Impact Behaviour of Aluminium Foam and Cork in Energy Absorption Systems

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Abstract: The authors study the behaviour of Aluminium foam and agglomerate cork, as filler materials in columns, in the dynamic regime. The main goal of this study is to evaluate the energy absorbing capabilities of both materials. A comparison with correspondent hollow-sections is performed. For the purpose of this comparison the authors consider the energy dissipation and the geometrical profiles of the deformed tubular structures. In order to perform these studies, three-dimensional finite element modelling dynamic analyses are carried out using both the ABAQUS^{TM}/Explicit and LS-DYNA^{TM} FEA codes. The authors try to achieve an in-depth study of the structural crash behaviour of tubular structures, during which energy needs to be absorbed in a controlled manner. A comprehensive comparative numerical study of the crush behaviour of Aluminium foam and agglomerate cork-filled sections undergoing axial compressive loading is performed. Results are also analysed with respect to the force-displacement relation, the absorbed energy and specific absorbed energy (*i.e.* per unit mass), the influence of the core material (both Aluminium foam and cork), the geometry of the cross-section and the thickness of the extrusions on the impact behaviour is also investigated.

Key-Words: Impact behaviour, energy absorption, dynamic behaviour, Aluminium foam, agglomerate cork, plastic dissipation, numerical simulation, finite elements.

1 Introduction

The evolution of the automotive industry, reflected in the increasing supplied power (and therefore of the attained velocities), needs to be carefully accompanied by the assurance of the passengers' safety. Therefore, the crashworthiness of vehicles is becoming increasingly important in the whole design process.

During the last decades steel has been adopted as the preferred material for the design of energy absorption devices and systems, essentially due to its low cost and excellent mechanical and physical characteristics (as, for example, its ductility). However, the competitiveness of the market forces automotive manufacturers to keep up with a constant investment in research areas, looking for solutions that better fit their needs in a persistent way. Moreover, ongoing needs have to be solved and future requests anticipated. Thus, different architectural/design configurations and innovative materials have been considered.

In the previous context, Aluminium foam is an advanced structural material that combines the mechanical properties derived from its cellular structure, in particular its lightness, with the typical behaviour of metals. An increasing industrial use for these materials has been attained in the last few years.

The multifunctionality of metal foams (and cellular materials in general) is a key factor and an additional benefit. The continuous improvement of the manufacturing processes leads to the possibility of low-cost and high-scale production, making these processes increasingly attractive for industrial purposes.

Axial folding of metal tubular structures is known to be an excellent energy absorbing mechanism. Several components based on this principle are commonly used in the automotive industry to absorb crash energy in a controlled mode. In this context, it should be noted that the characteristic stress-strain curves of most Aluminium foams exhibit a long plateau region over very large strains ranges. Hence, the high stiffness-to-weight ratio and the excellent energy-absorbing characteristics to withstand compression forces are relevant properties which, allied with a wide range of possible densities, make Aluminium foams specially adapted for impact energy absorption.

The application of Aluminium foams in Dual-Foam Components (DFC), such as foam-filled metal columns, has continuously been adopted, avoiding joining problems and assuring structural integrity. The industrial relevance of DFC has been increasing in the last decade, replacing the common steel hollow-sections often used as energy absorption systems and devices.

Early studies on the improvement of the performance of axially crushed tubes by the introduction of a filler material were based on the crushing of sheet metal tubes filled with low-density polyurethane foams [1, 2].

Several design formulae related to the crushing of foam-filled columns have been suggested based on numerical finite element simulations [3-5]. The filling of tubular structures with lightweight metallic foams in order to improve their energy absorption has also taken considerable interest in the past few years. Santosa *et al.* [6] found that the increase of the mean crushing force of a filled column has a linear dependence with the foam compressive resistance and the cross-sectional area of the tubular structure.

The mechanical behaviour of different types of foams used as fillers in Aluminium tubular structures, under static and dynamic loading, has been studied extensively in the last few years [7, 8]. In general terms, there is a significant increase of the average crushing force and, in some cases, a change on the deformation behaviour is observed because of the interaction effect between the tube and the foam itself [9, 10].

