Computational Simulations of Regular Open-Cell Cellular Structures with Fillers

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Abstract:

Cellular structures are often used as crash absorbers due to their high capability of impact energy absorption. During the impact the intercellular walls buckle and cells collapse which results in impact energy absorption through deformation. Cell fillers might be used to additionally increase the impact energy absorption capability. The filler is pushed out of the open-cell cellular structure during the compression and thus dissipates additional energy.

The paper presents results of parametric computational simulations of impact behaviour of cellular structures with open-cell morphology accounting for fluid fillers. A regular cellular structure has been modelled with the finite element method, while the fluid filler flow was modelled with the meshless method Smoothed particle hydrodynamics (SPH). Fully coupled fluid-structure interaction between the cellular structure base material and the fluid filler was considered. The cellular structure has been subjected to uniaxial compressive impact loading. The computational model has been analyzed with the explicit code LS-DYNA. Additional simulations have been performed also with the ANSYS CFX code in order to validate the SPH fluid models.

The computational results have shown that the fluid fillers in cellular structures can significantly influence the capability of impact energy absorption. It was observed that the filler influences are more pronounced in cellular structure with higher relative density than in cellular structures with lower relative density. With further computational simulations it was also determined that the increase of the filler viscosity results in increase of cellular structure stiffness which contributes to higher capability of deformational energy absorption.

Keywords:

Cellular structures, Open cells, Fluid fillers, Computational simulations, Finite element method, Smoothed particle hydrodynamics, LS-DYNA.

1 Introduction

Cellular structures have an attractive combination of physical and mechanical properties and are being increasingly used in modern engineering applications. Research of their behaviour under quasi-static and high strain rates is valuable for engineering applications such as those related to impact and energy absorption. Pore fillers might be introduced in this respect to increase the cellular structure global stiffness and thus also increase the capability of cellular structures crash energy absorption.

The presented computational models of open-cell cellular structures describe a dynamic, coupled problem, considering the interaction between the structure (cellular structure) and the fluid (filler) under large deformations. The base material properties have been determined with experimental measurements of specimens under quasi-static and dynamic uniaxial loading conditions. The analysis of the liquid filler inside the pores of the open-cell cellular structures has been performed with the combination of the finite element method and the meshless method Smoothed particle hydrodynamics using the LS-DYNA code. Additional validating simulations of filler flow through the cellular structure were performed by using the ANSYS CFX. The cellular structure models accounting for fluid fillers have been used to evaluate and simulate the influence of the cellular structure size, relative density, filler viscosity and its flow through the cellular structure. Consequently, the influence of these parameters on the macroscopic cellular structure behaviour has been determined.

2 Cellular materials

Cellular materials have a wide range of different arrangements and forms (Figure 1) with three typical structures: honeycomb, open-cell structures and closed-cell structures [1]. One of the most important parameters of cellular materials is their specific density (the macroscopic density, divided by the density of the base material). The advantages of cellular materials are low density (light-weight structures), high acoustic isolation and damping, high grade of deformation, high energy absorption, recyclability etc. The cellular metals (usually referred to as metallic foams) have some further advantages, like higher strength and heat permeability [2]. Usually they are made of aluminium alloys or polymer materials, with regular or random cell arrangement. Metallic foams have the potential for application in automotive, rail, naval and aerospace industry as heat exchangers, filters, bearings, acoustic dampers, bio-medical implants and elements for energy absorption.

