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DEVELOPMENT OF AN IMPACT ATTENUATOR FOR A FORMULA SAE VEHICLE

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Abstract. In the development of a Formula SAE vehicle, one of the requirements for the vehicle approval by the Society of Automotive Engineers (SAE) in the competition is the impact attenuator validation, which must pass through demanding rules of performance and format. Although there is no limitation of the type of material to be used, its design is one of the most challenging in the development of the car, once it involves iterative processes and a considerable knowledge in materials, manufacturing processes and finite element method. This work aims to show possible solutions for the impact attenuator, through a bibliography review of different models which are already developed by different teams around the world. So, four candidate models will be numerically tested in LS-Dyna, being chosen one of them to refine the model through material testing and a parametric numerical study. In this stage, different geometry will be tested, selecting the best one for the manufacture and final test of the attenuator in an impact hammer. As final stage, a full vehicle crash-test will be developed, intending to verify the structural behavior under frontal impact situation and the consequences of the impact for the driver, represented by a dummy.

1 INTRODUCTION

Formula SAE is a student engineering competition organized by the Society of Automobile Engineers (SAE), which exists since 1979 and is currently attended by hundreds of universities around the world. One of the most challenging requirements for a vehicle to participate in the competition is the impact attenuator, which should be able to absorb the energy from a frontal impact at 7 m/s of a 300 kg car, minimizing damage to the driver. This attenuator has a number of requirements regarding its shape and safety performance, however it does not have restrictions on the material to be used, being generally made of foams, honeycomb, plates of aluminium or carbon fiber reinforced polymer [2,8].

2 OBJECTIVES

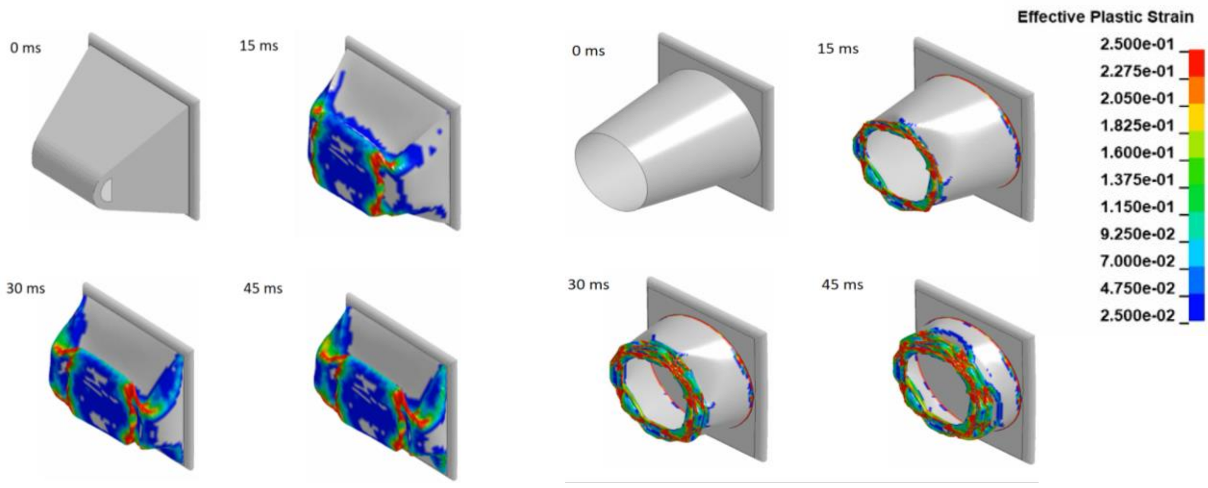
This work will be divided into two stages. The first objective is to develop a functional impact attenuator according to SAE rules, capable of absorbing at least 7350 J of energy, corresponding to an impact of a mass of 300 kg at 7 m/s, resulting in a deceleration peak smaller than 40 g and average deceleration smaller than 20 g. This attenuator shall have dimensions greater than 100 mm of width per 200 mm of height and 200 mm of length. In addition, it must be fixed in the anti-intrusion plate, which is welded to the bulkhead of the vehicle, and this assembly cannot undergo through permanent bending larger than 25 mm. This set must be tested experimentally, proving that the conditions required by the SAE rules are met.

In the second stage, a numerical model will be developed in finite elements of the vehicle structure, where a dummy will be positioned. This model will be used for a frontal impact analysis, in order to evaluate both the behavior of the structure and the possible injuries to the driver, through the analysis of regions such as head, neck, chest and femur.