Cork is a natural cellular material which forms the outer bark of cork oaks. Its unique properties, consequent from its microstructure, explain why it has been exploited by man for at least 2000 years, for insulation, indentation, friction for shoes and floor coverings, energy absorption and packaging, and of course, seals for bottles.

The *quasi*-static mechanical behaviour of agglomerate cork under axial compressive loading has already been studied by several authors [11]. In particular, Gibson *et al.* [12] investigated in great detail the structure and cell wall deformation characteristics of agglomerate cork when loaded, thus being able to compare the mechanical properties measured with theoretical expressions. However, papers on the dynamic uniaxial compressive behaviour of cork remain very few [13, 14], leading to a lack of knowledge on the behaviour of agglomerate cork especially when it has to withstand high deformation rates. Additionally, there are no published data neither on the numerical modelling of cork nor on its mechanical behaviour when used as filler material in metallic structures such as the front tubular structures used in automobiles for crash protection purposes.

In the present work, the authors investigate the impact behaviour of high aspect ratio Aluminium foam-filled and agglomerate cork-filled Aluminium tubes, in particular their force-displacement curves and their energy absorption capabilities. Three-dimensional finite element modelling analyses were carried out using ABAQUS^{TM}/Explicit and LS-DYNA^{TM}. The influence of the core material (Aluminium foam or agglomerate cork), the influence of the shape of the cross-section (square or circular) and the thickness of the skin material on the impact behaviour is thoroughly investigated.

2 Modelling

2.1 Constitutive model for the metal (Aluminium) foam

The isotropic hardening model adopted in the present work to simulate the behaviour of the metal foam, and included in the finite element code ABAQUS^{TM}/Explicit, is a simplified version of the self-similar model developed by Deshphande and Fleck [15].

The stress-strain relation for the selected Aluminium foam can be described with the following two relations [16], defining the elastic and non-linear regimes, respectively:

$$\sigma = E\varepsilon \quad \text{for} \quad \varepsilon < \varepsilon_y \tag{1}$$

and

$$\sigma = \sigma_y + \frac{a(\varepsilon - 0.03)}{\varepsilon_y + b - \varepsilon} \quad \text{for} \quad \varepsilon \geq \varepsilon_y \tag{2}$$

where $E = 0.177$ GPa is the Young's modulus (elastic modulus), $\varepsilon_y = 0.03$ is the yield strain, $\sigma_y = 5$ MPa is the yield stress and $a = 0.35$ MPa and $b = 0.681$ are material parameters.

2.2 Constitutive model for the cork

For the micro-agglomerate cork, the authors used a material model made available by the LS-DYNA^{TM} library (Ref. `26.1.*MAT_HONEYCOMB`), since it seems to be the most adequate to simulate this type of cellular material. The finite element simulation code has a library of material models dedicated to the simulation of foams or foam-like and rubber-like materials. However, most of these tend to be dedicated to specific applications. That is the reason why the authors chose a generic model that could globally capture the cellular nature and behaviour of natural cork and, consequently, agglomerate cork. The material parameters considered were the density $\rho = 293$ kgm^{-3}, the elastic modulus (Young's modulus) $E = 9$ GPa and Poisson's coefficient of the compacted material $\upsilon = 0.3$, as well as the stress-strain curve of the cellular material for similar loadings.

2.3 Constitutive model for the Aluminium alloy used in the extrusions

For the whole range of studies performed the authors considered that the tubular structures are made of 7075-O Aluminium alloy. The mechanical properties of this material in the elastic regime are the density $\rho = 2810$ kgm^{-3}, the elastic modulus (Young's modulus) $E = 71.7$ GPa and Poisson's coefficient $\upsilon = 0.33$. In the plastic regime, the stress-strain relation can be described using Hollomon's law, that is

$$\sigma = k\varepsilon^n ,$$

where $k = 400$ MPa and $n = 0.17$ are material parameters.

2.4 Geometrical modelling

The geometries of the tubes used in the simulations are defined taking into account the shape of the cross-section and the thickness of the wall of the extrusions. Circular and square sections with 80 mm of diameter or width are selected. The thicknesses considered for the extrusion wall are 1, 1.5, 2, 2.5 and 3 mm. The initial length of all the tubes is $L = 300$ mm.

