NUMERICAL MODELING OF THE DYNAMIC COMPRESSION OF A CLOSED-CELL ALUMINUM FOAM

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ABSTRACT

This research has been focused in study the compression behavior of a closed-cell aluminum foam, by means of the implementation of an isotropic hardening model contained in the finite element code ABAQUS. The dynamic compression of the material was simulated according to the procedure of split Hopkinson pressure bar (SHPB) tests, for strain rates of approximately 10^3 seg^{-1}. Steel and two different low impedance materials have been considered for the striker and the incident and transmitter bars, in order to evaluate the reliability of these materials to characterize the foam. Influence of both the composition and the dimensions of the bars on the resulting strain waves has been analyzed. These results have been useful to realize the proper material of the bars to be used during the SHPB test of the selected metal foam as well as establish the suitable dimensions that must have the equipment used in this task.

KEY WORDS: High strain rate, finite element method, cellular material, Nylon and PMMA bars.

1. INTRODUCTION

Aluminum-based metal foams have recently shown interesting properties for several industrial applications, most of then related to structures with high energy absorption capacity. Despite this fact its broader use has been limited by the lack of information regarding their mechanical behavior at high strain rates and the variability that these usually exhibit, even under quasi-static loading, mostly due to their inadequate characterization [1].

Because of its morphology and properties the metal foams can not be studied by several standard dynamic experimental techniques [2]. One of the dynamic tests that can be carried out on these materials and can provide complete stress-strain data of them as a function of the strain rate is the split Hopkinson pressure bar (SHPB) test. Since its introduction by Kolsky [3] such technique has been widely used to determine the dynamic properties of numerous engineering materials; like ferrous and non-ferrous alloys, polymers, ceramics, and concrete. Nevertheless, as well as many other soft materials, metal foams have a low mechanical impedance which makes them unsuitable for the conventional SHPB test [2,4,5], shown in Figure 1 and usually conducted by means of cylindrical steel bars. For such reason in the literature has been reported the use of some variants of the test in a search for attain reliable dynamic data of the foams [6,7]. Bars made from low impedance materials, primarily PMMA and Nylon [2,4,5,7,8,9], have also been used, owing to their ability increasing the sensitivity of the testing device.

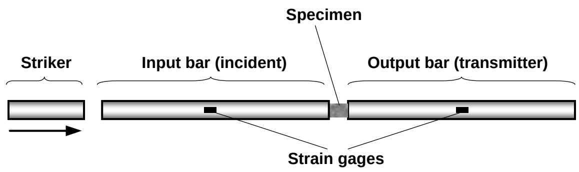

Figure 1. Scheme of the conventional SHPB test arrangement.

The absence of purely elastic materials made PMMA and Nylon a suitable viscoelastic option for the analysis of metal foams, hence, advantage should be taken of them with the intention of allow carrying out the conventional SHPB for cellular materials, either by experimentation or by numerical modeling through the finite element method (FEM).

In the present study was performed the numerical modeling of a closed-cell aluminum foam under conventional SHPB test conditions for three different materials, so as to determine the most appropriate of them to allow the dynamic testing of the foam and provide a well defined pulse with sufficient amplitude. Likewise three different lengths of the striker and diameters of the bars have been modeled with the aim of establish the appropriate dimensions that these must have. In addition, several impact velocities were assigned to the striker to estimate the range of strain rates that can be achieved by means of this testing. All modeling has been held with the aid of FEM-based software.

2. MATERIALS

2.1. Metal foam

Alporas foam was acquired as reference material for the modeling, owing to its wide information regarding geometry and mechanical properties. This closed-cell foam is produced by Shinko Wire Co. (Japan), through a batch casting process via stabilizing gas bubbles in an aluminum melt. The nominal chemical composition of the foam is Al-1.42Ca-1.42Ti-0.28Fe-0.007Mg (wt. %). Relative density (ρ^*/ρ_s) of the foam has been measured in six specimens and the average was estimated around 0.1 (10%).