3 DEVELOPMENT OF THE IMPACT ATTENUATOR

3.1 Preliminary simulations

Four configurations were analysed, two models made of aluminium sheets in pyramidal and conical shapes and two models made of polystyrene and polypropylene foams, known in the market by the names IMPAXX® and ARPRO®, respectively, which properties were extracted from [5,6]. The configurations of each impact attenuator used in preliminary tests and its deformations along time are seen in figure 1, and figure 2 shows the deflection of the anti-intrusion plate and the deceleration applied to the vehicle structure in these cases. As boundary conditions, an initial velocity of 7 m/s was used and a mass of 300 kg was coupled at the four ends of the bulkhead structure.



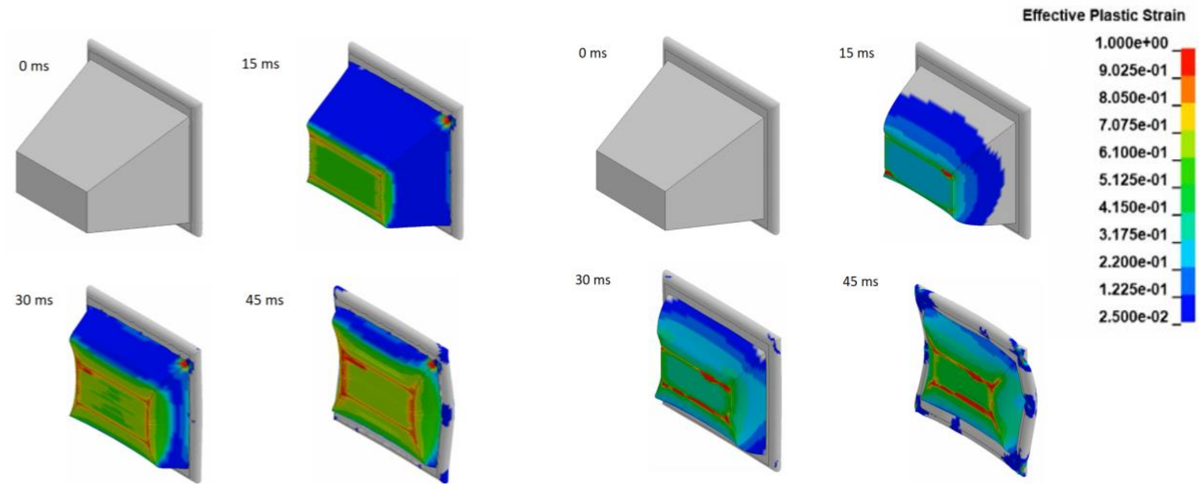


Figure 1: Initial configurations and evolution of the plastic deformations of the four impact attenuators tested in the preliminary stage (upper left: pyramid cone trunk, upper right: aluminium cone trunk, lower left: IMPAXX® foam, lower right: ARPRO® foam)

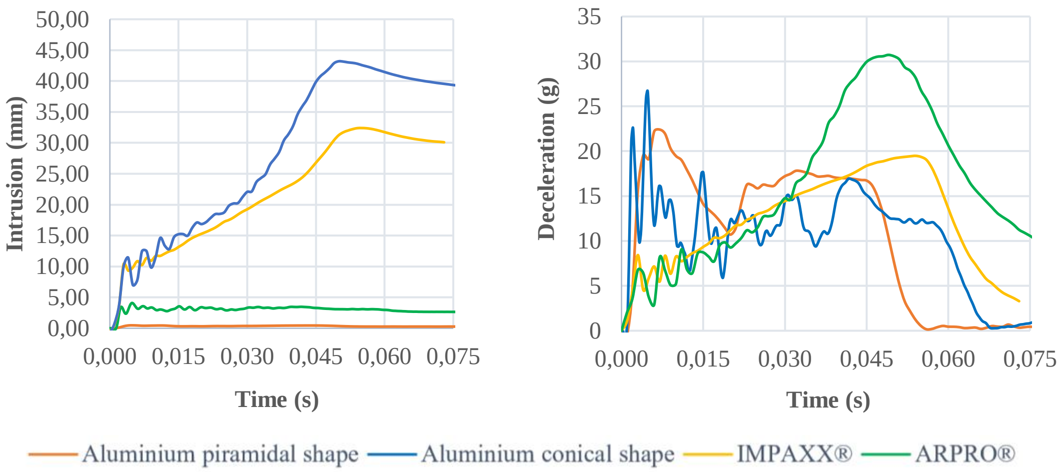


Figure 2: Left - Deflection of the structure. Right - Deceleration applied in the structure

