Performance Evaluation of CFRP-Rubber Shock Absorbers

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Abstract. In the present work a numerical investigation on the energy absorbing capability of dedicated structural components made of a carbon fiber reinforced polymer and an emulsion polymerised styrene butadiene rubber is reported. The shock absorbers are devices designed to absorb large amounts of energy by sacrificing their own structural integrity. Their aim is to cushion the effects of an impact phenomenon with the intent to preserve other structures from global failure or local damaging. Another important role of shock absorbers is reducing the peak of the acceleration showed during an impact phenomenon. This effect is of considerable interest in the case of vehicles to preserve passengers' safety. Static and dynamic numerical results are compared with experimental ones in terms of mean crushing forces, energy and peak crushing. The global performance of the absorbers has been evaluated by referencing to a proposed quality index.

Keywords: Shock absorber, Energy absorption, Rubber, CFRP.
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INTRODUCTION

During a collision phenomenon the parts involved undergo to a sudden change of speed; the initial kinetic energy rapidly decreases as the deformation energy increases. Land vehicles are generally equipped with components designed to absorb energy in order to preserve the safety of the passengers, in fact greater is the amount of energy absorbed by the whole structure less inertial effects were transferred to the occupants.

On the other hand, it could be necessary to limit the deformations of such components in order to prevent the collision among such parts and the occupants, laying them on the line. During an impact event, also the structural components of a land vehicle could significantly contribute to absorb impact energy. For this reason, during the design process, it is possible to orient the design choices towards structures able to absorb large amount of energy; in this way a double objective can be achieved: the structural performance of the vehicle is ensured, it is possible to increase its capability to absorb energy.

In the present work a numerical investigation on the energy absorbing capability of dedicated structural components [1, 2] made of a carbon fiber reinforced polymer and an emulsion polymerised styrene butadiene rubber is reported. The shock absorbers are devices designed to absorb large amounts of energy by sacrificing their own structural integrity. Their aim is to cushion the effects of an impact phenomenon with the intent to preserve other structures from global failure or local damaging. Another important role of shock absorbers is reducing the peak of the acceleration showed during an impact phenomenon. The latter effect is of considerable interest in the case of land vehicles due to the presence of passengers; it is known that during an impact phenomenon one of the most important prerogative of the designer is to limit the accelerations [3, 4] transferred to the occupants.

There are many types of shock absorbers and they are able to provide a wide range of performance in terms of amount of absorbed energy. In the railway industry, for example, regulations require maximum limit value of the reaction force of an absorber as a function of its deformation and such requirement restricts heavily the choices of the structural designers [5, 6]. Even the shape of the device affects its performance, where the choice of the optimal shape could depend also by manufacturing costs.

In this regard, it is useful to define an index capable of providing a measure of the effectiveness of the absorber. Scientific literature shows many indexes of efficiency that take into account dimensions, weight, economic aspects

related to the manufacturing process and absorbed energy. In this work a quality index based on the relationship between the weight and the amount of absorbed energy has been taken into account.

MATERIALS AND METHODS

In general, two main parts constitute a shock absorber: a structural part characterized by high stiffness (facing) and a filling component characterized by high values of plastic deformations (core); the combined mechanical properties of such parts influence the global behaviour of the absorber [7-10]. The facing can be composed of both metallic materials, such as aluminium and steel alloys, and composite materials, such as carbon or glass fibres [11]; the core is made of materials with reduced density, as metal foams or polymeric materials, with time dependent mechanical properties, even if in some cases the filling material can be omitted [12].

Many factors affect the capability to store energy of a shock absorber; in this work geometrical and material parameters were investigated and the global performances were evaluated in terms of absorbed energy and the ratio between such energy and the device's weight. Experimental tests were carried out at the Materials Science laboratory of the Second University of Naples.

For what concern the facing, the material adopted in this work is a laminate face-sheets; for its manufacturing a 411-350 vinyl ester resin was used in the infusion process with 5% cobalt napthanate promoter and methyl ethyl ketone peroxide initiator. The resin was mixed with 0.021% of cobalt napthanate and 1.05% of methyl ethyl ketone peroxide as a percentage of resin weight. Prior to infusion, the resin, initiator, and promoter were added to a medium surface fumed silica to form slurry that was applied to the surface of the foam and allowed to dry at 90°C for 2 h. Such silica and resin mixture increased the surface area of the foam to increase adhesion of the facing plies and also filled any depressions on the surface. The longitudinal and transversal elastic modulus of fibres are respectively 125 and 12 GPa; G_{12}=5 GPa; ν_{12}=0.26.

The filling material is the emulsion polymerised styrene butadiene rubber (E-SBR, hyperelastic material) whose mass density is 1125 kg/m^3; Poisson's ratio is assumed to be 0.49 that corresponds to a bulk modulus of 1594 MPa (room temperature). The relation between Poisson's ratio ν and the bulk modulus K is derived from the equation K=λ+2/3μ, where μ=G (shear modulus) and λ=2Gν/(1-2ν). The operating temperature is between -45 and +100C, it has a good resistance to cold, even if the glass transition occurs at -60 °C, and a low heat resistance. The mechanical properties taken into account in this work cover a temperature range between room temperature and 100°C [13, 14].

