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Metallic Profiles Filled With Aluminium Foam Used in Bus Structure to Improve the Performance in Semi-Frontal Crash and Rollover Sceneries

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ABSTRACT

The improvement of the safety of the road bus structure against impact scenarios and reduction of the injuries and death in traffic accidents is crucial in a country with continental dimensions like Brazil, where the road transport matrix is fundamental in the traffic of people and goods. In this context in the present work is explored the possibilities of the metallic tubes filled with aluminum foam as shock absorber in the bus structures. With this goal, an experimental campaign using tubes filled with aluminum foam was made. In these tests, uniaxial compression and three points bending tests were performed. The finite element method was implemented in LS-Dyna [2] and simulations were carried out, considering material and geometric non-linearities. The material properties were calibrated using the tests cited. Then, a bus structure modeled with finite element method was modified adding metallic tubes filled with aluminum foam to improve the structure performance in rollover and semi-frontal impact scenarios. Commentaries about all the results with the bus model are finally presented.

Keywords: Finite Element; aluminum foam; bus; impact.

1 INTRODUCTION

Aluminum foam has a wide range of applications (Figure 1), from the chemical, biological, thermal and mechanical sectors, as presented by [1]. In this work, the focus is on properties related to the capacity of a structure filled with aluminum foam to absorb kinetic energy resulting from an impact event and maintain integrity in occupant space, property called crashworthiness.

Figure 1- Adapted from [1]

2 DESCRIPTION OF MODEL USED

The experimental part of this study was based on compression and three-point bending for the test specimens. The models were represented by shell and solid elements, linked by contacts, for the representation of the tests.

2.1 Compression and Three-Point Bending Tests

For the compression and three-point bending tests was used the Universal Testing Machine model DL20000 manufactured by EMIC using procedure based on NBR norm NM-ISSO 7500 v.08 (Figure 2). The test speed used was 10 mm / min.

The process used to obtain the aluminum foam requires the heating of the sample and the tube, which may modify the properties of the tube. For this reason, three types of specimens were tested:

- Tube without filling and without heat treatment;
- Tubing without filling and thermally modified;
- Tube filled with aluminum foam.

For the heating process of the tube without filling, was followed the same heat treatment process used for foaming of the foam-filled test specimens. Three test specimens of each type were tested, so, a total of nine compression tests and nine three-point bending tests were performed.

Figure 2 – A) The machine device where were carried out the compression tests. B) The machine device where were carried out the three point bending tests.

2.2 Compression and Three-Point Bending Models

In this work, numerical models formed by shell and solid elements linked by contacts implemented within the software LS-Dyna [2] were used as evaluation tool (Figure 3). It was used The *Fully_Integrated_Shell* element to represent the shell elements and the *Constant_Stress_Solid* element to represent the metallic foam.

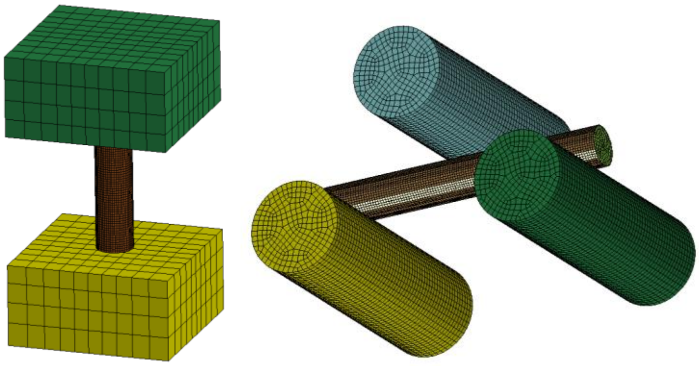

Figure 3 – Finite element models to simulate the compression and three point bending tests, respectively, using LS-Dyna [2].

The material model used in the analyzes was the *Piecewise_Linear_Plasticity* with a stress vs strain curve specified by tests for the tube. For the foam representation was used the *Low_Density_Foam* material model. It was used the same properties for the foam, as presented by [1]. The properties are presented in Table 1.

Table 1 - Material properties adopted for the aluminum foam [1].