From Figure 1 it is possible to observe that the aluminium attenuators presented the so-called progressive deformations, absorbing the energy of the impact through the programmed deformation of their structure. In addition, these models showed an adequate deceleration behaviour according to SAE rules and small anti-intrusion plate deflections, once the impact load is applied only in the corners of the plate, close to tubular structure. The foam attenuators showed acceptable decelerations, but the deformations of anti-intrusion plate were found to be above the allowed limit. One possible solution to avoid such deflection is the use of steel tubes of higher mechanical strength. Due to factors such as availability of material on the Brazilian market, manufacturing costs, process reliability and quality control of the prototype, the selected model was the ARPRO® foam, on which a more in-depth study and refinement of the model will be carried out.

3.2 Experimental apparatus

The experimental tests to characterize the foam and the steels used in the structure were performed at GMSIE (Group of Solid Mechanics and Impact in Structures) at USP. The quasi static tests were done in an Instron 3369 Universal test machine, and the impact test was done in a vertical hammer, able to perform tests up to 25 kJ.

3.3 Characterization of materials

After the foam samples were prepared in circular format of 38 mm in diameter by 10 mm in height, foams of three densities (60 g/l, 80 g/l and 100 g/l) were carried out at the deformation rates of 10^{-3} s^{-1}, 10^{-2} s^{-1}, and 10^{-1} s^{-1}, three samples were tested for each condition. The curves of the materials are shown in Figure 3. Datasheet [5] properties is also shown in dashed lines for 60 g/l and 80 g/l foams.

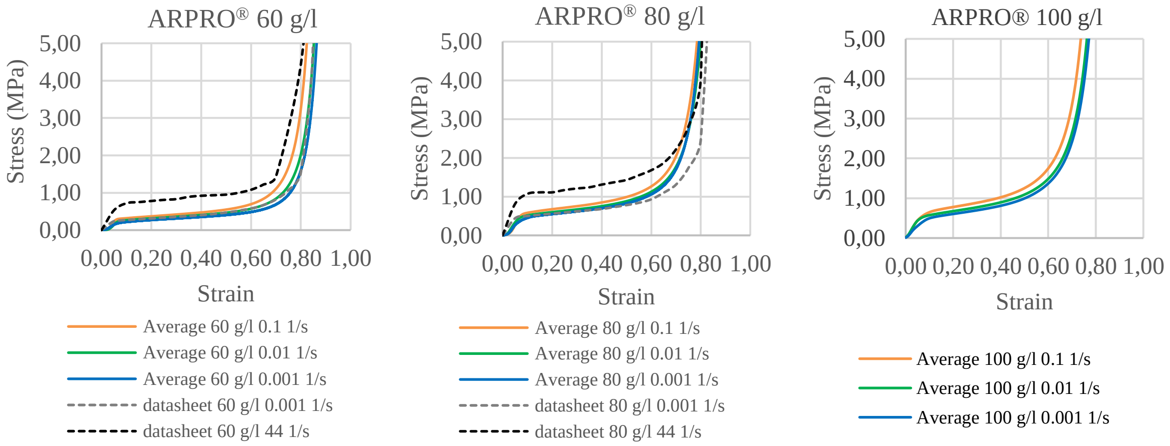


Figure 3: Strain-strain curves of ARPRO® foam in three densities

In addition, the properties of steels SAE 1020, SAE 1045 and SAE 4130, used in the vehicle structure, the anti-intrusion plate and the bulkhead, respectively, were raised and shown in Figure 4.

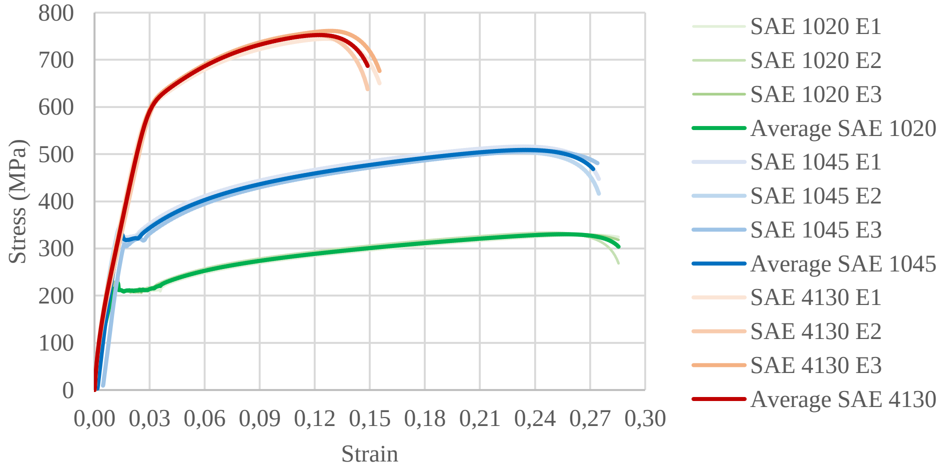


Figure 4: Stress-strain curves of the steels used in the vehicle structure

4.3 Solution refinement

Nine models of impact attenuators were tested, varying their volume and the density of the used foam. A comparison of the model dimensions and mass of each tested attenuator can be seen in Figure 5 and Table 1.

