STUDY OF THE IMPACT BEHAVIOR OF A METALLIC FOAM-BASED VEHICLE CHASSIS IN A CRASH TEST

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Abstract. The study of metal foams has become attractive to researchers from both the academic scientific and the industrial fields due to their properties. Metal foams have low density and peculiar physical, mechanical and acoustic properties, offering great advantages in terms of weight and strength. They also present an interesting combination of these properties, such as high stiffness with light specific weight, and high compressive strength with good energy absorption, which offers promising possibilities of the use of metal foams in the automotive industry. The emphasis of this work is on the use of metal foams in automotive design with the purpose of studying the mechanical behavior and possible project alternatives, which would use this material as a structural element (chassis) for impact energy absorption, through the modeling and subsequent computer simulation according to the case study – chassis of the "Sabiá 5" vehicle. The "Sabiás" are hyper-economical vehicles created to compete in the Design category of the Shell Eco-marathon. This competition is noticeable for the creation of experimental vehicles which are built by schools and universities around the world. For the structural analysis, the finite element software Abaqus/CAE is used. Many cellular materials have a high capacity of energy absorption under impact conditions, presenting high energy absorption at constant stress levels. In crash tests, the criteria used to determine the speed, impact directions and barrier depend on the test objectives. These tests are considered an excellent engineering tool and thus constitute a powerful method to evaluate and propose solutions for the technical evolution process, with regard to the passengers' protection in case of a car crash. For the passenger compartment protection it is important that the structure and the impact energy-absorbing elements are able to absorb as much kinetic energy as possible, so that it does not reach the interior of the vehicle. For this purpose, according to the results of the virtual crash tests performed, metal foams demonstrated to be the ideal choice, as the metal foam-based structure presents slower deceleration and higher plastic dissipation, transferring most of the impact energy to the material instead of the passenger of the vehicle. In this regard, using these lighter and stronger materials, without mass increase, it is possible to achieve more effectiveness in impact situations.

Key words: *Automotive design, metal foam, finite element method, computer simulation, crash test.*

1. INTRODUCTION

Automobiles have affected deeply not only the economic development and the means of production, but also society's lifestyles, environment and urban spaces. They stand out as one of the biggest groups of business activities in the world, guiding the development and launch of new products, processes and materials, and serving as a reference for other sectors. New production concepts, materials and methods are created every day, improving the performance of these vehicles and reducing the time needed for development, simulation, production and launch. In this new setting, more complex requests have to be met, integrating performance, safety, economy, practicality, technology and sustainable development, among others. In this regard, it is necessary to innovate with design research, project methodology, materials and technologies for projecting and producing vehicles. In the search for new materials, metal foams are demonstrating to be very helpful for the construction of lighter and stronger structures. Nowadays there is still lack of computational studies covering the characterization and application of these materials.

This work aims to contribute, both to the academic and industrial fields, relating automotive design, materials selection and computer simulation. This last activity is performed through software, which uses the finite element method, for modeling and structural analysis in a virtual crash test. The simulation uses the metal foam in the case study of the chassis of the vehicle "Sabiá 5" – UEMG (Figure 1). A comparison between the structural behavior of different materials is also presented in this paper.

1.1 Objectives

The present work intends to study, characterize and simulate in a computer environment the application of a new material, the metal foam, in automotive design, in the particular case of compact cars, as a possible alternative for individual demand in urban areas. To analyze the behavior of metal foams in comparison to other frequently used solid materials, such as steel and aluminum.

To arouse interest in new materials, their characterization and applications. Besides, to emphasize designers' responsibilities and possibilities in the development of products with reduced environmental impact, through interaction with other areas of knowledge and presentation of the possible application of these materials.

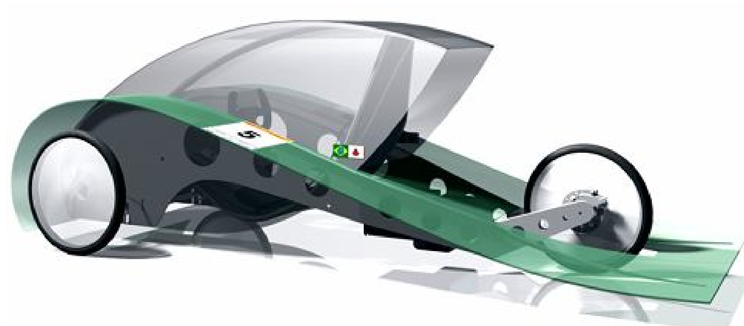


Figure 1. Vehicle "Sabiá 5". Source: Câmara (2008).

