ON THE MODELLING OF COMPRESSIVE RESPONSE OF CLOSED-CELL ALUMINIUM FOAMS UNDER HIGH-STRAIN RATE LOADING

P. Koudelka [1] , P. Zlámal, T. Fíla [2]

Summary: *Porous metals and particularly aluminium foams are attractive materials for crash applications where constructional elements have to be able to absorb considerable amount of deformation energy while having as low weight as possible. Compressive behaviour for medium impact velocities can be experimentally assessed from a series of drop-tower impact tests instrumented with accelerometer and high-speed camera. However to predict such behaviour a proper modelling scheme has to be developed. In this paper drop-tower impact tests of Alporas aluminium foam were used for development of a material model for explicit finite element simulations of high-strain rate deformation process using LS-DYNA simulation environment. From the material models available low density foam, Fu-Chang's foam, crushable foam and modified crushable foam models were selected for simulations using smoothed-particle hydrodynamics and solid formulations respectively. Numerical simulations were performed in order to assess constitutive parameters of these models and identify material model describing deformation behaviour of Alporas with the best accuracy.*

Keywords: *aluminium foam, high strain-rate compression, finite element modelling*

1 Introduction

Metal foams are a new type of prospective engineering materials that are by their nature suitable for designing of multifunctional and lightweight structures combining several physical properties in one constructional element. In transportation and defence industries aluminium foams are being looked at as an effective solution to improve of safety of transported persons during various impact scenarios [1, 2, 3]. The considered applications include protection of passengers during transportation accidents on the civil side and protection of military personnel from blasts, flying shells and debris produced primarily by mines and improvised explosive devices. For this purpose certain types of aluminium foams and therefrom derived materials offer the possibility to utilize strain rate dependent mechanical properties to absorb deformation energy of the impacting objects.

Strain rate dependency of mechanical properties can be into the considered aluminium foams introduced by different methods: i) by producing material with closed-cell microstructure, ii) by filling open cell foam by a strain rate dependent material forming metal porous polymer composite, iii) by coating open cell aluminium foam by a metallic (e.g. nickel) layer, iv) by utilizing auxetic microstructure and v) combination of listed options. In either case proper modelling scheme has to be developed in order to fully utilize the material's energy absorption characteristics for the considered application.

In this paper drop tower tests of Alporas aluminium closed cell foam are used to identify material model

[1]Petr Koudelka, Czech Technical University in Prague, Faculty of Transportation Sciences, Konviktská 20, 110 00 Prague 1, Czech Republic, email: xpkoudelka@fd.cvut.cz

[2]Petr Zlámal, Tomáš Fíla, Institute of Theoretical and Applied Mechanics AS CR, v.v.i., Prosecká 76, 190 00 Prague 9, Czech Republic, email: {zlamal,fila}@itam.cas.cz

suitable for prediction of the foam's deformation characteristics under high strain rate compressive loading. From both available groups of material models (compressible and crushable) two material models were selected and used in a set of parametric finite element (FE) simulations in LS-DYNA [4]. The numerical results were evaluated against experimental drop tower test and optimal material model was identified.

2 Material and methods

2.1 Alporas

Material considered in the study is closed cell aluminium foam Alporas. It was developed in Japan in 1980s and is in mass production by Shinko Wire co., Ltd. since 1986. Unnormalized alloy composed of $97\,\%$ of aluminium, $1.5\,\%$ of calcium and the same amount of titanium is used for its production. Blowing agent is used for the foam's production and the resulting microstructure exhibits approx. $90\,\%$ porosity (controllable to a certain amount during the foaming process). The pores have polyhedral shape, mean cell size $4.8\,\mathrm{mm}$ and typical cell wall thickness $100\,\mu\mathrm{m}$ [5]. The material is suitable for lightweight applications including self-supporting sound absorbers, thermal insulators, electromagnetic wave shielding and particularly vehicle deformation energy absorption elements.