ρ	E	TC	HU	Damp
600 kg/m³	5 GPa	1e-3	1	0.25

In Table 1, ρ indicates the foam density, *E* represents the elastic longitudinal modulus, *TC* is the strain at cutoff stress, *HU* is the hysteretic unload factor (when its value is equal the unity no dissipation happen in the discharge) and the *Damp* coefficient characterizes the damping material behavior, detailed in [2].

A force vs displacement curve used for the solid element was loaded into the foam database according to Figure 4. This curve is added by the *DEFINE_CURVE* command and is then associated to the foam by the *LCID* command on the *MAT_LOW_DENSITY_FOAM* table.

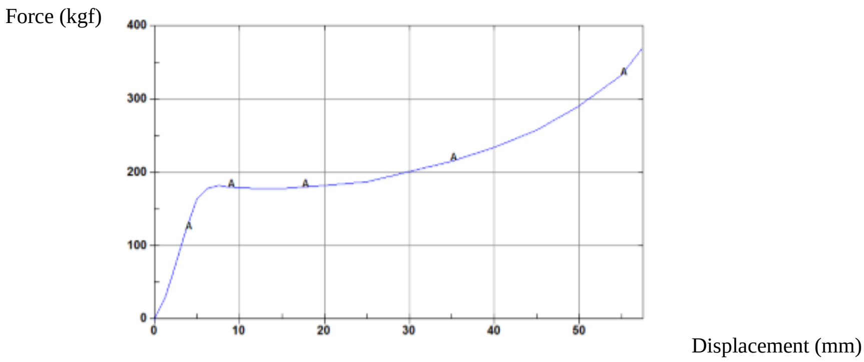

Figure 4 – Force vs Displacement curve for the aluminum foam solicited to compression.

The contact established between the steel tube and the supports and between the steel tube and the punch was the *Contact_Automatic_Surface_To_Surface*. This type of contact is recommended in analyzes involving collisions, since they do not allow penetration between the components of the analysis. The friction coefficients adopted were, static equal to 0,3 (FS) and dynamic equal to 0,15 (FD), proposed in [3]. The contact between the tube and the foam was represented by the *Contact_Tiebreak_Nodes_to_Surface* command, with factors of static and kinetic friction equal to 0,3 and 0,15, respectively.

The boundary condition applied to the punch was *the boundary_prescribed_motion_rigid*, with displacement as a function of time, using a quasi-static analysis, which does not take into account the effects of inertia.

2.3 Numerical Model of a Road Bus

The model used is a 4x2 road bus with rear engine with a total gross weight of 18.500 kg (Figure 5). The bus peripherals such as air-conditioning, tires, windows, engine, seats and tank were simplified for analysis purposes, with each component retaining its original center of gravity. It was used the *Belytschko-Tsay* shell elements formulation and *Constant_Stress* solid elements formulation.

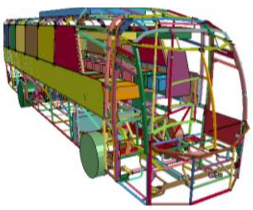

Figure 5 – Layout of the Bus Model used in LS-Dyna [2].

The mesh of the model followed the parameters presented in Table 2. The mass scale control was used to control the time step,in order to reduce the time of analysis, taking care to add a maximum of 5% of added mass to the model and keeping the auto deformation energy (Hourglass) below 5%.

Table 2 - Quality parameters of the mesh

Quality Parameters	Allowed min./max.
Maximum length	0,005
Maximum length	0,1
Maximum Aspect Ratio	5
Maximum warpage angle	15
Percentage triangular elements	5

2.3.1 Rollover Analysis

The model used in the rollover analysis is described in this chapter. An overview of the mesh is presented in Figure 6. The purpose of this analysis is to evaluate the structural behavior of the vehicle and the influence of the use of aluminum foam as a structural filling of the tubes of the structure.

