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Dynamic crushing behaviour of aluminium tubes filled with cork

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Abstract. Cork is a natural cellular material with unique remarkable properties such as low density, great elasticity, chemical stability and resilience, no permeability to liquid and gases and resistance to wear and fire. Besides, it is ecological, hygienic, easy to maintain and a very durable material. Unfortunately, there are still application fields that have not been explored yet for the use of cork, possibly due to the fact that it is a complex cellular material, characterized by very variable mechanical properties which clearly depend on its microstructure. The fundamental aspects of the static and dynamic mechanical behaviour of natural and agglomerate cork, used alone and as filler inside a tube with small dimensions, under axial compressive loading, have already been studied by the authors. Aluminium cork-filled tubes and their empty counterparts were tested experimentally and numerically at quasi-static and dynamic strain rates from 10^{-3}s^{-1} to 600 s^{-1} . Data from the Split-Hopkinson Pressure Bar and “deconvolution” techniques were used to generate stress-strain curves for the structures composed of natural and agglomerate cork. The numerical simulations of the dynamic compression of the specimens were carried out using the finite element method software LS-DYNATM and showed quite good agreement with the experimental results. Hence, in this work, in order to extend the study started previously and investigate the possible advantages of cork-filling in longer tubes with a different section, the authors simulate, using the same software, the influence of the introduction of agglomerate cork in square and circular aluminium tubes with a diameter/width of 80 mm, a length of 300mm and a variable thickness. The mechanical properties of the structures composed of cork may constitute a potential for this material to be used in innovative applications related to diverse fields such as automotive, transport, ships and military applications.

1. INTRODUCTION

Energy-absorbing systems of various kinds are being extensively used in many engineering applications such as automotive and transport vehicles. Indeed, during an impact event, the energy of the crash and the manner in which the loads are transmitted through the system, are very important points. As a consequence, the axial crushing behaviour of thin-walled structures, which are efficient energy absorbers, has been a topic of great interest for many researchers.

Steel has been extensively used in energy absorption systems, due to low prices combined with excellent ductility. But the importance of the reduction of structural components mass has increased in the recent years. That's why the use of aluminium tubes with different shapes and geometries, and thus energy-absorbing efficiencies, has been frequently promoted [1, 2]. Furthermore, computational mechanics has been an important tool in the assessment of the crash behaviour of various structures since numerical simulations enable new design and materials to be evaluated without extensive testing [3]. Many authors examined the parameters which could influence the crushing pattern of square and cylindrical tubes under quasi-static and dynamic axial loading since collapse mode transitions of thin tubes strongly influence the energy absorption [4-8]. Furthermore, the question of whether the performance of axially crushed tubes could be improved by introducing a filler material has also been asked several times during the past two decades [9-14].

Cork is a complex natural cellular material, with quite unknown or not well understood properties. The fundamental aspects of the mechanical behaviour of cork under static compressive loading have already been discussed in several studies [15]. However, the mechanical behaviour of cork when

subjected to axial impact has been investigated very recently, when quasi-static and dynamic uniaxial compressive tests performed on natural and agglomerate cork were compared by the authors [16-17].

Hence, the purpose of this study is to analyse the energy-absorption improvements caused by the use of cork as filler inside aluminium tubes subjected to uniaxial impact loading. Thus, circular cork-filled aluminium tubes of 50mm length were impacted using an experimental device in nylon called block-bar, inspired in Hopkinson pressure bars. Numerical simulations were carried out using the finite element code LS-DYNA™, and globally showed good agreement with the experimental results. The validated numerical model was then used to study the energy absorption capacity of cork-filled square and circular aluminium tubes with a diameter/width of 80mm, a length of 300mm and a variable thickness, impacted at 10 and 15m/s. The aim of this systematic study was to analyse if the mechanical properties of the structures composed of cork may constitute a potential for this material to be used in innovative industrial applications.

