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COMPOSITE IMPACT ATTENUATOR WITH SHELL AND SOLID MODELLING

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Abstract. Composite have been increasingly used in cars for their advantages of lightweight, high strength, corrosion resistance and easy manufacturing. Recently, carbon fiber reinforced plastic (CFRP) gains growing popularity in numerous advanced and high performance applications for crashworthiness thanks to its superior impact resistance, respect to metals or other composite materials. Maximising impact protection of carbon fibre reinforced plastic laminated composite structures, predicting and preventing the negative effects of impact on passengers are paramount design criteria for ground vehicles. In this paper the impact modelling of a frontal impact attenuator for a specific racing car will be investigated. The current work is based on the application of an explicit nonlinear finite element code, such as LS-DYNA, and on the experimental verification of the results, by means of an appropriately instrumented drop weight test machine. The thin-walled layered structure was numerically analysed using both shell and solid elements in order to reproduce the laminate as closely as possible, taking into account also the possibility during crushing of an interlaminar failure which plays a significant role during energy absorption mechanism. The proposed models are able to predict, with a good level of accuracy, the deformation process of such impact attenuator when subjected to dynamic loading as those imposed by technical regulation.

1 INTRODUCTION

Composites have been increasingly used in cars for their advantages of lightweight, high strength, corrosion resistance and easy manufacturing [1]. Recently, carbon fiber reinforced plastic (CFRP) gains growing popularity in numerous advanced and high performance applications for crashworthiness [2] thanks to its superior impact resistance, respect to metals or other composite materials. 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 has become indispensable parts to take into account during design. The present work is dealing with the lightweight design and the crashworthiness analysis of a composite impact attenuator for a Formula SAE racing car [3,4]. Such structure (Figure 1) has a geometry very similar to a square frusta in order to obtain a progressive deformation confined at impact wall maintaining a nearly constant strength during the axial crushing [5-7].

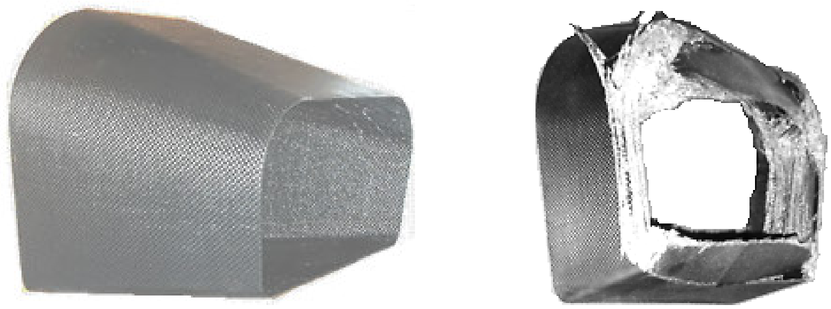

Figure 1: Impact attenuator before and after axial impact

During the design of this structure it is important to pay attention not only to the material distribution in various zones 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 resin. To reduce the development and testing costs of a new safety design, it is recommendable to use computational crash simulations for early evaluation of safety behaviour under vehicle impact test. The dynamic analysis was therefore conducted both numerically, using explicit finite element code 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. The impact attenuator was 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 it 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 observed values for these variables.

2 IMPACT ATTENUATOR DEFINITIONS

The analysed impact attenuator has a geometry very similar to a square frusta (Figure 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 the highest energy absorption ability, respect to the other deformation modes. 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 trigger which consists in a progressive reduction of the wall thickness to reduce the resisting section locally, thus avoiding force peaks and ensuring 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.

