Influence of micro- and meso-topological properties on the crash-worthiness of aluminium foams

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1 Abstract

Metallic foams can be compacted at a relatively constant stress level which qualifies them for energy absorption applications. Their mechanical behaviour is influenced by imperfections caused by the foaming process. Spatial variations in the cell size distribution and imperfect cell wall geometries are studied as examples for such imperfections. Using 2D finite element unit cell models the interaction of different model topologies and cell wall deformations is examined. The topologies include hexagonal cell arrangements, big cells surrounding clusters of small cells and "rings" of small cells surrounding big cells. Imperfections on the cell wall level comprise sinusoidal wiggles and curved cell walls.
By simulation of large strain compressive deformations the interaction of non-uniform cell size and cell wall imperfections is examined, and their mutual influence on the crash-worthiness of the cellular structure is assessed. From such simulations conclusions can be drawn with respect to production strategies in order to fulfil quality requirements for metallic foams used in energy absorbing elements.

2 Introduction

The advantageous properties of cellular materials in applications such as packaging, protective padding or as a core in lightweight structural sandwich panel have motivated many studies on the mechanical behaviour of metallic foams. Guo and Gibson [2] have examined the effects of imperfections on strength, stiffness, elastic buckling and post yielding behaviour of large regular honeycomb models before and after the removal of single or whole clusters of cells. Silva and Gibson [3] studied strength and stiffness of both periodic and non-periodic (Voronoi type) two-dimensional cellular solids along with the effects of removing cell walls on the properties of the cellular structures. They found the uniaxial collapse stress of non-periodic honeycombs to be 30-35 % lower than the one of comparable periodic honeycombs, which agrees very well with one of the results of this study. Imperfections of the cell wall were also considered: Simone performed unit cell analysis of honeycombs with curved and corrugated cell walls in [4]. Grenestedt [1] has produced bounds on the elastic stiffness of cellular solids with wavy imperfections.
In this study both kinds of imperfections and their interaction are accounted for. The cell wall imperfections under consideration (sinusoidal wiggles and parabolic curvature of the cell walls) are combined with variations and perturbations of the underlying micro-topology to gain insight in the mutual influence of these two kinds of imperfections. Both the uniaxial and biaxial behaviour is considered in the linear and the post-collapse regime.

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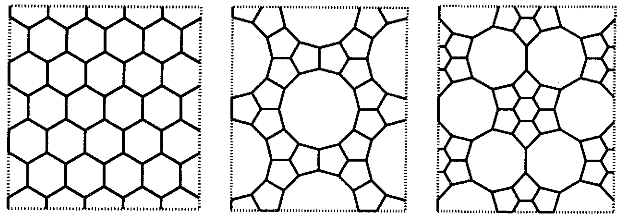


Figure 1: The three different (undisturbed) micro-topologies.

Bulk Material Parameters		
Density	$\rho =$	2.7 Mg/m^3
Young's modulus	$E =$	70 GPa
Poisson ratio	$\nu =$	0.33
Yield stress	$\sigma_{\text{yield}} =$	200 MPa
Hardening modulus	$E_t =$	700 MPa

Table 1: Summary of the bulk material parameters.

3 Description of the Finite Element Model

Besides a regular honeycomb, which serves as a reference model, two different periodic topologies are proposed, which can be described as a cluster of small cells surrounded by big cells on the one hand (see Fig. 1, right) and isolated big cells surrounded by a ring of small cells (see Fig. 1, middle) on the other hand. The former model is abbreviated by "SBS", the latter is designated "BSB", and "HC" stands for the honeycomb model. With the introduction of the SBS and the BSB topologies two extreme examples of a non-uniform periodic micro-structure are presented. The deformation behaviour in the large-strain regime is studied for all three topologies.

In addition, imperfections in terms of distortions of the cell geometry and - on an even lower level - imperfections of the cell walls are examined. The former are created by moving the vertices connecting the cell walls. Whereas the direction of the vertex displacement is randomly chosen, the magnitude of the displacement is defined by the standard deviation $\overline{n}$ of the Gaussian normal distribution. Beyond this geometry distortions the cell walls themselves can be pre-deformed by a superposition of sinusoidal wiggles and/or a parabolic curvature. The amplitude of these imperfections is defined relative to the original strut length. The direction of curvature is chosen so that the cell walls of the smaller of two neighbouring cells are curved outwards. The aforementioned topologies and imperfections can be combined arbitrarily. This offers the possibility to study their respective influence not only in isolation but also in interaction with each other.

