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ANALISYS OF THE INFLUENCE OF INTERACTION BETWEEN METALIC FOAM AND TUBE WALLS ON THE MAXIMUM LOAD TRANSMITTED BY A FOAM FILLED TUBULAR ENERGY ABSORBER DURING AN IMPACT EVENT.

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Abstract. *The design of mechanical structures dedicated to transportation purposes must consider the dynamic loads that can affect the structure during its lifetime. Impact loads can affect structural performance, and even cause catastrophic damages, that can imply in serious risks to structure occupants or loads. The use of crash absorbers, structural components dedicated to deform themselves to absorb kinetic energy from an impact, is a very important way to protecting vulnerable parts and occupants from effects of forces and resulting deformations. Tubular energy absorbers are largely used in transport structures, like cars, trains, and aircrafts, due to easy manufacturing, high efficiency and reduced packaging. The efficiency improving of this kind of component is very desired and numerous researches are in course to analyze effects of using innovative materials, improved geometries and hybrid structures like foam filled tubes. The goal of this paper was to study the influence of the interactions between filler and tube walls during the initial impact events, when the maximum transmitted force is achieved, before the first fold is formed. Numerical simulations using CAE softwares were done using elasto-plastic material models for an aluminum foam block inserted into a steel tube. The behavior of the tube was monitored during the first millisecond of the impact, with measure of transmitted force, stress distributions on tube walls and plastic strains on foam. The collapse modes were qualitatively analyzed to verify differences between the filled and non-filled cases. The results indicated that the use of aluminum foam filling doesn't caused rise on maximum load transmitted by the absorber when compared to non-filled tube.*

Keywords: *.Impact. Energy absorption. Foam. Steel.*

1. Introduction

Mechanical structures that are subject to impact loads under operation, may suffer damages resulting from high levels of accelerations and forces during the impact event. Occupants and loads can be exposed to these accelerations and may also be affected, in different levels. Human body for example, have different acceptable limits to forces and accelerations, beyond which, body parts can be affected leading to injuries or even death. Dangerous loads also need to be preserved during impacts, in order to avoid environmental, physical and social accidents. The capacity of a structure to absorb energy during an impact and control transmitted force levels during deformation is a important parameter to be considered during mechanical design.

1.1. Energy absorbers and acceleration effects

Energy absorbers can be used in order to protect main structural members and avoid or mitigate impact effects on loads or occupants. When impacted, these components will deform plastically, absorbing energy and reducing forces transmitted to the main structure. Tubular energy absorbers are widely used to this purpose, due to its compact size, high efficiency, easy construction and affordable cost. A tipical tubular energy absorber, when submited to an axial impact, presents a folding collapse mode, where the fold formation will respond for a part of energy absorption. The fold formation also will imply in variation of the force transmitted by the tube to subjacent structures. The resulting force will be characterized by a higher peak on the first fold formation, and succesive minor value peaks for the next folds, maintaining a mean force level during collapse, until achieve a totally collapsed configuration, when when energy will be no more absorbed with rise in the transmitted force. This behavior will directly impact in the mode, values and duration of the transmitted accelerations to structure and occupants.

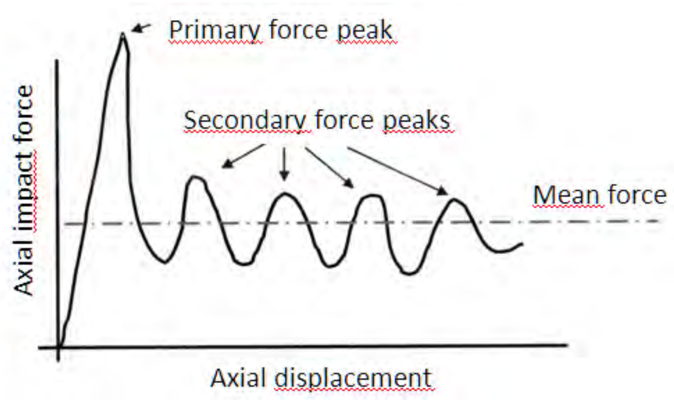

Figure 1. Tipical transmitted force curve during crushing of a tubular mettalic energy absorber unde axial impact loading (Birch 2005).