Knowledge of the quasi-static compression curve has been important to the study, because it is helpful as basis of the constitutive model to be implemented for the Alporas in the computational code.

To determine the quasi-static response of the foam, four prismatic specimens were cut having a square cross section of about 40 x 40 mm and a height of about 60 mm (Fig. 2) and then uniaxially compressed in a servohydraulic testing machine Instron 8516 at a cross head speed of 1 mm/min. This compression of the foam specimens was carried out up to approximately 70% of their nominal strain. Mean stress-strain curve obtained for the foam is shown in Figure 3. Respective strain rate was $3*10^{-4}\ s^{-1}$.

Figure 2. Alporas specimen for quasi-static compression ($\rho^*/\rho_s = 0.1$).

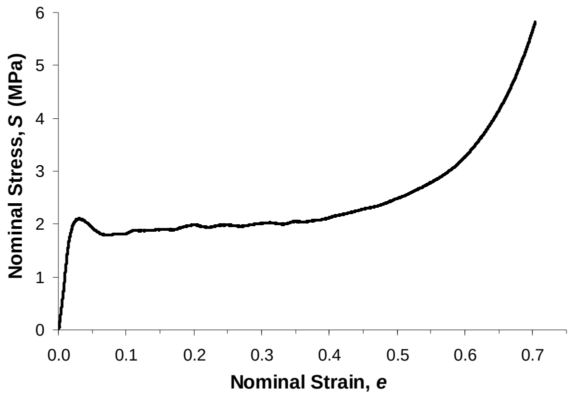

Figure 3. Stress-strain curve from quasi-static compression of the aluminium foam (Alporas 10%).

In the following table (Table 1) are summarized the most important mechanical properties of the mentioned Alporas, some of them achieved from the stress-strain data shown in Figure 2. These properties are the Young's modulus (E), the yield stress at 0.2% of the total strain (σ_y), the compressive strength (σ_c), the plateau stress (σ_{pl}) and the densification strain (ε_D).

Table 1. Compressive mechanical properties of the aluminum foam (Alporas 10%).

E (GPa)	σ_y (MPa)	σ_c (MPa)	σ_{pl} (MPa)	ε_D (%)
1.1	1.86	2.17	1.95	60

Both relative density and mechanical properties were similar to that reported by Mukai *et al*. [10].

2.2. Bars composition

Steel and two (2) low impedance materials have been considered for the striker (projectile) and for the incident (input) and transmitter (output) bars with the aim of evaluate the sensitivity of the arrangement with each material, in terms of the incident and transmitted strain waves. Low impedance materials where PMMA and Nylon, which have been used in previous work for characterization of cellular materials at high strain rates [2,4,5,7,8,9]. Main properties of these materials used for the analysis are listed in Table 2.

Table 2. Properties of the materials considered for the striker and the input and output bars.

Material	Density, ρ (kg/m^3)	Young's modulus, E (GPa)	Poisson's ratio, ν	Elastic wave speed, C (m/s)
Steel	7850	205	0.30	5110
PMMA	1190	3.4	0.35	1690
Nylon	1130	3.0	0.33	1625

3. FEM MODELING

3.1. Constitutive model for the foam

The modeling of the dynamic compression of the metal foam in accordance with the split Hopkinson pressure bar (SHPB) test was accomplished by means of the computational program ABAQUS 6.7.5. [11]. Thus, the crushable foam plasticity model contained in the code has been implemented for the Alporas, considering isotropic hardening with associated flow potential, having the form:

$$G = \sqrt{q^2 + \beta^2 \cdot p^2} \tag{1}$$

where p is the is the pressure stress, q is the Mises stress and β represents the shape of the flow potential envelope and is related to the plastic Poisson's ratio ν_p, according to:

$$\beta = \frac{3}{\sqrt{2}} \sqrt{\frac{1 - 2 \cdot \nu_p}{1 + \nu_p}} \tag{2}$$

Based on the above relationship becomes evident the possibility of include associated plastic flow in the isotropic model providing the value of ν_p, although for many low-density foams such as the Alporas the plastic Poisson's ratio is nearly zero. Having this in mind ν_p was assumed zero. The remaining input parameters of the model, including strain hardening data, were extracted from quasi-static properties aforementioned. The use of quasi-static strain hardening data has been considered an acceptable approximation since few studies available on aluminum-based foams have not revealed significant influence of strain rate on their yield strength [1].