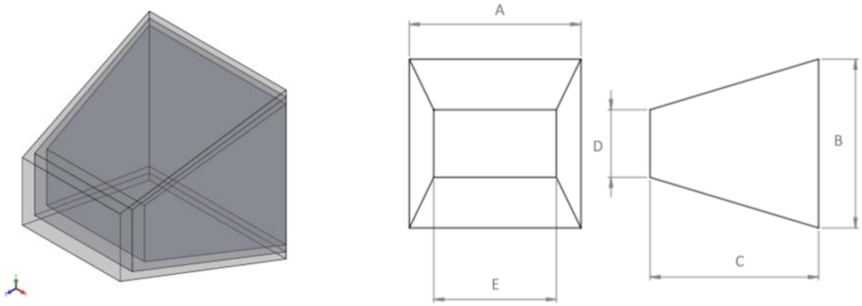


Figure 5: Comparison of the tested models

Table 1: Dimensions of the tested models

	Dimension (mm)					Mass (g)		
	A	**B**	**C**	**D**	**E**	**60 g/l**	**80 g/l**	**100 g/l**
Model 1	280	250	250	100	200	675 g	901 g	1126 g
Model 2	280	275	275	110	200	817 g	1090 g	1362 g
Model 3	280	300	300	120	200	951 g	1268 g	1585 g

The meshes were generated and the properties of the three densities of the ARPRO® foam were defined and used as input parameters in the LS-Dyna software. The material model used to represent the foam was MAT_083_FU_CHANG, which allows considering strain rate effects. A comparison between the initial and final instants can be seen in Figure 6, and Figure 7 shows the deflection of anti-intrusion plate and the deceleration of the vehicle structure.

