Advanced Simulations of Cellular Structures with LS-DYNA

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ABSTRACT

Cellular structures have an attractive combination of physical and mechanical properties and are being increasingly used in modern engineering applications. In this study the influence of different parameters (type of base material, type of pore filler, relative density, size of the cellular structure, strain rate) on behaviour of open- and closed-cell cellular structures under impact loading was investigated by means of computational simulations using the explicit finite element code LS-DYNA. The influence of gas filler inside the closed-cell cellular structure was analysed using the representative volume element and the airbag model. The analysis of the fluid filler behaviour inside the open-cell cellular structures was done with combination of the Finite element method and the Smoothed particle hydrodynamics meshless method. The base material properties and macroscopic behaviour of cellular structures with and without fillers were determined with experimental measurements of appropriate specimens under quasi-static and dynamic uniaxial loading conditions. Computational simulations show that the base material has the highest influence on behaviour of cellular structures under impact conditions. The increase of relative density and strain rate results in increase of the cellular structure stiffness. Parametric computational simulations have also confirmed that the filler influences macroscopic behaviour of the cellular structures, which depends on the loading type and the size of cellular structure. In open-cell cellular structures with higher filler viscosity and higher relative density, increased impact energy absorption is observed.

KEYWORDS
Cellular structures, Coupled simulation, FEM, SPH, LS-DYNA.

INTRODUCTION

A cellular structure (Figure 1) is made of an interconnected network of solid struts or plates which form the cell's edges and faces. The most important parameters of the cellular structures are the base material, morphology (open or closed cell), the geometry and topology (regular or irregular structure), relative density (ρ/ρ_s - cellular material density divided by the base material density) and possible filler type. To achieve adequate properties of the cellular material, the base material has to be carefully chosen in regard to its mechanical (strength, stiffness) and thermal properties (thermal conductivity).

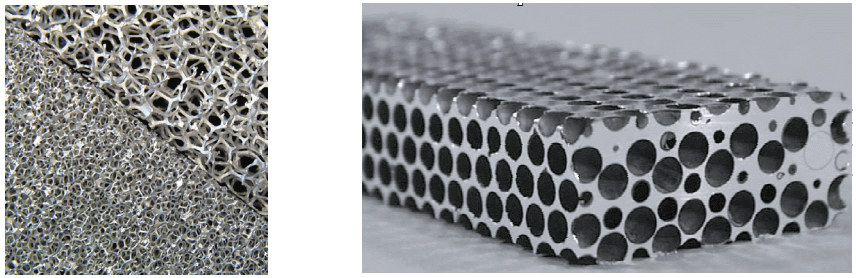

Figure 1: Open-cell (DUOCEL® - left) and closed-cell cellular metals (Körner et al. - right)

The advantages of cellular materials are low density (light-weight structures), high acoustic isolation and damping, hydrophobic (low water absorption), relatively high grade of deformation, relatively high energy absorption, durability at dynamic loadings and fatigue, recyclability [1]. Their micro- and macroscopic properties make them very attractive for use in automotive, rail, naval and aerospace industry as heat exchangers, filters, bearings, acoustic dampers, bio-medical implants and elements for energy absorption. One of the most important areas for the future application of cellular materials is in the automotive industry, where their excellent impact energy absorption through deformation is of crucial importance for increasing passive safety of vehicles [1, 2].

Cellular materials have a characteristic stress-strain relationship in compression, which can be divided into four main areas (Figure 2). After initial quasi-linear elastic response, the cellular materials first experience buckling, plastic deformation and collapse of intercellular walls in the transition zone. Under further loading the mechanism of buckling, and collapse becomes 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. During this process the cellular material is able to accumulate the mechanical energy through its deformation.