2. DYNAMIC TESTING

2.1 Material

The dynamic tests were performed on circular tubes with and without micro-agglomerate cork-filler. Actually, the advantage of agglomerate cork is that it is produced industrially and available in many shapes and sizes, making possible to use it in diverse applications. The micro-agglomerate cork filled in the tubes contained 0.5 to 2mm cork particles joined with an adhesive. The circular tubes had an outer diameter of 25mm, a thickness of 1.5mm and were cut for a length of 50mm. The aluminium alloy was in accordance with the standard AW 6060/6063 and was submitted to a T5 heat treatment.

2.2 Experimental tests

An experimental technique that has been used often to obtain constitutive relations at high strain rates is the classic Split Hopkinson Pressure Bar. The first use of a long thin bar to measure stresses under impact conditions has been reported in [18]. The experimental setting with two long bars widely used today is pioneered by Kolsky [19]. However, one of its limitations consists in the fact that the strain for which one can obtain values for the stress in the tubes is limited. Actually, the time of loading applied to the sample is related to the striker length and the wave speed in the bars and determines the maximum strain considered in the sample for a given strain rate. That is the reason why the authors used an equipment device, called “block-bar” which is being developed in the *Laboratoire de Mécanique des Solides (Palaiseau, France)*. This equipment allows carrying out force-displacement curves for higher strains. Basically, it consists of a nylon bar (diameter 81.7mm, length 8.923m), equipped with three strain gages and two zimmers. A steel striker (diameter 78.5mm, length 2m) impacts directly the sample which is placed strictly before the nylon bar. The analysis of the transmitted and reflected waves by deconvolution methods [20], associated to the equilibrium hypothesis of the sample, gives the forces and velocities for each face of the sample. The shifting of waves to specimen ends takes account of the dispersion (which means that the speed of the waves depends slightly on their frequency) and for damping. The authors use a dispersion relation that is the first mode solution of Pochhammer [21] and Chree [22] equation, generalised to the case of viscoelastic bars by Zhao and Gary [23].

The speed of the striker was fixed to 5.5m/s, corresponding to a strain rate of approximately 100s^{-1} .

2.3 Modelling studies

The numerical simulations were performed using the finite element method software LS-DYNA™. The material model used for cork was 26.1.*MAT_HONEYCOMB, which is adequate to honeycomb and foam materials with real anisotropic behaviour. Some of the parameters used in the model were the

result of experimental conclusions whereas others were found in the literature [15]. The stress-strain curve imported was the average dynamic curve obtained as a result of the dynamic tests performed on cork in nylon Hopkinson Pressure Bars and referenced in [17].

The tubes tested experimentally with and without cork were modelled with the material 24.1.*MAT_PIECEWISE_LINEAR_PLASTICITY. This material models an elastic-plastic material with an arbitrary stress-strain curve and an arbitrary strain rate dependency can be defined. For the circular tubes (EN AW 6060/6063-T5), the data from the aluminium tensile curve were used and strain rate was accounted for, using the Cowper-Symonds model.

For the micro-agglomerate cork, the meshing consisted of 8-nodes hexahedral solid elements with 8 nodes and 3 degrees of freedom per node, for 8 points of integration (complete integration, with no problems of hourglass). Cork was meshed with 1mm elements along the volume. The circular aluminium tubes were drawn by their middle surface. The elements used were Belytshko-Tsay shell elements, with 7 integration points along the thickness and 1.5mm thickness at each node. No gap was introduced between the cork and the tube. Two rigid walls (modelled as rigid bodies) were placed next to the base and upper section of the samples. One of the rigid walls was fixed whereas the other impacts the material while associated to a mass and a velocity. The friction coefficient adopted was 0.25. The velocity introduced was the impact velocity experimentally tested (5.5m/s), and the mass was chosen so that the final deformation of the tube was at least equal to the maximum deformation observed experimentally. For each tubular structure, the Automatic_Single_Surface contact was used to prevent self-penetration of the lobes during deformation and the Automatic_Surface_to_Surface contact permitted to avoid the mutual penetration of the two coupled materials. For the tubes, the displacements of the nodes in contact with the compression rigid walls were not allowed, except the displacement of the upper nodes along the impact axis.