For the human body, the acceleration pulse shape and initial acceleration slope (rate of onset in g/second) and the acceleration magnitude are among the main factors to be considered to survivability capacity (Van der Merwe Meintjes, Huyssen and Theron, 2004).

Tests made by The naval safety Center, aeromedical Division et al., 1995, presented critical values of acceleration limits to human body, as presented in table 1 and figure 2.

Table 1. Survival capacity limits to restrained occupant subjected to different acceleration directions (Van der Merwe Meintjes, Huyssen and Theron, 2004)

Direction	**Acceleration and duration**
+Gz (feet to head)	25g over 0.1s
-Gz (head to feet)	15g over 0.1s
+Gx (back to chest)	45g over 0.1s
-Gx (chest to back0	45g over 0.1s
+Gy (right to left)	11.5 to 20g over 0.1s
-Gy (left to right)	11.5 to 20g over 0.1s

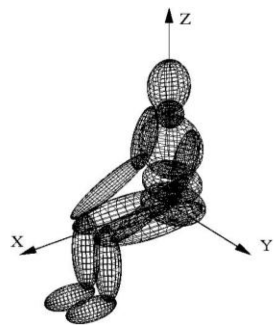

Figure 2. Axis convention to refererence accelerations on table 1 (Van der Merwe Meintjes, Huyssen and Theron, 2004).

The main goals to an energy absorption guided design are to minimize forces and accelerations transmitted to main structural parts, occupants and loads. The use of alternative materials, improved geometries and combined materials structures is been studied around the world. In this scenery, the use of foam filled structures is an important research line.

Due to its mechanical behavior under compression loads, foams are considered good energy absorbers (Croop, Lobo, 2009). The behavior of foams when compressed, can be approximated to an ideal energy absorber, presenting a first force raising and a large plastic deformation plateau, under constant load until the total collapse, when load increases or fracture occurs, as cited by Wang, Jing and Zhao (2011).

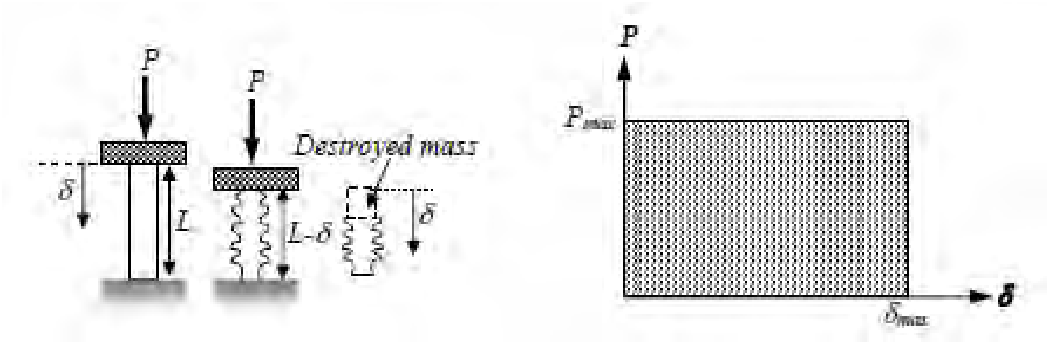

Figure 3. Force vs. displacement of an ideal energy absorber (Ahmad, 2009)