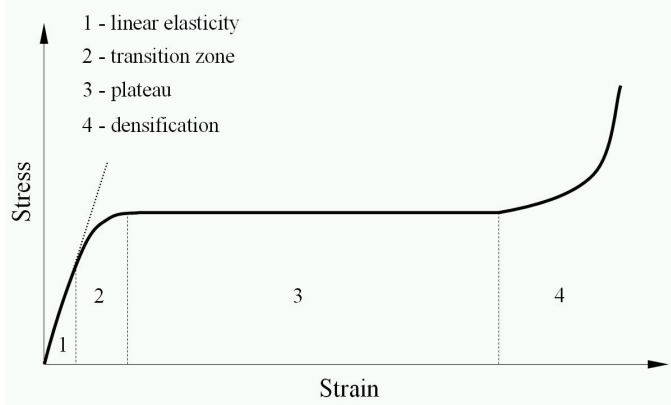

Figure 2: Characteristic stress-strain behaviour of cellular materials at compression

This paper investigates the influence of different parameters on the behaviour of open- and closed-cell cellular structures under impact loading by means of computational simulations using the explicit finite element code LS-DYNA [3, 4].

COMPUTATIONAL MODELLING OF CLOSED-CELL CELLULAR STRUCTURES

Detailed modelling of cellular material structure is usually not possible due to insufficient computer capabilities. The cellular materials are therefore usually modelled by considering a ″representative volume element″, which serves for detailed studies of their mechanical behaviour. A regular closed-cell cellular structure was used in this study (Figure 3) to reduce the computational times. The used representative volume element (Figure 4) was cube-shaped with the edge length of 1,8 mm and a spherical pore with radius of 0,75 mm. This corresponds to a relative density of 70 %. Aluminium alloy AlCuMg1 was used as the base material [5, 6]. The strain rate effects were considered by implementing the Cowper-Symonds constitutive relation [3, 4, 6, 7, 8]. The base material was meshed with fully integrated 8-noded brick elements.

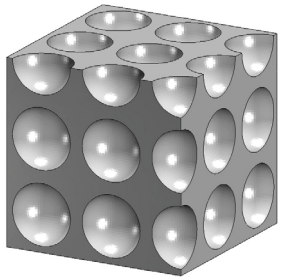

Figure. 3: Regular cellular structure

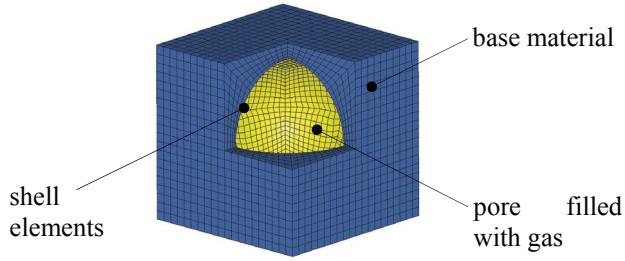

Figure 4: Representative volume element

The change of pressure, volume and temperature of the gas inside the pore was computed using a special airbag definition subroutine in the LS-DYNA [4, 6, 7]. It was presumed that the gas inside the cell has ideal properties (pV/T = const). The surface of the pore was meshed with shell elements (Null Shell [4, 5]). The structure deformation (change of the pore volume) results in change of gas temperature and internal pore pressure which acts on the structure. The initial pore (gas) pressure was defined with a load curve pressure vs. time. Different initial pressures (0,5, 5, 50 and 100 MPa) were used.

The load was displacement controlled and applied to the upper surface of the cell to reach a strain rate of 100 s^{-1} (common for impacts). Two cases were studied: compressive and tensile loading. The lower surface was fixed in the vertical direction. Special periodic boundary conditions were prescribed at model side surfaces, where all nodes on a surface have the same displacement in the normal direction to the surface [6]. The pore surface elements were defined as one contact group, thus effectively accounting for multiple self-contacting regimes at very large deformations during computational analyses. The static and dynamic friction between all parts was set to 0,1 and 0,05, respectively.

In the first millisecond of the analysis only the pressure was build up in the pores and only then the structure was exposed to displacement controlled mechanical load. The time step for explicit transient dynamic analysis was automatically set by LS-DYNA to 0,1 μs with regard to the lowest resonant frequency of the structure. The analysis time interval was set to 10 ms, with results output required every 0,001 ms

Figures 5 and 6 illustrate the difference between cell deformation at higher and lower initial pore pressure. As expected, the pore compresses more in case of lower initial

pore pressure than in case of higher pore pressure. High pore pressure also results in higher base material deformation (Figures 5 and 6).