2.2 Drop tower testing

To obtain reference data for calibration of the constitutive material models and validation of numerical results samples of Alporas with dimensions $50 \times 50 \times 50\,\mathrm{mm}$ were subjected to medium strain rate compressive loading using drop tower. The drop tower used was custom designed according to bicycle helmet testing standard [6] allowing to test samples at different impact velocities (up to $5.86\,\mathrm{ms}^{-1}$) and energies by setting the initial height and dead weight of the impactor. The device consists of: i) impactor, ii) carrier and iii) rigid frame manufactured using aluminium profiles. The impactor is attached to a carrier (sledge) guided during the free fall by sliding bearings. Accelerogram of the studied deformation process is acquired by triaxial accelerometer (EGCS3, Measurement Specialties, USA) with $\pm 1000\,\mathrm{g}$ range and $52\,\mathrm{kS/s}$ analogue input module. Due to open pores and fragments on the outer faces of specimens evaluation of deformation process was carried by utilizing custom digital image correlation (DIC) tool [7] based on Lucas-Kanade tracking algorithm [8]. The specimens were observed by two high speed cameras with $3.25\,\mathrm{kfps}$ (IDT NX3, USA) and $10\,\mathrm{kfps}$ (Photron FASTCAM SA5, Japan) frame rate at resolution $1120 \times 856\,\mathrm{px}$ while the scene was illuminated by two high performance white light $60\,\mathrm{W}$ LED sources (Constellation 60, Veritas, USA). During the experiments the specimens were fixed to the bottom plate to avoid slip after the impact. The tests were performed with impactor mass $6030\,\mathrm{g}$ at three different impact velocities $4.32\,\mathrm{ms}^{-1}$, $5.27\,\mathrm{ms}^{-1}$ and $5.86\,\mathrm{ms}^{-1}$ and set of three samples was tested at each impact velocity.

2.3 Constitutive modelling

Deformation response in compression of the studied material can be divided into three zones. The initial linear elastic region is after the yield point followed by compaction region of constant (plateau) stress in wide range of deformation (up to ≈ 0.65 strain). When the cellular microstructure of the material collapses and the cell walls begin to touch each other the last densification stadium takes place. Furthermore, due to gas contained in the closed cells stiffness, both yield point and plateau stress increase with increasing strain rates because the compressed air inflicts damage to the microstructure. It is then evident that numerical modelling of such large deformation transient process is not a trivial task as the constitutive model has to reflect all these complex characteristics [9, 10]. The available material models can be divided into two groups distinguished by treatment of unloading properties and damage to the microstructure during loading. The first group of compressible (reversible) foam material models was originally developed for modelling of polyurethane foams and includes unloading part of the material's deformation response. From this group low density foam and Fu-Chang's foam models were used in the study. The other group of material models, crushable (irreversible) material models incorporates damage inflicted to the foam's during deformation and unloading is not considered. From this group crushable foam and modified crushable foam models were used in the simulations. The Fu-Chang's foam and modified crushable foam material models are in the solver implemented in order to accept stress-strain diagrams at different strain rates on order to calculate their constitutive parameters.

2.4 Impact simulations

To identify and develop material model for prediction of deformation characteristics of the studied material under high strain rate compressive loading virtual experiments (i.e. simulations of the drop tower tests) were performed in LS-DYNA explicit FE solver.

The numerical model was generated to accurately represent the drop tower tests using three fundamental entitities: i) impactor, ii) specimen and iii) bottom plate. The virtual impactor with physical dimensions $100 \times 100 \times 20\,\mathrm{mm}$ (length, width, height) was represented by 200 constant stress (reduced integration) solid elements. Its material was considered perfectly rigid in order to neglect its influence on deformation behaviour of the foam itself. Impact energy of the impactor was set according to experimental testing by imposing mass density and initial velocity at the beginning of the simulated experiment. The bottom plate was modelled as a solid shell with dimensions $100 \times 100 \times 1\,\mathrm{mm}$ (length, width, thickness) and consisted of 100 elements. Similarly to the impactor its material was set perfectly rigid.

Volume of the foam specimen was modelled in two different ways according to implementation of the considered material models. Smoothed particle hydrodynamics (SPH) was used in case of low density foam, Fu-Chang's foam and crushable foam material models. SPH is a meshless formulation which does not require numerical grid and allows for efficient formulation of history dependent problems of material deformation. Main advantage of this approach is that SPH does not suffer from instabilities of the simulations due to highly distorted elements. However this method is still affected by stability problems and issues with inconsistency and conservation. To overcome these problems and to assess performance of standard Lagrangian formulation of the problem a set of simulations using the modified crushable foam material model was performed using volume of the specimen represented by reduced integration solid elements.