For this purpose the cellular structures are modelled with three-node, quadratic beam elements using the finite element program ABAQUS (element type B22). The model bulk material is characterised as a J_2-flow theory solid with isotropic, linear hardening. The bulk material properties are chosen corresponding with those of aluminium alloys typically used for metallic foams (see Table 1). The periodic unit cell method is employed to represent the macroscopic material.

4 Results and Discussion

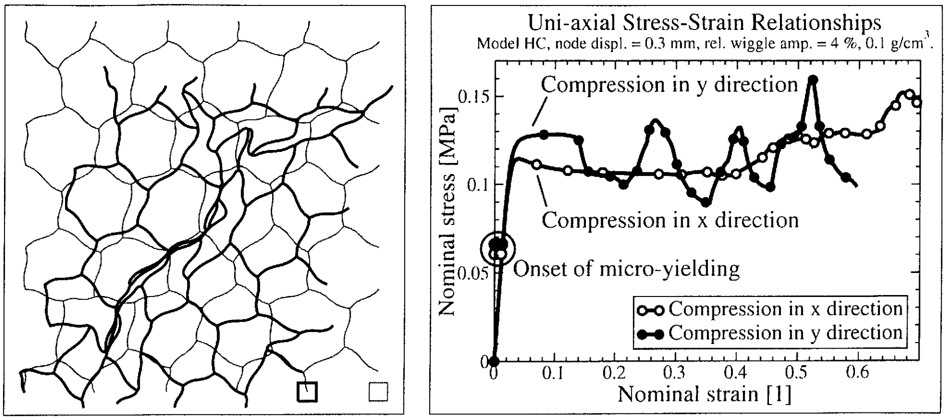
Boundary conditions: When dealing with unit cells, the question how the boundary conditions (BCs) influence the result arises. An imperfect honeycomb model was chosen to assess this influence. It can be shown that in the linear regime symmetric boundary conditions give results which are within a few percent of those obtained with the more general periodic boundary conditions. Generally, symmetric BCs were found to cause a slightly stiffer response of the micro-structure. The collapse stress of the structure is also hardly affected by the BCs. Yet the post-collapse deformation behaviour can highly depend on the additional constraints symmetric BCs impose on the structure. Here, periodic BCs soften the non-linear response to a significantly higher extent than is the case in the linear regime.

Without any symmetric or periodic boundary conditions the micro-deformation tends to localise at the free, unconnected cell walls at the loaded boundaries of the cell. In simulations this is usually avoided by surrounding the representative volume with a layer of closed cells so that no cell wall intersects the bounding box of the control volume (e.g. [2]). Accordingly, care should be taken that in experiments surfaces where forces are applied are filled and smoothed with e.g. resin to make sure that the response under small loads is not dominated by the deformation of those free walls. This supporting effect can also be assumed if the foam specimen is covered with a skin of higher apparent density. It should be noted that these boundary effects may be somewhat less pronounced for three-dimensional foam micro-structures.

Unit cell size: The size of the unit cells was chosen sufficiently large to allow for non-trivial deformation patterns (see Figures 2a and 3). The insensitivity to the type of the BCs and the comparably small oscillations in the stress-strain curves (see Fig. 2b) due to cell collapse and cell self contact indicate that the unit cells are big enough. The collapse of a whole layer of cells causes a distinct peak in the stress-strain curve. This can be observed very well for the collapsing honeycomb in Fig. 2b. The curve becomes smoother when the collapse bands develop diagonally to the load direction or the micro-structure does not favour singular events like the simultaneous collapse of a cell layer.

