transverse compressive strength	0.556 GPa
Compressive strength in direction 12	0.084 GPa
In plane shear strength	0.084 GPa