In either case volume of the foam consisted of 15.625 elements. Three different contact types were utilized in the simulations. Between the foam block and impactor node to surface and surface to surface contact types were used with the SPH and Lagrangian formulation of the foam respectively. On the impactor-foam interface static coefficient of friction $\mu_{\mathrm{s}} = 0.15$ was used. To reduce computational costs of the simulations planar rigid wall contact was set between the foam and bottom plate. The simulations were carried out in parallel mode using four threads of the Intel i7-3820 CPU.

3 Results

3.1 Experimental

To obtain data for calibration of constitutive models and validation of numerical results a series of compression tests with DIC evaluation of strain field was performed. Prior to drop tower testing a set of quasi static tests was performed in order to obtain deformation response of the material at zero strain rate loading. From elastic parts of the obtained stress-strain diagrams Young's modulus $E = 1.2\,\mathrm{GPa}$ was calculated.

Then drop tower tests at three different impact speeds $v_{\mathrm{i}} = \{4.32, 5.27, 5.86\}\ \mathrm{ms}^{-1}$ (deformation rates $\dot{\varepsilon} = \{86.43, 105.56, 117.92\}\ \mathrm{s}^{-1}$) were performed. Stress-strain diagrams from the dynamic tests were evaluated based on acceleration data and DIC evaluation of strain field. As can be seen in Fig. 1 the material showed lower stiffness and higher plateau stress with increasing strain rate.

3.2 Numerical

To identify material model suitable for description of deformation behaviour of Alporas under moderate strain-rate loading performance of individual material models was assessed using virtual experiments and by comparing numerical results to stress-strain diagrams obtained during drop tower testing. Numerical stress-strain diagrams from impact simulations comparing results of individual material models can be seen in Fig. 2.

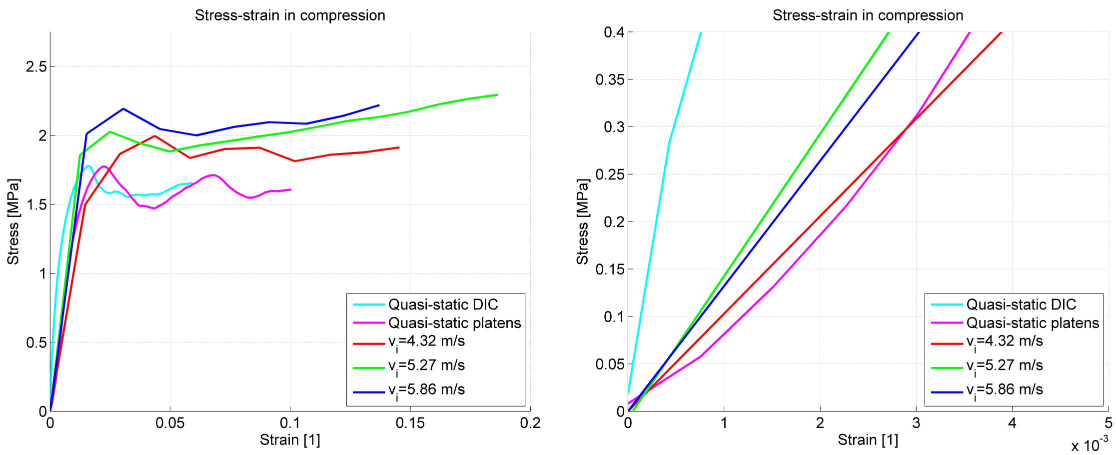

Figure 1: Calculated stress-strain curves (average for 3 measurements for each impact velocity) based on DIC and comparison with quasi-static results (left), detailed view of the elastic region (right).

