Computational Simulations of Unidirectional Cellular Material UniPore Subjected to Dynamic Loading

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Abstract

The paper focuses on behaviour of a newly developed cellular UniPore structure with unidirectional pores under dynamic loading. The computational model of the cellular structure was based on realistic (reconstructed) irregular geometry of the manufactured specimens and analysed using the code LS-DYNA. The mechanical properties have been investigated by means of parametric computational simulations considering various material and geometrical parameters. Furthermore, with computational simulations also the influence of the anisotropy has been evaluated.

1 Introduction

Cellular structures have an attractive combination of mechanical properties and are increasingly being used in modern engineering applications [1]. Consequently, the research of their behaviour under quasi-static and dynamic loading is valuable for engineering applications such as those related to mechanical energy absorption through deformation [2, 3]. However, the structure of industrial cellular materials in terms of shape, size and distribution of cellular pores cannot be fully controlled with existing mass production technologies. This results in a certain scatter of mechanical and thermal characteristics of these materials and their components. Some recently developed fabrication methods of porous metals result in more homogeneous pore structures [4-7]. In search for cellular materials with even more regular distribution of pores, constant wall thickness and pore size a different and innovative manufacturing approach has been taken into account. With explosive compaction thin-walled tubes are being compressed together forming a cellular structure with straight unidirectional pores – UniPore structure. The advanced geometrical properties of the UniPore structure assure a huge opportunity for its application due to its particular and unique mechanical and thermal properties.
This research focuses on mechanical behaviour of the UniPore structure with unidirectional pores under dynamic loading. UniPore material was recently developed at Shock Wave and Condensed Matter Research Center at Kumamoto University in Japan. The prototype samples were produced by compressive blast loading. The manufacturing procedure consists of following steps (Fig. 1): (i) the outer pipe is tightly packed with thin-walled inner copper pipes of much smaller diameter, (ii) the inner pipes are filled with wax preventing their complete compaction at compressive blast loading, (iii) the structure is placed in the centre of an explosive chamber and surrounded with the explosive, (iv) the explosive charge is detonated with an electric detonator and high pressure blast loading causes compaction of the structure, where the outer and inner pipes walls are bonded by diffusion and (v) the removal of wax by heat treatment.

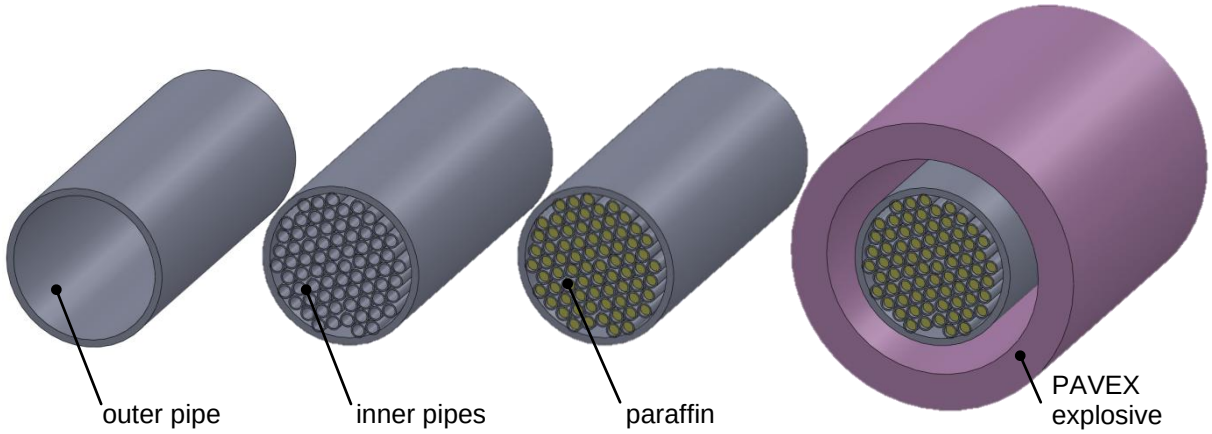
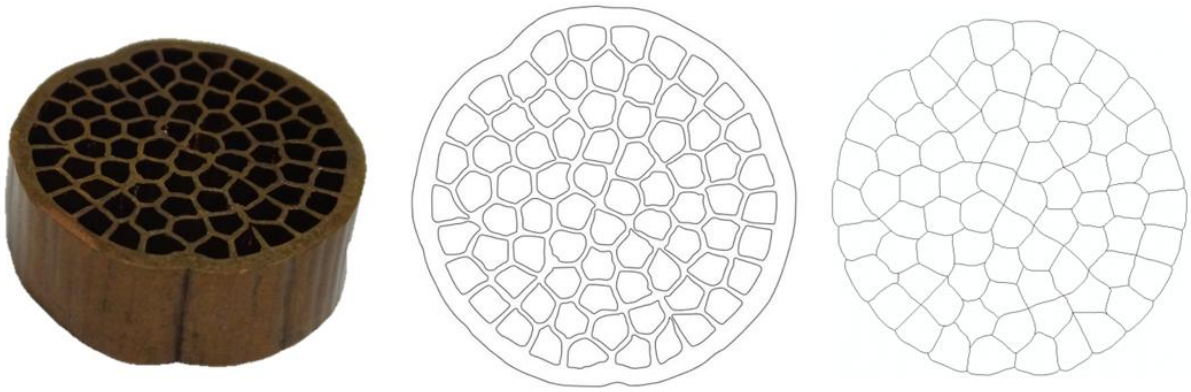