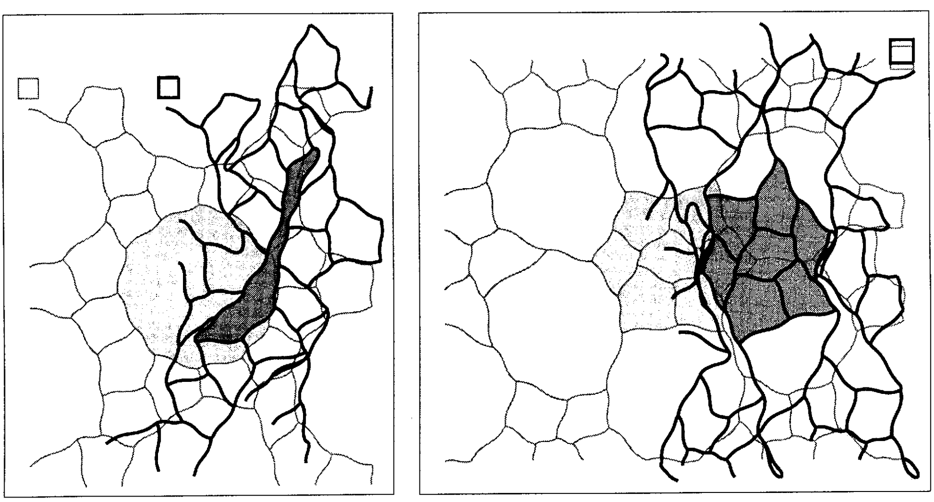
Influence of micro topology: Simulations with models of identical, distorted geometry have shown that the yield stresses are proportional to the square of the cell wall thickness indicating that bending stresses dominate the failure of the imperfect geometry. Accordingly, the stiffness is scaled proportional to the third power of the cell wall thickness. This, however, cannot be generalised for all model topologies. The expected ranking SBS $<$ HC $<$ BSB of the mechanical properties due to the increasing cell wall thickness at the same apparent density is not followed for the examined, imperfect models. Too many other factors seem to be contributing to the overall behaviour. The stiffness of the SBS and BSB models was about 20 % higher than the honeycomb's, the uniaxial yield strength was approximately the same.

Characteristics of the post-collapse behaviour can be obtained from Fig. 3. It can be noted that big cells are prone to collapse first regardless of the size of their neighbours.



(a) (b)

Figure 2: a) Undeformed (grey) and deformed (black) configuration of a bi-axially compressed imperfect honeycomb model and b) uni-axial stress-strain relationships for this model.



(a) (b)

Figure 3: Undeformed (light grey) and deformed (dark grey/black) configurations of imperfect SBS (a) and BSB models (b). One of the big cells of model SBS is filled in both configurations to show its collapse behaviour (a). The surrounding small cells remain relatively unaffected. Similarly, the cluster of small cells in model BSB keeps its shape amongst highly deformed big cells (b).

Influence of cell wall wiggles and curved cell walls: A distinction has to be made between the undistorted and the distorted geometry: in the perfect, regular HC model under biaxial compression the beams fail due to normal stresses exclusively, which leads to a strongly elongated overall initial yield surface, characterised by the onset of micro-yielding, in the $\sigma_x - \sigma_y$ stress plane (see Fig. 4a). As a matter of fact, the yield surface is truncated by the failure surface for bifurcation buckling in the case of a regular HC micro-structure and very thin cell walls (see Fig. 4a). This stays valid even if small wiggles are overlaid. The buckling failure surface shows a kink due to a change of the buckling mode. At wiggle amplitudes ≥ 6 % of the cell wall length micro-yielding alone triggers the failure of the structure.
The impact of wiggles and curved cell walls on the yield surface of an originally distorted HC micro-geometry (Fig. 4d) is much less pronounced (see Figs. 4b and 4c). The displacement of cell vertices causes the yield surface to shrink even more than the one caused by severe wiggles (10 % relative amplitude). Furthermore, the biaxial yield stress is reduced by approximately 35 % at the highest relative wiggle amplitude (10 %). Note that the uniaxial micro yield stresses are hardly affected by wiggles or cell wall curvature. Curved cell walls generally follow the same principles as wiggles (Fig. 4c). It was however surprising to find that cell walls curved with a low amplitude (2 % cell wall length) can slightly increase the biaxial micro yield stress.