2.5 Numerical modelling

The boundary conditions adopted for the materials subjected to compressive loading correspond to the introduction of two rigid walls (modelled as rigid bodies) placed next to the base and upper sections of the tubes. One of these rigid walls is fixed whereas the other is associated to a specific and predefined mass and impact velocity. The latter boundary wall compresses the tube. This procedure is schematically represented in Fig. 1.

The tube is free at one end and attached at the opposite end to a rigid and fixed plate. The free rigid plate has an associated mass $m = 800$ kg and an initial velocity $v = 10$ ms^{-1} (see Fig. 1). The condition of automatic surface-to-surface contact was used in order to prevent self-penetration of the tubes and to avoid the mutual penetration of the two associated rigid walls. No friction was considered between the extrusion and the filler materials.

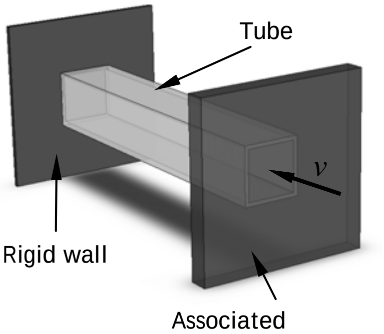

Fig. 1 – Schematic representation of the procedures used to perform the numerical simulations.

The extrusions were discretized with 3 mm 4-node doubly curved thin or thick shell elements with 7 integration points along the thickness, reduced integration, hourglass control and finite membrane strains. The rigid plates were modelled with bilinear rigid quadrilateral elements.

The foam cores were modelled with 3 mm hexahedral 8-node continuum elements, reduced integration and hourglass control. The isotropic hardening model developed by Deshpande and Fleck [15] (implemented in ABAQUS^{TM}/Explicit) was used to predict the behaviour of the Aluminium foam.

The finite element mesh of the micro-agglomerate cork consisted of 8-node hexahedral solid elements with an average size of 3 mm and 3 degrees of freedom per node, for 8 points of integration (full integration, with no problems of hourglass). The material used was `26.1.*MAT_HONEYCOMB`, from the LS-DYNA^{TM} library.

3 Results and Discussion

In the next sections, results are discussed analysing and comparing force-displacement curves, deformation patterns and average force and energy absorption capabilities.

3.1 Average force analysis

The results in Fig. 2 show the evolution of the average force with the displacement for the tests performed on 2 mm thickness tubes. As expected, the average force for the filled tubes is higher than for the empty tubes. Additionally, within the empty tubes, the ones with circular sections have a slightly higher average force. However, the average force for the filled tubes with square section is higher. While the average force slightly increases for the cork-filled tubes, when compared to the empty ones, the increase for the Aluminium foam-filled tubes is more pronounced.

The peak loads vary from 80 kN (for the empty square tube) to 150 kN (for the Aluminium foam-filled square tube). Tubes with square sections have higher peak loads. Similar peak loads are obtained for empty and cork-filled tubes with the same section shape.

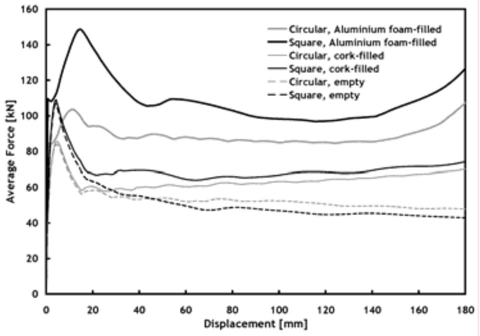

Fig. 2 – Evolution of the average force with the displacement for all tests performed on tubes with the extrusion wall thickness of 2 mm.

Fig. 3 shows the average force for the tests performed on filled square tubes with 1, 2 and 3 mm thicknesses. It can be seen that the average force increases with the thickness. However, the average force of the cork-filled tubes 2 and 3 mm thick is very close to the one of the Aluminium foam-filled tubes of 1 and 2 mm thicknesses, respectively. This means that, in terms of average force, it is equivalent to use, for example, an Aluminium foam-filled tube 1 mm thick or a cork-filled tube with 2 mm thickness.