2.4 Results and numerical validation

The experimental and numerical force-displacement curves of 50mm empty and filled tubes are shown in figure 1. As seen, the agreement between experimental and numerical average load values is quite satisfactory. The numerical mean force is slightly superior since the model does not take into account the possible defects of the tube material. Besides, the model deformed shapes (concertina mode) and number of lobes exactly matched to the experimental deformed shapes, which again confirmed the agreement between model and experiments (figure 2). Of course, the numerical model did not capture the dimensions recovery of the filled cork but the overall behaviour is well described (figure 3). It is also noted that, for this type of tube geometry, the introduction of cork brought little benefits of energy-absorption, since the loads supported by the filled tubes are quite similar to the forces supported by the empty ones.

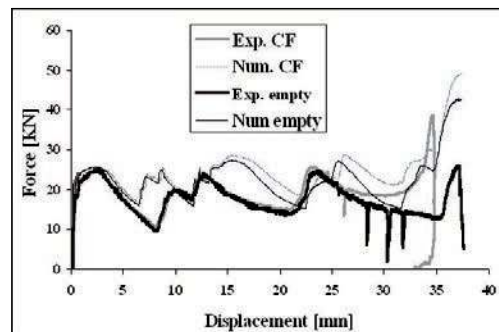


Figure 1. Experimental and numerical force-displacement curves for empty and cork-filled (CF) tubes.

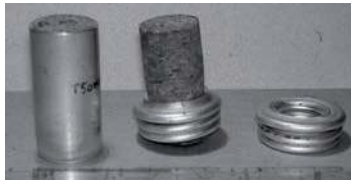


Figure 2. Shape histories of the tubes tested experimentally.



Figure 3. Shape histories of the tubes simulated (empty tubes on the left, cork-filled [CF] on the right).

3. SQUARE AND CIRCULAR TUBES FILLED WITH CORK

The validated numerical model was then used to study the energy absorption capacity of longer square and circular thin-walled sections with varying thickness from 1mm to 3mm. In fact, the energy absorption performance of thin-walled tubes is very dependent on the section shape and on the slenderness ratios (diameter/thickness or width/thickness and length/thickness) [24]. Thus, numerical simulations were performed using the same software, in order to describe and better understand the influence of the impact velocity, the section shape and the thickness values on the energy absorption of 300mm length aluminium tubes with and without cork filler (figure 4). The external diameter or width considered was 80mm, independently of the thickness focused. The modelling parameters imported to the software were identical to the ones used for the 50mm length tubes. And the dimension of the elements used to mesh the tubes and the cork were fixed at approximately 3mm.



Figure 4. Geometry of the tubes numerically studied.

The tubes considered were impacted at 10m/s and 15m/s and the mass of the rigid wall was always chosen so that the tube suffered at least 75% deformation. The study mainly focused on the mean collapse load, on the energy absorption and on the specific energy absorption of the tubes considered. For the thicknesses considered, the filled and non-filled circular and square tubes did not show significant mean collapse load differences, and thus relevant energy absorption differences, when the impact speed increased from 10m/s to 15m/s. This result was expected since the aluminium alloy chosen is known to be almost strain rate insensitive and the micro-agglomerate cork shows similar force-displacement behaviour in the range of strain rates focused in this study [16-17].

3.1 Circular tubes

As seen in figure 5, the mean collapse load increases with increasing thickness and the load supported by the cork-filled tubes is always higher than the force supported by the empty ones, for a same thickness. This fact did not occur for the smaller circular tubes tested experimentally. It is also obvious that there is a critical value of the displacement for which a filled structure supports higher forces than the corresponding empty tube of thickness immediately superior, ie 0.5mm higher (see dashed line on figure 5). The displacement for which this transition occurs also increases with increasing thickness. However, the critical displacement value is never inferior to approximately 125mm. The peak loads may vary from 30KN (for 1mm thickness) to approximately 140KN (for 3mm thickness).

