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NUMERICAL MODEL OF OPEN HOPKINSON PRESSURE BAR AND ITS UTILISATION FOR INVERSE NUMERICAL ANALYSIS OF CLOSED-CELL ALUMINIUM FOAM

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Abstract: *Research into the mechanical behaviour of lattice structures and metal foams at high strain rates using experiments based on a direct impact Hopkinson bar (DIHB) method has been recently proposed to overcome several limitations of the conventional split Hopkinson pressure bar (SHPB). Especially, the so-called open Hopkinson pressure bar (OHPB), a modification of DIHB with strain measurement points on both bars, has been proved to be a suitable experimental technique for testing of materials with low mechanical impedance. However, experimental testing is usually limited in terms of resources and, hence, it is convenient to employ numerical methods to predict the results of experiments and, if necessary, adjust the parameters of the experimental procedure based on the preceding numerical analysis of the problem. Developing a numerical model of the whole experimental set-up is, thus, a key method to achieve a reliable analysis. In this paper, we present a numerical model of an OHPB apparatus and demonstrate its suitability for inverse numerical simulations of the closed-cell aluminium foam.*

Keywords: Numerical analysis, Open Hopkinson pressure bar, Cellular solids, Alumunium foam.

1. Introduction

Dynamic impact testing is an important method that allows for understanding and describing the deformation mechanisms occurring in materials during high strain rate loading. It has been shown that dynamic testing can be reliably performed with the employment of Hopkinson bar experimental techniques to yield consistent results (Fíla et al., 2021). Cellular materials such as metal foams, hybrid foams or lattice structures and metamaterials are currently extensively studied for their superior properties compared to conventional materials. Simultaneously, special attention has been paid also to the development of suitable experimental set-ups optimized for dynamic testing of such low impedance cellular materials to describe their behaviour under dynamic loading. In this field, the application of direct impact Hopkinson bar (DIHB) has been proved to be beneficial as it has overcome several limitations of the conventional experimental techniques (Deshpande and Fleck, 2000). Furthermore, the methods of two-sided instrumentation of the DIHB set-up have been studied. Govender and Curry (2016) have introduced the Open Hopkinson Pressure Bar (OHPB) setup which is, in principle, a DIHB instrumented by conventional strain-gauges on both the incident and transmission bar. It was demonstrated that the technique is simple and suitable for testing of low impedance materials with many benefits. However, experimental testing, in general, is very demanding in terms of precision and resources and it is vital to complement it with numerical analysis of the problem. Here, a reliable numerical analysis of the experimental procedure allows for prediction of the results and even adjustment of the experimental procedure or its parameters, if necessary.

Numerical modelling of dynamic impact loading of metal foams and 3D printed structures is a very complex problem from the viewpoint of theoretical mechanics, thermodynamics, material science, and numerical

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solution itself. Several phenomena have to be included in the correct modelling of such scenarios including inertia effects, wave propagation in solid bodies, contact constraints on boundaries and inside the objects including friction, nonlinear geometrical effects of large displacement and large rotation kinematics. At the level of constitutive models, the response of materials respecting large elasto-plastic behaviour including strain-rate effect, fracture properties, internal material friction and damping, and effect of temperature due to dissipation of deformation energy into heating have to be taken into account. For these reasons, the accurate and robust numerical solution of the impact problems of metal foams and 3D printed structures is not a trivial task. Here, the explicit time integration in finite element analysis (FEA) is preferred due to the possibility to deal with the problems concerning the fast impact response of materials and to consider wave propagation phenomena (Belytschko et al., 2014). Although an intensive effort is concentrated on developing new methods in FEA including local and global searching algorithms, or explicit methods for time integration, commercial software packages such as LS-DYNA are suitable for modelling contact-impact problems related to OHPB testing.

In this paper, we demonstrate the possibility of numerical modelling of the OHPB impact testing. Explicit time integration in LS-DYNA FE solver and a numerical model of the experimental setup is used for virtual OHPB testing of the Alporas foam represented by two different constitutive models. We show that it is not only possible to use a relatively simple and computationally inexpensive material model to simulate the compressive response of the foam with sufficient accuracy, but that it is also possible to study the related wave propagation phenomena numerically.

2. Materials and Methods

To complement the experimental testing with numerical simulations, we have developed a numerical model of the OHPB setup in LS-DYNA. To be able to perform simulations with arbitrary geometry of the specimens, a fully three-dimensional representation was chosen and calibrated despite its increased cost over the alternative axisymmetric discretization, which is, however, limited to the cylindrical sample geometry. The FE representation of the OHPB is depicted in Figure 1.