Fig. 1: Manufacture procedure of UniPore.

This manufacturing procedure results in making a porous material with perfectly parallel unidirectional pores (Fig. 2a). To avoid extensive and superfluous testing of: i) manufacturing procedure parameters and ii) various geometrical and material properties of pipes, computational simulations have been chosen to support the development of this new porous material.



a) b) c)

Fig. 2: UniPore sample and reconstruction of its structure:
a) UniPore specimen, b) CAD reconstruction, c) mid-surface representation.

2 Computational model

The specimens in this study consist of the outer pipe with reference diameter, reference thickness and length of 30 mm, 2 mm and 60 mm, respectively. The outer pipe was packed with inner pipes with the reference diameter, reference thickness and length of 3 mm, 0.2 mm and 60 mm, respectively. The outer and inner pipes were made of phosphorus deoxidized copper (Cu 99.98 % and P 0.02 %). The computational model of the cellular structure was based on realistic (reconstructed) irregular geometry of the manufactured specimens (Fig. 2b and Fig. 2c). In the subsequent computational simulations the mid-surface geometry was used. Varying the thickness of outer pipe (T) and the thickness of inner pipes (t) nine different porosities (from 74 % to 41 %) have been considered in this study. The mechanical properties of the base material (copper) are given in Table 1 [11].

Table 1: Mechanical properties of copper

Mechanical property	Copper
Density [kg/m^3]	8,940
Young's modulus [MPa]	110,000
Poisson's ratio [-]	0.35
Yield stress	180
Tangent modulus [MPa]	965
Failure strain [-]	0.2

The response of the UniPore structure accounted for inertial effects due to dynamic loading as well as the base material strain rate sensitivity [2, 12-14]. For this purpose the Cowper-Symonds constitutive model has been used [8, 15, 16]

$$\sigma = \sigma_0 \left(1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}\right), \tag{1}$$

where σ_0 represents the quasi-static response, $\dot{\varepsilon}$ the actual strain rate and $C = 1.8 \cdot 10^6$ s^{-1} and $p = 4.4$. The UniPore structure was supported at the lower part and loaded at the upper part with displacement controlled loading, as shown in Fig. 3. A single surface contact model has been accounted for. The preliminary computationally simulations have shown that due to the uniform geometry in the longitudinal direction it is possible to use only a thin slice with appropriate boundary conditions. Therefore, the period boundary conditions (allowing equal displacement for of all nodes per surface) were prescribed to the front and back surface of the model.