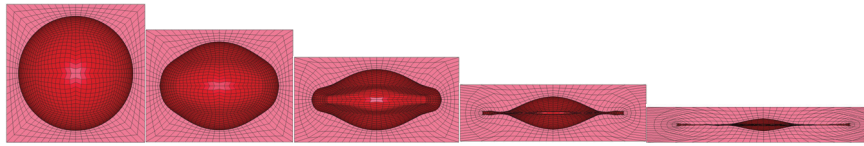

Figure 5: Cell deformation at compressive loading with initial pore pressure 0,5 MPa

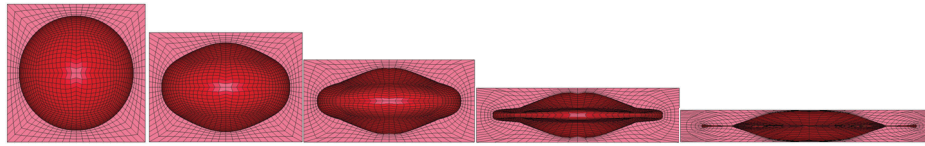

Figure 6: Cell deformation at compressive loading with initial pore pressure 100 MPa

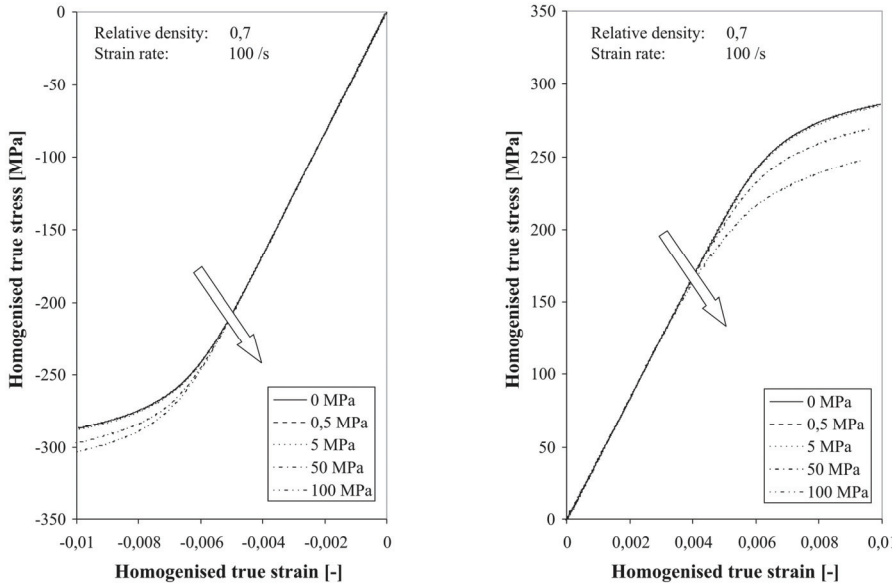

Figure 7: Influence of the pore pressure at compressive (left) and tensile loading (right)

Figure 7 illustrates the simulated behaviour of the closed-cell cellular structure under compressive and tensile impact loading with different initial pore pressures at a strain

rate of 100 s^{-1}. Under compressive loading the pore volume decreases and consequently the internal pore pressure increases. This mechanism leads to increase of the homogenized yield stress (e.g. increase of 10,6 % for considered example), since the pressure inside the pore acts in the opposite direction than the external loading. With higher pore pressure the cellular structure exhibits higher stress levels during the plastic deformation and thus absorbs more impact energy. Furthermore, higher pore pressure contributes to delayed and slower densification of the cellular structure, which occurs at a higher strain. During tensile loading the higher pore pressure lowers the homogenised yield stress (e.g. decrease of 18,7 % for considered example). With higher pore pressure the cellular structure exhibits lower stress levels during the plastic deformation and thus absorbs less impact energy. A higher effect of the internal pore pressure was observed at lower relative densities.