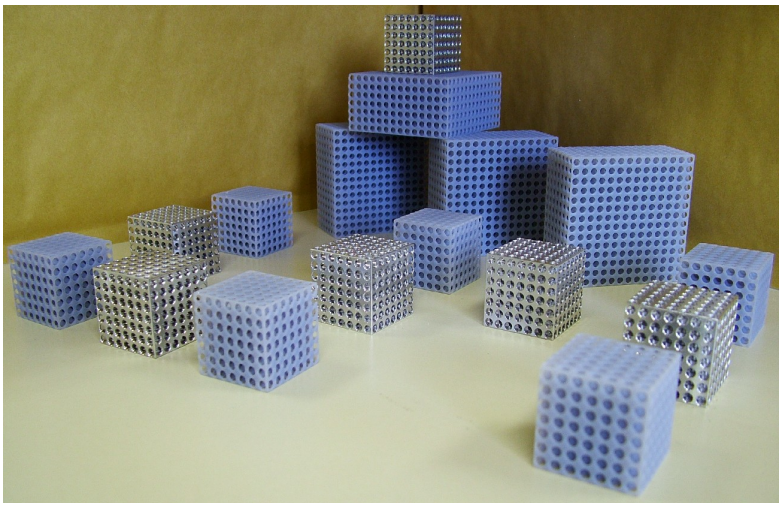


Figure 1. Regular open-cell cellular structures

Cellular materials have a characteristic stress-strain relationship in compression, which can be divided into four main areas as shown in Figure 2. After initial linear elastic response the cellular materials first experience buckling, plastic deformation and collapse of intercellular walls in the transition zone. Under further loading the mechanisms of buckling and collapse become even more pronounced, which is manifested in large strains at almost constant stress (stress plateau) until the cells completely collapse (densification). At this point the cellular material stiffness increases and consequently converges towards the stiffness of the base material.

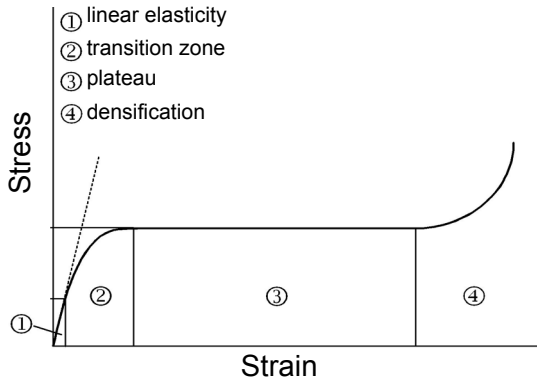


Figure 2. Characteristic stress-strain behaviour of cellular materials under compressive loading

The cellular material is able to absorb significant amount of energy through its deformation during the loading process. The absorbed energy is a sum of energy accumulated during elastic deformation and energy absorbed by the plastic deformation. The latter is very important for crash energy absorption and is more pronounced for metal foams than for polymers. It is worth noting that the energy absorption is also strain-rate dependent. The higher the strain-rate, the higher is the capability of energy absorption through deformation.

A logical solution to increase the energy absorption in open-cell cellular materials is by filling the cellular structure with viscous fluid. Such fluid offers certain level of flow resistance during collapse of cellular structure due to its viscosity, which in turn increases the structure stiffness during the deformation process. Preliminary investigations have shown that in combination with high strain-rate loading this result in substantial increase of energy absorption [4].

Therefore, it is reasonable to investigate the filler influence on the macroscopic behaviour of cellular metals by means of computational simulations. Parametric computational simulations of the open-cell cellular structures under impact conditions liquid fillers were performed in this respect.

3 Computational model

3.1 Base material

The behaviour of open-cell cellular structures accounting for fluid fillers has been analyzed using the finite element code LS-DYNA [6, 7]. In order to avoid enormous computational times, regular and periodic pore geometry (Figure 3) has been considered. The open-cell cellular structure with three relative densities ρ/ρ_0 = 0.37, 0.27 and 0.16 was modelled in presented computational study. This corresponds to the basic geometry dimensions of d = 3 mm and a = 4.5, 4.0 and 3.5 mm.