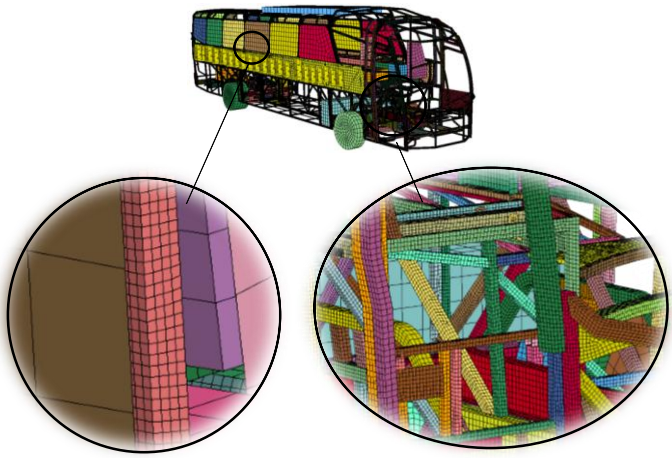

Figure 6 – Finite Element Mesh used in the roll over analysis.

In order to reduce the computational cost, the model is rotated until the moment before the impact with the platform and its rotation speed is calculated by the Equation (1)

$$E_k = 0{,}75Mgh \qquad (1)$$

where *M* is the bus mass, *g* is gravity acceleration and *h* is the difference between the heights of the bus center of gravity in the unstable point at the platform and before the contact with the ground. Equation (1) transforms the potential energy into rotational kinetic energy E_k.

In order to define the most efficient places to use aluminum foam, the study carried out by [4] was used, which simulated a rollover event in a bus and verified that the main plastic hinge on the bus is the connection between the base of the passenger lounge and the side structure of the bus. Following this methodology, 5,118 kg of aluminum foam was added to the lower spar of the side structure of the bus, in the position indicated in Figure 7.

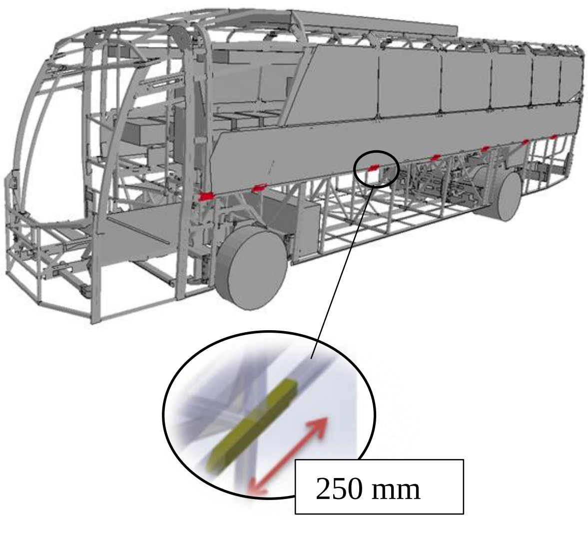

Figure 7 – Position of the aluminum foam in the Rollover test.

Templates were used to represent the survival space described in the rollover norm [5] . These templates were fixed in the base bars, in the regions of the window's columns, respecting the dimensions stipulated in the norm. The Figure 8 indicates the position of the structure templates representing the survival space (Indicated by numbers 1, 2, 3 e 4).

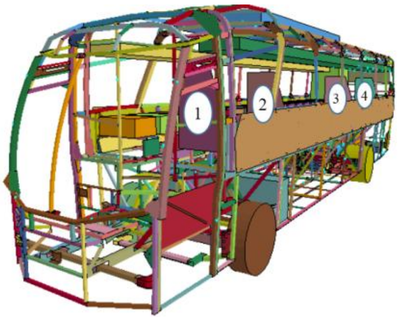

Figure 8 – Templates representing the survival space.

Failure criteria were not used for the material, since there were no stresses above the ultimate stress of the material and due to previous tests, it was found that there were no welded joints failure. Another reason for disregarding material failure is the computational cost due to the refinement of the mesh required in the analysis.

In rollover tests no strain rate is used, considering this effect in the safety coefficient for the analysis, as the increase of the strain rate would increase the strength of the structure.

2.3.2 Semi-Frontal Impact Analysis

The objective of this analysis is to evaluate the structural behavior of the vehicle and to evaluate the influence of the use of aluminum foam as structural filling in the bus tubes.