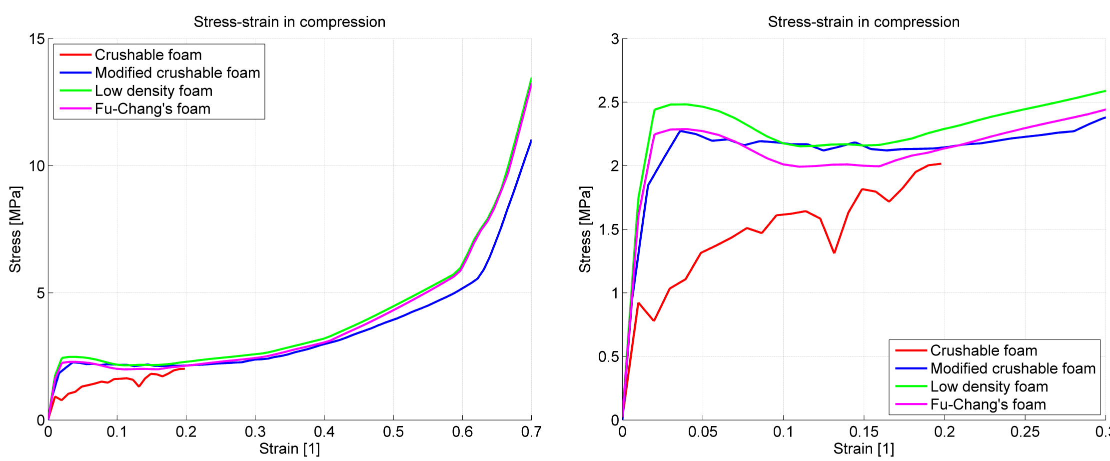

Figure 2: Comparison of all numerical models for intermediate impact speed $v_{\mathrm{i}} = 5\,\mathrm{ms}^{-1}$ (left), detail of elastic region and initial part of constant stress plateau (right).

It is evident that performance of the crushable foam model is insufficient when no apparent elastic part, yield point nor compaction region was acquired in stress-strain diagram. The other material models showed better results where all three zones of the compressive behaviour of the foam were reliably captured. Both yield point and plateau stress of the low density foam model were approx. $10\,\%$ higher than experimentally acquired values while Fu-Chang's foam and modified crushable foam matched the experimental stress-strain curve with the same accuracy.

4 Conclusion

Experimental tests using instrumented drop tower and explicit numerical simulations in LS-DYNA were performed in order to identify material model suitable for prediction of compressive characteristics of Alporas to predict its behaviour under high strain rate loading. To assess behaviour of both compressible (reversible) and crushable (irreversible) material models the following constitutive models from LS-DYNA database were used in the simulations: i) low density foam, ii) Fu-Chang's foam, iii) crushable foam and iv) modified crushable foam. Numerically obtained stress-strain curves were compared to experimental results. The comparison shows that both Fu-Chang's foam and modified crushable foam models can be used for numerical modelling of Alporas during high strain rate loading.

5 Acknowledgment

The research has been supported by the Czech Science Foundation (project no. P105/12/0824) and by grant agency of the CTU in Prague (project no. SGS12/205/OHK2/3T/16) and by RVO: 68378297. All the financial support is gratefully acknowledged.

References

[1] Gibson, L.J. & Ashby, M.F.: *Cellular Solids: Structure and Properties, second ed.*, Cambridge University Press, Cambridge, 1999.

[2] Ashby, M.F. et al.: *Metal Foams: A Design Guide*, Butterworth Heinemann, 2000.

[3] Banhart, J. *Manufacture, characterisation and application of cellular metals and metal foams*, Progress in Materials Science 46(6), 559-632 (2001).

[4] Hallquist, J.: *LS-DYNA Keyword User's Manual*, Livermore, CA: Livermore Software Technology Corp, Livermore, 2006.

[5] Němeček, J., Králík, V. & Vondřejc, J. *A two-scale micromechanical model for aluminium foam based on results from nanoindentation*, Computers and Structures 128, 136-145 (2013).

[6] E/ECE/324, E/ECE/TRANS/505, Regulation No. 22, *Uniform provisions concerning the approval of protective helmets and of their visors for drivers and passengers of motor cycles and mopeds*, 2002.

[7] Jandejsek, I., Valach, J. & Vavřík, D. *Optimization and Calibration of Digital Image Correlation Method*, Experimental stress analysis 2010 121–126 (2010).

[8] Lucas, B.D. & Kanade, T. *An Iterative Image Registration Technique with an Application to Stereo Vision*, Proceedings of Imaging Understanding Workshop 121–130 (1981).

[9] Deshpande, V.S. & Fleck, N.A. *High strain rate compressive behaviour of aluminium alloy foams*, International Journal of Impact Engineering 24, 277-298 (2000).

[10] Zhang, Y. et al. *Identification of material parameters for aluminum foam at high strain rate*, Computational Materials Science 74, 65-74 (2013).