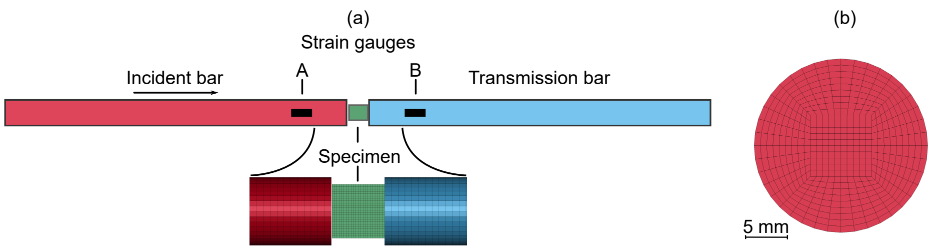

Fig. 1: Visualisation of the OHPB numerical model (a) and discretized cross-section of the bar (b).

The FE representation of the bars was selected on the basis of two parametric sensitivity studies with different OHPB components and initial conditions. In the sensitivity studies, the element size, element formulation, hourglass control algorithm, and time-step size were varied. Sensitivity analysis was treated as a multi-parametric problem and the assessed data were analysed contextually in consideration of other properties of the FEA such as numerical frequency damping, time-step sizing, and considering in this case frequency of 200 kHz as a reasonable upper frequency limit for physical oscillations in the aluminium bars. Taking the computational costs into account, the best performing set of parameters was achieved for the constant stress single point hexahedral solid element formulation (ELFORM1) with the element edge length of 5 mm in the direction of the OHPB longitudinal axis.

The specimen was modelled in the FEA as a solid block with the same ELFORM1 discretization using constant stress solid elements. This formulation was selected for the specimens as it is computationally efficient and accurate also at large deformations when correct hourglass stabilisation measures are taken. Due to the dimensions of the sample exceeding the circumferential edge of the bars, the element size of 0.7 mm was selected to capture the influence of the outreaching parts at high deformations. For the hourglass stabilization of the virtual OHPB, the quintessential bending incompressible (QBI) hourglass control by Belytschko and Bindeman (Belytschko and Bindeman, 1993) was used. In all simulations, attention was paid to the overall energy balance including the hourglass energy, particularly at the final stages of the virtual experiments.

In the simulations, the initial condition in terms of translational velocity of the incident bar was imposed with the velocity value of $v_{\text{initial}} = 7\ \mathrm{m} \cdot \mathrm{s}^{-1}$ measured in the respective experiment. No body forces nor boundary conditions reflecting the slide bearings carrying the bars of the OHPB apparatus were considered. The geometry of the bars was assumed to be ideal, i.e., without imperfections in terms of plan-parallelism or surface roughness. The mechanical results from the numerical simulations were extracted by defining virtual strain gauges at the same locations, where the measurement points were established in the OHPB experiments and the strain versus time and velocity versus time histories were acquired and used in further post-processing using the same mathematical methods utilised for the experimental evaluation.

The two-way surface-to-surface contacts were established between the solid bodies, i.e., the impactor-foam interface and the foam-transmission bar interface. Despite the cost of the surface-to-surface contact definition, where all the surfaces of the bodies are considered in the contact routines, this contact definition was selected due to the contact-interface damping performance superior to other contact definitions, particularly the node-to-surface contact. Static and sliding coefficients of friction were defined on both interfaces. Further measures applied to the contact interfaces included the definition of exponential decay coefficient, coefficient of viscous friction, and viscous damping coefficient.

The linear elastic material model (MAT1) was selected for the bars of the virtual OHPB based on the fundamental assumption that the bars have to be subjected to elastic deformation only. Here, MAT1 not only fulfils the physics of OHPB testing, but is also the most efficient formulation. The constants of the model were calibrated from the experimental void tests yielding the mass density 2.75 $\mathrm{kg} \cdot \mathrm{cm}^{-3}$ and Young's modulus of 70 GPa. The Poisson's ratio used in the simulations was 0.3. The low-density foam (MAT57) and Fu-Chang's foam (MAT83a) constitutive models were used to simulate the compressive properties of the Alporas foam.

3. Results and discussion

From the numerical simulations, the strain and velocity histories were extracted at the location of the virtual strain gauges and subjected to further analysis. Figures 2 and 3 show the comparison of experimental results and the FEA for both constitutive models of the Alporas foam.