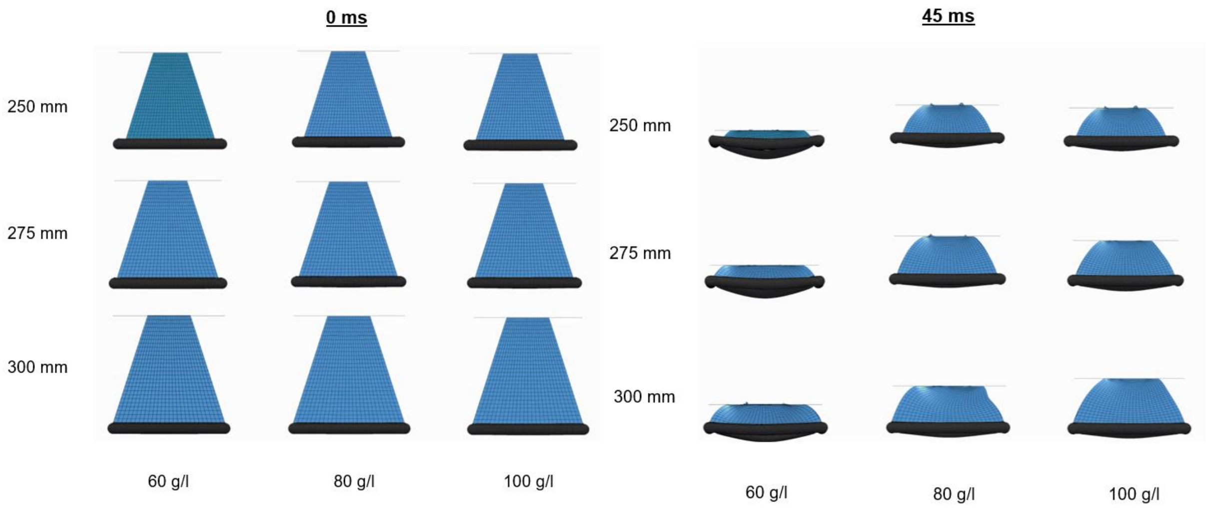


Figure 6: Parametric analysis of nine impact attenuators configurations

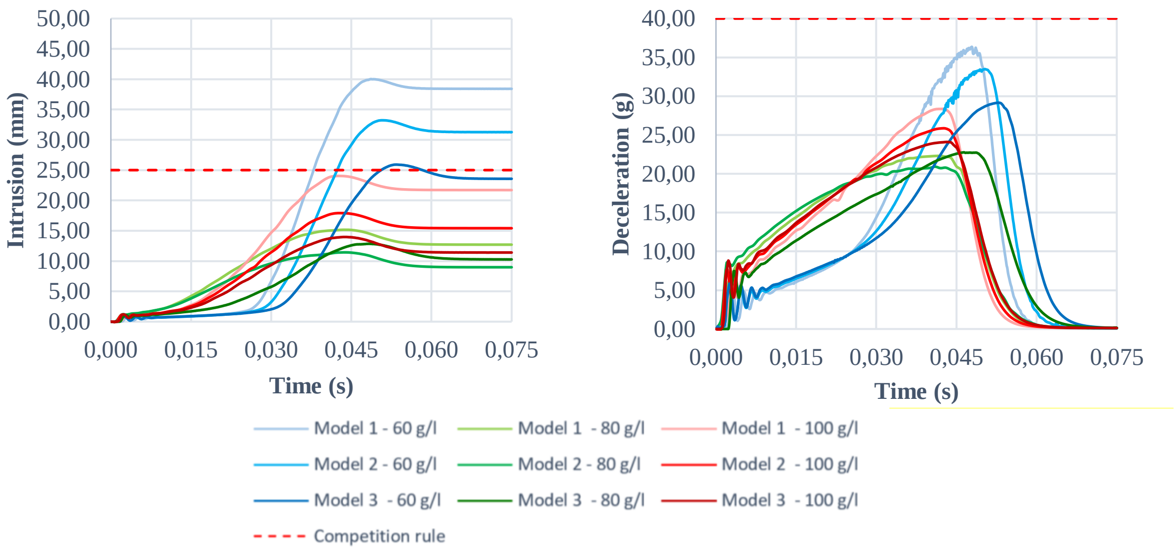


Figure 7: Left - Deflection of anti-intrusion plate. Right - Deceleration of the vehicle structure

It is possible to verify that the attenuators with foam of 60 g/l suffered greater deformations in comparison with the models of higher density. This behavior is explained by the low resistance of the foam, which deforms until reach densification, causing a very high load at this point. Text [4] has a in-depth approach of this phenomena in cellular solids, and explain the behavior found in Figure 7 . The higher densities showed a good behavior, and the figure above shows that the lowest bulkhead deceleration peaks and deformations occurs with the density of 80 g/l, especially in model 2. Thus, due to its lower mass and better results in the simulations the 80 g/l impact attenuator model 2 was selected for prototyping and experimental testing.

3.4 Selection of the best solution

In a more in-depth analysis of the refined solution it is possible to verify through Figure 8 how the foam and structure behaved along time.

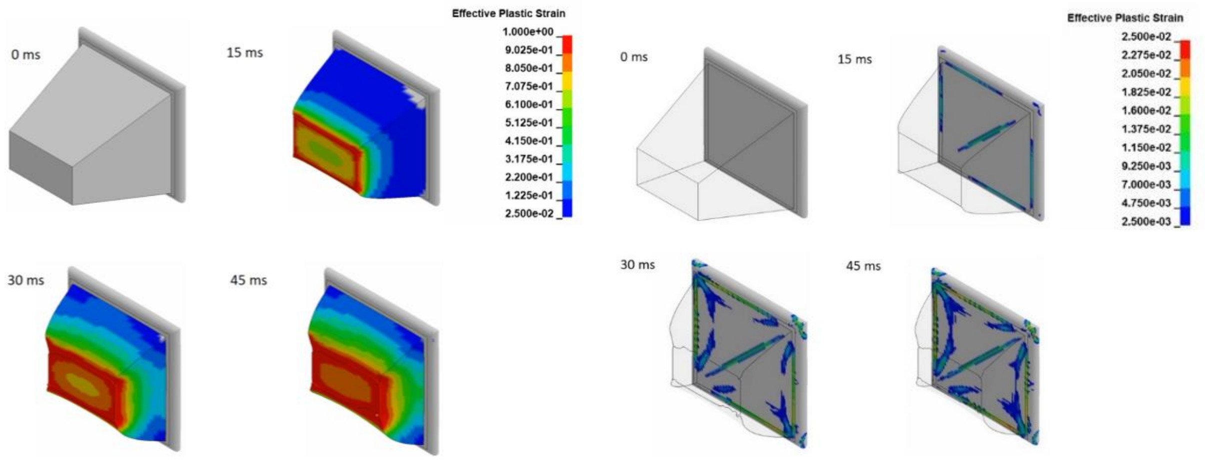


Figure 8: Development of plastic deformations in the foam, anti-intrusion plate and bulkhead structure

