CRASH ANALYSIS OF COMPOSITE SACRIFICIAL STRUCTURE FOR RACING CAR

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INTRODUCTION

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 the construction of aerospace structures. In case of impact, the kinetic energy of the vehicle should be dissipated in a very fast but stable, regular and controlled way so that passengers can survive. In metallic structures, this energy absorption is achieved by plastic deformation, while in composite structures it relies on the material diffuse fracture: i.e. on a completely different mechanism. Excellent performance of composites, sometimes better than those of the metallic similar structures, can be obtained by choosing appropriately the mechanical (the stacking sequence, the number of layers, the type and quantity of fibres and matrix) and geometrical (the beam section shape, the wall thickness, the extremity joints) design parameters [2].

This paper is presenting the design and numerical simulation of impact event for the frontal safety structure of car body for the formula SAE vehicle developed by the Polytechnic of Turin team. On figure 1 we can see the final solution of the racing car, which was produced in the collaboration with partner enterprises in Turin and successfully demonstrated in several racing competitions in Europe. 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.

Figure 1: *The racing car of Polytechnic of Turin*

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After initial analysis of the response of the designed impact attenuator in aluminium, which is presented in previous activities [3], it is developed the same sacrificial structure but in composite. Since the composite is relatively new material, requires constant evaluation in automotive applications to ensure equal if not greater performance than their metallic counterpart. The main scope of this work is the comparison of crashworthiness response of composite and aluminium impact attenuators and development of optimal solution that can be implemented in final production.

The performed numerical simulations put in evidence the needs for the design of a good energy absorbing structure and also the requirements for a good design of the links between attenuator and Body in White. The idea is to develop an efficient solution in terms of absorbed energy versus weight ratio, which leads to lightweight approach.

Complete geometry was done by means of the software for 3D modelling Catia. The finite element model of the structure was developed by means of the software code Hyper Mesh. Finally the crash event simulation has been developed by means of the Radioss code.

The main aspects of the research were oriented toward the dissipation of the kinetic energy during the front impact that should be as progressive as possible and toward the evaluation of the initial deceleration which has to be as little as possible. It is well known that the optimal solution in absorbing energy for this type of application is to obtain a nearly flat diagram of the impact force, that means a nearly constant value of the deceleration [6]. All initial requirements, which gave good results at the end of simulation, were done regarding the 2008 Formula SAE rules. These constraints are mainly oriented to dimensions of the attenuator, mounting of the parts, material selection, construction of attachments and final results requirements.

GEOMETRY OF THE MODEL

The Society of Automotive Engineers has introduced a series of regulations to ensure that race cars conform to stringent safety requirements and build quality, in order to be granted race-worthiness certification. These criteria include a series of static loads applied to the chassis, which guarantee the strength and integrity of the survival cell and a series of requirements on the location and impact characteristics of the energy-absorbing device [8]. Each year the number and severity of these requirements increases in line with ongoing research and development in crashworthiness or in response to real life accidents.

In order to meet the requirements of Formula SAE 2008 competition, the attenuator must guarantee specific performances in terms of average deceleration values and minimum acceptable dimensions during impact. Moreover the assembly of the sacrificial structure is subjected to the following conditions according to reference [21]:

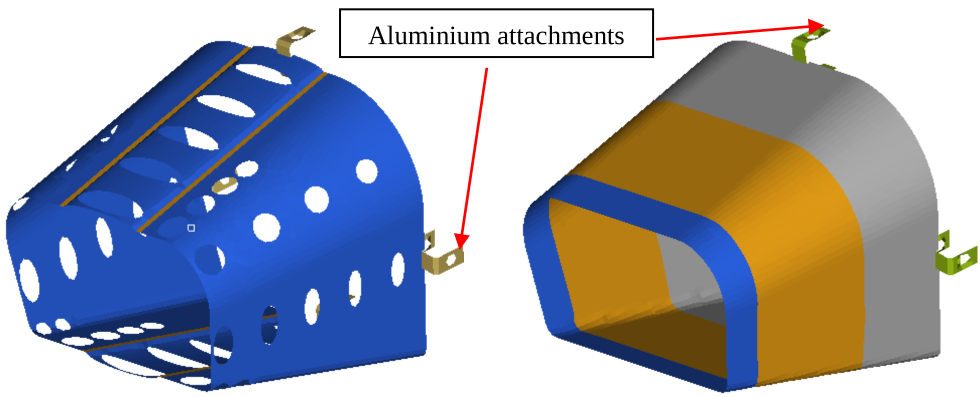
- The impact attenuator must be installed in front of the bulkhead;
- It must be at least 200 mm long (along the main axis of the frame), 200 mm wide and 100 mm high;
- It must not penetrate the front bulkhead in case of impact;
- It must be attached to the front bulkhead by welding, or at least, 4 bolts (M8, grade 8,8);