The simulation of the original bus structure was performed to understand its behavior under impact. As a test, a semi-frontal impact was chosen between two identical buses where one of them is stopped and restricted in the longitudinal direction in its rear and the other one moves with a speed of 36 km/h. This preliminary evaluation does not take into account hardening effects due to strain rate. Afterwards, an aluminum foam filling will be incorporated into the absorber structure and its effect will be evaluated in case of semi-frontal impact.

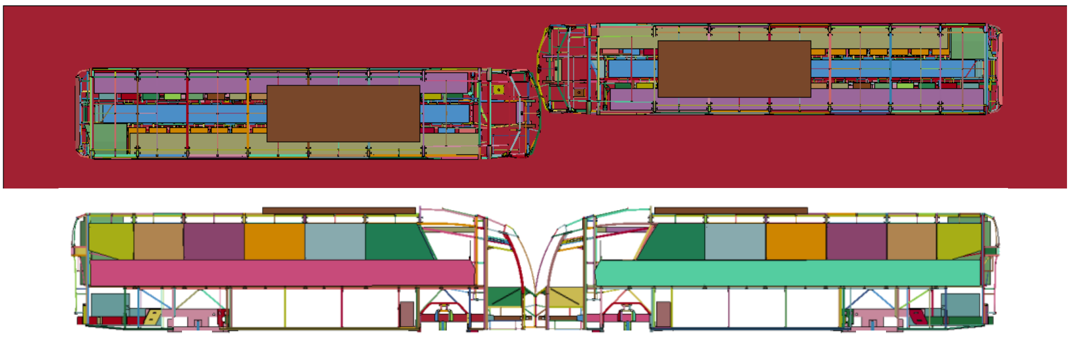

Figure 9 – Layout of semi-frontal impact scenario to be analyzed in LS-Dyna [2].

An overview of the chassis with the proposed shock absorber is presented in Figure 10 where the components in red represent the shock absorber. The shock absorber structure shown in Figure 10 weighs 70 kg and is manufactured entirely with high strength and low alloy steel. The chassis used in this study is for a road bus with front and rear modules linked by the bus structure and with total gross weight of 18500 kg. The chassis chosen is one of the most used in Brasil. For the development of the shock absorber were computed index related with the mode of the absorber deformation, the absorber weight, feasibility of assembly and safety requirements.

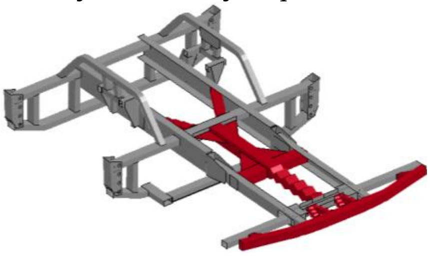

Figure 10 –Detail of the bus chassis with the shock absorber in red.

Aluminum foam was used in regions where greater energy absorption was sought, at points where it was desired to avoid material rupture or on plastic hinges considered critical for safety. Ten kilograms of aluminum foam was added to the structure, at the location indicated in Figure 11.

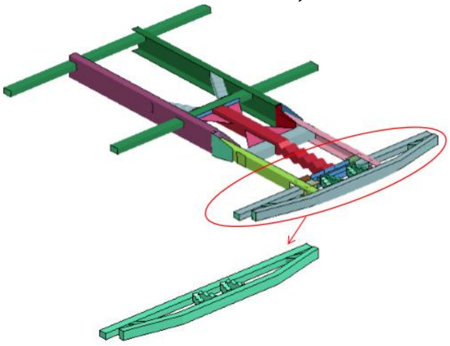

Figure 11 – The part of the shock absorber that was filled by aluminum foam is indicated with a red ellipse.

3 RESULTS

3.1 Compression and Three-Point Bending

In Figure 12, the compression test results in terms of global force vs global dispacement are presented for the tube without filling, thermally modified tube and the foam-filled tube. The results for the specimens that obtained the median values in relation to the energy absorption are presented, for comparison with the numerical results. The foam-filled tube had the highest force peaks and the highest energy absorption. Notice that, for the tubes without filling, the peak of force happens in the first folding of the tube followed by the decay of the maximum force peak. For the foam-filled tube, while the tube is kneading, the force required for flattening the tube increases due to the foam compression.