If we compare Figure 1 with Figure 8 it is possible to verify the evolution of the assembly, once after increasing the impact attenuator volume, foam density and improving the tubular steel strength, the structure showed a smaller deflection and it has decelerated with a lower peak. In addition, Figure 8 shows a stress concentration in the welding region, between the anti-intrusion plate and the bulkhead. These stresses are generated due to the traction of the plate in this region, showing the great importance of the welded union with a continuous and good quality welding fillet.

3.5 Impact hammer test

For this test, a rigid mass of 315.0 kg was initially positioned at a height of 2.38 m over the upper face of the impact attenuator. At the moment of impact, the mass was found to be at 6.71 m/s. Figure 9 shows the initial and final configurations of the experimental test performed on the impact hammer.

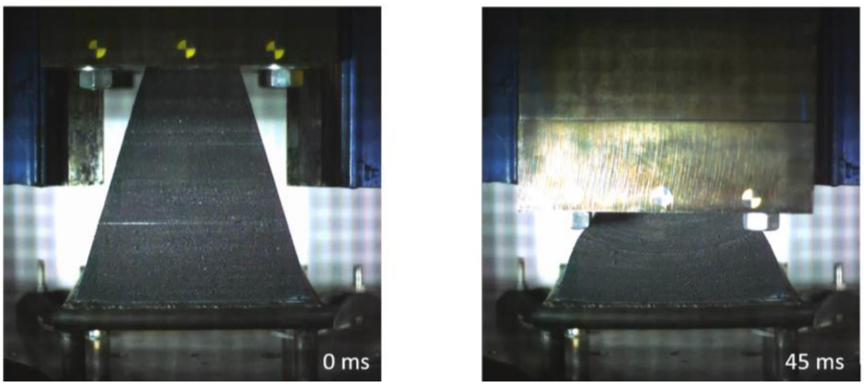


Figure 9: Experimental impact test

It is possible to verify that the assembly behaved in the expected way, absorbing the energy of the impact and presenting a practically negligible deformation of the structure. Figure 10 shows the mass deceleration and energy behavior curves in a comparison between the actual and the numerical test, and Table 3 shows a comparison between the values obtained.

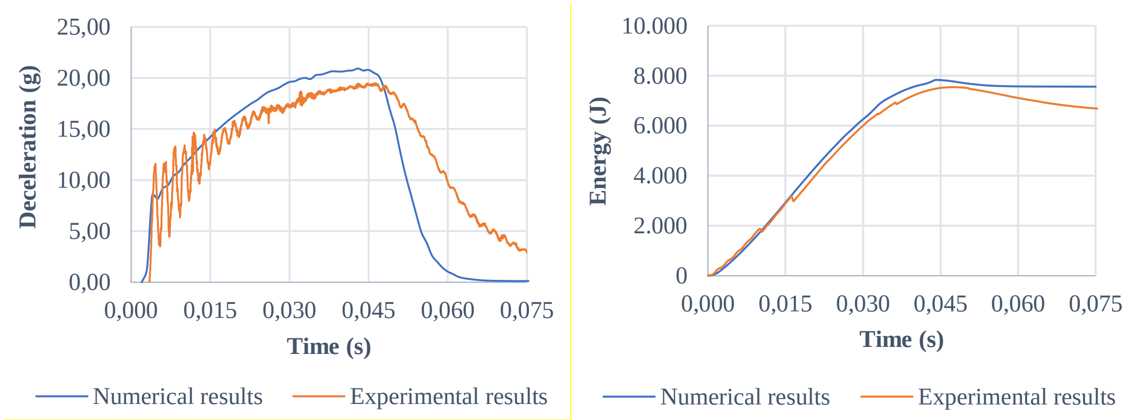


Figure 10: Comparison between experimental and numerical results. Left - Deceleration of the mass. Right – Absorbed energy

Table 2: Comparison between experimental and numerical results

	Peak deceleration (g)	Average deceleration (g)	Energy (J)	Peak force (kN)
Experimental test	19,41	12,51	7543,73	54,97
Numerical test	22,21	12,75	7671,97	59,03
Deviation (%)	12,62	1,86	1,67	6,88

In general, it is possible to see that the impact attenuator showed the requirements to be approved according to SAE criteria, with maximum deceleration below 40 g, average deceleration below 20 g and absorbed energy exceeding 7350 J. Also, it was found a good correlation between the data obtained numerically and experimentally. It should be remembered that the experimental test occurred with a mass of 315 kg and an initial velocity of 6.71 m/s and the numerical test happened with a mass of 300 kg and velocity of 7 m/s, which justifies the difference of 12.62% between the deceleration peak values.