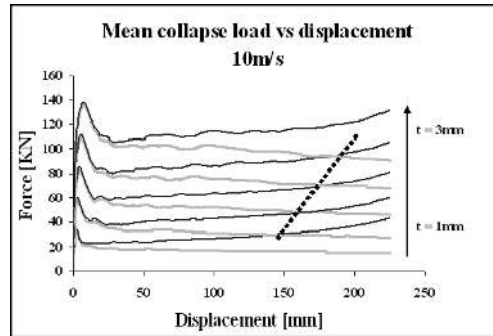


Figure 5. Mean collapse load vs displacement for the circular tubes impacted (— filled, - - - not filled).

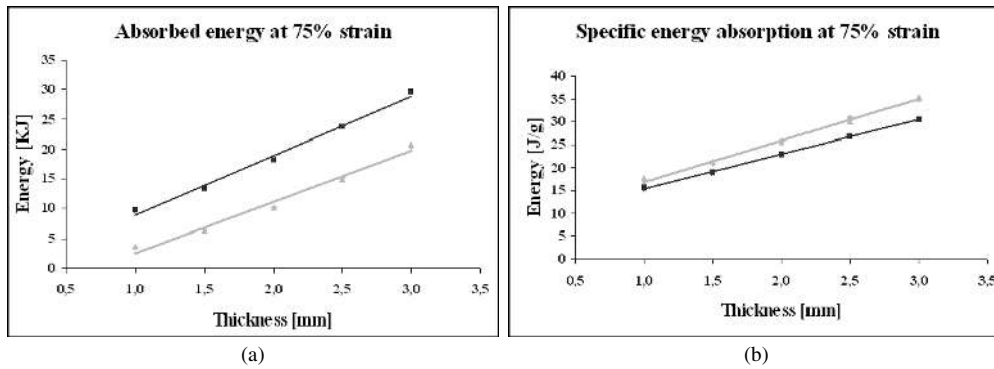


Figure 6. Energy (a) and specific energy absorption (b) at 75% strain vs thickness (— filled, - - - not filled). 10 and 15m/s impacts.

As expected, the energy absorption of the non-filled and filled tubes increases with thickness. It appears that the structures filled with cork absorb more energy than the empty ones, for each thickness studied. Concerning specific energy absorption (SEA) values, the contrary occurs: the empty tubes are more efficient for the same thickness. Indeed, the introduction of micro-agglomerate cork considerably increases the mass of the whole structure. This can be a problem if weight-saving is an important goal. Apparently, only filled tubes with a thickness inferior to 1mm (thus very instable tubes with respect to global bending) could show a higher SEA than the corresponding empty tube (figure 6). In figure 8, one can see that the difference of energy absorbed (in %) between an empty tube and the same tube filled with cork, decreases with the increase of thickness. Thus, the thicker the tube is, the less the use of cork as a filler is positive in terms of energy absorption performance. For the tubes considered, the increase of energy due to the introduction of cork can vary from 50% to approximately 170%. Of course, this fact is strongly related to the possible collapse mode transitions, or deformation pattern transitions which can occur after the introduction of cork, as shown in figure 7.

3.2 Square tubes

The same parameters were observed: mean collapse load, energy and specific energy (SEA). As for circular tubes, the figure 9 highlights the fact that the mean collapse load increases with increasing thickness. The dashed lines represent the evolution of the displacement values for which using a cork-filled tube of lower thickness (0.5mm and 1mm lower) would be preferable to the use of an empty tube, in terms of mean collapse load. The peak loads may vary from 50kN (for 1mm thickness) to

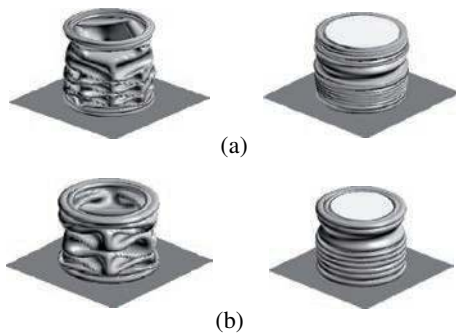


Figure 7. Deformation patterns of the circular tubes tested for 1mm thickness (a) and 3mm thickness (b).