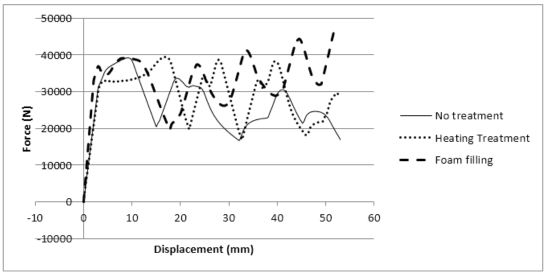

Figure 12 – The compression test. Results in terms of global force and displacement.

In the tube filled with aluminum foam it is possible to identified regions where the cellular structure detach of the tube wall and regions where the foam accompanied the deformation of the steel structure (Figure 13). These results are important for the correct representation of the foam in the finite element method.

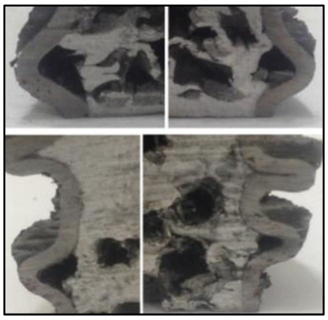

Figure 13: Details of the interface detached between tube wall - aluminum foam in compression test.

The numerical results and a comparison between numerical and experimental results are presented in Figure 14 and Figure 15. Using the tested properties of the material and representing the compression test numerically, the comparison show a very good correlation bettween the experimental and numerical results.

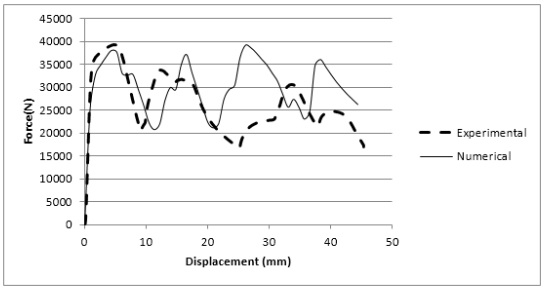

Figure 14 Comparison between numerical and experimental results.

The numerical and experimental tubes without filling submitted to compression are presented in Figure 16.

Figure 15 – Comparison between experimental and numerical results in terms of final configuration in the compression test.

The results presented below are related to the test pieces filled with aluminum foam in the test of compression. The Figure 16 shows the reaction forces during the compression test and Figure 17 show a comparison between numerical and experimental tubes tested. Both the experiment and the model show the same behavior in terms of global force vs displacement behavior. The force reaches the first peak and after it presents a series of peaks and valleys, where the maximum force of each peak increases with the increase of the foam compression.

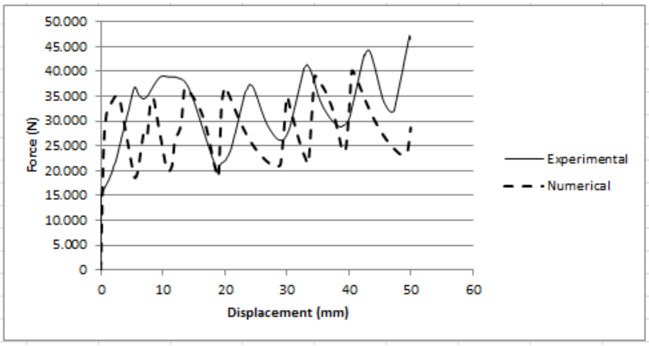

Figure 16 : Compression test comparison between numerical and experimental results, considering the tube filled with the aluminum foam.

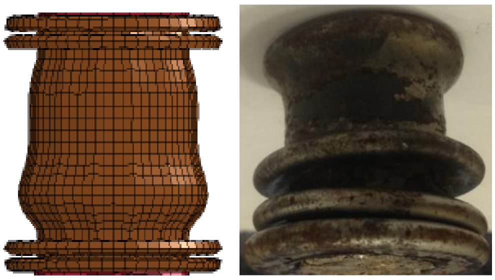

Figure 17 : Compression test comparison between the numerical and experimental results in terms of deformed configuration, considering the tube filled with the aluminum foam.