Appointed constitutive model was originally proposed by Deshpande & Fleck [12].

3.2. FE model

Considering the arrangement showed in Figure 1 and taking into account the dimensions of the equipment available in the Mechanical Characterization Lab of the University Carlos III of Madrid, both incident and transmitter bar were modeled with a diameter of 22 mm and a length of 1 m. Likewise, the striker had 330 mm in length and the same diameter. Meanwhile the specimen was 14 mm in diameter and 7 mm in length. The bars and the striker were modeled as elastic materials with the properties listed in Table 2.

An assembly containing all parts (bars, striker and specimen) was modeled using three-dimensional solid 8-node linear brick elements, with reduced integration and hourglass control (C3D8R in ABAQUS library). The bars and the striker had 96 elements in their cross section, whereas the specimen had 320 elements in such area. Along their length the bars and the striker had 80 and 24 elements, respectively, whereas the specimen had 7 elements. All meshing was structured and in both bars with a little refinement where the gauges were placed and in their ends. Mesh configuration of the metal foam specimen appears in Figure 5, while in turn Figure 6 presents a detail of the model assembly in the region of contact between the specimen and both bars. In the same figure (Fig. 6) may be noted the refinement of the mesh at the ends of the input and output bars.

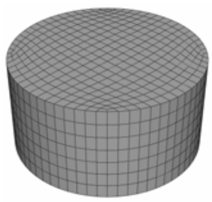

Figure 5. Mesh of the foam specimen model.

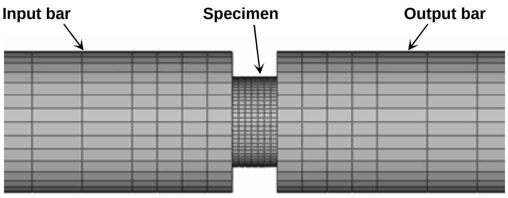

Figure 6. Detail of the model assembly at contact between the specimen and the bars.

The incident velocity of the striker was set to 9 m/s by means of a predefined velocity field. Contacting surfaces were defined as frictionless. Initial boundary conditions were applied to the striker, bars and specimen such that only movement in one direction was allowed. Reference points acting as gauges were placed on input and output bars, specifically to half the length of them, with the purpose of collect incident, transmitted and reflected waves.

Based on the consideration that both bars and the striker must have the same diameter (D), three different relative lengths of the arrangement were also modeled, trying to identify the appropriate dimensions these should posses. Being L_b the length of the bars (same for input and output) and L_p the length of the projectile, previous experimental works concerning SHPB test on metal foams involve relative lengths L_b/L_p ranging from 2 to 6 [5,7,8,9]. Since for the dimensions initially modeled $L_b/L_p = 3$, two changes in the length of striker were introduced so as to obtain additional relative length values of 2 and 5 and then elucidate the effect of this geometrical parameter by examination of resultant transmitted waves. Something similar has been done with the diameter D of the arrangement (i.e. striker and bars), which was modified in terms of a parameter L_p/D. This parameter, representative of the relative size of the striker, typically lies between 3 and 20 [5,7,8,9]. Values of 5, 15 and 20 were then assigned to this parameter with the intention of determine its influence on the longitudinal waves transmission.