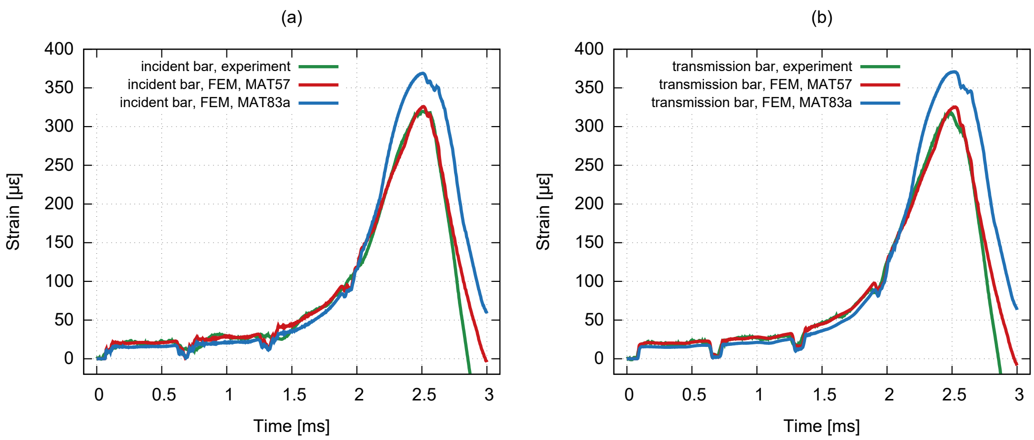

Fig. 2: Longitudinal strain in the bars at the strain-gauge locations calculated by numerical simulations using two different material models compared with the experiment: incident bar (a), transmission bar (b).

The Figure 2 depicts the strain versus time at the incident (Figure 2(a)) and transmission bar (Figure 2(b)). It can be seen that such raw data unprocessed with the wave separation procedure exhibit the effects of wave propagation notable as cyclic decreases and increases of the measured strain, which is present also in both the numerical models. Comparison of numerical models with the experiments shows that the MAT57 constitutive model captures the compressive response of the foam with high precision in all stages of the dynamic impact. In contrast, the numerical simulation based on MAT83a constitutive model underestimates the strains at both bars in the plateau region and the initial stages of densification. This is followed by a steeper slope and the resulting overestimation of the ultimate strain by approximately 10%. Consequently, this model exhibits a discrepancy in the unloading part, where the curve has the same slope as the experiment, but it is significantly shifted to higher strains. After postprocessing of the data using the

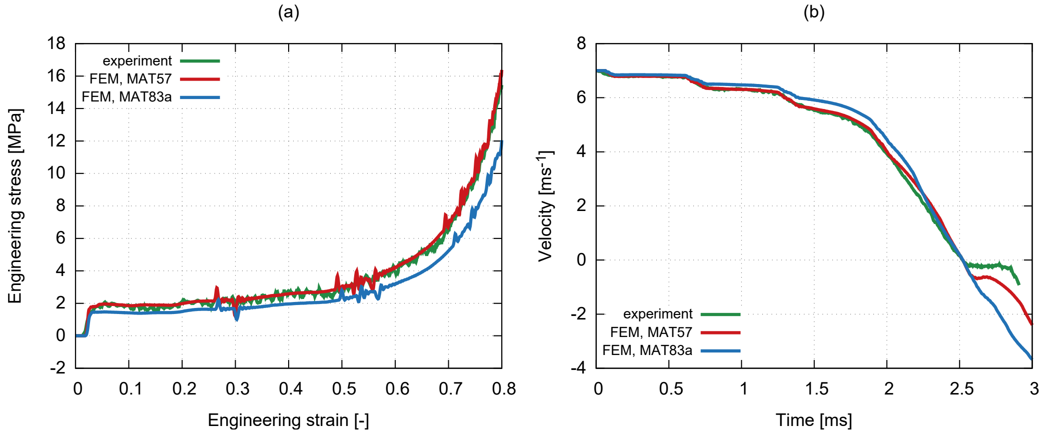

Fig. 3: Diagrams evaluated using the wave-separation method from FE longitudinal strain data and velocities compared with the experiment: stress-strain curve (a), impact velocity (b).

wave separation procedure (Fíla et al., 2021), it was possible to plot the stress versus strain curves and the velocities for comparison of experimental and numerical results as shown in Figure 3. Cyclic increases and decreases can be seen in the numerical stress-strain curves that are the artefacts produced due to oscillations in the calculated strains arising from numerical modelling of the wave propagation. Similarly to the comparison of the calculated strains, the MAT57 model captures the behaviour of the foam with very high precision and the MAT83a model underestimates the stresses in all stages of the diagram. This discrepancy is then also transferred to the velocity profile as the MAT83a model predicts lower deformation energy mitigation during compression of the foam, while the MAT57 model is nearly similar to experimental data up to the velocity of $4\ \mathrm{m} \cdot \mathrm{s}^{-1}$. Notable are the discrete decreases of the velocity caused by the wave propagation, which is also precisely captured using the MAT57 model.

4. Conclusion

Presented numerical simulations based on the numerical model of the OHPB apparatus showed that it is possible to simulate and predict the compressive response of Alporas closed-cell aluminium foam subjected to such an impact scenario with high confidence. Of the two considered constitutive models of foam, the low-density model (MAT57) showed significantly higher accuracy than the Fu-Chang's model (MAT83a) as the experimental and numerical strain histories, velocity histories, and the calculated stress-strain curve were all nearly precisely predicted by the MAT57 model up to the initial part of unloading stage. Moreover, the numerical simulations showed the ability to describe also the wave propagation phenomena encountered in the experiments. Conversely, it was possible to successfully utilise the wave separation procedure on the numerical strain histories to obtain the resulting precise stress-strain diagram of the foam.

Acknowledgements

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