5 Conclusions

Failure due to elastic buckling seems to be significant only for extreme cases of near-perfect micro-geometries and very thin cell walls. For the imperfect micro-geometry elastic buckling would occur at stresses roughly one magnitude higher than those leading to yielding.
The elastic stiffness of the honeycomb model was hardly influenced by vertex irregularities or cell wall imperfections. A perturbation of the vertices actually increased the stiffness by a few percent in both directions. Curved cell wall and cell wall wiggles consistently reduced the stiffness (minus 20 % at 10 % relative wiggle amplitude). The stiffness is however highly sensitive to changes of the apparent density and, consequently, of the cell wall thickness since the bending stiffness is proportional to the 3^{rd} power of the cell wall thickness. The uniaxial yield stress of the honeycomb model was reduced by 40 percent by a perturbation of the cell vertices only. The subsequent superposition of cell wall imperfections influenced the yield stresses only in the range of a few percent.
Imperfections in terms of irregular node vertex arrangements have a much stronger influence on the yield surface than wiggles on the cell walls of a regular micro-structure. With respect to simulations of the behaviour of cellular materials it can be concluded that an irregular micro-geometry is paramount to get a realistic prediction of the deformation characteristics of foams. This is especially true when dealing with multi-axial loads or deformations. As soon as irregularities of the cell vertex arrangement are provided, other imperfections like non-uniform topologies or cell wall imperfections become secondary and the stiffness (and, to a lesser degree) the strength of the foam are mainly influenced by the cell wall thickness and thus by the apparent density of the material.

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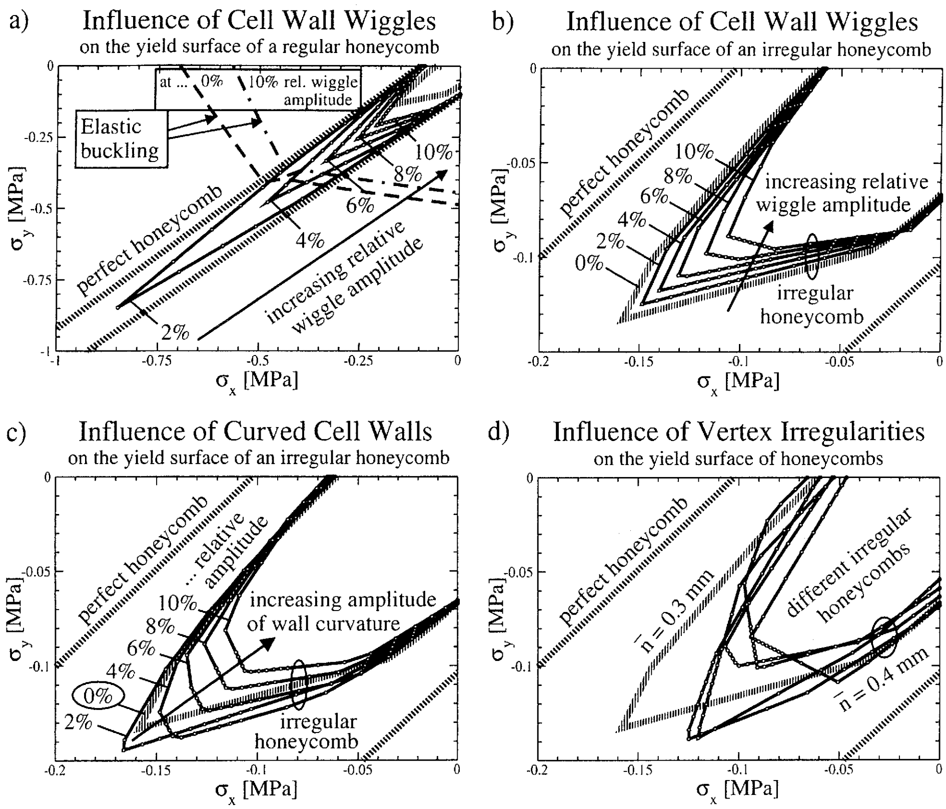

Figure 4: Yield surfaces for regular and irregular honeycomb models with different types and degrees of imperfections (imperfection amplitudes are given relative to the individual strut length; in (d) the standard deviation $\overline{n}$ of the vertex displacement is given at an average cell diameter of 3.4 mm).

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