1.2. Justification

Despite the enormous progress made in recent years through research on the different areas of knowledge which are close to design, great technological challenges still remain. It is needed to research, know, characterize and validate, through computer simulation for example, the application of more sophisticated and specialized materials and, at the same time, with possible application in the market, enabling cost and/or environmental impact reduction. This approach is proposed in this work, by using metal foams and applying them in automotive design, since automobiles have become a symbol of mobility and freedom, being essential in modern days. Taking this into consideration, it is not surprising that this market is the biggest group of business activities in the world and that, at the same time, the most frustrated user's expectation is to find a traffic-free way, both in urban areas and the main roads, and the heavy flow poses a challenge to be solved by researchers from several areas, including designers.

In the search for new materials, metal foams are demonstrating to help construction of lighter and stronger structures, economizing and keeping good performance. According to Banhart (2000), nowadays there is still lack of computational studies and bibliography covering the characterization and structural application of these materials, so reaffirming the importance of this work.

Furthermore, computer simulation as a product development tool is able to promote ideas with the most speed and reliability, which are fundamental to the competitiveness of companies, providing reduction in investments in tests and prototypes, improvements in quality and reliability of the results with real data, and reduction in time spent with product changes. According to ARBOR (2008), virtual simulations and prototypes can be up to 95% more economical than physical models.

2. DESIGN

According to Denis (2000), the word "designer" was first used in the seventeenth century by the Oxford English Dictionary. In the dictionary, it refers to a plan, purpose and/or project. It could be then defined as a creative effort related to the configuration, conception, elaboration and specification of something, usually oriented by an intention and towards the solution of a problem; that is, creation with intention. Design, according to Löbach (2001), is an idea, project or plan for the solution of a given problem. It is the concretization of an idea in the form of a project or model, through construction and configuration, resulting in an industrial product subject to mass production. According to Gomes (2003), in design all the desired qualities are planned, conceived, specified, tied to their nature of technology and to the other processes which are part of their production. Design enables the conception, innovation, technological development and elaboration of objects which, in a systematic approach, make it possible to gather, integrate and harmonize several factors related to its project methodology.

According to Ashby (1999), design is the process of translating a new idea or market need into detailed information of a product to be manufactured. To the author, materials can be considered the design filling and processes shape this raw material of design.

Design innovation can be then related to the use of a new material, in the creative combination of the product form with the new material, its production processes or even with the combination of a new material, its production processes and the possibility of creation of new forms from them. These forms can be related not only to the production, but also to the project conception.

2.1 Materials Selection in Automotive Design

The universe of means of transportation offers an extensive field to the research and application of new materials, mainly because of the amount of production and sales. According to Anfavea (2006), Brazil alone has produced 36,000,000 automobiles since 1957 and currently has an installed capacity to produce 3.5 million vehicles a year. According to ABAL (2008), modern automobiles are a source of opportunities for new materials and technologies. The use of aluminum reduces the weight of vehicles; being lighter they consume less fuel and consequently release less pollutants. Studies show that the main advantages of aluminum to the automotive industry are safety, economy, drivability, recycling, durability and lightness. The same potential is achieved by using aluminum foams. According to Ashby (2000), the economy made by applying lighter materials in transportation design can reach US$ 10,000 in a spacecraft, according to Table 1.

Table 1. Economy made by reducing weight of transport vehicles. Source: Ashby (2000).

Transportation System	US$ ($/kg)
Car (fuel saving)	0.50 – 1.50
Truck (payload, fuel saving)	5.00 – 10.00
Civil Airplane (payload, fuel saving)	100.00 – 500.00
Military vehicle (performance payload, fuel saving)	500.00 – 1.000.00
Space vehicle (payload, fuel saving)	1.000.00 – 10.000.00
Bicycle (performance)	1.00 – 1.000.00

3. APPLICATIONS OF METAL FOAMS

According to Oliveira (2008), cellular metals are a new and still not perfectly characterized class of materials. A cellular metal is a material composed by a metal matrix with internal holes, called pores or cells, as Figure 2. Metal foams have low density and peculiar physical, mechanical and acoustic properties, offering great advantages in terms of weight and strength. The cell (open or closed) structure determines the macroscopic behavior of these materials, which display mechanical behavior and physical properties that differ greatly from the solid materials, in which there is no air incorporated. According to Banhart (2002), they present interesting combinations of physical and mechanical properties, such as high stiffness combined with very light specific weight.