Complementing the FE modeling three impact velocities V_p were implemented with the objective of estimate the range of strain rates that can be reached through the original dimensions of set-up. In this sense, such as referred laboratory equipment can reach impact velocities of the striker (V_p) in the range 6-20 m/s, values of 6, 12 and 18 m/s were chosen. Transmitted waves have been recorded in each case and strain rate has been calculated by differentiating in time of the expression developed by Kolsky [3]:

$$\varepsilon_s(t) = -\frac{2 \cdot C_0}{L_s} \int_0^t \varepsilon_r(t) dt \tag{3}$$

where $\varepsilon_s(t)$ is the strain experienced by the specimen, L_s is the length of the specimen, $\varepsilon_r(t)$ is the strain reflected in the input bar and C_0 is the wave velocity within the bars, calculated as:

$$C_0 = \sqrt{\frac{E}{\rho}} \tag{4}$$

being E and ρ the Young's modulus and density of the bars, respectively.

Then, the strain rate during the test has the form:

$$\dot{\varepsilon}_s(t) = \frac{d\varepsilon_s(t)}{dt} = -\frac{2 \cdot C_0}{L_s} \varepsilon_r(t) \tag{5}$$

Plotting the strain rate obtained for each velocity as function of the time t was possible to attain its mean value during the dynamic compression.

3.3. Validation of the SHPB test conditions

In order to verify that the numerical model reliably reproduces the real conditions of the test the following tasks have been accomplished:

- *Lagrange diagram*: A Lagrange diagram has been constructed to confirm that there was no interference in wave propagation during the test.
- *Wave dispersion*: It was corroborated that the dispersion of the wave has not been significant.
- *Uniaxial stress condition*: The uniaxial stress state was verified in the numerical simulations, so that, the hypothesis of one-dimensional elastic wave propagation can be considered.

4. RESULTS AND DISCUSSION

4.1. On the bars material

As result of the SHPB test simulation with ABAQUS of the metal foam ($\dot{\varepsilon} \approx 10^3$ s^{-1}) were obtained the incident, reflected and transmitted strain waves shown in Figures 7 and 8, respectively. In both figures is possible appreciate the strain wave found for each material considered in the composition of the bars.

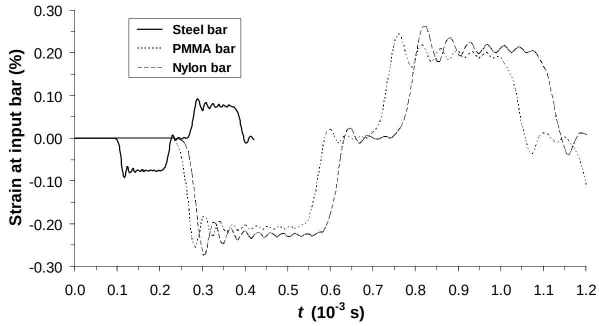

Figure 7. Incident and reflected strain waves obtained from dynamic compression of the metal foam (Alporas 10%) for different material bars.

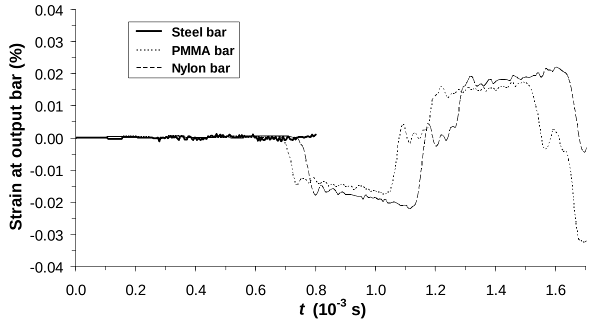

Figure 8. Transmitted strain waves obtained from dynamic compression of the metal foam (Alporas 10%) for different material bars.

Figure 7 clearly shows how the incident wave amplitude in the steel bars is less than a half that achieved in the bars of PMMA and Nylon. The same happened with the wave period. Hence, is possible to infer a difference in the strain wave of the output bars, like can be evidenced in Figure 8. In this figure can be seen that the transmitted wave in the steel bars has no significant amplitude and therefore it is not useful for dynamic characterization of the Alporas. This fact becomes more relevant taking into consideration that the transmitted wave is small compared to the incident and reflected ones, as can be appreciated in Figure 9 for the particular case of PMMA bars. Such figure shows the incident, reflected and transmitted strain waves generated by the striker with a velocity of 9 m/s as obtained from the strain gauges.