Table 3 summarizes the experimental and numerical results in terms of dissipated energy. It will be seen that the foam-filled tube dissipated 37,5% more energy when compared to the tubes without heat treatment. The numerical tube filled with aluminum foam absorbed 7,1% more energy than the numerical tube without filling. This lack of energy in the numerical model could be produced because in the analysis the foam material properties not was correctly calibrated (it was used directly the foam properties presented by [1]). This detail will be improved in a future adjustment of the present model.

Table 3 - Comparison between the different analyses in terms of dissipated energy in the compression test.

	Percentage
No Treatment Exp.	100
Heat Treatment Exp.	111,5
Foam-filled Exp.	137,5
No Foam Numerical	112,8
Foam-filled Numerical	119,9

Transversal sections over the lenght of the test specimens tested in three-point bending are showed in Figure 18.

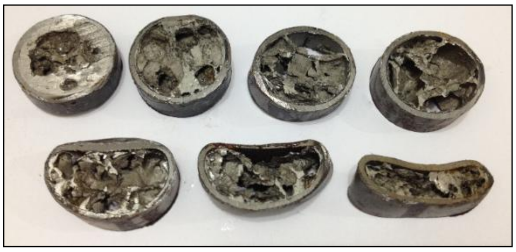

Figure 18 – Transversal views in different tube section.

During the three point bending tests the aluminum foam / steel tube interface detached, as can be seen in the Figure 19.

Figure 19 – Details of the interface detached between tube wall – aluminum foam in three point bending test.

The results of the three point bending tests are shown in Figure 20, where the results of the test specimens that obtained the median values in relation to the energy dissipated are presented. A considerable improvement in the flexural strength of the tube filled with aluminum foam is observed, with energy dissipation 27,4% higher when compared to the tube without heat treatment. Notice in the Figure 21 that in the unfilled tubes and in the unfilled and heat treated tubes the force reached the maximum and remained constant, but in the tube with foam, the reaction force in the three point bending test showed a tendency to increase during all the test.

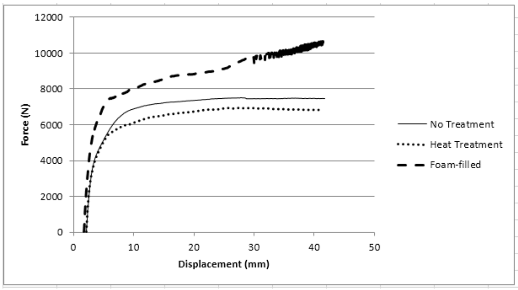

Figure 20 – Experimental results for three point bending test, in terms of global reaction force vs global displacement.

Figure 21 shows the numerical result and a comparison with the experimental unfilled an unfilled heat treated tubes.

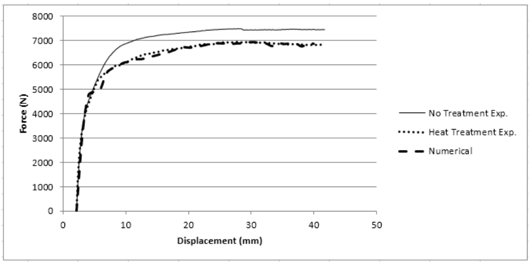

Figure 21 - Three point bending tests for unfilled tubes, the comparison between numerical and experimental results in terms of global reaction force vs global displacement.

The graph of Figure 22 shows a comparison between the numerical and experimental foam-filled tubes tested under three point bending. The results of two test specimens and of the numerical model are presented in Figure 22.

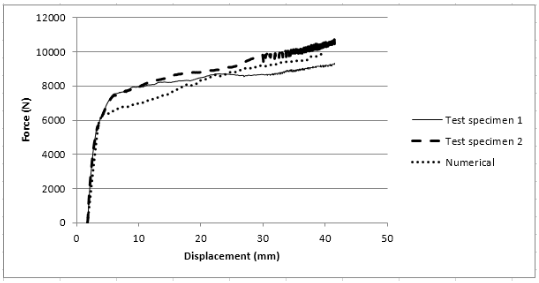

Figure 22 - Three point bending tests for the foam-filled tubes, the comparison between experimental and numerical results in terms of global reaction force vs global displacement.