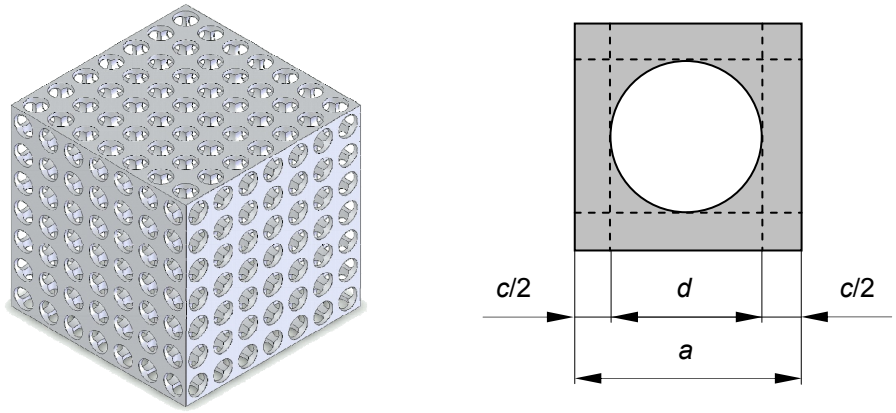


Figure 3: Geometry of the open-cell cellular structure

A polymer was used as the base material of cellular structure with different mechanical properties for the tensile and compressive loading, as shown in Figure 4. The material properties of the polymer are listed Table 1. The strain rate effects were also considered by implementing the Cowper-Symonds constitutive relation [6, 7]

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

where σ' is the stress at the strain rate $\dot{\varepsilon}$ and σ is the stress at quasi-static conditions. *C* and *p* are material parameters which characterize the strain rate sensitivity of aluminum alloy [8, 9].

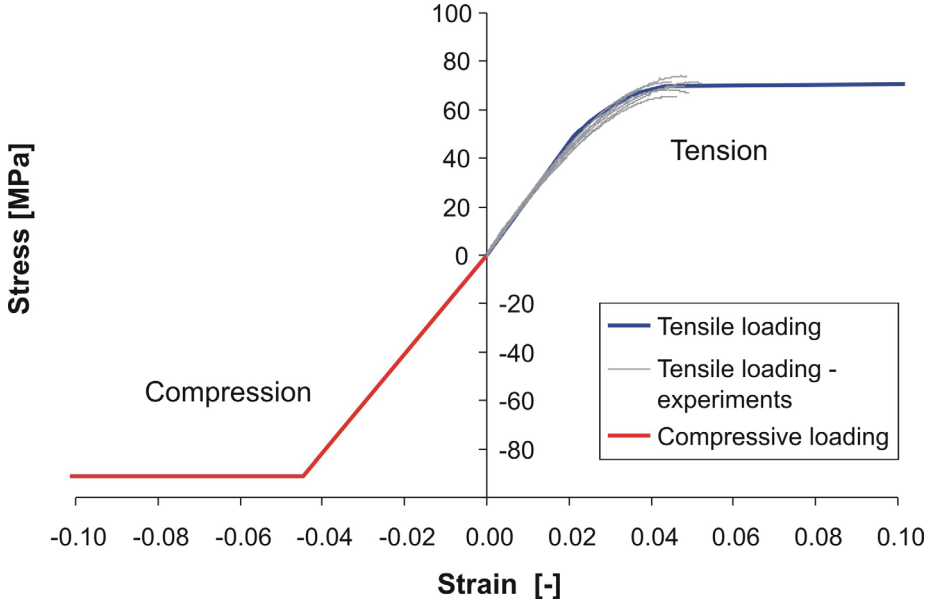


Figure 4. Mechanical properties of the base polymer material under compressive and tensile loading

Table 1. Mechanical properties of the base polymer material

	Young's modulus	Poisson's ratio	Yield stress	Cowper-Symonds *C*	Cowper-Symonds *p*
Tension	2323 MPa	0,3	48,9 MPa	1050 s^{-1}	3,5
Compression			91,0 MPa		

The cellular structure base material was discretised with 8-noded fully integrated quadratic solid elements. With additional parametric analyses the proper mesh density ($l \approx 0.1$ mm) and time step size ($\Delta t \approx 0.04$ µs) have been determined to assure adequate precision of computational results [10]. The cellular structure was loaded with displacement controlled compressive load at a strain rate of 1000 s^{-1}. Symmetry boundary conditions have been applied due to regular geometry of the cellular structure [11, 12].