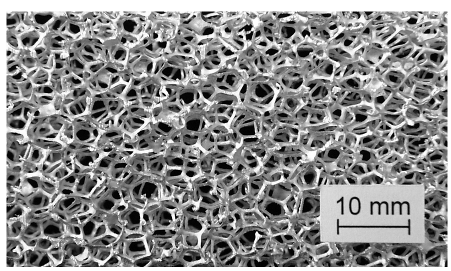


Figure 2. Aluminum foam with open cells (DUOCEL®). Source: Oliveira (2008).

According to Jorge and Arruda (2008), a material must have a density less than or equal to thirty percent of the density of the solid matrix material to be classified as cellular. Among the ones produced by man, the polymer foams are currently the most disseminated. However, it is less known that both metals and alloys can be produced as cellular materials or foams, and that they inspire new applications because of the interesting combination of their properties.

3.1. Applications of Metal Foams in the Automotive Industry

In relation to the applicability of cellular materials, the automotive industry has demonstrated to be one of the most promising fields for the use and feasibility of their cost through mass production for a big market.

The growing demand for safety in the automotive sector stimulated the search for stronger and at the same time lighter vehicles. There is also a demand for reducing the acoustic emissions of cars with new sound “absorbers” and for increasing the safety of so compact cars, in which the safety zone in impacts is also reduced by the size of the vehicle.

According to Banhart (2000), metal foams offer the possibility of solving some of these problems. An ideal application would be the one in which the same component has a reduced weight, is able to absorb energy in case of an impact and isolates sound and/or heat. It is clearly difficult to find such multifunctional properties in a single material.

In this regard, the Figure 3 shows some potential applications of metal foams in the automotive industry include sandwich panels, structural reinforcement, impact-absorbing elements, vibration damping, among others, meeting the market trends: weight reduction for better performance and less fuel consumption, in addition to safety improvements.

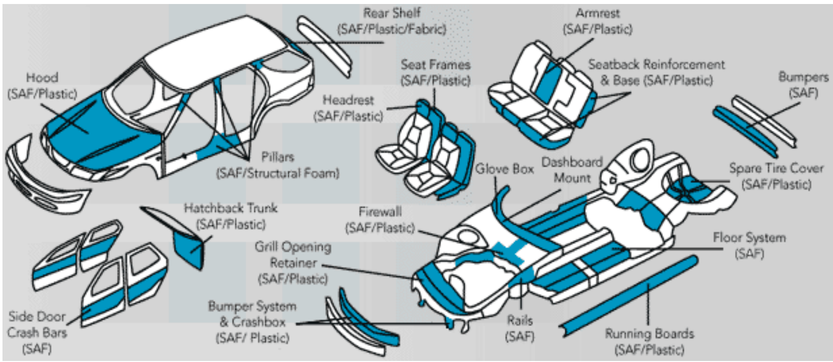


Figure 3. Application of metal foams in automotive design. Source: ALUSION (2008).

3.2. Energy Absorption in case of an Impact

According to Banhart (2000), in the studies of applications to absorb energy in case of an impact, plastic deformation is an item to be explored. Many cellular materials are excellent energy absorbers, presenting great deformations at practically constant stress levels. Such behavior is illustrated in Fig. 4, which represents the schematic stress-strain curve for a metal foam. The plateau represents the high capacity of energy absorption under constant stress. It can be verified that under compression the metal foam body behaves as expected from a cellular material, with an initial elastic phase followed by a transition zone, a plateau and densification, as in Figure 4.

In the plastic phase the curve presents an extremely low slope, characterizing a plateau, in which a little increase in force causes a great deformation. This happens as a consequence of the progressive deformation of the cellular structure.

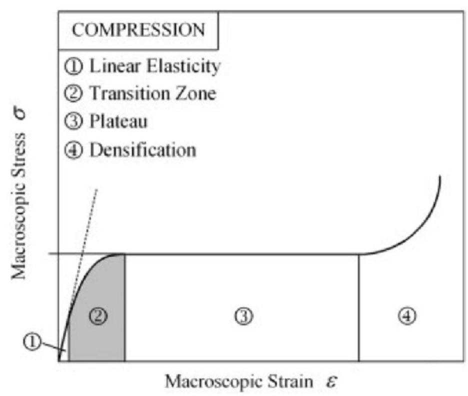


Figure 4. Stress-strain curve of metal foams showing their capacity of energy absorption under constant stress. Source: Öchsner (2003).