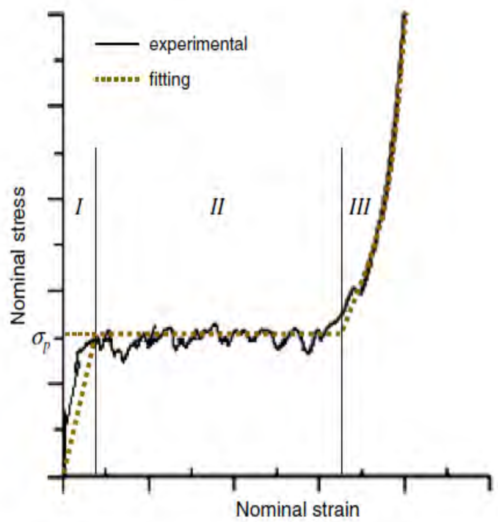

Figure 4. Force vs. displacement of a mettalic foam (Shujuan, 2009)

In this paper, a computer aided engineering simulation using LS-Dyna software was made, in order to verify the influence of aluminum foam filler on the maximum peak load and initial folding pattern of a tubular absorber during impact.

2. Model description

A quadrangular tube made of DP600 steel, was modeled, with dimensions of 200mm height, 100mm width x 100mm deep, and wall thickness of 1,5mm. An Alporas foam block was modeled, and used as filling to the tube. The block dimensions were 198,5mm height x 97mm width and 97mm deep, and the block was mounted internally on the tube, not bonded to tube walls. A deformable base, made of DP600 steel, was used to support the tube, and also was used to measure the transmitted force through its section. The base dimensions were 200mm width x 200mm deep and 40mm height. The base was restrained in all degrees of freedom in its bottom surface.

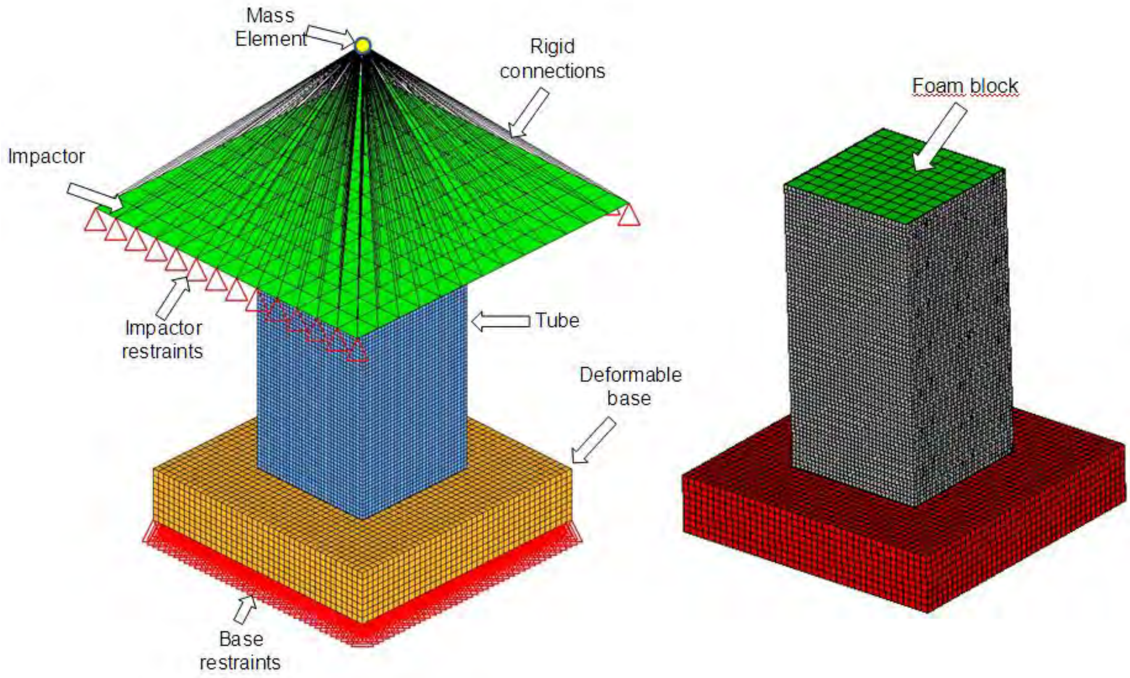

Figure 5. Model configuration.