3.2 Fluid filler

The fluid filler was modelled with the Smoothed particle hydrodynamics method (SPH), where the analysed system state is represented by a set of particles (Figure 11). The particles possess individual material properties and move according to the governing conservation equations. The SPH method is a meshfree, Lagrangian, particle method [13].

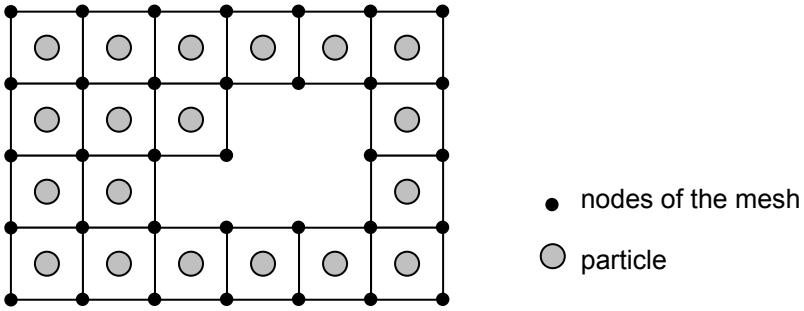


Figure 5: Domain discretisation with finite element mesh and mesh-free particles

The most significant is the adaptive nature of the SPH method, which is achieved at the very early stage of the field variable (i.e. density, velocity, energy) approximation that is performed at each time step based on a current local set of arbitrarily distributed particles. Because of the adaptive nature of the SPH approximation, the formulation of the SPH is not affected by the arbitrariness of the particle distribution. Therefore, it can handle problems with extremely large deformations without any difficulties. Another advantage of the SPH method is the combination of the Lagrangian formulation and particle approximation. Compared with Eulerian description, it is more effective, since only the material regions of interest need to be modelled, and not all the regions where material might exist. However, the SPH technology is relatively new compared to standard mesh-based Lagrangian and Eulerian descriptions, with remaining known problems in the areas of the stability, consistency and conservation [13, 14].

The relationship between the change of volume and pressure in this study has been represented with the Mie-Grüneisen equation of state [6, 7] as water (ρ = 1000 kg/m^3 at 293 K) was used for the cellular structure filler. An optimal distance between the SPH particles ($l \approx 0.112$ mm) and mass of single particles ($m_i \approx 1.42$ µg) has been determined with separate parametric simulations. The outflow of the liquid filler was validated and verified with the computational fluid dynamics code ANSYS CFX. Additional simulations have proven that the surrounding medium (water or air) has very little influence on the macroscopic behaviour of the cellular structure and can thus be neglected. Furthermore, it was established that under compressive load approximately 96 % of the filler mass flow is in the horizontal direction of the open-cell cellular structure, as illustrated in Figure 6. Hence, only one layer of cellular structure was discretised and used in computational simulations, which essentially contributed to shorter and more reasonable computational times.