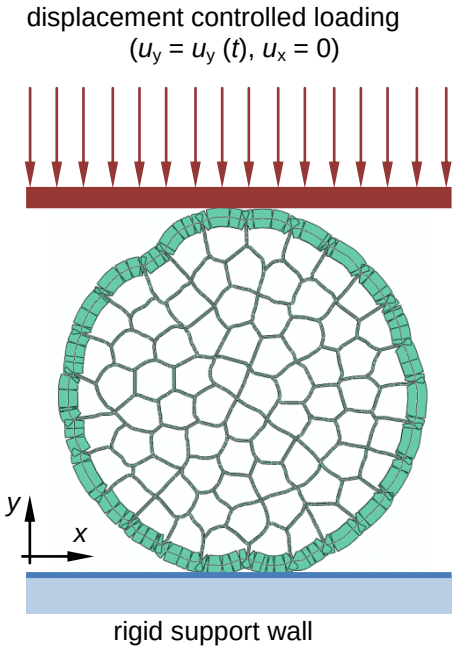


Fig. 3: Applied boundary conditions.

The UniPore structure was discretized with fully integrated quadrilateral shell elements with quadratic shape function. The computational models have been analysed using the single precision engineering explicit code LS-DYNA MPP 971s R5.1.1 (revision 65543). The initial computational simulations have been performed in order to validated and confirm the proper spatial and time discretization as well as the most efficient number of used parallel processors (speed-up test). LS-DYNA enables massively parallel processing (MPP) with the MPICH message passing library for communication between processes. In the framework of this research the NEC Nehalem cluster with 700 Dual Socket Quad Core Intel Xeon (X5560) Nehalem @ 2.8 GHz (8MB Cache), 12 GB RAM per node and theoretical peak performance of 62TFlops on Scientific Linux SL release 5.3 was used at the HLRS Stuttgart [20]. The speed-up simulations were set to determine effectiveness of the used cluster and the MPP code. The total CPU time, computational time and speed-up for different number of processors for same

computational model with different mesh densities consisting of 53,892 and 1.373,634 53,892 DOFs are shown in Fig. 4 and 5. From the results it is obvious that it is reasonable to use 32 processors (for some cases up to 64 processors) per simulation, since the speed-up drastically decreases in case of using more than 64 CPUs. Because the nature of this study was to perform a high number of simulations (to analyse several parameters), a much higher efficiently was achieved submitting several parallel simulations with lower number of CPUs. Additionally, if the simulation was submitted on the cluster with lower number of CPUs the queue time was much shorter. Therefore, the subsequent parametric analyses have been performed using 32 CPUs.

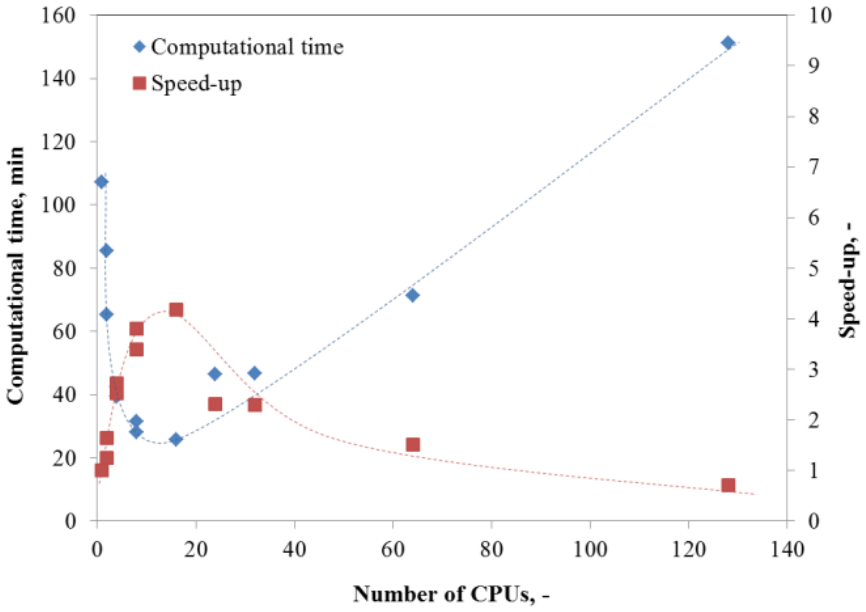


Fig. 4: Time and speed-up comparison for the HLRS Nehalem cluster: model with 53,892 DOFs.