According to Jorge and Arruda (2008) this plateau characterizes, as mentioned above, a high capacity of the cellular material to absorb mechanical energy under constant stress. After this phase the slope of the curve starts to increase, indicating the collapse of the structure and therefore the compression and densification of the material.

Metal foams can perform much better than other ones, as for example the polymer foams, because they are much stronger. What makes aluminum foam more attractive is its low rebound in case of dynamic impacts, at a rate of less than 3%, while cellular polyurethane foams present in studies rates of up to 15%. According to Ashby (2000), different impact situations can be mentioned in the regular safety of vehicles, for example when there is collision and the energy is dissipated in certain areas, protecting the passenger compartment.

At low speeds (3-10 km/h) the impact can be reversibly absorbed by elastic materials or impact hydraulic devices. At speeds above 20 km/h a planned deformation is predicted in elements designed for collision, the crash boxes[1], which

[1] Crash box – A system to absorb impact energy.

can be simple round aluminum tubes, as Figure 5. These elements can be easily replaced after the collision, making the repairs affordable. Only at high speeds the chassis is irreversibly deformed by serious damage.

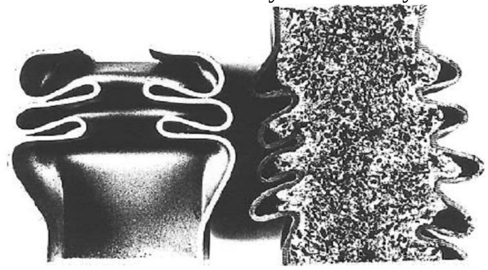


Figure 5. Cross section of tubes with and without metal foam inside, after partial impact. Source: Ashby (2000).

Metal foams also have an application in the Civil Construction industry, in panels for facing and application in buildings frontage, in the structuring of these panels and in elevator panels. They are also used in special packaging and decoration, for example in internal panels, furniture, facing and signaling. In the biomedical industry metal foams are used in implants. In the sports industry, they are used in high-performance equipment, for example special shin guards with light weight and high impact absorption. Finally, in the transportation industry they are used in the airspace, naval and railroad sectors, usually in the form of structuring or closing panels.

4. METHODOLOGY

- Data collection: obtain the technical details such as geometry, load and boundary conditions of the structure to be used as the case study;
- Three-dimensional modeling of the case study part using AutoCAD;
- Representation of the metal foam behavior, researching its general, physical and mechanical properties with the program for materials selection CES EduPack, for later simulation with Abaqus/CAE;
- Analysis of the metal foam structure using the finite element software Abaqus/CAE in static and dynamic tests, including the crash test;
- Evaluation of the results achieved using the metal foam in the proposed structure in comparison with other materials.

4.1. Data collection: materials selection and properties

Data selection and collection for later application in the computer simulations were performed with the software CES EduPack (Cambridge Engineering Selector® - Granta Design®), through LdSM – Design and Materials Selection Laboratory of the Universidade Federal do Rio Grande do Sul. This program has virtually enabled the cross tabulation of information with distinct properties. Using a predefined database the materials which meet the requirements are sorted out in progressive cross tabulation steps, eliminating those which do not present the characteristics required by the designer.

4.2. Modeling methods and computer tools

Before the mesh can be generated in the finite element software, the modeling of the solids is necessary for later import in Abaqus/CAE. The geometry must often be simplified so that the generated mesh can represent the analysis in question. At the time of import, the finite elements (shell, solid, beam, etc.) are defined, according to the physical phenomena they are able to represent and the needs of each case, mainly related to computational complexity and available time.

The proper definition of the elements, their properties and the mesh density (number of elements) determines the accuracy of the answers obtained. For the correct operation in the simulation software, the object was modeled with AutoCAD 2007 and exported as a single three-dimensional solid element with its parts joined. When this is done for objects which have two or more parts formed from different materials, the parts can be exported separately or in a single file, but not joined. In this part of the work the structure of the ViD Virtual Design – Virtual Design Laboratory of the Universidade Federal do Rio Grande do Sul – is used.