The peak loads vary from 51 kN (for the cork-filled tube with 1 mm thickness) to 221 kN (for the Aluminium foam-filled tube with 3 mm thickness). For the same thickness, the Aluminium foam-filled tubes have higher peak loads.

3.2 Energy and specific energy absorption

The dependence of the absorbed energy and specific absorbed energy with the tube thickness, for all filled tubes at 50% deformation, is shown in Fig. 4, for the square section, and Fig. 5, for the circular section tubes.

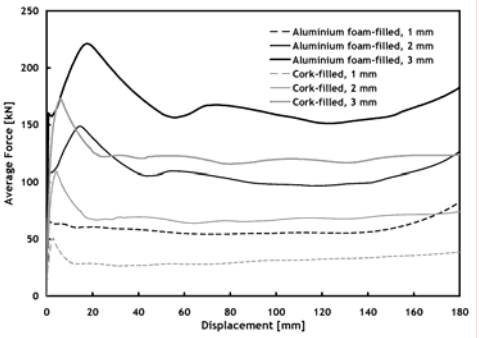

Fig. 3 – Evolution of the average force with the displacement for all tests performed on square section filled tubes (Aluminium foam and cork).

For the square section tubes (*vd.* Fig. 4) the increase of thickness also increases the overall absorbed energy. The absorbed energy values vary from 8.9 to 23.7 kJ for the Aluminium foam-filled tubes whereas, for the cork-filled tubes, they vary from 5.2 to 18.3 kJ. The specific energy absorbed for Aluminium foam-filled tubes, if the thickness of the tube is between 1 and 2 mm, is higher than the one of the cork-filled tubes. The opposite is true for thicker tubes. All the points of the specific energy curve of the Aluminium foam-filled tubes are still below the absorbed energy curve, while for the case of the cork-filled tubes it only happens for thicknesses above 2 mm.

For the circular section tubes (*vd.* Fig. 5) the observations concerning absorbed energy are equivalent to the ones of the square section tubes. All energy values are higher for the Aluminium foam-filled tubes. They vary from 7.2 to 20.6 kJ, for the Aluminium foam-filled tubes whereas, for the cork-filled tubes, they vary from 4.5 to 17.2 kJ. However, in terms of specific absorbed energy, the cork-filled tubes are more efficient, for tubes with thicknesses above 1.5 mm. All the points of the curve of specific energy for the cork-filled tubes are above the corresponding absorbed energy curve. However, in the case of the Aluminium foam-filled tubes the opposite happens, except for the 1 mm thickness tubes. The specific energy absorbed is higher than the energy absorbed if the mass of the filled tube is above 1 kg. Cork-filled square tubes, with equivalent mass, absorb more energy.

The energy values are higher for circular tubes, but square tubes have higher values of specific energy.

The relative difference between absorbed energy and specific absorbed energy at 60% deformation, compared to empty Aluminium tubes, for both filler materials are shown in Fig. 6 and Fig. 7.

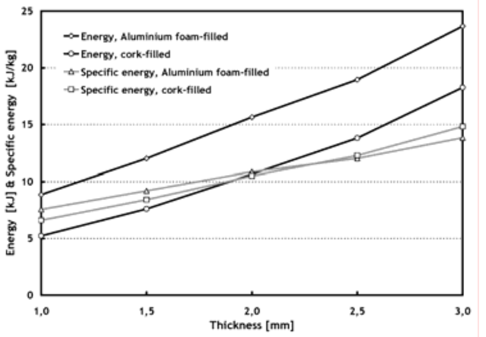

Fig. 4 – Energy and specific energy absorbed at 50% deformation for cork and Aluminium foam-filled tubes with square section.

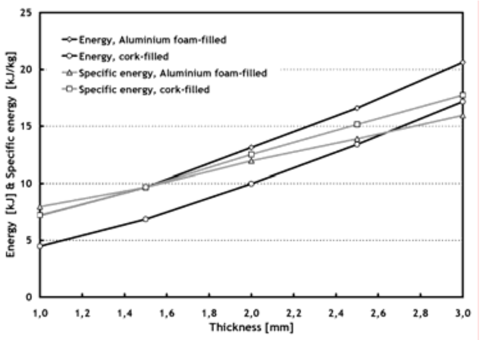

Fig. 5 – Energy and specific energy absorbed at 50% deformation for cork and Aluminium foam-filled tubes with circular section.