From resulting incident and transmitted waves becomes evident that SHPB test either with Nylon or PMMA bars can provide information about the dynamic response of the Alporas, unlike what would happen if conventional steel bars were used. This undoubtedly confirms (as previously reported) their ability for increase the sensitivity of the arrangement during the SHPB test.

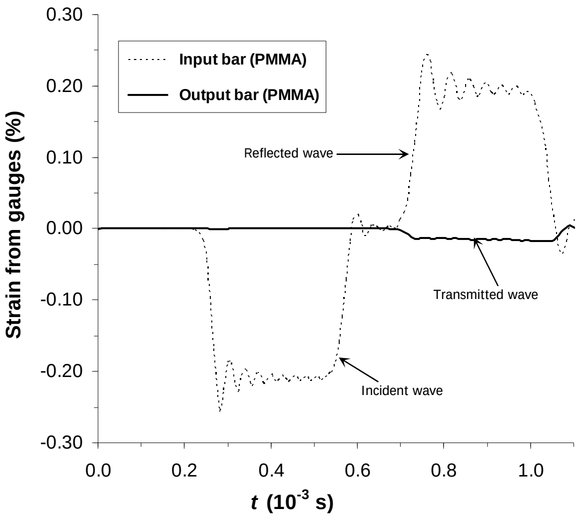

Figure 9. Incident, reflected and transmitted strain waves obtained from dynamic compression of the metal foam (Alporas 10%) for PMMA bars.

Due to its suitability for dynamic modeling of the Alporas and reliability data, the PMMA was chosen as constituent of the bars and striker to accomplish the rest of the numerical analysis.

4.2. On the striker dimensions

In figure 10 are presented the transmitted strain waves corresponding to selected values of the relative length (L_b/L_p) as measured on the strain gauge position. Can be observed that, like ratify the expressions of the one-dimensional theory of waves, if increases the length of the striker, the same happens with the pulse duration and the amount of strain. For the particular case of metal foams this implies that varying the length of striker is possible to conduct the SHPB test on foams with different relative densities (ρ^*/ρ_s) and therefore different crushability.

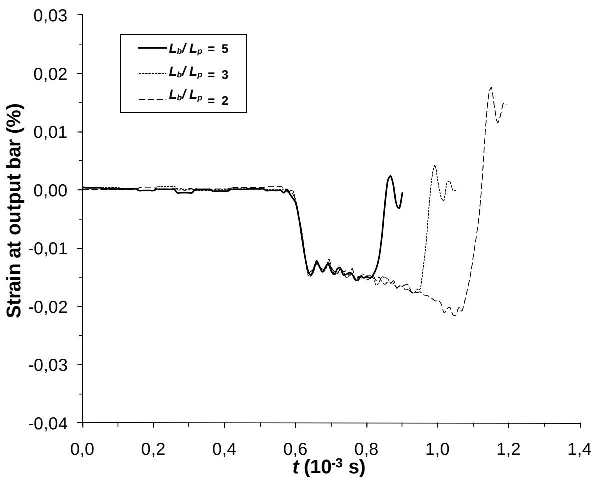

Figure 10. Transmitted strain waves obtained from dynamic compression of the Alporas ($\dot{\varepsilon} \approx 10^3$ s^{-1}) for PMMA bar at different relative lengths (L_b/L_p).

Knowledge of the relation between the length of striker (L_p) and the pulse period is very useful to choose the proper length for attain a suitable transmitted wave, even more considering that metal foams usually transmit a pulse of reduced amplitude, as was proved before.

Concerning relative size of the striker, L_p/D, figure 11 shows transmitted waves obtained on the output bar (at strain gauges) for all three values of this parameter. In the figure can be noted that by decreasing the diameter (D) of the bars increases slightly the pulse period and significantly the strain. For this reason can be argued that length of the striker, L_p, is the geometrical parameter most important for dynamical testing of metal foams.