COMPUTATIONAL MODELLING OF OPEN-CELL CELLULAR STRUCTURES

The influence of viscous pore fillers on behaviour of open-cell cellular structures subjected to impact loading was also studied with dynamic computational simulations. Three different relative densities of the open-cell cellular structure have been considered: 0.37, 0.27 and 0.16 with the basic geometry shown in Figure 8 (d = 3 mm and a = 4,5 mm). The FullCure 720 polymer was used as the base material with the following mechanical properties: E = 2323 MPa, ν = 0.3, R_e = 48,9 MPa (tension), R_e = 91 MPa (compression), C = 1050 s^{-1} and p = 3.5 (Cowper-Symonds model).

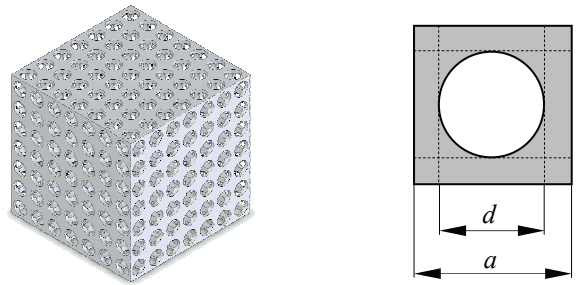

Figure. 8: Geometry of the open-cell cellular structure

The viscous pore filler (ρ = 1000 kg/m^3 and $\eta = 10^{-3}$ Pa·s at 293 K) was modelled and discretised with the meshless Smoothed particle hydrodynamics method (SPH) [3, 6, 9]. The relationship between the change of volume and pressure has been represented with the Mie-Grüneisen equation of state [3, 4, 6]. The outflow of the liquid filler was validated with the computational fluid dynamics code CFX. Furthermore, it was established that approximately 96 % of the filler mass flow occurs in the horizontal direction at compressively loaded open-cell cellular structure. Hence, cellular structure models with only one layer were used in further simulations, which essentially contributed to shorter and more reasonable computational times.

The cellular structure was loaded with a displacement controlled compressive load on the upper surface achieving the strain rate of 1000 s^{-1}. Due to regular geometry of cellular structure, the symmetry boundary conditions have been applied. The cellular structure surface elements were defined as one contact group to account for possible self-contact at very large deformations.

Figure 9 shows the outflow of the filler as a consequence of the cellular structure deformation.

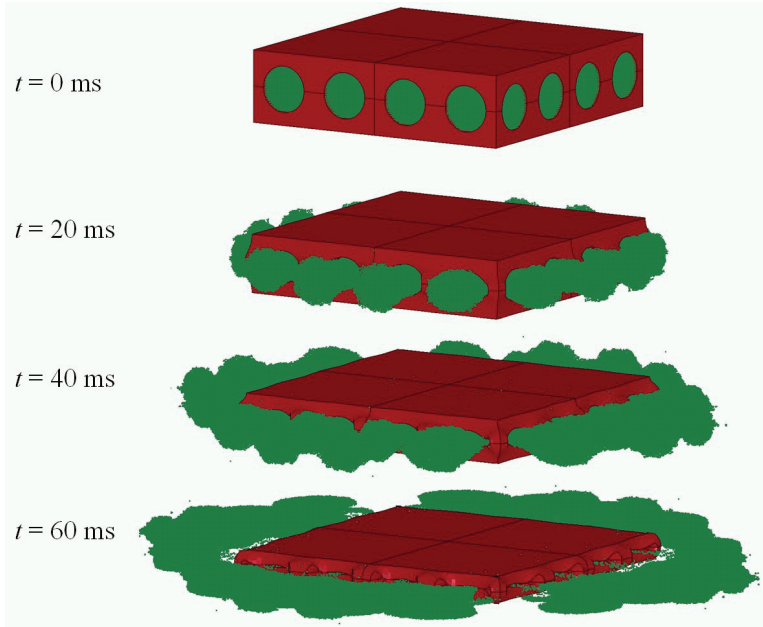

Figure9: Deformation of the cellular structure and the fluid filler outflow

Figure 10 illustrates the influence of relative density and the filler. As predicted, the stiffness increases with increasing the relative density. It can also be observed that the filler influences more the behaviour of a cellular structure with a higher relative density than a cellular structure with a lower relative density. The reason for this effect can be found in the pore sizes of the cellular structures. In the case of cellular structure with high relative density the pore sizes are smaller than in the case of cellular structure with lower relative density. Hence, the filler is subjected to higher resistance during the outflow in the open-cell cellular structure with a higher relative density, which consequently contributes to the increase of cellular structure macroscopic stiffness.