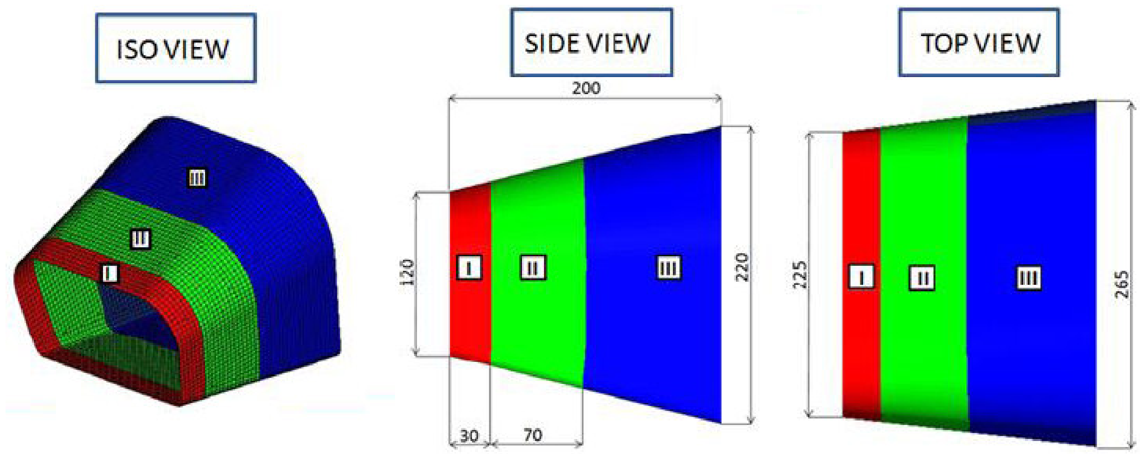

Figure 2: Geometrical configuration of the impact attenuator

The manufacture 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. In particular, the composite material is plain weave prepreg with carbon fibres and epoxy resin [3]. 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 Bending (DCB) and the Four Point End Notched Flexure (4ENF) procedures were utilised.

3 COMPOSITE MATERIAL MODELLING

Traditionally, layered composites structures are modelled as thin structures using shell elements. This approach is valid when designing thin parts, such as hollow tubes; but when the parts are more massive using shell elements is not appropriate. In such cases, both stress in the direction of the thickness and shear stresses out of plane are significant, and solid models are required. Solid elements are also appropriate when loads are applied in the direction of the thickness or when the structure is subject to large deformations. While defining thin-layered composites poses several challenges, the definition of solid composites is even more complex. The design of products made of layered solid composites starts by examining the layer definition, based on the same method as used for thin structures, then moves on to create solid composites by extrusion. This is followed by the assembly of composites parts, culminating in analysis of potential failure of the overall structure.

The composite impact attenuator taken into account was modelled using both these techniques: reproduction of the only middle surface of the structure with shell elements and implementation of the total geometry using solid elements. The FE model was discretized with elements of 5 mm x 5 mm, both for shell and solid configuration; this has resulted in a number of 6159 shell elements and 35695 solid ones, increasing the calculation time of 60 times in the second case.

Composite constitutive models implemented in LS-DYNA code are continuum mechanics models. Composites are modeled as orthotropic linear elastic material within a failure surface. The exact shape of the failure surface depends on the failure criterion adopted in the model. Beyond the failure surface, the appropriate elastic properties are degraded according to the assigned degradation laws. Depending upon the specific degradation law used in a model, the continuum mechanics models can be divided into two broad categories: they are either progressive failure models (MAT 22, 54/55, 59) or continuum damage mechanics ones (MAT 58, 161, 162). Progressive failure models have shown success [8,12] in axial crush simulations of composites exhibiting brittle fracture; therefore for this study the linear-elastic model #MAT_ENHANCED_COMPOSITE_DAMAGE was used. In such case damage occurs as soon as one of the four stress-based criteria by Chang/Chang [9] is met. Moreover it is possible to define failure strains, using DFAILx values in MAT54; in such case, the stress level after meeting the Chang/Chang criteria is kept at a constant level until the failure strains are reached.

Using a shell approach, the laminate lay-up can be defined by one integration point for each single ply with the respective ply thickness and fiber orientation angle. Once all single layers of the shell element have failed, the whole element is eroded and it simply disappears from the calculation. Underintegrated shell elements of the Belytschko-Tsai type (ELFORM=2) with the stiffness-based hourglass control (IHQ=4) were used for the modelling. This was justified since the hourglass energy in the final impact simulations was negligible, about 473J that is less than 1% of the total energy (7350J).

In order to capture also the interlaminar failure, i.e. the separation of two laminate layers, which plays a significant role in impact loading of composite thin-walled structures as an energy absorption mechanism and a degradation factor of structure stiffness a solid approach was implemented. In LS-DYNA there are two common techniques how to include delamination failure: use of tiebreak contact and implementation of cohesive elements. In this study the second method has been adopted, having available the energy release rates G_I and G_{II} for a crack propagating in adhesive layer from one crack tip obtained from dedicated Double Cantilever Beam (DCB) and 4-Point End Notched Flexure (4-ENF) tests on the used material. In order to make reasonably short the calculation time each ply was not modeled as a separate layer of solid elements with cohesive elements in-between, but a model with two, three and four separate layers of solid elements were generated for each zone, respectively, covering a certain number of different plies (Figure 3). In particular in the first zone the wall thickness was divided into one solid element 0.83 mm thick, one cohesive element 0.02 mm thick and another solid element 0.83 mm thick. In the second zone, instead, over the previous subdivision another cohesive layer and another layer of composite solid elements 0.46 mm thick were added. Finally, in the last zone, another cohesive layer and another layer of composite solid element 0.22 mm thick were implemented.