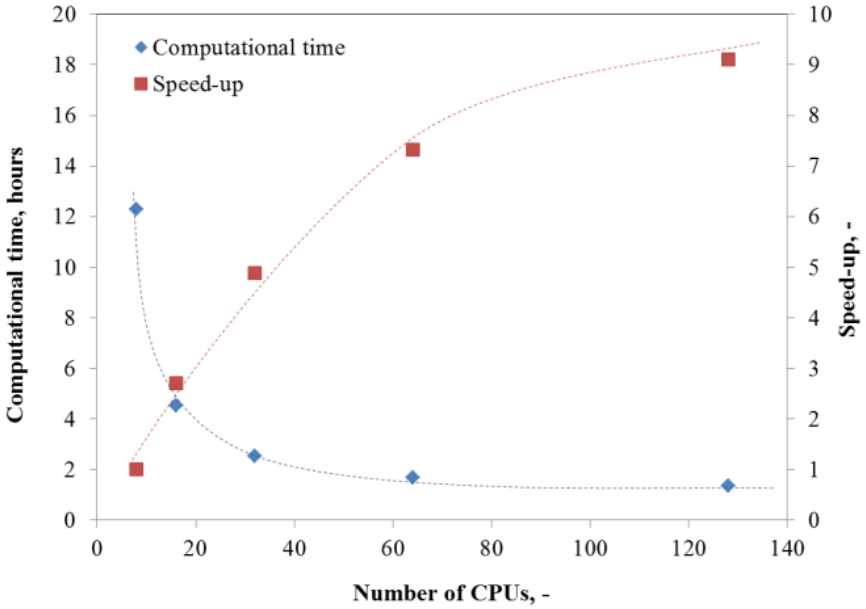


Fig. 5: Time and speed-up comparison for the HLRS Nehalem cluster: model with 1.373,634 DOFs.

3 Computational results

The compressive deformation behaviour of the UniPore structure with the porosity 57 % (outer tube thickness T = 1.5 mm and inner tube thickness t = 0.4 mm) is show in Fig. 6.

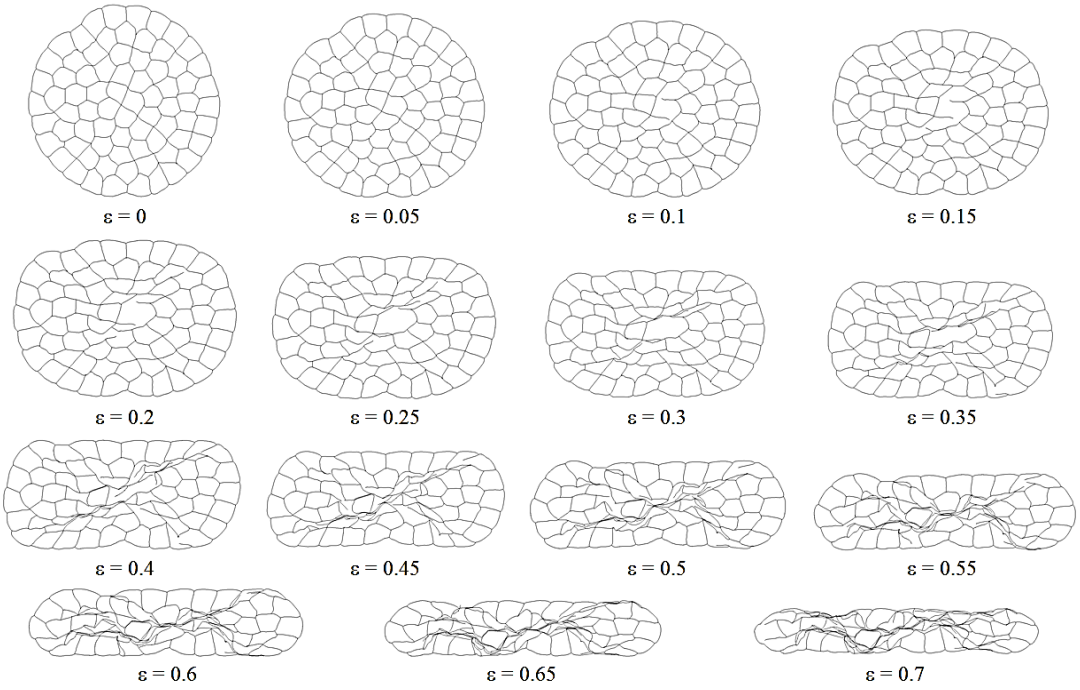


Fig. 6: Deformation mechanism of the UniPore structure.