The relative difference of energy absorbed between an empty tube and the same tube filled with cork or Aluminium foam decreases with the increase of the tube thickness. The thicker the tube, the less relevant is the use of fillers, in terms of energy absorption performance. Depending on the thickness, the relative absorbed energy increase due to the introduction of cork varies from 25 to approximately 230%. For the Aluminium foam-filled structures the increase varies from 68 to around 590%. The results shown in Fig. 6 and Fig. 7 prove that the contribution of the Aluminium foam to the increase of energy absorption is approximately three times the one of cork, for the same section.

The results in terms of the increase of specific energy were different since the tubes studied showed globally a decrease of specific energy absorption as a consequence of the additional weight of the filler materials (especially for the circular section tubes).

The square Aluminium foam-filled tubes remained the ones that suffered the largest increase of specific energy. The square section cork-filled tubes suffered a less important decrease of specific absorption energy than the Aluminium foam-filled circular tubes. Square shapes promote a larger increase of specific absorption energy.

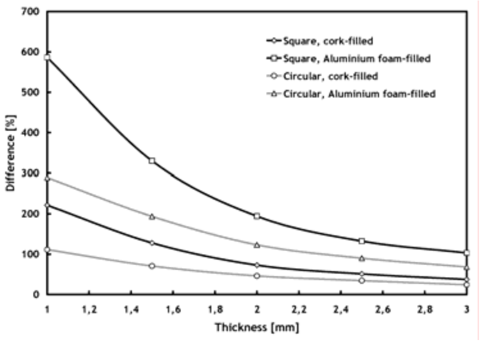

Fig. 6 – Relative difference of absorbed energy (percentage relative to the empty tubes) at 60% deformation for cork and Aluminium foam-filled tubes.

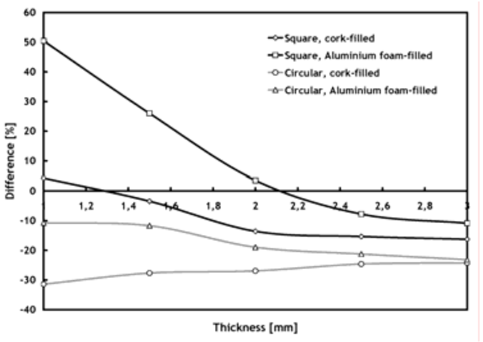

Fig. 7 – Relative difference of specific absorbed energy (percentage relative to the empty tubes) at 60% deformation for cork and Aluminium foam-filled tubes.

4 Conclusions

A significant amount of work has been done on the investigation of the benefits of using Aluminium foam-filled tubes instead of empty tubes, in structural applications, namely in impact protection applications. On the other hand, the utilization of cork-filled tubes for impact applications has never been considered and is a recent research topic. Consequently, a comparison of the potential of both filler materials is of the utmost importance.

In the present work, results are analysed with respect to the force-displacement relation, the absorbed energy and specific absorbed energy. The influence of the core material (Aluminium foam or cork), the cross-section shape and the thickness of the extrusions on the impact response are also investigated.

Both the Aluminium foam and the cork proved to be viable materials for applications in the dynamic range, namely in energy absorption structures (for impact protection). Structural components with Aluminium foam as filler can absorb more energy, but the cork-filled components, mainly for thicker tubes, have high values of specific absorbed energy. This is because of the lower weigh of the cork. Moreover, relative to the equivalent empty tube, both Aluminium foam-filled and cork-filled tubes can absorb much more energy, mostly for tubes with lower thicknesses. However, in general terms, the tubes filled with Aluminium foam have better energy absorption capability.

The shape of the cross-section also has an important role in terms of impact energy absorption. For this analysis, both circular and square sections were studied. The tubes with square section proved to have better performances for energy absorption applications, both in terms of absorbed energy and specific absorbed energy.

The introduction of Aluminium foam or cork as filler materials in empty tubes, to be used as impact energy absorption structures in crash applications, significantly increases the energy absorption capabilities of these components. The Aluminium foam showed best properties for this kind of applications. However, the utilization of the cork is also viable and provides good results.

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