4.3. CAE technology – the finite element method – Abaqus/CAE

According to Alves (2007), by using finite element software such as Abaqus/CAE it is possible to divide a complex geometry into an arrangement of simple geometry elements (finite element mesh), for example triangles, quadrilaterals, tetrahedrons, parallelepipeds, etc. This means the structure is formed from the arrangement of individual elements, connected by nodes; this is the great difference in relation to the analytic world. In the finite element models just the displacement of these nodes is initially defined, rather than all the points in the structure. It is believed that when the number of nodes is chosen properly, they are able to accurately determine the stress and strain of the structure. According to Moreira (2007), the industry nowadays is powered by three major technologies: CAD, CAM and CAE. The last one, which stimulates the economy, is responsible for increasing engineers' and designers' productivity, improving the design and quality of products and consequently their operation. Many companies have been developing their products using modern analysis tools such as CAE, applying the finite element method (FEM) in the solution of structural and/or mechanical problems in order to have high-quality and high-performance products.

5. CRASH TEST

The importance of automobiles safety is recognized by users around the world. For some decades this characteristic of the vehicles, along with design, fuel consumption, comfort and power, is present in the most renowned automotive publications.

According to Bertocchi (2005), during a car crash all the kinetic energy has to be dissipated until the bodies (vehicle and passengers) come to rest. For the vehicle the energy will be dissipated by its motion and the deformation of its structure. For the passengers the energy will be dissipated by damping of the components in the compartment. Nowadays there are several components which act passively in order to protect passengers during a collision. The risk to passengers is directly associated with the manner and how fast they lose speed at the moment of the collision.

5.1. Virtual crash test

According to the EURO NCAP (2009), the criteria to define the speeds, impact directions and barriers depend on the objective of the test. For homologation tests, the regulations used are those in force in the target market. In Europe for example, a frontal impact on the driver's side at 56 km/h against a deformable aluminum barrier, which is at least 40% of the size of the car, is required, as Figure 6.

Another legal requirement in Europe is a side impact against a standardized moving barrier at 50 km/h. There are also criteria which are defined by consumers' institutes and trade magazines. The German magazine Autobild, for example, tests frontal impacts between two vehicles at 50 km/h each.

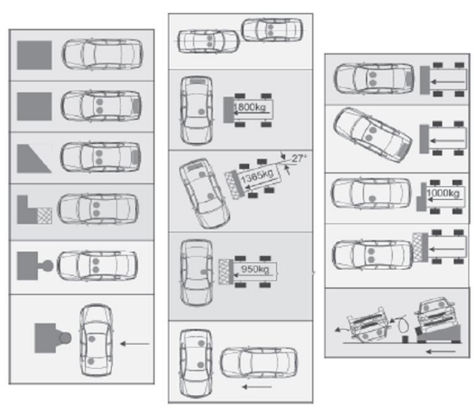


Figure 6. Common vehicle crash tests and their procedures. Source: Bertocchi (2005).

The geometry of the case study was defined in order to perform the crash test, from the previous dynamic tests and in three different models: whole aluminum (14mm), whole metal foam (14mm) and 1 mm sandwich panel with 12 mm metal foam filling.

In Figures 7 and 8 the von Mises stress and the equivalent plastic deformation are presented for the sandwich composition model. The following are the crash test results for the metal foam model in Fig. 9 and 10 and for the whole aluminum model in Fig. 11 and 12. The vehicle was impacted against a stiff barrier at a speed of 50 km/h in all cases.

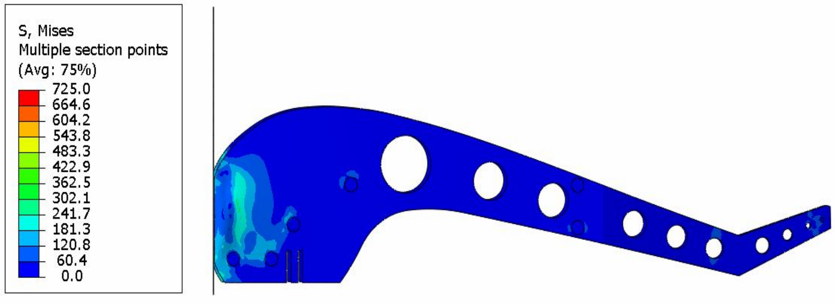


Figure 7. Crash test von Mises stress. Model with aluminum sides and metal foam filling.
Source: Generated in association with Smarttech – SP (2009).