It is possible to observe that after the point of maximum deformation a difference of the numerical and experimental curves becomes more evident. This divergence occurs because no tests were performed to identify the material behavior in the unloading phase, once the scope of this work was focused only on the first loading deformation of the material.

4 VEHICLE SAFETY ANALYSIS

In this section, a vehicle safety analysis will be performed, checking the behavior of the structure during the impact and impact severity for the dummy, through measurements of stresses and accelerations in critical regions as head, neck, chest and femur and comparison with the Brazilian standard NBR 15300 [1].

For the frontal impact simulation, a finite element model of the Formula SAE Poli Racing Team vehicle structure was developed. To represent the mass distribution due to the components of the vehicle, four 10 kg nodes were positioned in the wheel region, representing the inertia effect of the non-suspended mass. In addition, a mass of 55 kg was positioned in the rear region of the vehicle in order to represent the powertrain assembly. To represent the pilot, a Dummy 50th Percentile Hybrid III, available from the Livermore Software Technology Corporation (LSTC) [7], weighing 79.5 kg and representing an adult man was positioned. The dummy was restricted by a six-point seat belt, similar to that used in the vehicle, and a rigid plate was placed in the region of the feet to represent the contact of the feet with the accelerator and brake pedals. To represent the inertial effects of the helmet, a mass of 1.5 kg was positioned in the center of gravity of the dummy's head. So, the assembly was positioned in front of a rigid barrier with a velocity of 7 m/s. The mesh was composed of a total of 712.268 elements. Figure 11 shows the initial configuration and after 100 ms of the impact.

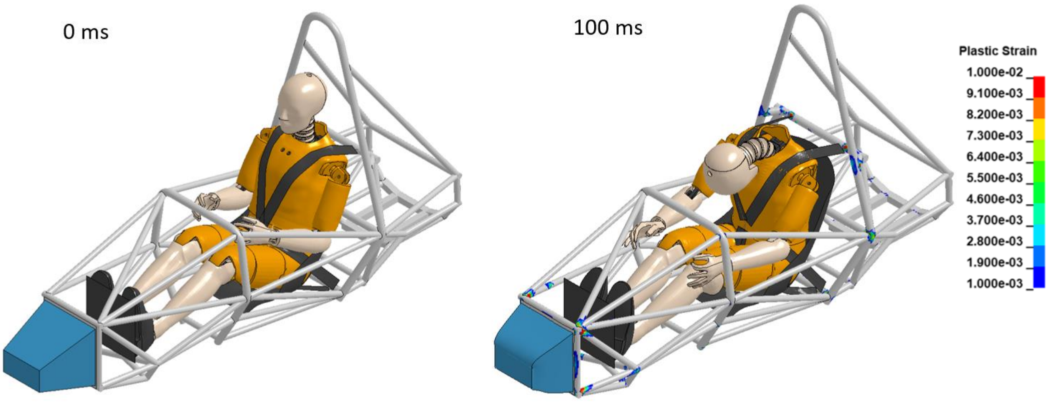


Figure 11: Full Crash test numerical analysis

In general, it is possible to affirm that the structure behaved as a survival cell, presenting very small and localized plastic deformations, which did not compromise the integrity of the occupant. Small stress concentrators were found in the corners of the bulkhead, where all the impact loads are transmitted to the structure, and in the seatbelts anchorage points, but any of these compromised the structural integrity during the crash. Still from Figure 11, it can be seen that the occupant has remained stable in the vehicle seat, demonstrating the efficiency of the six-point seat belt.

However, there is clearly a large neck flexion at the instant of 100 ms, which was caused mainly by two reasons: first, the seatbelt has small elongation, which generates a considerable acceleration in the occupant's chest. Second, the added mass of the helmet contributes to the so-called whiplash effect, increasing efforts in that region. Table 3 shows the values of the loads and accelerations obtained with the numerical simulation in the analyzed regions, as well as a comparison with the limits allowed by the standard NBR 15300, responsible for regulating the safety of urban vehicles marketed in the country. In addition, the probabilities of injury in the regions analyzed are shown in Table 4, according to the Abbreviated Injury Scale (AIS), which is explained in [3].