A 1,000kg impactor was modeled, using a deformable rectangular wall, made of DP600 steel, connected rigidly to a mass element. Only one degree of freedom was unrestricted, to assure that the impactor would collide axially to the tube. The wall dimensions were 260mm x 260mm sides and 10mm thick.

The impactor collided with the top of tube with a speed of 5m/s, with a total kinetic energy of 12,500J. The friction coefficient between parts was defined to 0.2, and was defined based on Westerberg (2002) study. The transmitted force was measured transversally to base cross section.

The impact simulation used Finite Element Analysis to verify the foam behavior inside the tube, and the influence over the load transmitted during the initial millisecond of impact. At this time interval, the peak load and the initial fold formation were observed. The transmitted force, stress wave modes and effective plastic strain of the Alporas foam block were monitored.

2.1 Finite element model description

The LS-Dyna version 971 solver was used to explicit simulation, and modeling specifications are detailed on table 2.

Table 2. Model specifications.

Component	Element type	Mean element size	Number of elements
Tube	Shell - Quad - Belytschko Tsay - 5 integration points on thickness	3mm	9933
Foam	Solid hexahedral – 8 nodes – 1 reduced integration point	10mm	2000
Impact wall	Shell - Quad - Belytschko Tsay - 3 integration points on thickness	20mm	169
Base	Solid hexahedral – 8 nodes – 1 reduced integration point	5mm	12800

A mass element with 994.93kg was connected by 197 rigid elements to the wall (mass= 5.07kg), totalizing a 1,000kg mass. The initial velocity was applied directly to the mass element. This modeling procedure proportioned a simplified deformable impactor, with good computational efficiency. Automatic single surface contact algorithm was used to the model.

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2.2 Material models

Constitutive material models validated by literature were used on this work, and these models are described on next sessions.

2.2.1. Steel model

For the steel, a modified Johnson Cook model, cited by Yu, Youngjin e Xinmin (2009), was used.

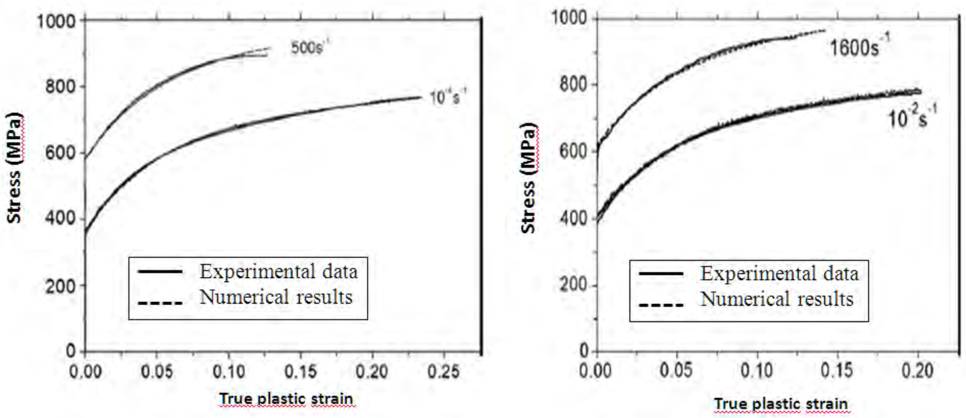

Figure 6. Numerical and experimental curves of DP600 Steel constitutive model under different strain rates (Yu, Youngjin and Xinmin, 2009)

Stress vs. strain curves were used with strain rates of 1x10-4s-1, 5x10-1s-1, 5s-1, 50s-1, 500s-1, 1000s-1 and 1500s-1. This range of strain rates is adequate to this kind of impact, as described by Abedrabbo et. al (2009) and Yu, Youngjin and Xinmin (2009). Further mechanical properties of the material are presented in table 1.