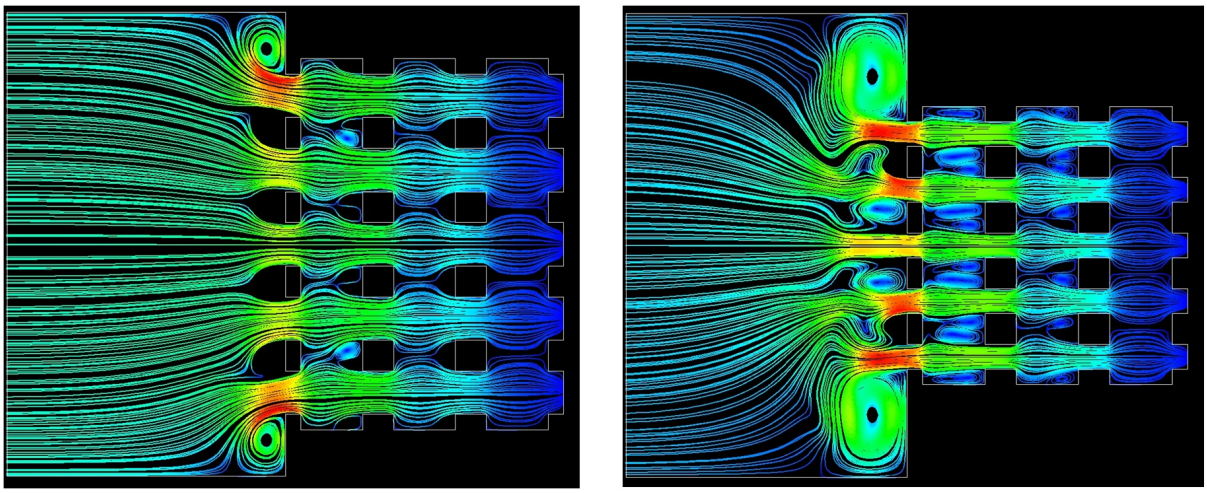
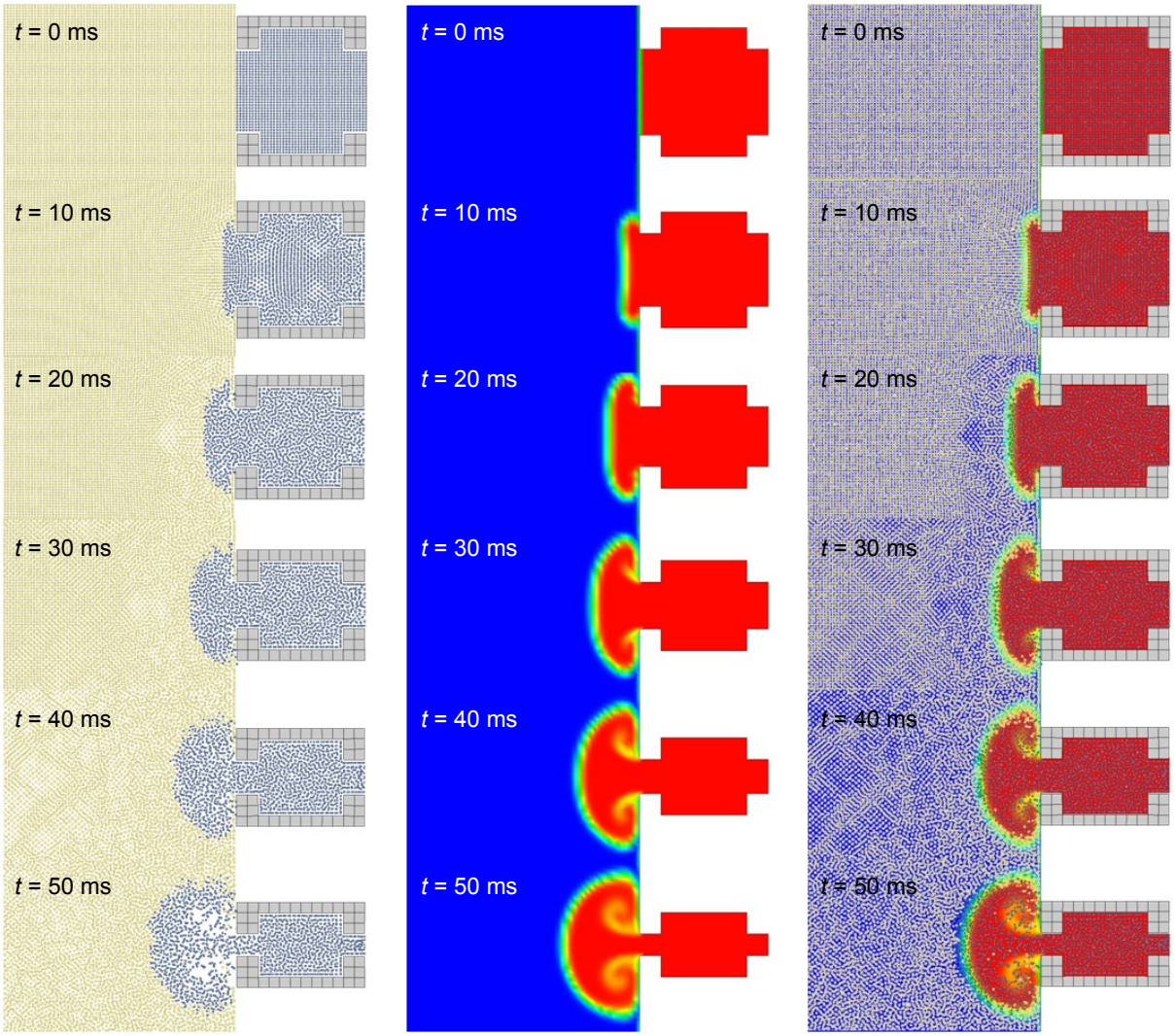