- It must guarantee safety in case of off-axis and off-centre impact;

The analysed energy absorber (figure 2) consists of a truncated pyramidal structure with an almost rectangular section. The pyramidal structure allows to obtain a major stability during the progressive crushing, while the rectangular section has rounded edges to avoid stress concentrations.

In the picture of figure 2(a) which is showing the aluminium impact attenuator structure, some holes are well visible in all the four side walls of the impact attenuator structure. They are operating as triggers, that means have both the scope to decrease the weight of the structure itself and to obtain a better crush behaviour by decreasing the first peak of the collapse force. By putting holes at appropriate positions, especially on fillet surfaces, it is obtained the sacrificial structure in aluminium with good impact performance and in particular, smaller initial deceleration pick during the crash test.

In the picture of figure 2(b) is shown the absorbing device in composite. In comparison with the same one in aluminium, it doesn't have holes and properly shaped aluminium plates. The design of sacrificial structure has been completed with a trigger which consists in a smoothing (progressive reduction) of the wall thickness in order to reduce locally the resisting section. This trigger is intended both to reduce the value of the force peak and to initialise the structure collapse in a stable way. Three different wall thickness are introduced and shown with different colours on figure 2 (b). Also, the carbon fibre component is offering great deal of weight saving with respect to the aluminium structure. Comparing the masses, the composite structure is 40 % lighter.



(a) Mass=0,544kg (b) Mass=0,307kg

Figure 2: *Impact attenuator structure: (a) in aluminium; (b) in composite*

One of the important SAE constraints is about the construction solution of attachments between impact attenuator and bulkhead. After several consultations with judges of SAE 2008 from Germany, the final solution for the design of links was chosen, which gave good results from the point of view both of practical implementation and, finally, of good impact behaviour, i.e. desired amount of absorbed energy and suitable level of deceleration.

These final links are C shaped. These links are independent parts of the system. They require bolts for the connection between car body and impact attenuator. In the images of the figure 3, we can see the front impact attenuator structure and the links assembled to that structure.

In the picture of figure 3, we can see complete structure; it consists of three different parts: car body frame, impact attenuator and links.