Table 3. DP600 steel mechanical properties (Data from Westerberg, 2002).

Parameter	Value	Unit
Density	7900	kg/m^3
E	210	GPa
Yield stress	350	MPa
Poisson ratio	0,3	

Stress vs. strain curves were calculated using constitutive model and are showed in fig. 7.

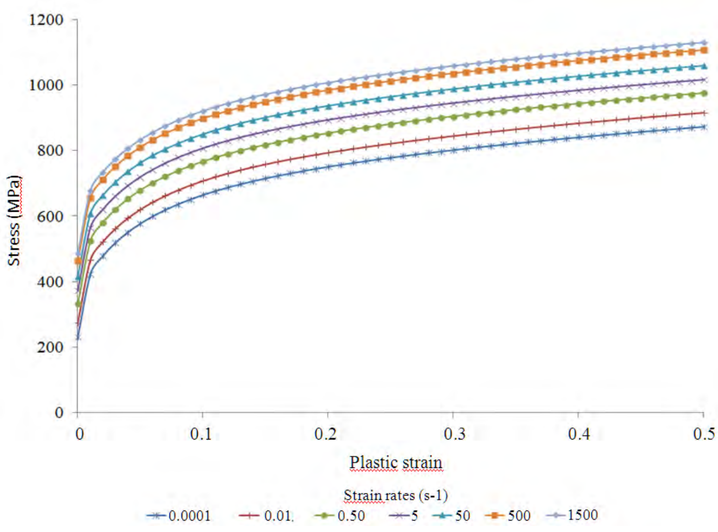

Figure 7. Stress vs. strain curves calculated using Yu Youngjin e Xinmin (2009) model.

2.2.2. **Aluminum foam modeling**

The Ls-Dyna material MAT154 (Deshpande Fleck Foam) was used to represent aluminum foam. Styles, Comptom and Kalayanasundarm (2008) validated a model to Alporas Foam, as presented in fig. 8. The same parameters were used on this work, and are presented on tab. 4.

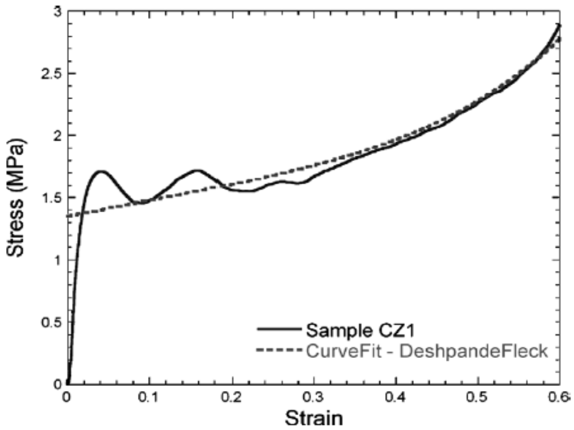

Figure 8. Deshpande Fleck model and experimental stress vs. strain curves comparison of Alporas aluminum foam (Styles, 2008)

Table 4. LS-DYNA MAT-154 material model parameters for aluminum foam, as described by Styles, Compton Kalyanasundaram, 2008.

ρf (g/cm3)	**E (GPa)**	**υp**	**α**	**γ (MPa)**	**εD**	**α2 (MPa)**	**β**	**σp (MPa)**	**Cfail**
0,23	1,1	0,0	2,12	3,12	2,4629	0,368	4,47	1,35	0,2

2. RESULTS AND DISCUSSION

During the first millisecond, transmitted force, stress wave propagation on tube walls and plastic strain of the foam block were measured. A comparison between filled and unfilled absorbers was done.

Table 5 illustrates the peak force variation between absorber versions. The values were basically the same for the two versions, with a variation of +0,4% in the foam filled tube.

Table 5. Peak force values on the energy absorbers.