Figure 6. Streamlines of the filler during outflow

Figure 7 illustrates the comparison between the computational results obtained with the SPH model using LS-DYNA and the finite volume method using ANSY CFX.



a) b) c)

Figure 7. Filler outflow simulations: a) LS-DYNA (SPH model);
b) ANSYS CFX (finite volume method);
c) comparison between a) and b)

Very good agreement of results from both codes can be observed, which in turn validates suitability of the SPH model to accurately simulate the filler flow through the cellular material.

Described computational model has been used for several parametric simulations with aim to determine the influence of the fluid filler viscosity and its flow through the cellular structure, the size of cellular structure (number of cells) and the relative density. A single analysis run of the model with 16 cells lasted approximately 12 hours on a PC-cluster of 4 units with Intel Pentium IV 3200 MHz processors and 1 GB RAM each.

4 Computational results

Figure 12 shows the deformation of the cellular structure with liquid filler under impact loading at different time sequences.

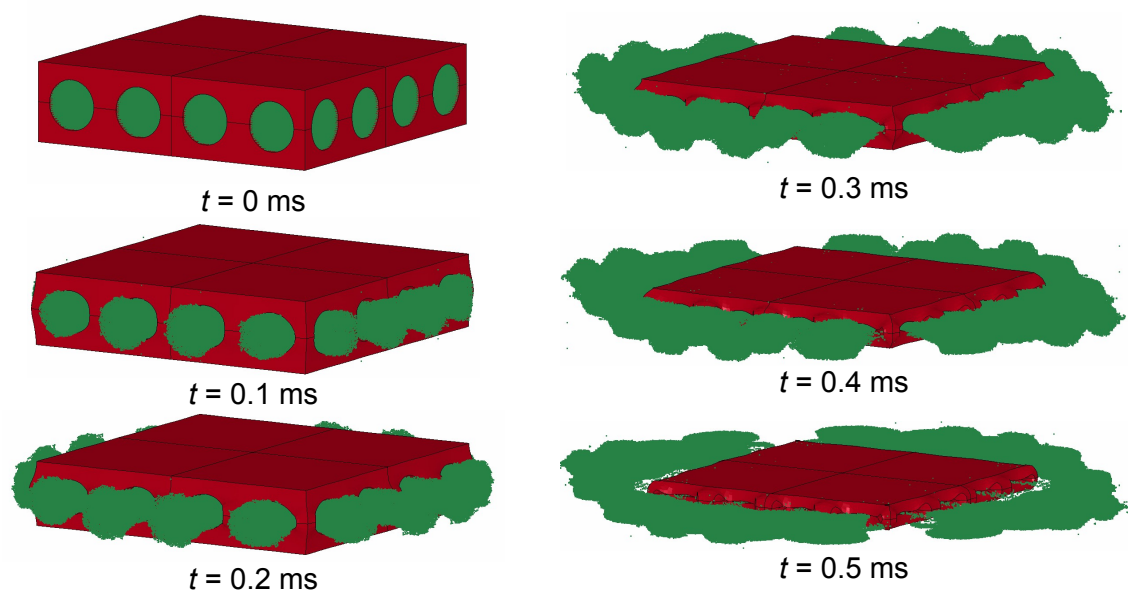


Figure 8. Deformation of the open-cell cellular structure with fluid filler under impact loading