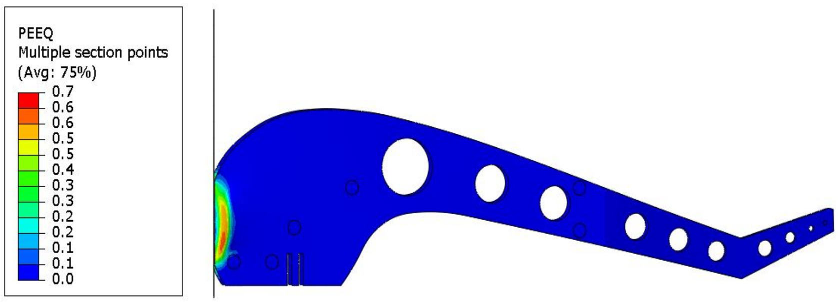


Figure 8. Crash test equivalent plastic deformation. Model with aluminum sides and metal foam filling.
Source: Generated in association with Smarttech – SP (2009).

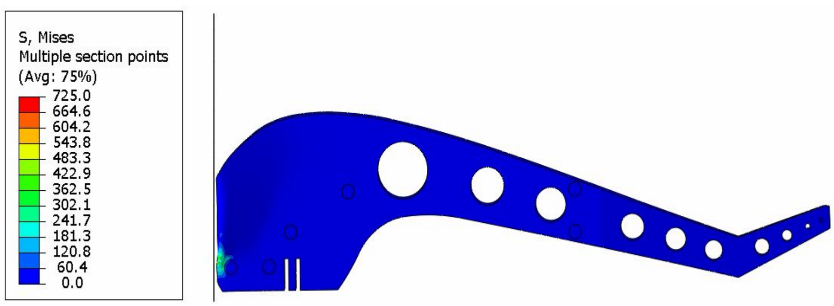


Figure 9. Crash test von Mises stress. Metal foam model. Source: Generated in association with Smarttech – SP (2009).

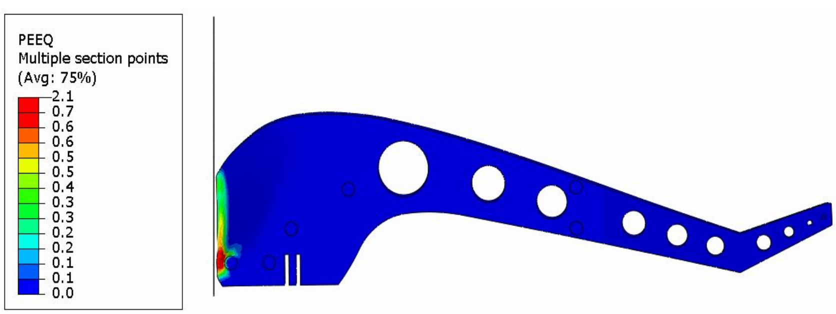


Figure 10. Crash test equivalent plastic deformation. Metal foam model.
Source: Generated in association with Smarttech – SP (2009).

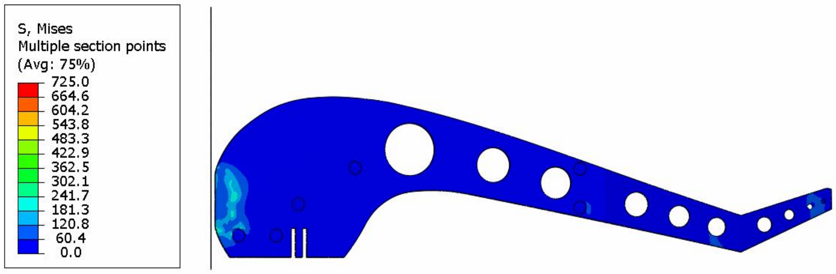


Figure 11. Crash test von Mises stress. Aluminium model.
Source: Generated in association with Smarttech – SP (2009).