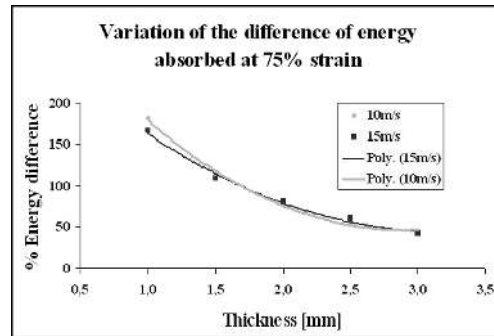


Figure 8. Absorbed energy difference (empty vs CF tubes) at 75% strain, for 10 and 15m/s impacts.

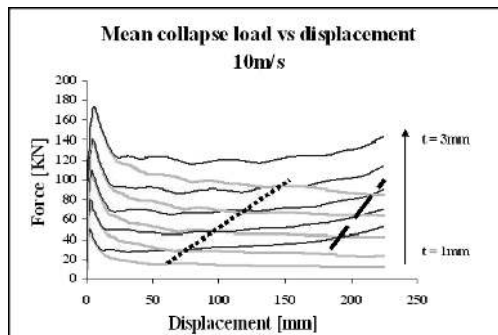


Figure 9. Mean collapse load vs displacement for the square tubes impacted.

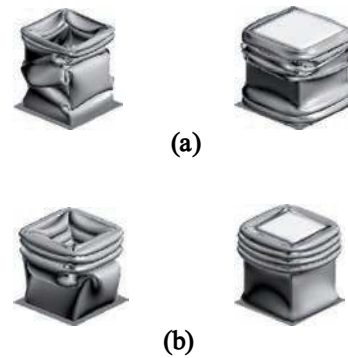


Figure 10. Deformation patterns of the square tubes tested for 1mm thickness (a) and 3mm thickness (b).

approximately 170kN (for 3mm thickness). In the range of thicknesses considered, the energy absorbed by the structures tested increases with increasing thickness. However, the difference of energy absorbed by a filled tube and the same empty tube at 75% strain tends to stabilise for thicknesses higher than 2.5mm (figure 11). Note that the increase of energy due to the introduction of cork in the square tubes studied can vary from 50% to approximately 360%.

Concerning the SEA values, it seems that filling aluminium tubes with cork is very positive above 3mm thickness. Indeed, in that range, the specific energy absorbed by the cork-filled tubes is well above the SEA absorbed by the empty tubes (the % difference can be up to 50%, see figure 12). This result may constitute a potential for this material to be used in innovative applications that focus on energy-absorbers performance. Obviously, all the square tubes studied show a change of the deformation pattern (from diamond to concertina), after the introduction of cork (figure 10). This could explain why cork-filled aluminium square tubes could be good energy absorbers when compared to the same empty tubes.

3.3 Comparison

The numerical results obtained for the circular and square aluminium tubes filled, or not, with cork allow to make a few interesting comparisons. First of all, the introduction of cork increases the energy absorption performance, and for some of the square tubes, the SEA performance of the tubes studied.