The simulations also shown that the UniPore structures exhibit characteristic cellular material behaviour, i.e. after the initial elastic response onset of yielding which is then manifested in typical stress plateau followed by the final densification (Fig. 7). From the figure it can be observed that using thinner inner pipes results in more smooth and uniform behaviour in comparison to thicker inner pipes. This can be attributed to the failure mechanics of the base material and consequently to the failure of the cellular structure.

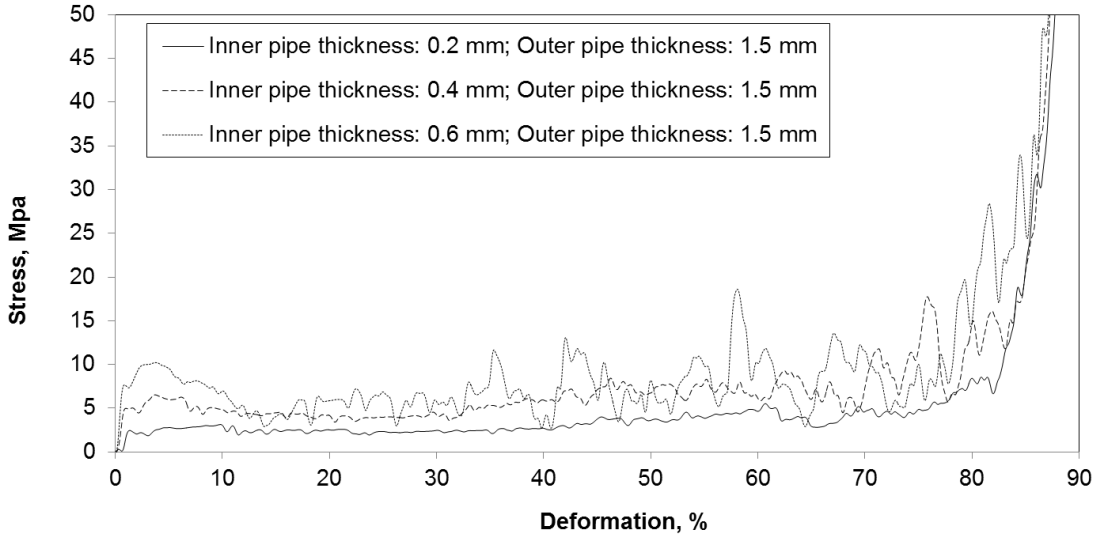


Fig. 7: Influence of the inner pipe thickness on the compressive behaviour of UniPore structure at strain rate of 100 s^{-1}.

In this study also the anisotropy of the UniPore structure was analysed by using six different loading directions (changing by an angle of $\Delta\varphi$ = 30°). The behaviour of the UniPore structure (outer tube thickness T = 1.5 mm and inner tube thickness t = 0.4 mm) subjected to different loading direction is shown in Fig. 8.