The LS-Dyna® code was used to perform the numerical simulations. Before to build the adopted numerical model a wide number of preliminary numerical model was built in order to investigate the features of global response. The geometries of the absorbers are shown in Fig. 1, circular thin-walled tubes, tubular rings, square, rectangle tubes, multicorner columns, top-hat and composed walled sections were investigated. In this work the square thin-walled configuration was subjected to uniaxial compressive static and dynamic load.
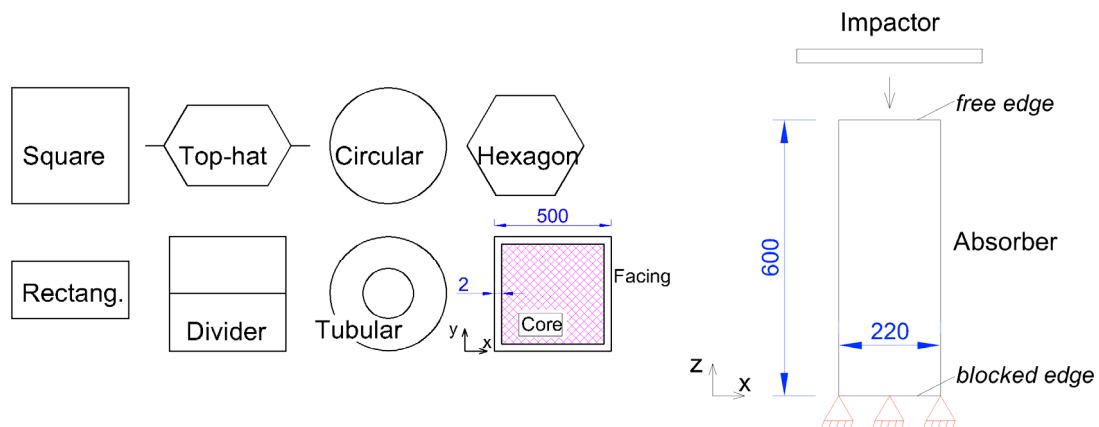

FIGURE 1. Cross sectional areas and geometry (mm).

The Belyschko-Tsay quadrilateral element was used to model all the shapes; the reference plane of the element was located at the bottom surface of each tubes in order to avoid any small gap between the facing and the core. The constant stress 8-noded (3 dof's per node) element was used to model the cores of the absorbers. Several contact algorithms were used to connect the tube shell element to core solid ones and the surfaces between the absorber and

the impactor. All the facings were modeled as four layers composite, using [0,90,±45] stacking sequence. The integration points were located through the thickness at the mid-plane of each layer. The numerical models consist of 4200-7120 elements and 5090-8230 nodes.

The constitutive material model 54-55 of LS-Dyna® code was chosen to model the facing while model 127 was used to model the core. Material model 54-55 implements interesting failure criteria [15, 16], as matrix and fibers cracking, also implemented in the model; such criteria take into account the post failure degradation of the material.

All the tubes were constrained (all degrees of freedom) to the bottom side, while the upper side is free. The load was applied by using a rigid wall that moves in a longitudinal direction. Two different compression velocities were investigated: 10 mm/s (static compression) and 20 m/s (dynamic compression). The impactor was displaced using a prescribed motion curve that assures a constant motion of the wall during the run time.

During a real impact scenario the entire absorber length can be involved in the crushing deformation; in this work it was considered a deformation of 70% respect to the initial length. Such length is enough to evaluate the energy absorption capability of the tubes. For all the absorbers the mean crushing force, absorbed energy and peak crushing force were evaluated. Both static and dynamic axial crushing were simulated. Five values of operating temperature are evaluated between room temperature and 100°C while one stacking sequence is implemented in the numerical models. For what concern the transversal section, the maximum amount of available space is a square (side 220 mm); in this way the absorber named Square is the biggest one while the other absorbers are inscribed into such figure. All the absorbers measure 600 mm height and in this work the manufacturing costs have not been taken into account. The absorber quality index is presented in order to summarize the obtained results.

RESULTS AND DISCUSSION

Fig. 2 shows the results of the reference tests; the numerical models appear to provide a good correlation with the experimental ones. Such numerical models were adopted for the other virtual simulations.
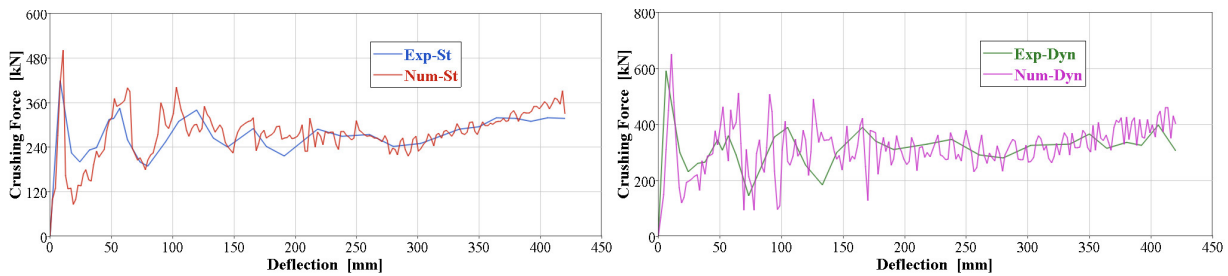

FIGURE 2. Numerical-Experimental results, circular section (static and dynamic analyses).