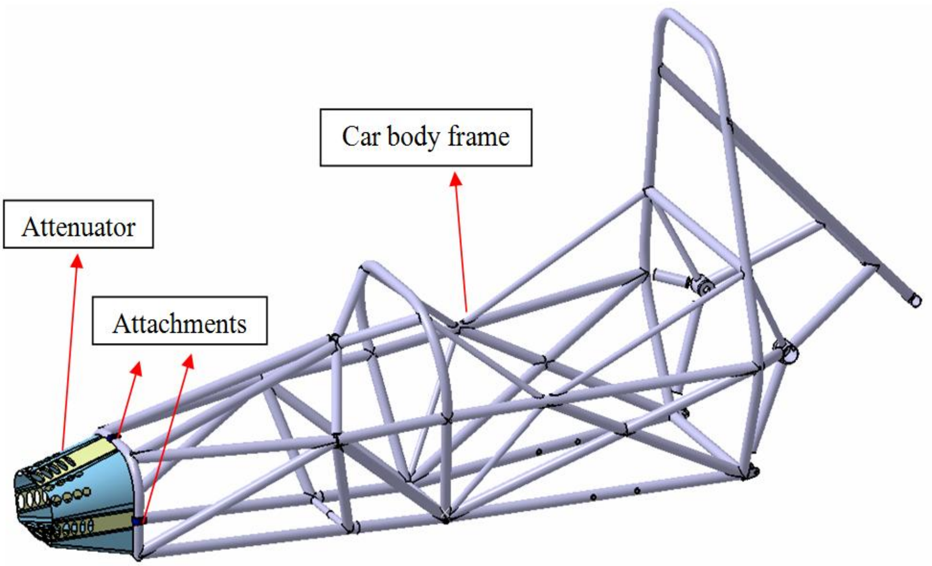


Figure 3: *Complete race car structure*

FINITE ELEMENT MODEL

Complete simulation was done using finite element model developed in Hyper Mesh software. It is very important to notice that it was not used all car body structure, but only the frame that is the most important part from the point of view of the vehicle front impact and driver safety. Unnecessary parts were cut off before making the mesh of the finite element model.

Three different types of materials are used: steel S275JR UNI EN 10025 (Fe430), 6082T6 aluminium alloy (this type of the alloy is anticorrosion material good for energy absorption but quite hard for bending) and composite T300/5208 carbon-epoxy.

Aluminium impact attenuator and links were made of previously mentioned aluminium alloy and the car body frame was made of steel. Also, this type of attenuator includes two beams which have different properties in comparison with the rest of attenuator. The properties of parts are: impact attenuator shell thickness is 1.5mm, impact attenuator beam thickness is 3mm, attachment thickness is 3mm and tube thickness is 2.5mm. Parts of the aluminium sacrificial structure with attachments are presented on figure 4.

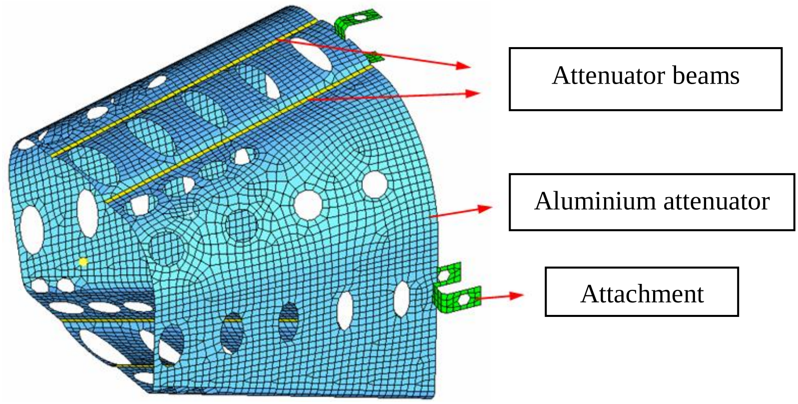


Figure 4: *Parts of the aluminium impact attenuator*

For this simulation materials were modelled as isotropic with elastic – plastic characteristics. The description of the material characteristic will be made by means of the usual Ramberg–Osgood plastic law together with the Johnson – Cook factor to account for the strain rate effect (Law 2 in RADIOSS). Adopted values of modelling parameter can be seen in table 1.

Table 1: *Material properties used for aluminium attenuator simulation*

Property	**Aluminium alloy 6082T6**	**Steel S275JR UNI EN 10025 (Fe430)**
Density	2.7 * 10-3 g/mm3	7.8 * 10-3 g/mm3
Poisson's ratio	0.33	0.3
Young's modulus	70000 MPa	206000 MPa
Yield strength	428.5 MPa	275 MPa
Hardening parameter	327 MPa	591.4 MPa
Hardening exponent	1	0.7108
Strain rate coefficient	0.00747	0.03
Ultimate strength		430 MPa

The finite element model of the composite absorbing structure is shown on figure 5. As previously mentioned, the triggering mechanism is introduced in terms of progressive reduction of wall thickness. In particular, there are three different wall thickness zones that are presented on next figure by green, red and blue colour:

- Green zone - laminate thickness = 0,8 mm simulated with 4 plies
- Red zone - laminate thickness = 1,3 mm simulated with 6 plies
- Blue zone - laminate thickness = 1,4 mm simulated with 7 plies

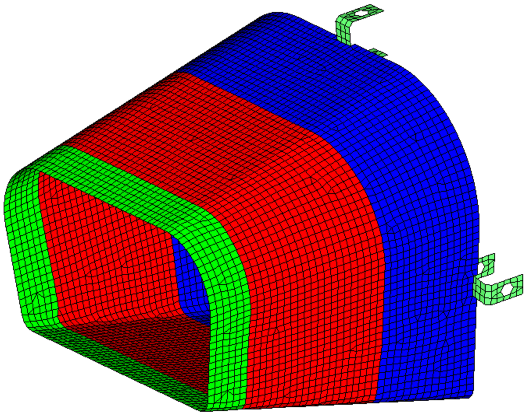


***Figure 5**: Composite impact attenuator*

The composite T300/2508 is modelled with stacking sequence [0°,90°] and unidirectional fibre. The element property type used for modelling composites in solver Radioss v44 is Type10-Composite Shell. It allows the possibility of modelling up to 100 layers with constant thickness, variable layer orientation, constant material properties and constant reference vector. Integration is performed with constant stress distribution for each layer. The used material law is COMPSH (25) with orthotropic elasticity, two plasticity models and brittle tensile failure. The plasticity model is based on the Tsai-Wu criterion which allows to model the yield and failure phases [17]. In table 2 are presented material characteristics, necessary for composite modelling.

***Table 2:** Material properties used for composite attenuator simulation*

Property	**Composite T300/5208 carbon-epoxy**
Density	1.6 * 10-3 g/mm3
Young modulus in fibre longitudinal direction	181 GPa
Young modulus in transverse direction	10.3 GPa
Poisson’s ratio	0.280
Shear modulus $_{12}$	7.170 GPa
Shear modulus $_{23}$	4.020 GPa
Shear modulus $_{31}$	7.170 GPa
Longitudinal tensile strength	1.500 GPa
Transverse tensile strength	0.040 GPa
Longitudinal compressive strength	1.500 GPa
Transverse compressive strength	0.246 GPa
Compressive strength in direction 12	0.246 GPa
In plane shear strength	0.040 GPa

A rigid wall with a mass of 300 kg is added, it models the obstacle impacted during the test. The structure is moving with initial velocity of 7m/s. There is friction between the rigid wall and attenuator. The friction coefficient has the value of 0,2 between attenuator components and 0,4 between rigid wall and attenuator.

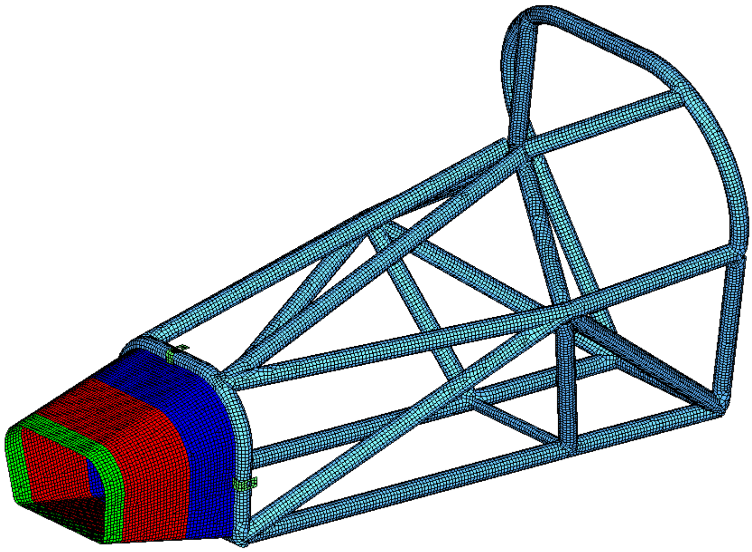


Figure 6: *Finite element model of the structure with composite attenuator*

When analysing the impact attenuator structure linked to the body frame, not all the body frame was modelled. Constraints were added in substitution of the rear part of car body, that was cut off, because it is not relevant for the present analysis.