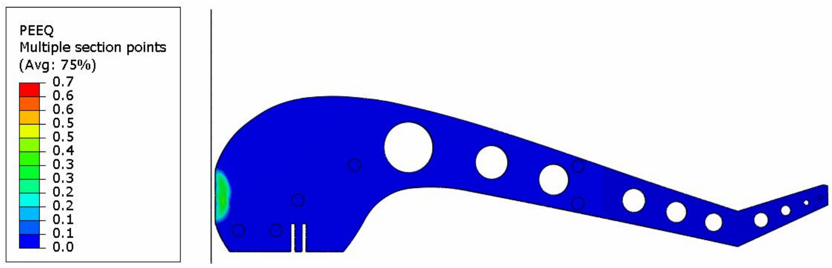
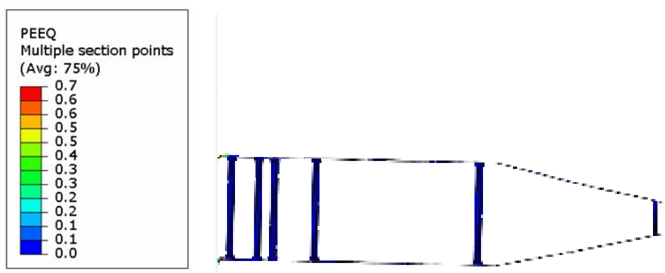
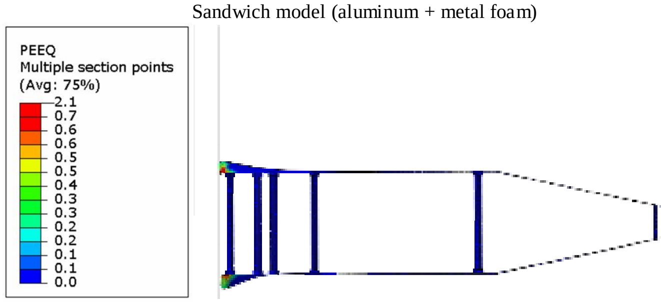


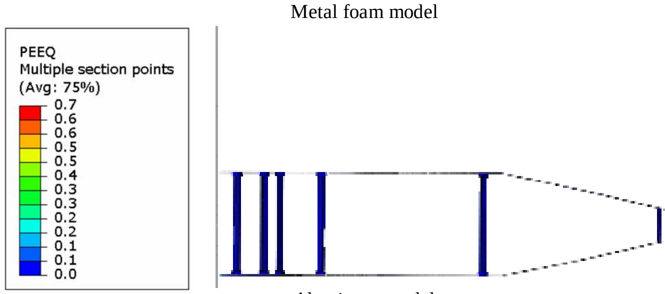
Figure 12. Crash test equivalent plastic deformation. Aluminium model.
Source: Generated in association with Smarttech – SP (2009).



Sandwich model (aluminum + metal foam)