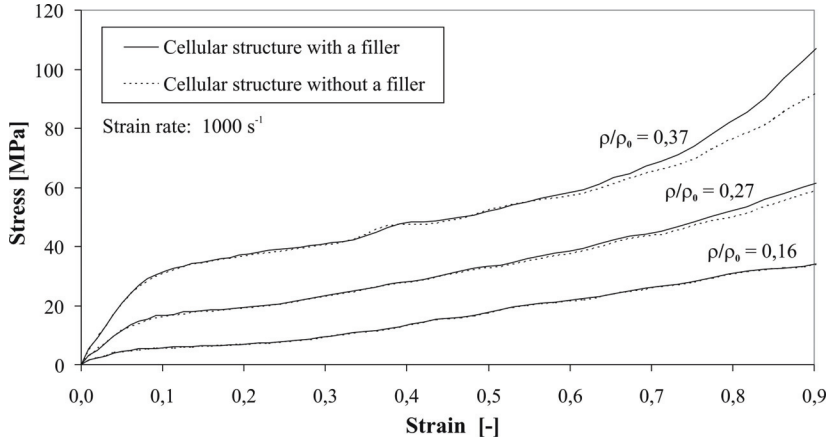

Figure 10. The influence of filler and relative density on cellular structure behaviour

Figure 11 illustrates the influence of relative density and cellular structure size on relative Young's modulus. From the figure it can be observed that the Young's modulus increases with increase of cellular structure size and relative density.

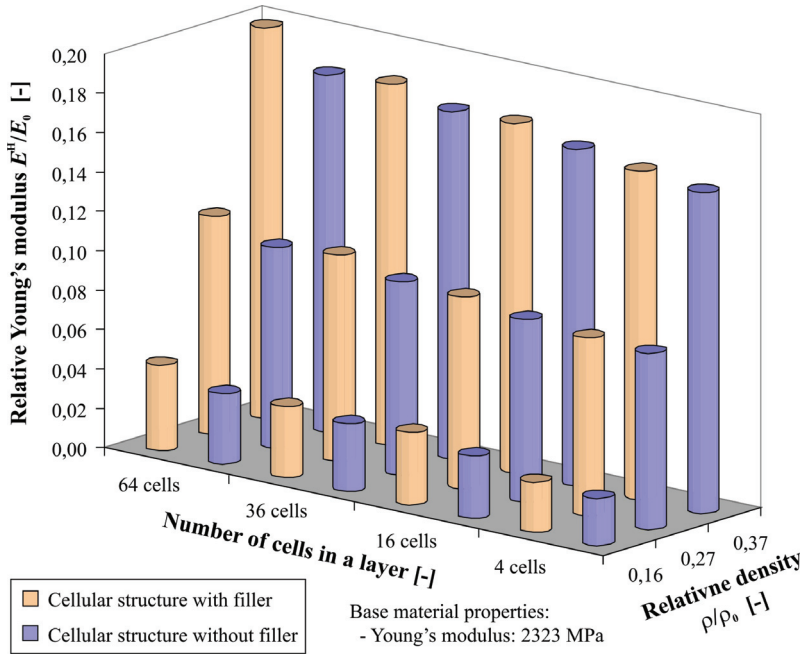

Figure 11: The influence of relative density and cellular structure size on relative Young's modulus

CONCLUSIONS

The paper presents computational simulations of closed- and open-cell cellular structures behaviour when subjected to impact loading and very large deformations, accounting for the influence of fluid filler inside the cellular structure's pores.

The results of the closed-cell cellular structure simulations show that the gas inside the pores influences the macroscopic behaviour of the cellular structure. The gas influence is more pronounced at lower relative densities of the cellular structure. The pore gas pressure influence changes regarding the loading type, i.e. has positive effects under compressive loading and negative under tensile loading. Computational results of the open-cell cellular structure have shown that the filler influence increases with increasing the relative density, the size of the cellular structure and the number of cells.

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

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