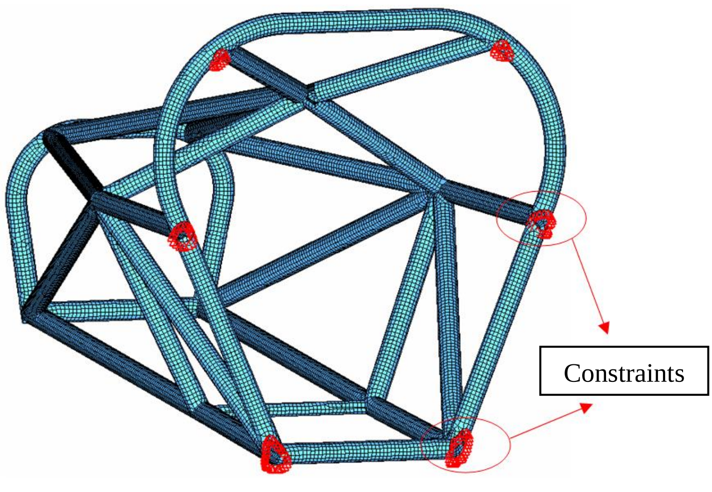


Figure 7**:** *Finite element model with specific view on constraints*

In finite element model, there are several contacts between parts which do not allow for penetration. In pictures of figures 6 and 7, we can see the representation of finite element model with mesh and constraints.

The complete model, which consists of composite impact attenuator, linkages and front part of the car body, has 215590 elements and 38194 nodes. We used 3 node and 4 node element types.

RESULTS

Most of the relevant results obtained by the performed analysis will be illustrated and discussed in the following paragraphs.

First of all we will see the results obtained in the simulation of the structure with impact attenuator in aluminium in comparison with the results obtained in the simulation of the solution of the composite impact attenuator linked to the frame structure. Results have been analysed by means of the software code Hyper View. The duration of the simulation is 60ms. In figures 8 and 9 we can see the crushed shape of the two different models in two subsequent positions during the impact: in figure 8 we are about at 14ms of the crash event while in figure 9 we are at the end of the crash. On the left side we see the results obtained when considering the impact attenuator structure made in aluminium while on the right side we see the results obtained with the impact attenuator made in composite. Both structures have almost the same behaviour and absorption of the energy in the first half of the simulation, which is presented on figure 8. But, at the end of the simulation, we can see on figure 9 that the aluminium impact attenuator is more deformed, in particular in the lateral walls. The difference in displacement and deformation is almost 50% with respect to the composite attenuator at the end of the simulation. This means that the composite structure is showing better crash behaviour.

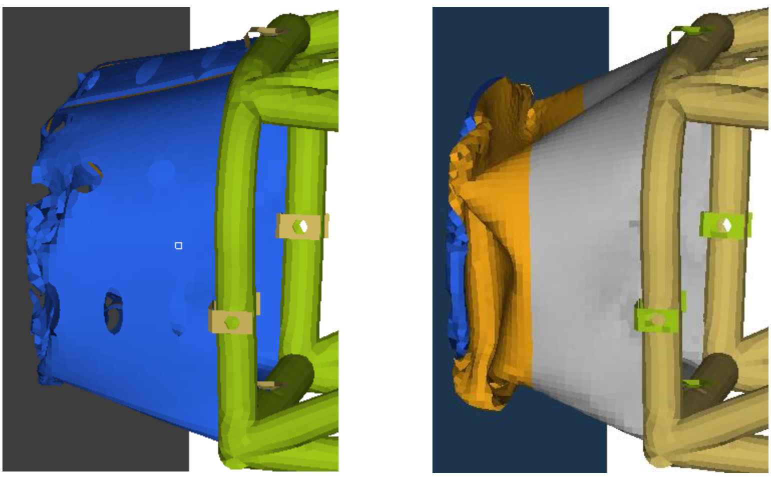


Figure 8: *The position of two structures during the impact at 14ms of crash event*