Specimen	**Description**	**Peak force (kN)**	**ΔF (%)**
1	Unfilled tube	538,5	0,0
2	Foam filled tube	540,4	+0,4

On the figure 9, the force curve is presented, and the curve slope of the maximum peak was unaltered between versions.

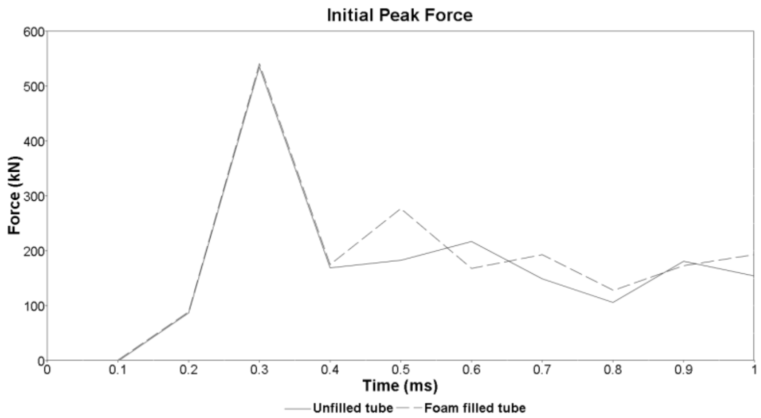

Figure 9. Transmitted force from absorbers to base during the first millisecond of impact.

On 15μs, fig. 10, the stress waves propagation was practically identical, evidencing on that moment no influence of foam in the absorber behavior. Also stress levels are identical on that time.

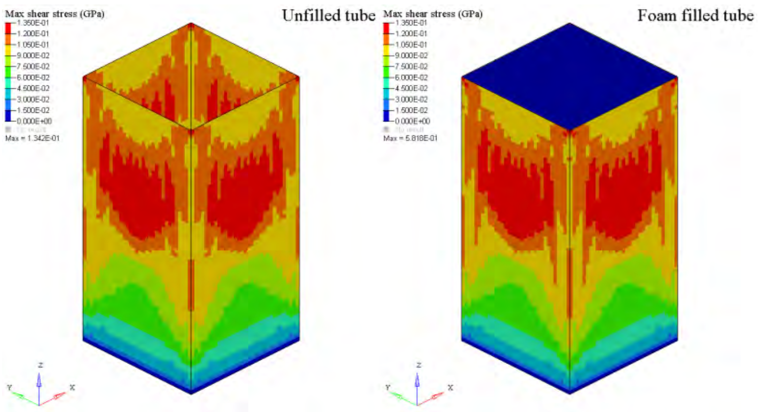

Figure 10. Stress waves propagation in the non-filled (left) and foam filled tube (right). Time=15 μs

The results at 30μs, fig. 11, pointed to similar stress distribution on both cases, and plastic strain was observed on foam block top, like showed in fig.12. No plastic strain was founded on block lateral surfaces, indicating that foam was compressed top-down, with no interaction with tube walls.

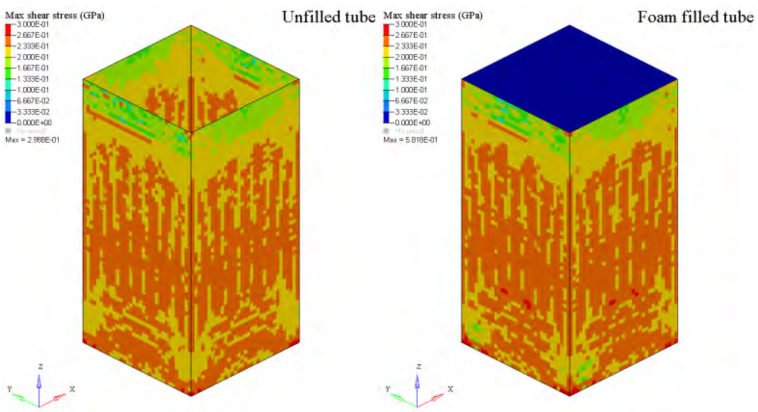

Fig.11. Max shear stress in the non-filled (left) and foam filled tube (right). Time=30 μs