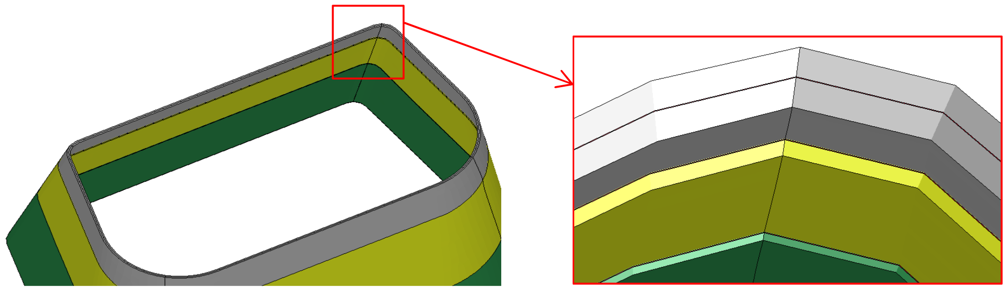

Figure 3: Solid element modelling with cohesive elements

Such methodology can be seen as a first approach to evaluate if delamination occurs and if it is an additional energy absorption mechanism [10].

The material properties used for the prepreg material modelling are summarized in Table 1.

Table 1: Overview of CFRP elastic and failure properties

ρ [kg/mm^3]	E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	ν_{12} [-]	X_T [MPa]	X_C [MPa]	Y_T [MPa]	Y_C [MPa]	S_C [MPa]
1.45e-6	53.6	55.2	2.85	0.04	618	642	652	556	84

DFAILT	DFAILC	G_{IC} [N/mm]	G_{IIC} [N/mm]
0.05	-0.03	0.5	0.7

4 EXPERIMENTAL DYNAMIC TESTS

In order to assess the quality of the simulation results, experimental tests were performed on the samples of the analyzed impact attenuator at the simulated impact conditions [11] using a drop tower suitably instrumented [3,4]. In particular a mass of 300 kg is moved upwards by an electromagnet to the desired falling height in order to obtain an impact velocity of 7 m/s; once released by disconnection of the magnet electric supply, the hammer falls in free-fall going to impact the structure constrained with a flange support at the tower base. During the test variation of acceleration with time are acquired and filtered with a CFC60 filter in order to eliminate high frequency content introduced by vibration and noise.

While performing the dynamic impact test, it is noticed that the manufacturing process of the composite impact attenuator has a significant influence on structural crashworthiness. A lamination process that does not take into account a planned overlap of prepreg zones distant from the corner edges can cause a catastrophic behavior of the impact attenuator (Figure 4) with an energy absorption capacity very low respect to that it is possible to obtain from the same geometry by changing only the manufacturing process (Figure 5).

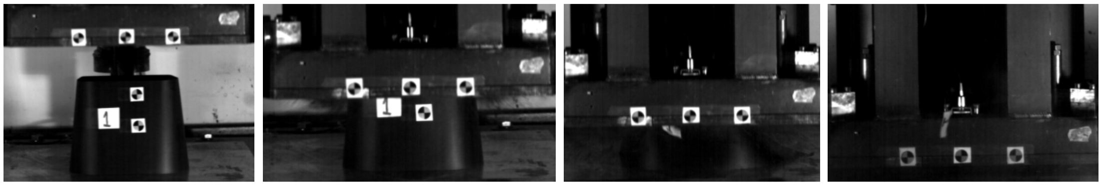

Figure 4: Impact frames of the impact attenuator without lamination attention

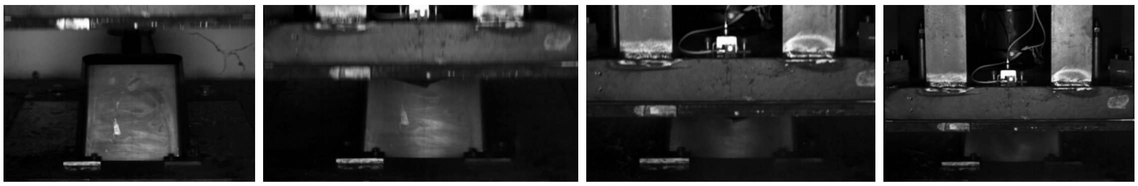

Figure 5: Impact frames of the impact attenuator with lamination improvement

Also from the deceleration signals for the two tested configurations it is possible to note such absorption characteristic: the area under the blue solid line in the diagram of figure 6, that refers to the improved crash-box, is greater than that under the dashed black line, that refers to the filtered data of the impact attenuator made without attention to the lamination process. In this second case it is evident that the impact attenuator is able to absorb energy only up to about half of the deformation process; this drawback phenomenon is not more evident in the other case.