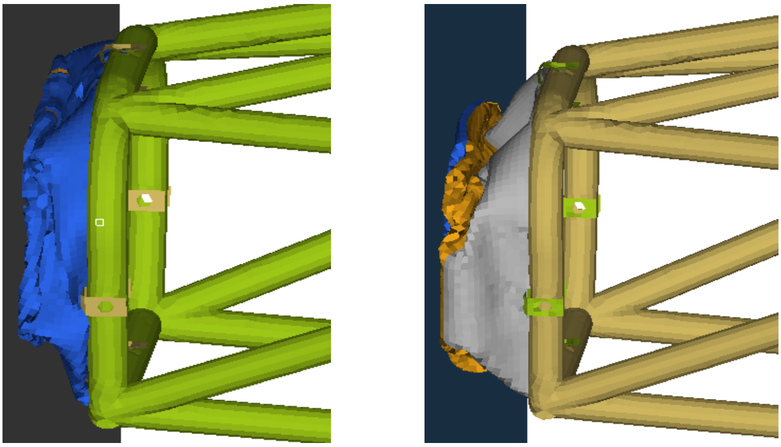


Figure 9: *The final position of two structures during the impact*

Figure 10 shows the diagram of the trend of kinetic energy in time, the responses of two different models are reported: the car body with impact attenuator in aluminium and the same one in composite. It is worth of note that all curves are starting from the initial energy value of 7350 J. The behaviour of the composite attenuator structure during the crash impact is better with respect to the aluminium one almost from the begin of crash evolution. In particular, the kinetic energy is absorbed faster by the composite structure than by the aluminium one. The zero value of the kinetic energy is reached after 38 ms of the simulation in the case of composite device and 47 ms when we have the aluminium attenuator. This means that the composite structure has a more progressive collapse.

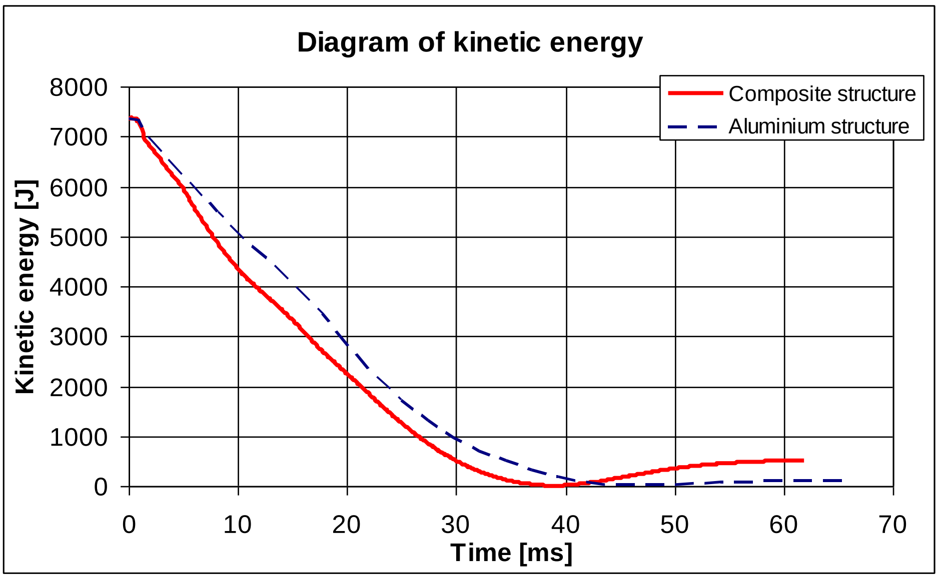


Figure 10: *Comparison of kinetic energy of the models with aluminium and composite sacrificial structure*

On figure 11 we can see the diagram of the history of the velocity in x direction for both cases. The before mentioned results are confirmed in the same manner.