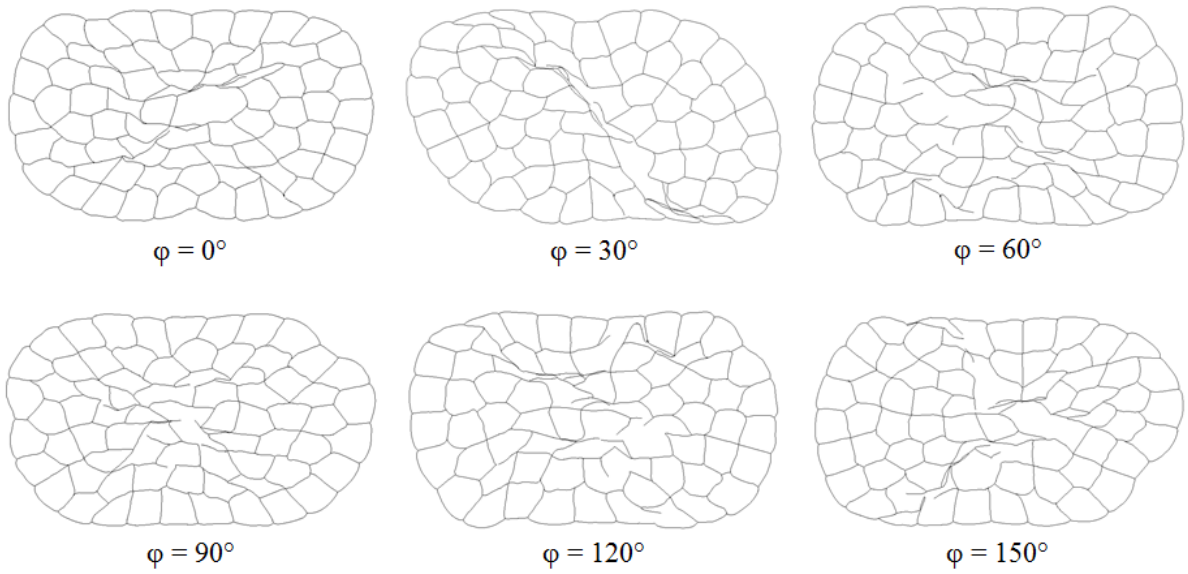


Fig. 8: Influence of the loading direction on the deformation mechanism of the UniPore structure at the strain ε = 0.3.

Although it can be observed (from Fig. 8) that the loading direction influences the deformation behaviour of UniPore structure it does not significantly influence their mechanical properties (i.e. plateau stress and energy absorption), which is shown in Fig. 9. Accordingly, it can be concluded that the UniPore structure is an orthotropic material.

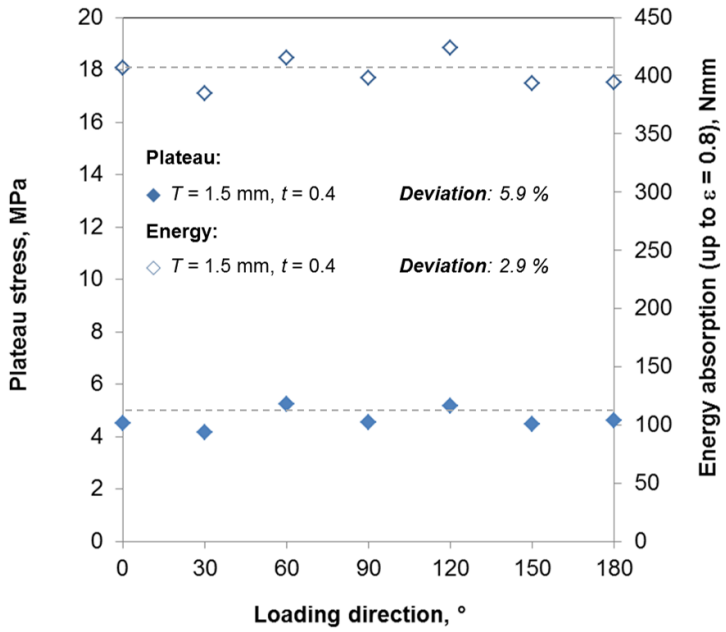


Fig. 9: Influence of the loading direction on the plateau stress and energy absorption.

4 Conclusions

Computational simulations of UniPore structures have provided efficient representation of the behaviour of these materials when subjected to dynamic mechanical loading conditions. The access to the high performance clusters allowed an extensive analysis of parametrical models, where the variations of the UniPore base material, porosity, pore size, wall thickness and loading direction were considered and evaluated. Using the reconstructed models accounted for realistic geometry a very wide spectrum of mechanical properties was found. Although, additional research on mechanical properties of UniPore structures is needed, especially experimental testing.

Acknowledgement

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