Figure 23 shows a comparison between the numerical and experimental deformed configuration, for foam-filled tubes.

Figure 23 – Comparison between experimental and numerical results in terms of deformed configuration, for the three point bending test, in the case of the foam-filled tubes.

Details about the detachment between the foam material and the tube wall are presented in Figure 24 for the model and for the test specimen. This comparison let conclude that the numerical model present a good correlation with the test.

Figure 24 – Details about the detachment between the foam material and the tube wall. Numerical and experimental details are presented.

Table 4 presents a summary of the three point bending analysis. It was found that the foam-filled tube dissipated 27,4% more energy when compared to the empty tube without heat treatment. The numerical foam-filled tube absorbed 22,7% more energy than the numerical unfilled tube.

Table 4 - Comparison between the different analyses in terms of dissipated energy in the three point bending test.

	Percentage
No Treatment Exp.	100
Heat Treatment Exp.	94,1
Foam-filled Exp.	127,4
No Foam Numerical	96,2
Foam-filled Numerical	118,9

3.2 Rollover Simulation

The Figure 25 shows the model without foam before impact and at the moment of maximum deformation. The results presented will be related to the distance of the vehicle structure to the survival region.

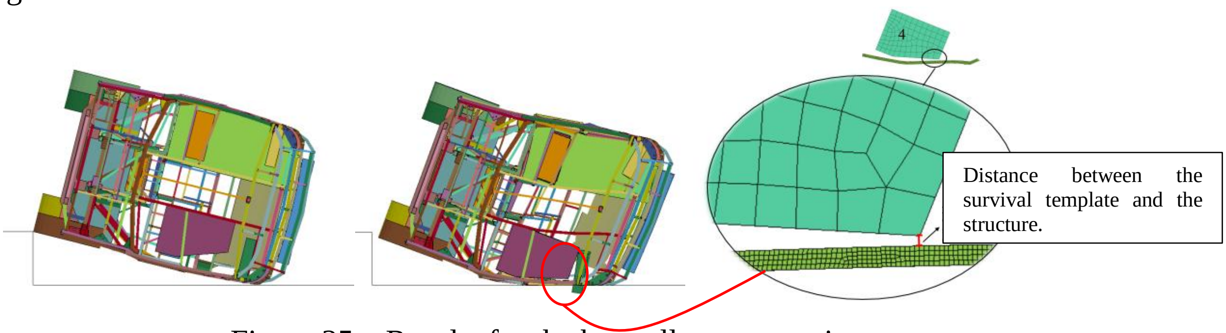

Figure 25 – Results for the bus rollover scenarios.

The relative distances from the survival templates to the vehicles structure are shown in Table 5 . There was an improvement of almost 17% in the structure's resistance to rollover, measured in terms of the averaged relative distance between the survival space and the structure, comparing the models with and without aluminum foam.

Table 5 - Relative Distance between the survival template and the bus structure for rollover simulation.

Survival template	Model without aluminum foam (mm)	Model with aluminum foam (mm)	Relative Diference (%)
1	32,31	37,37	15,6
2	34,54	34,54	0
3	34,96	41,21	17,9
4	24,02	32,2	34

3.3 Semi-Frontal Impact

The bus structure of the bus with shock absorber in the time of 0,3 seconds is presented in Figure 26. It is noticed that despite the kneading of the frontal structure there is still a space of survival for the driver.

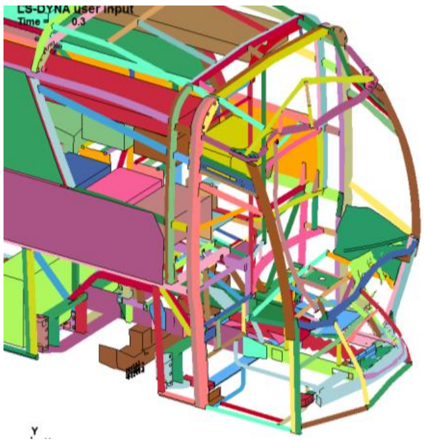

Figure 26 – Deformed structure in a semi-frontal impact simulation.