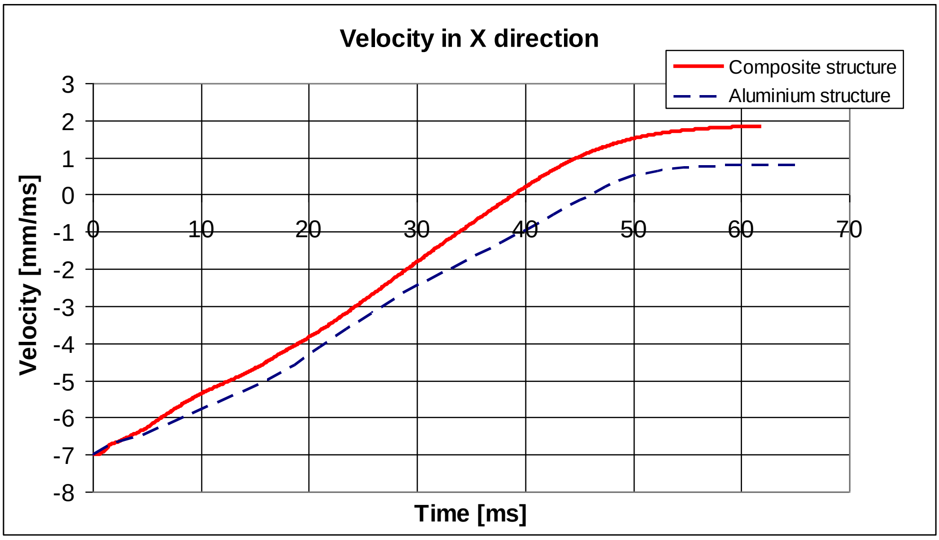


Figure 11: *Numerical results of the velocity of the aluminium and composite impact attenuator*

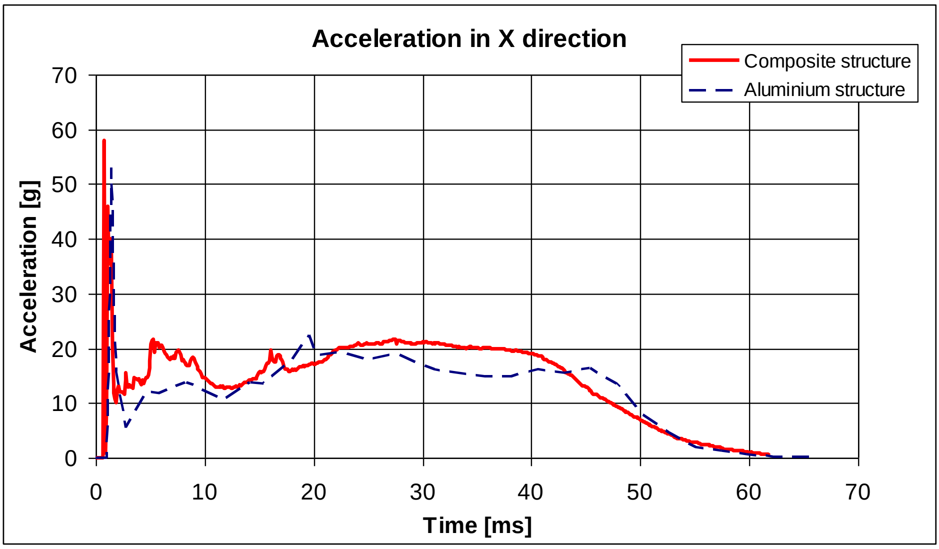


Figure 12: *Comparison of decelerations for two attenuator models: in aluminium and in composite*

On figure 12 we can see the diagram of the evolution of deceleration during the time for both solutions. The first peak is due to the initialisation of the structure collapse and, for aluminium sacrificial structure, has the value of 0,52 mm/ms^2, which is 52g. This value in the case of composite attenuator is almost the same, and it became 58 g. Between 6 and 25 ms of the simulation process, the behaviour of these two structures is almost the same. On figure 13 the force displacement diagram is presented. The force is directly dependent on acceleration, and that's why the behaviour is almost the same. The first maximum peak of the aluminium structure is about 145 kN and for composite structure 155 kN.