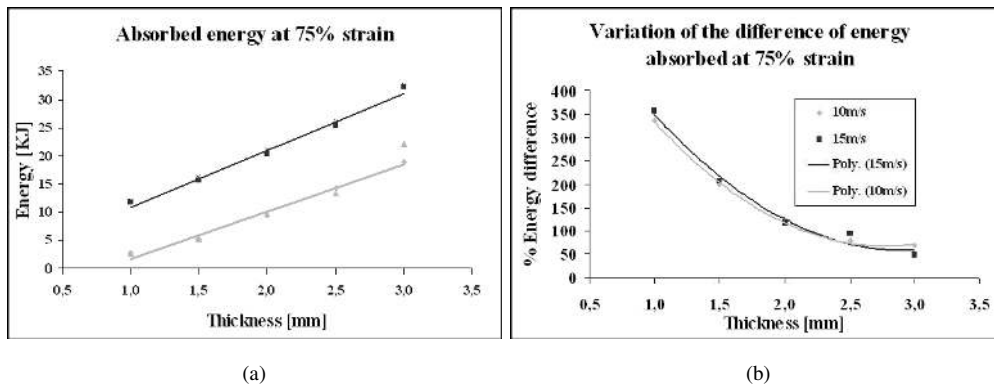


Figure 11. Energy (a) and energy difference empty/cork-filled (b) at 75% strain vs thickness.

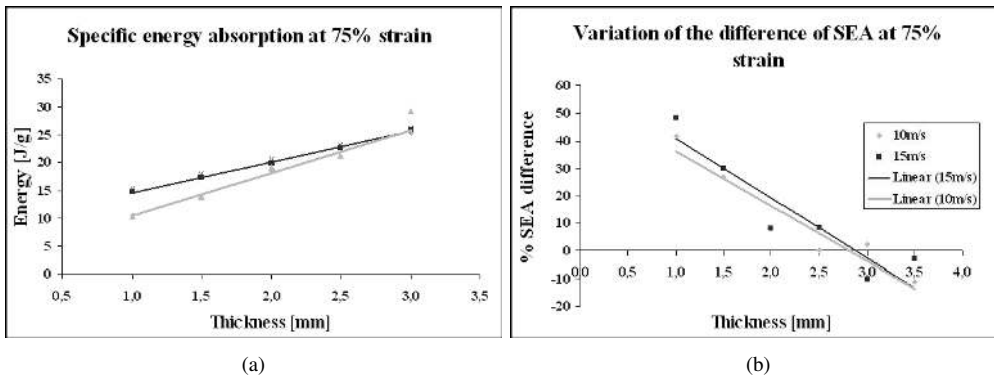


Figure 12. SEA (a) and SEA difference empty/cork-filled (b) at 75% strain vs thickness (— filled, — not filled). 10 and 15m/s impacts.

Additionally, the benefits of square tubes over circular tubes of similar dimension are obvious and consist of:

- the decrease of the critical displacement for which using a tube with lower thickness is positive in terms of collapse load. For some displacements, decreasing the thickness of a square tube of 0.5 or 1mm, and filling it with cork can be very efficient in terms of mean collapse load.
- the increase of the mean collapse load and peak load supported, for the same thickness.
- the increase of the difference of energy absorbed (empty vs cork-filled tube) values for the same thickness at 75% strain.
- the increase of the maximum thickness above which filling a tube with cork is a positive point in terms of energy-absorption capacities and specific energy absorption performance.

4. CONCLUSION

This work studied some aspects of the use of micro-agglomerate cork as filler inside aluminium tubes with different thicknesses and section shapes, impacted at 10 and 15m/s. After testing experimentally 50mm length aluminium tubes, with and without cork-filler, the numerical results obtained with the finite element method software LS-DYNA™ were validated since they showed a good agreement with the dynamic tests performed. However, such tubes showed a bad performance as energy absorbers.

As a consequence, more simulations were performed in longer tubes, with square and circular cross-sections and variable thicknesses, in order to assess if they may have good energy-absorbing properties. The numerical results showed that, considering applications for which the use of tubes with a diameter/width of 80mm is indispensable, the square tubes present better energy-absorbing properties. This study also enhanced the fact that, depending on the application, on the mean collapse load values, SEA values, absorbed energy values and thickness required, filling aluminium tubes with agglomerate cork may be very beneficial. Concerning the increase of impact speed, it seems that it had no visible influence on the behaviour of the different structures tested.

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