The computational simulations have confirmed that the size of the model and the number of the cells influence the macroscopic behaviour of the cellular structure, as shown in Figure 9. Higher number of cells results in higher stiffness of the cellular structure and consequently in higher capability of energy absorption, since the filler is subjected to higher flow resistance and needs more time during its outflow.

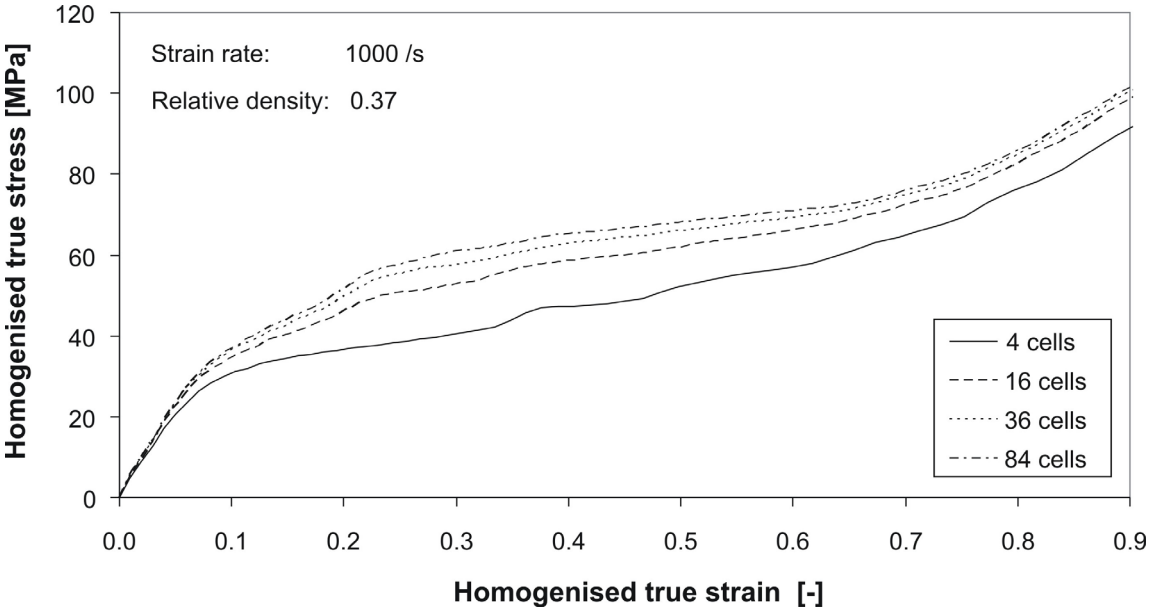


Figure 9. Influence of the cell number on cellular structure behaviour

Figure 10 illustrates the influence of the relative density and the filler. As already known from previous investigations, the stiffness increases with increasing the relative density. Computational simulations have shown that the filler influences more the behaviour of cellular structure with a higher relative density than the cellular structure with a lower relative density. The reason for this effect can be explained by smaller pore sizes in a cellular structure with high relative density, which offers higher resistance during the filler outflow, which consequently contributes to the increase of cellular structure macroscopic stiffness.