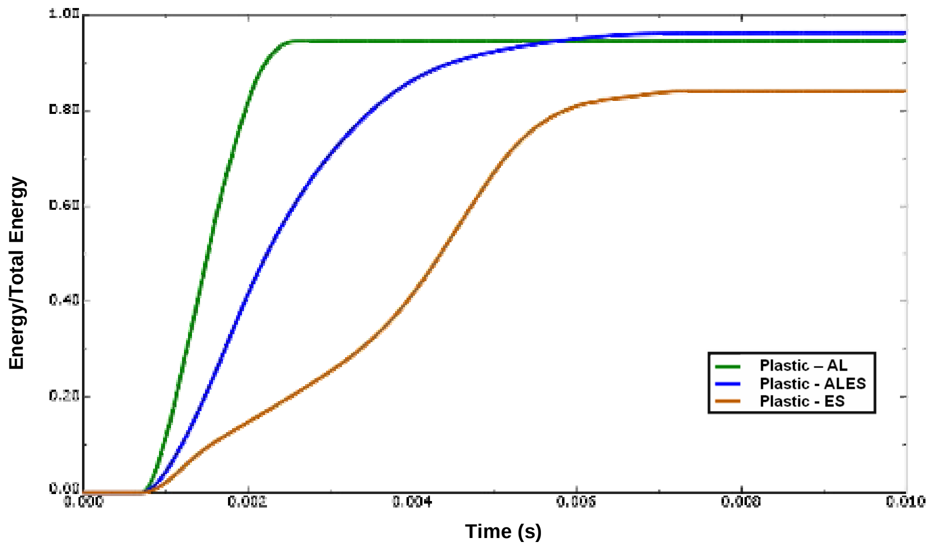
Metal foam model



Aluminum model

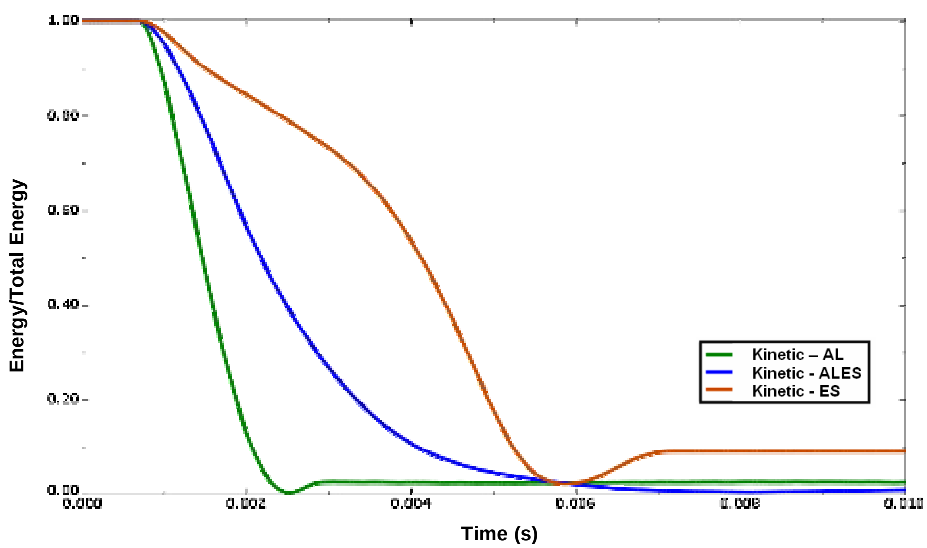
Figure 13. Comparison of the plastic deformation distribution in the system for the three types of material.
Source: Generated in association with Smarttech – SP (2009).

Figure 13 shows the comparison of the plastic deformation distribution in the system for the three models. Figure 14 presents the equivalent plastic deformation distribution for the model with the three different materials composition. As in the previous tests, the sandwich composition model combined the properties of both materials (aluminum and metal foam), being stiffer and presenting less deformation and better impact energy absorption when compared to the whole aluminum model. On the other hand, the metal foam model suffered the greatest plastic deformation; however, as shown in Fig. 14 and 15 this model had the slowest deceleration, taking three times longer to reach the same level as the whole aluminum model. In the crash test the behavior of the metal foam as a good impact energy absorber is evident, since it is the material which decelerates the slowest and consequently has the greatest plastic dissipation (strain), transferring to the material most of the impact energy, instead of the passenger.



AL: whole aluminum / ALES: aluminum + metal foam / ES: whole metal foam

Figure 14. Comparison of the plastic dissipation in the system for the three types of material.
Source: Generated in association with Smarttech – SP (2009).



AL: whole aluminum / ALES: aluminum + metal foam / ES: whole metal foam

Figure 15. Comparison of the kinetic energy in the system for the three types of material.
Source: Generated in association with Smarttech – SP (2009).

In order not to hit the passenger compartment, the important factor during the impact is that the frontal structure is able to absorb as much kinetic energy as possible, so that it does not reach the interior of the vehicle and hit the passengers. According to the crash tests performed, the metal foam demonstrated to be the ideal choice for this purpose.

The most effective structures for impacts are those made from light and strong materials (which do not imply mass increase), which serve as reinforcement and are designed according to a suitable conception.

6. FINAL REMARKS

The participation of the vehicle structure in the energy absorption process during a collision is extremely important. In frontal collisions, for example, vehicles with low frontal stiffness will deform faster, then reducing the time the passengers have to come to rest. On the other hand, if the vehicle has a very stiff front the deceleration will be greater and compensation in the passenger retention system will be needed, by using airbags and crash boxes, for example. The most important point is to manage the energy involved in the collision.

As mentioned before, the passengers' protection during an impact depends mainly on three factors: an efficient conversion of kinetic energy into deformation, low deceleration levels for the passenger and maintenance of the passenger compartment integrity. According to the tests performed and these criteria, the metal foam presents good behavior to meet the first two factors, then contributing to the third one as well.

Also, during the development of a vehicle its performance in low-speed collisions is evaluated with regard to the repair cost. The objective is that after this kind of accident the least number of parts is damaged, and only some metal foam components in impact energy-absorbing systems are repaired, such as crash boxes.

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