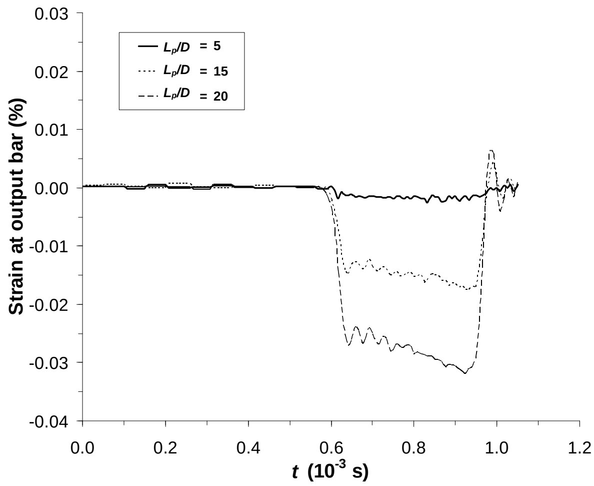

Figure 11. Transmitted strain waves obtained from dynamic compression of the Alporas ($\dot{\varepsilon} \approx 10^3$ s^{-1}) for PMMA bar at different relative sizes of the striker.

Although the modification of diameter of the bar is not operative for SHPB testing, since it leads to substantial changes in the geometry of the equipment, should be considered because diameter must be as large as to avoid cell size effects on the foam, i.e., at least seven times the cell size [1].

4.3. On the impact velocity

Figure 12 presents the strain rate ($\dot{\varepsilon}$) values estimated for all three impact velocities (V_p) through the expression (5) as function of the time (t). It is evident in this figure the strong dependence that has the strain rate with the impact velocity. The curves shown allow distinguish that strain rates are in the range of 500 to 2000 s^{-1}. This data is relevant for testing because allow knowing the suitable impact velocities that can be reached and the range within the user could make his selection.

From figure 12 mean values of the strain rate have been estimated and then listed with their respective impact velocity in Table 3.

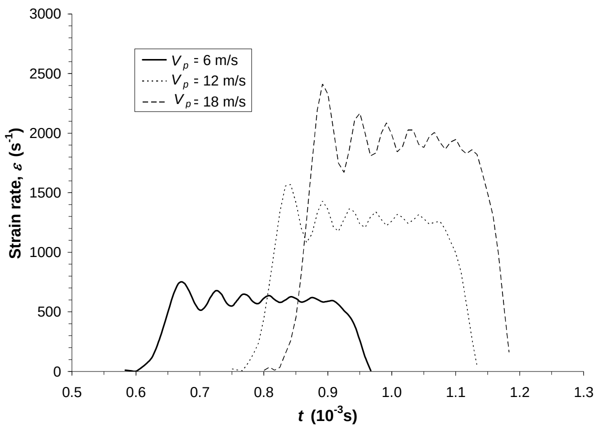

Figure 12. Strain rates reached from dynamic compression of the Alporas with PMMA bars at different impact velocities (V_p).

Table 3. Strain rates estimated for the dynamic compression of the Alporas with PMMA bars at different impact velocities.

Impact velocity, V_p (m/s)	Strain rate, $\dot{\varepsilon}_s(t)$ (s^{-1})
6	600
12	1300
18	2000

5. CONCLUSIONS

A detailed FE model of the split Hopkinson pressure bar (SHPB) compression test of an aluminum foam specimen has been developed and analyzed.

Nylon and PMMA were considered in the composition of the bars and the striker and afterward have been compared with conventional steel bars, finding that both materials are very suitable for dynamical compression testing of the Alporas aluminum foam under SHPB conditions.

From the geometry and configuration of the SHPB available as reference for this study have been proposed the necessary modifications, in terms of striker length and diameter, for carry out an appropriate and reliable dynamic compression test of the aluminum foam in such device.

It was found that diameter (D) of the bars and striker is the most determinant geometrical parameter for prescribing in the metal foam specimen a wide range of strain rates ($\dot{\varepsilon}$), going from 600 to 2000 s^{-1}. As the impact velocity is directly associated with the specimen size, it is indirectly limited by the cell size of the foam.

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