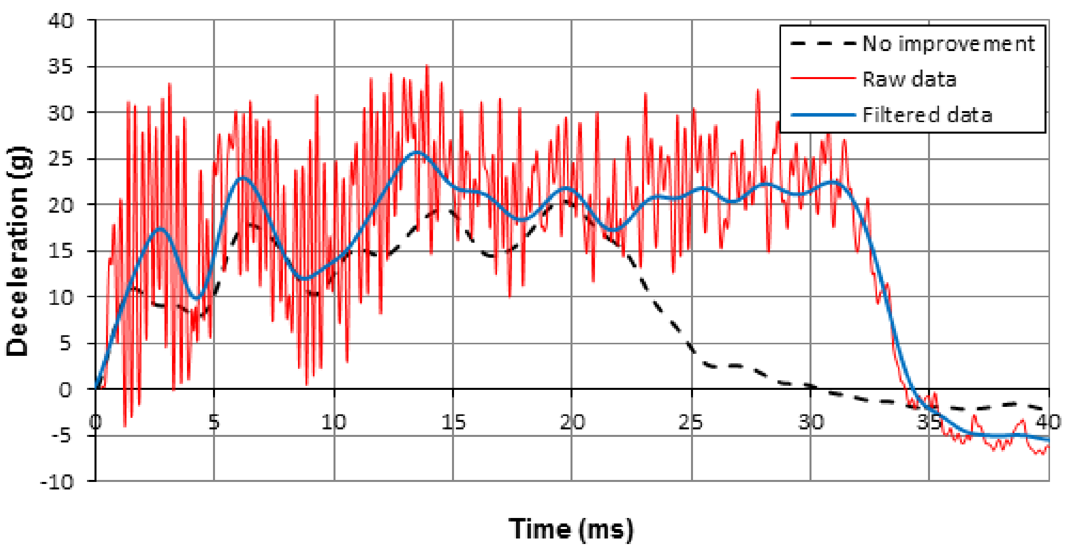

Figure 6: Comparison of deceleration vs. time of attenuator without (only filtered data) and with lamination improvement

5 COMPARISON BETWEEN SIMULATION AND EXPERIMENT

The comparison between the numerical results, for both modelling techniques, and the experimental ones in terms of deceleration versus time (Figure 7) shows a good capability to capture the crushing process of such structure, even though the complexity and heterogeneity of the CFRP composite material used. Such correspondence is also evident in the final deformation shape. Figure 8 shows that by using solid modelling it is possible to reproduce the sharp break of the laminate in a specific zone of the impact attenuator, while Figure 9 shows that by using shell elements it is also possible to reproduce the flexion of the straighter wall under compression.