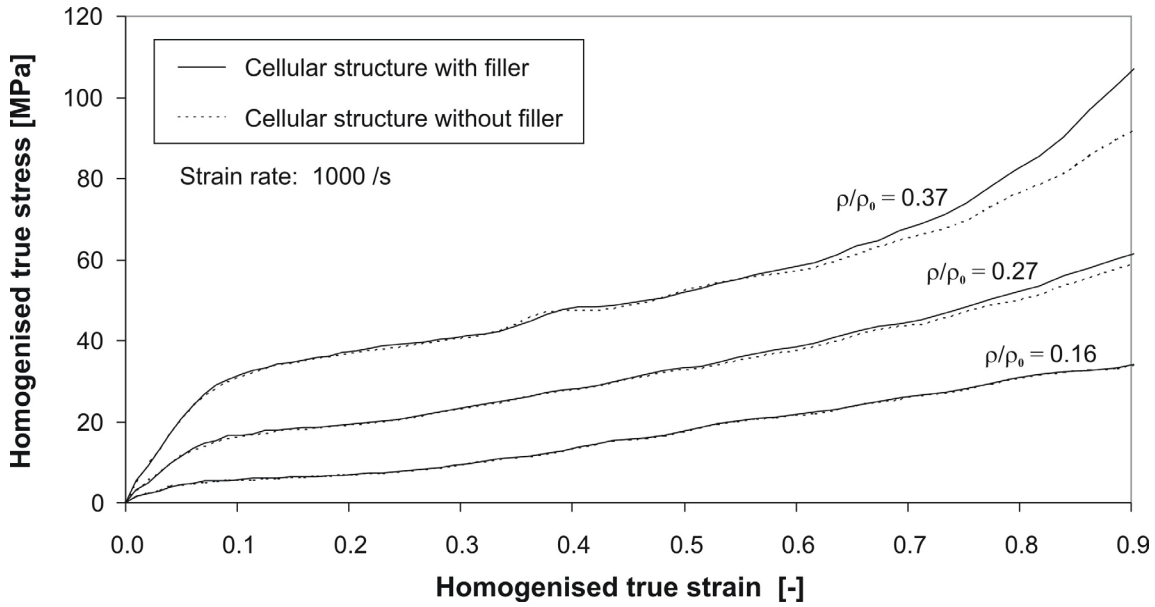


Figure 10. Influence of the pore filler

With further computational simulations it was also shown that the increase of the filler's viscosity results in increase of yield stress and Young's modulus and consequently in higher stiffness of the cellular structure.

5 Conclusion

The paper presents new computational model of open-cell cellular structure with fluid fillers for simulation of their behaviour under impact loading conditions by means of fully coupled dynamic interaction between the structure (cellular structure) and the fluid (filler). The fluid flow due to the cellular structure deformation is described with the Smoothed particle hydrodynamics method (SPH). Fluid filler motion simulated with the SPH method in LS-DYNA corresponds well to the results of similar simulations performed with specialised computational fluid dynamics code ANSYS CFX. Additional simulations have shown that the fluid medium which surrounds the cellular structure and the mass flow in the loading direction are negligible [10].

The computational results have shown that the size of the specimen influences its behaviour. The larger the specimen, the higher is its relative stiffness. When accounting for the filler in large specimens, the filler needs more time to flow through the cellular structure, which consequently results in increase of the cellular structure stiffness and higher impact energy absorption. Computational simulations have shown that the filler influences more the behaviour of cellular structure with a higher relative density than the cellular structure with a lower relative density. The reason for this effect can be explained by smaller pore sizes in a cellular structure with high relative density, which offers higher resistance during the filler outflow, which consequently contributes to the increase of cellular structure macroscopic stiffness. It was also shown that the increase of the filler viscosity results in higher stiffness of the cellular structure and higher capability of deformational energy absorption.

Future research work will be focused on experimental testing and detailed study of cellular structure subjected to multi-axial impact loading conditions.

6 Reference

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