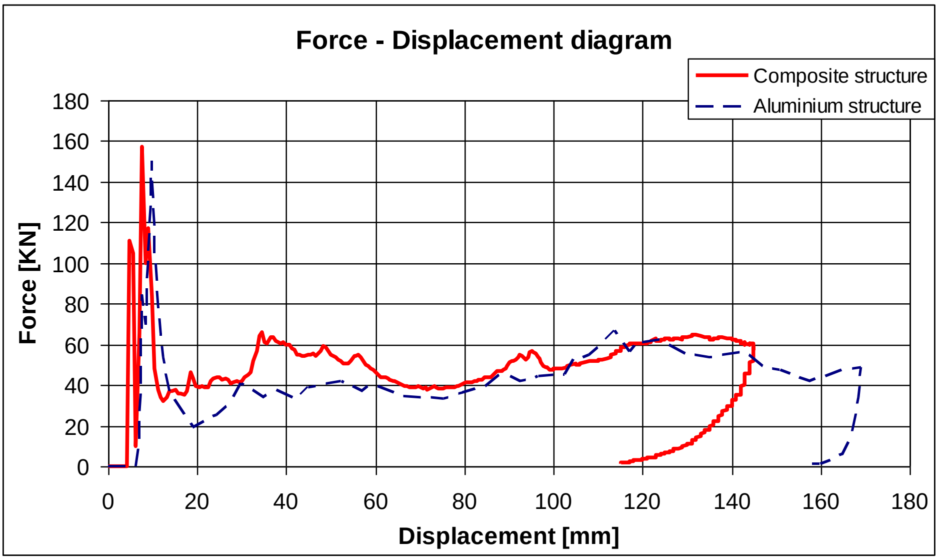


Figure 13: *Force – displacement diagram for aluminium and composite attenuators*

In both diagrams of figures 12 and 13 it is well visible that the composite impact attenuator response is quite good being close to the optimal absorber one from the aspect of initial pick of the force and acceleration. After initial peaks, we obtain a nearly flat diagram of the impact force, that means a nearly constant value of the deceleration. Also, it is recommended in SAE rules that "average deceleration of the vehicle must not exceed 20 g". On figure 12 it is well visible that the average acceleration of the assembly that consists of car body and aluminium impact attenuator is about 14 g and in the case of composite attenuator is higher but not exceeding 20 g.

CONCLUSIONS

The paper has developed a careful analysis of the crash behaviour of the impact attenuator structure that has been designed to equip the formula SAE car of the Politecnico di Torino racing team. The simulations performed by the finite element methods permit to point out some very important facts, that are giving strong arguments about the quality of results got in this work.

First of all the design of the energy absorbing structure has to allow a progressive evolution of the phenomenon avoiding as much as possible the presence of force peaks (that means deceleration peaks). The ideal solution is a flat diagram of the resisting force in time.

As a second capital point, achieved results put in evidence that the adoption of composite materials not only leads to lighter structure but also gives the possibility to design structures that have crash performance even better than aluminium structures. The composite impact attenuator is lighter 40% respect the same one in aluminium.

From the analysis of the diagrams, we can conclude that the collapse evolution of both suggested attenuators is progressive and stable. It is also possible to note the presence of a quite high first peak of the load that is due to the initialisation of the structure collapse. In any case the value of the maximum deceleration (that is in correspondence to the first peak) in the case of aluminium attenuator structure is about 0.52 m/ms^2 (52g). In the case of composite structure the maximum deceleration is about 58g, that means a very small difference with respect to previously mentioned and reliable solution. Also, the average deceleration of the aluminium structure is 14g and in the case of composite solution also less than 20g. This values fits well with the requirements of SAE 2008 rules, as they require that the adopted solution leads to an average deceleration lower than 0.2 m/ms^2 (20g). It means that crush initialisation triggers improved significantly the structural response, that is very important for composite sacrificial structure. Also, the absorption of the kinetic energy of the composite attenuator showed stable behaviour and better response respect to the aluminium solution.

All these results confirm that the composite attenuator structure is very good from the point of view of frontal impact and it is possible to absorb energy on good way.

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