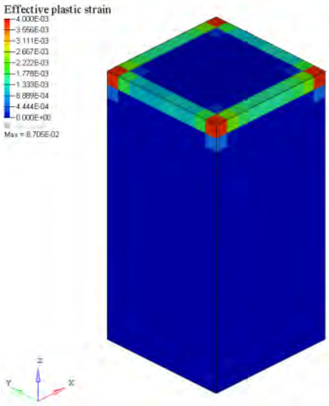

Fig.12. Effective plastic strain in the aluminum foam block on the filled tube . Time=30 μs

Near to 50μs, fig. 13, was verified a difference in the transmitted force between the tested absorbers. The force on the unfilled absorbed was smaller than the filled absorber, in the interval between 40 and 45 μs , with a force of 58.7kN for the unfilled absorber and 141.9kN on the filled absorber soon after first peak. The mean force was greater on the filled absorber.

The second peak of force of the foam filled tube occurred at 48μs, with value of 311,9kN. For the non-filled tube, the second force peak occurred at 54 μs , with value of 269,7kN.

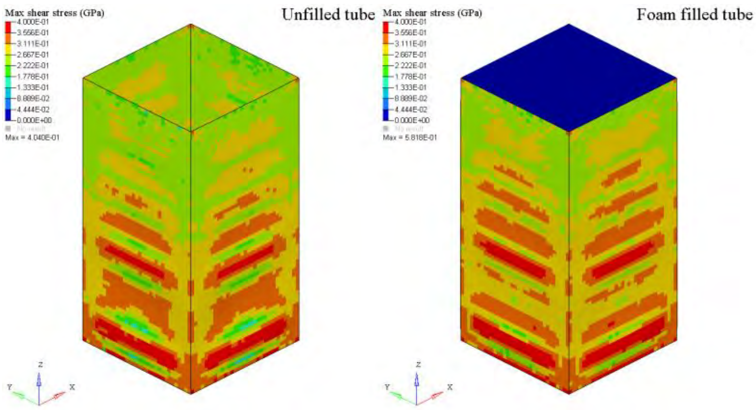

Figure13. Max shear stress in the non-filled (left) and foam filled tube (right). Time=50 μs

On the deformation map, showed in fig.14, is evidenced the interaction between foam block and tube walls, and the plastic strain is distributed along the bottom, mid and top portions. This interaction can be the responsible for the differences in force levels between the two cases.

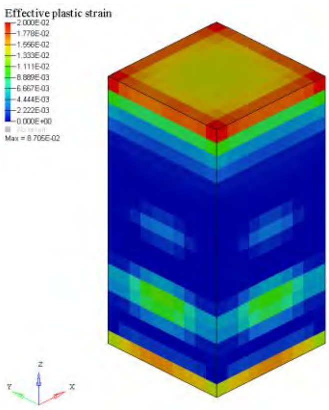

Figure 14. Effective plastic strain in the aluminum foam block on the filled tube . Time=50 μs

At 75µs, fig. 15, there was a difference in stress distribution on the absorbers bottom portion. A secondary stress line was clearly delineated on the non-filled tube, meanwhile in the foam filled tube this pattern was less defined. Despite higher stress values on the filled tube, it apparently was concentrated on the bottom of the tube.