In the Table 1 is reported a first comparison among the seven configurations (Fig. 1) for static numerical analyses at room temperature. The table shows the absorbed energy, the peak and mean crushing forces and the quality index.

TABLE 1. First comparison among base configurations (static loading).

Shape	Absorbed energy [J]	Peak crushing force [kN]	Mean crushing force [kN]	Quality index [kJ/kg]
Square	115750	498	276	3.37
Hexagon	89988	444	213	4.01
Circular	102040	432	243	3.79
Rectangle	69039	325	164	3.93
Top-hat	88873	419	212	4.10
Divider	146096	570	347	4.21

The performance of the absorbers decreases with temperature as shown in Fig. 3. At room temperature a top-hat cross sectional model can absorb about 89 kJ; at 100°C the same device absorbs 69 kJ (-22%); for the same DT a circular cross sectional model shows a quite different behaviour, in fact at room temperature it absorbs 102 kJ while at 100°C it absorbs 87 kJ (-15%). Fig. 4 shows the quality indexes for some configurations from room temperature to 100°C.
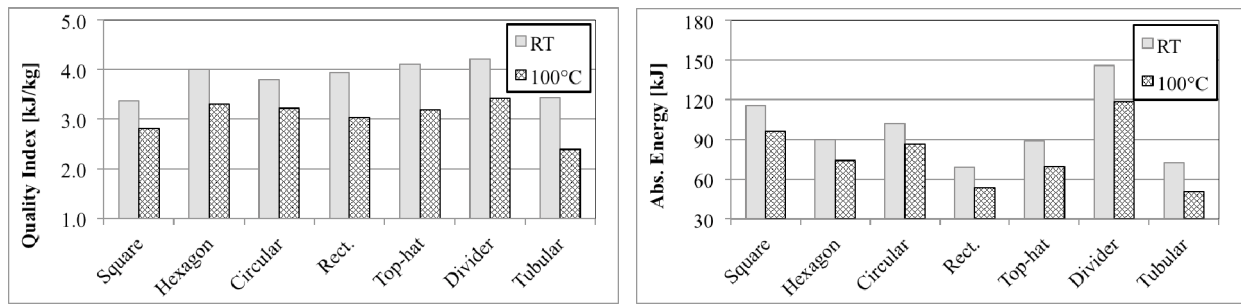
FIGURE 3. Quality index and absorbed energy for all the configurations at RT and 100°C.
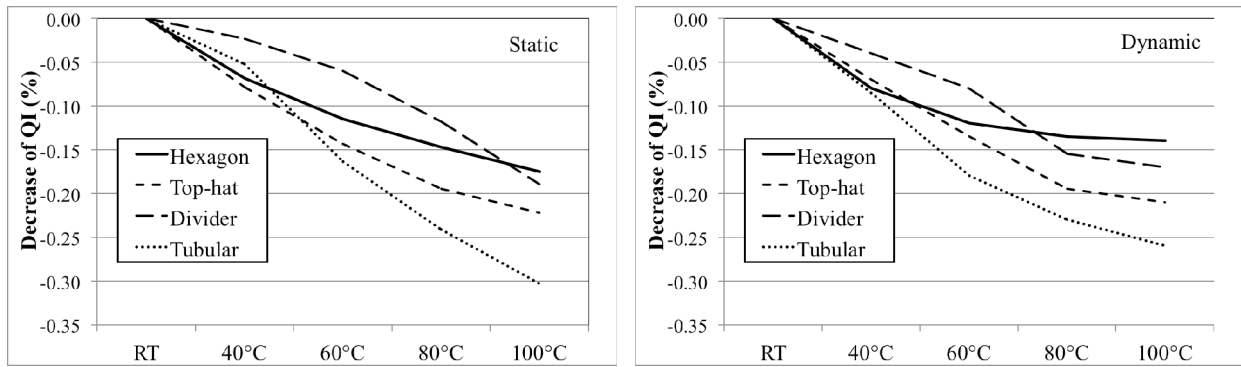

FIGURE 4. Quality index variation for static and dynamic loading conditions.

Fig. 4 shows that the performance of the absorbers, as the temperature increases, depend on the ratio between the mass of the facing and the mass of the core. The section having such maximum ratio, tubular section, also presents the maximum decreasing of the quality index. In the case of dynamic loads, the cross sectional areas with the best quality index at room temperature show a rapid decreasing in performance. As the temperature increases, the quality index tends to a plateau value.

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