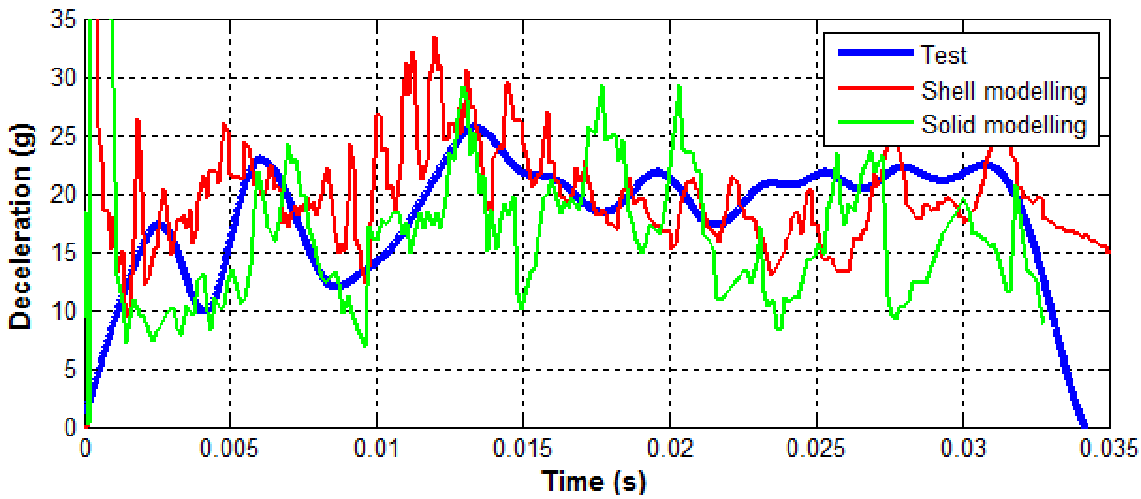

Figure 7: Comparison of experimental and numerical results in terms of decelerations in time

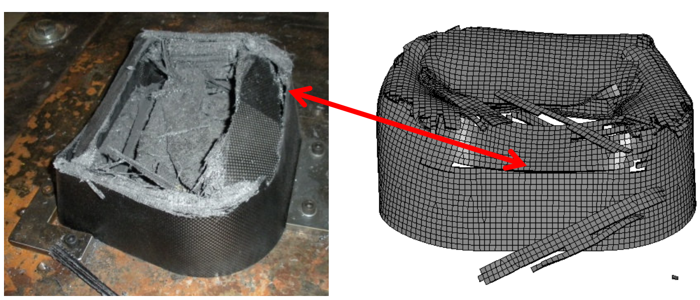

Figure 8: Reproduction of the sharp break of the laminate in the last impact stage through solid modelling

The kinetic energy during impact is absorbed by the composite structure through a progressive brittle behaviour, maintaining deceleration values near to 20 g as required by Formula SAE technical regulation. Both the shell and solid modelling techniques are able to capture the total crushing, using the same parameters for the composite material. The combination of solid and cohesive elements allow to reproduce some interlaminar fracture phenomena that are reproducible by using only shell modelling. The use of solid elements, nevertheless, leads to a substantial increase in computing time which often cannot be accepted if the dimensions of the total system are great.

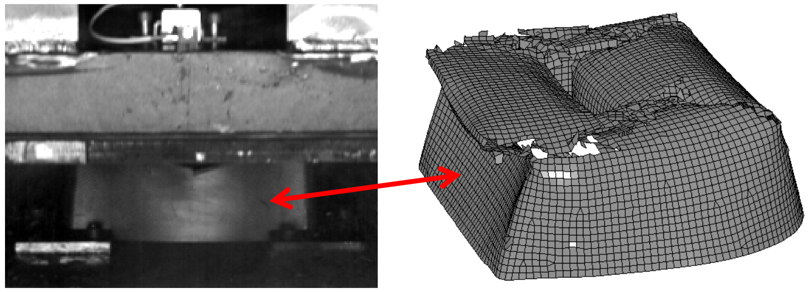

Figure 9: Reproduction of the flexion of the straighter wall through shell modelling

6 CONCLUSIONS

The present work summarizes the efforts conducted during the finite element modelling of a specific structure in CFRP composite material to adopt as frontal impact attenuator in a Formula SAE racing car. In particular the FE model was implemented with the non-linear dynamic code LS-DYNA using two different approaches in the structural modeling: shell elements and solid ones. The second configuration involves a much higher calculation time, but claims the capacity to show the stress in the direction of the thickness, the shear stresses out of the plane and, combined with cohesive elements, the interlaminar failure.
Experimental tests, performed using a drop tower suitably instrumented, confirmed stable behavior of the impact attenuator if specific attention is paid in the lamination process.
The kinetic energy imposed by Formula SAE technical regulation is absorbed by the composite structure through a progressive brittle behavior, maintaining deceleration values near to 20g as required.
Both the shell and solid modeling techniques are able to capture the deformation process: both the force time history and the final deformation shape are well reproducing the experimental results. Further Figure 8 shows that by using solid modelling it is possible to reproduce the sharp break of the laminate in a specific zone of the impact attenuator, while Figure 9 shows that by using shell elements it is also possible to reproduce the flexion of the straighter wall under compression.
Finally it is worth to point out that in the case of thin-walled structures where during crushing it is not evident a splaying with axial splitting in the section seems more reasonable to adopt a 2D modeling technique in order to reduce the calculation time. On the contrary, if there is the need to reproduce also the delamination phenomenon a 3D approach with the use of cohesive materials can lead to a detailed reproduction of the physical phenomenon.

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