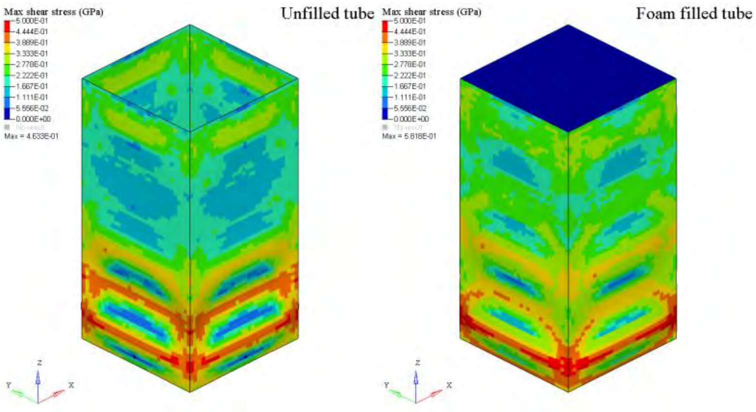

Figure 15. Max shear stress in the non-filled (left) and foam filled tube (right). Time=75µs

On the plastic strain map, fig. 16, higher values of deformation were found on the second fold formation region. This indicates that interaction between foam and tube sidewalls occurred, and that resulted on reduced stress values on the tube walls on the region.

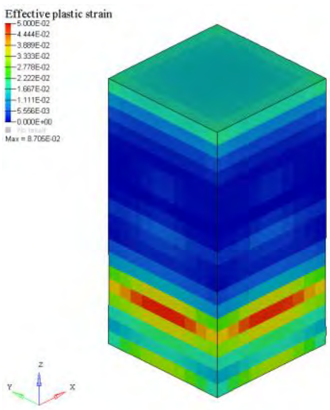

Figure 16. Effective plastic strain in the aluminum foam block on the filled tube . Time=75µs

At 100µs, fig.17, different folding formations modes are evidenced between the two absorbers, and the interaction between foam and tube walls is again confirmed by the plastic strain map for the foam block, fig.18.

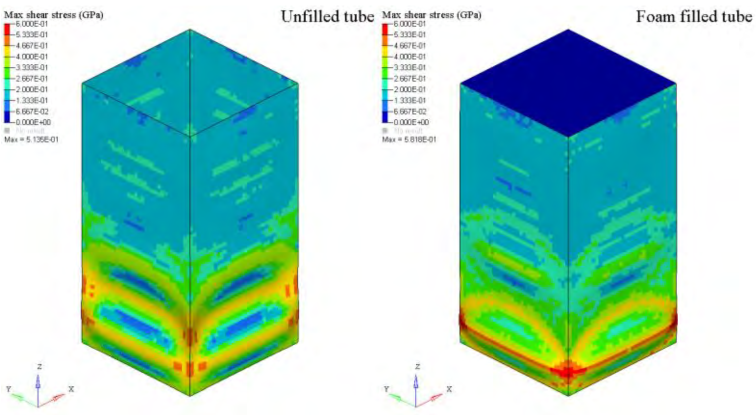

Figure 17. Max shear stress in the non-filled (left) and foam filled tube (right). Time=100µs

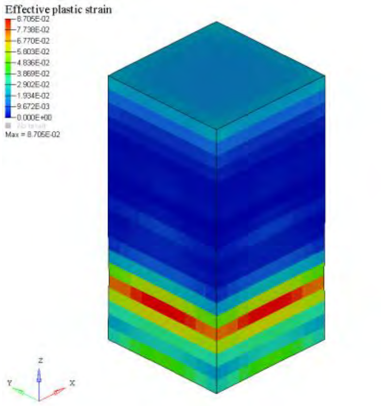

Figure 18. Effective plastic strain in the aluminum foam block on the filled tube . Time=100µs

3. CONCLUSION

The proposed model was adequate to the objectives of this work, and its behavior was coherent with literature references. The use of aluminum foam as an energy absorber filler didn´t caused the elevation of maximum peak force during tube crushing. This can have a significantly positive effect on the subsequent structures design, because these structures must support the peak force during an impact event without plastic deformation.

As the aluminum foam do not affected maximum force level and acted as stabilization factor, it can be added to an existing structure to improve energy absorption without need to modify the main structures to resist to increased levels of peak forces. But, despite not being a theme on this paper, the mean force is crucial to the design and must be taken in account when designing structures.

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