As a parameter for comparison between the structures, the distance between the front structure of the bus and the driver's station was measured (Figure 27).

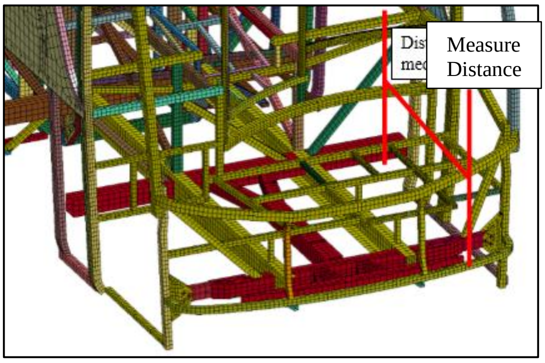

Figure 27 – Distance between the bus front and the driver seat.

Table 6 shows the relative distance for all models evaluated.

Table 6 - Distance between the driver seat ant the bus front.

Original Distance	1050 mm
Without shock absorber	190 mm
With shock absorber	680 mm
With shock absorber and aluminum foam	692 mm

Accelerations were measured at the driver's station during the impact event and the results are shown in Figure 28. There are very high acceleration peaks, reaching 24g for the model without shock absorber and 23g for the model with shock absorber and foam. From the accelerations collected in the simulations, the acceleration peaks last around 0,02 seconds and reach a maximum of 24g at the driver's seat. For a pulse of this duration, accelerations of up to 60g do not cause serious injury to humans [6].

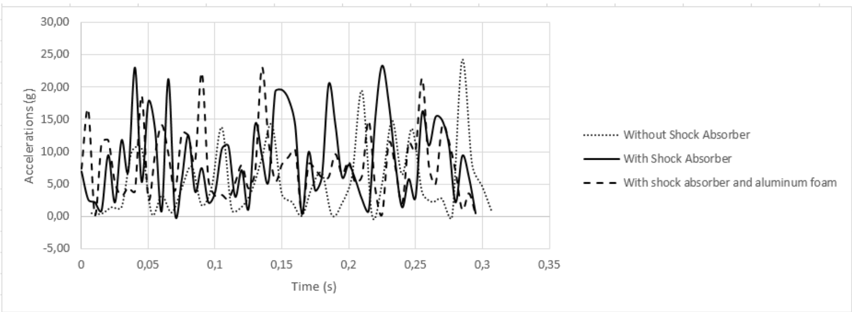

Figure 28 – Global accelerations measured in the driver seat during the event of semi-frontal impact.

Table 7 shows the energy dissipated in the analyzes. It was found that the model with shock absorber dissipated about 30% more energy than the original model while the foam-filled model absorbed 33% more energy than the original model.

Table 7 - Dissipated energy in the different semi-frontal analysis.

Original Model	Model with Shock absorber	Model with absorber and aluminum foam
4,08e8 kJ	5,919E8 kJ	6,078E8 kJ

4 CONCLUSION

In this work, experiments were carried out on the manufacture of aluminum foam as a filling of thin-walled tubes. With the specimens manufactured, compression and bending tests were performed and a numerical correlation was found for the representation of the sandwich structure. Then the mechanical properties of the composite structure were raised and foam applications were studied, such as tube filling, in events of semi-frontal impact and rollover. With the simulations performed, it is possible to present the following conclusions:

The numerical models developed, with and without aluminum foam filling, presented a good correlation with the experimental results, validating the methodology used to represent the materials used.

During the rollover analysis, the use of aluminum foam assisted in meeting the test standard presented with an increase of only 5,12 kg in the bus weight and result in a relative improvement of almost 17% in the residual space of survival.

The maximum accelerations during the impact analysis were below critical levels for the human body at the speeds used for the bus. The absorber structure guaranteed a minimum space of survival for the driver and increased the protection for the occupants.

5 ACKNOWLEDGEMENTS

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