Table 3: Severity of impact to the occupant

	Criteria	Maximum allowed (NBR 15300)	Simulation Results
Head	Deceleration (g)	80.00	25.89
	HIC 15	700.00	33.97
Neck	Tensile (N)	4170.00	1675.30
	Compression (N)	4000.00	241.50
	Extension (N.m)	57.00	30.48
	Flexion (N.m)	57.00	40.00
	N_{te}	1.00	0.47
	N_{tf}	1.00	0.38
	N_{ce}	1.00	0.26
	N_{cf}	1.00	0.16
Chest	Deflection (mm)	75.00	7.01
	Deceleration (g)	60.00	36.45
Femur	Normal force - Left (N)	10000.00	2717.20
	Normal force - Left (N)	10000.00	3050.00

Table 4: Injury probability for the occupant

Index	**Injury probability (%)**						
	Head	**Neck**				**Chest**	**Femur**
		N_{te}	**N_{tf}**	**N_{ce}**	**N_{cf}**		
Moderate (AIS2+)	0.027	41.875	40.203	38.448	36.984	17.275	3.288
Serious (AIS3+)	0.011	23.483	22.021	20.619	19.553	3.295	1.825
Very serious (AIS4+)	0.002	14.352	13.303	8.499	11.333	0.848	-
Risk to life (AIS5+)	0.000	3.722	3.329	3.722	2.607	0.020	-

From this analysis, it is possible to observe that there is a very low probability of injury in the head region. This is due to the low HIC obtained during impact and the low deceleration peak in this region. One of the responsible for this behavior was the neck, which due its great flexion, resulted in little head restraining. This behavior, however, was responsible for generating average lesion probabilities of almost 42% in the neck, and one of the main reasons was the mass of the helmet added, which caused considerably high normal loads and bending moments. In this case, it would be appropriate the usage of the so-called Head and Neck Support (HANS) device, which would avoid an exaggerated flexion of this region, creating a support between the shoulders and the pilot's head.

Furthermore, it has been found that there is a 17.3% probability of a moderate injury in the occupant's chest, and a serious injury of about 3.2%. This is due the restriction of the six-point seatbelt, which restrains the occupant more severely than a conventional three-point seatbelt. Finally, it was found that the probability of an average lesion in the femur is about 3.2%, while a serious lesion is 1.8% likely to occur, indicating adequate safety for the driver of the vehicle in this region.

5 CONCLUSIONS

5.1 Impact attenuator

The preliminary studies showed to be essential for a better understanding and selection of the best impact attenuator model for the Poli Racing Team of Formula SAE. It was found that the initial model was not capable of absorbing the impact energy within the SAE rule conditions. However, the change of the geometry and density of the used foam, associated to the replacement of the structure steel allowed the design of a light, robust and approved by SAE rules impact attenuator. The numerical simulations were essential for the correct selection of the parameters of the new model, which shown good correlation when compared to experimental test.

In addition, the analyses in finite elements showed that the use of a continuous welding fillet were essential to ensure the structural integrity during impact, once the traction in this region improves the resistance of the assembly, and better distributes the loads around the tubular structure.

The results obtained can be considered satisfactory, once both the deceleration peak and average values were considerably below the rule limit and the structural deflection can be considered negligible. This indicates that the assembly would be able to withstand higher energy impacts, still showing deceleration peaks below 40 g, with average of less than 20 g and a deflection of less than 25 mm.

5.2 Vehicle safety

This study showed that for a frontal impact at 7 m/s in rigid barrier the vehicle did not present considerable plastic deformations in its structure. However, through measurements of biomechanical parameters of the driver, it was found a probability of about 41.9% of the average neck injury or 23.5% of a serious injury. This behavior occurs mainly by the mass of the helmet, which increases the inertia of the head region, and by the six-point safety belt, which allows practically no displacement of the dummy. A possible solution to reduce the risk of neck injury is the use of the Head and Neck Support (HANS) device, currently used in most motorsport categories.

The chest region also presented a considerable injury probability, reaching 17.3% for moderate injuries and 3.2% for serious injuries. The femurs, on the other hand, presented values of about 3.3% of average lesions and 1.8% of serious lesions. The head was the region where the probability was found to be the lowest, being well below 1% risk of some type of injury.

As recommendation to further works, the development of a helmet mesh could better represent the real phenomena and allow the coupling of the HANS device in the model. This case probably would reduce the neck stresses and increase the head acceleration, once the device restrains the head directly to driver’s shoulders.

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