Modeling of ductile damage in metal foams

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Abstract

A numerical model for the elasto-plastic and ductile damage behaviour of a low-density open-cell metal foam is presented based on a three dimensional random network of slender struts. The finite element formulation for the behaviour of the struts makes use of the Timoshenko beam theory. A layered approach is adopted to simulate the progressive growth of plasticity and void volume fraction in the struts due to ductile damage effects from the extreme fibers towards the neutral axis. The result is an efficient numerical model for a representative volume element of the foam which can be used as material model in each integration point of a macroscopic Finite-Element-Model. The numerical studies indicate that the collapse of the foam structure on the meso-scale is initiated by a few randomly distributed struts. The bending and buckling of the struts lead to formation of plastic hinges with localized growth of ductile damage.

Keywords: open-cell metal foam, ductile damage, unit-cell, Timoshenko beam.

1 Introduction

Cellular metals have shown to experience fatigue and damage degradation in tension and in compression loading [1, 2]. This is a result of the specific deformation mechanism within these materials. For low-density open-cell foams considered in this paper bending of the struts dominates the mechanical response of the foam at low strains. At large compressive strains the buckling of the cell struts cause a significant decrease of the stiffness. At large tensile strains the axial deformation of the struts becomes the dominating deformation mechanism [3]. The material response to mechanical loads is linked to the properties of the basic material and to the internal pore structure of the foam.

The main objective of this paper is the presentation of a numerical concept for
the modeling of the elasto-plastic and ductile damage behaviour of a low-density open-cell metal foam. Due to the manufacturing process, the individual struts of the foam contain microcracks, micropores and particles. They initiate damage mechanisms after the onset of plastic deformation. Until now, only a few studies have been performed concerning the effects of microstructural imperfections on the mechanical behaviour of the foam structure [4]. Here, using a continuum damage model the growth of micropores within the struts will be followed in detail. The foam is modeled on the meso-scale to separate the influence of the foam structure and the material behaviour on the deformation process.

2 Methods

2.1 Generation of the artificial foam

The computations make use of a unit-cell filled with an artificially generated foam structure. The framework of slender struts of the foam is generated by a Voronoi tessellation in the three dimensional space. This technique has been used successfully to model the nonlinear elastic behaviour of a polymer foam [5] and to model the elasto-plastic deformation behaviour of metal foams [6, 7]. The algorithm of the Voronoi tessellation imitates the foaming process quite well. Starting from randomly distributed seed points which are the centers of the cells, a constant growth rate of the cells is assumed. The cells meet in the middle between the seed points and straight cell vertices are formed. Figure 1 shows a photograph of the open-cell foam Duocel produced by ERG Aerospace [8] which serves as a model for the numerically generated foam structure.

Within the unit-cell around 15% of the struts are randomly removed to introduce imperfections into the foam which also exist in the real material in form of unconnected cells or curved struts. Studies concerning the elastic properties have shown that the model otherwise overestimates the stiffness and Poisson ratio [9]. This way, the modified model is geometrically close to the real foam morphology.
2.2 Constitutive material behaviour

The metallic struts of the foam are assumed to behave elasto-plastically. For the plastic deformation an extended flow potential will be used in order to describe the ductile continuum damage in the cross section of the struts. It is defined by the modified flow potential of Rousselier [10]:

\[
\Phi = \left( \frac{\sigma_v}{1 - F} Y \right) + q_1 q_2 F \exp \left( \frac{\sigma_h}{(1 - F) q_2 Y} \right) - 1 = 0 .
\]  

(1)

Here, \(\sigma_v\) is the von Mises stress, \(\sigma_h\) the hydrostatic stress and \(Y\) the current yield stress of the strut material, while \(q_1\) and \(q_2\) are the damage growth parameter. The damage is measured by the scalar parameter \(F\). Starting from the initial void volume fraction \(F_0\), the evolution of the damage parameter follows from the incompressible material behaviour of the metal:

\[
\dot{F} = (1 - F) D_{ii}^p ,
\]  

(2)

where \(D_{ij}\) is the tensor of the plastic strain rate. Beams are subjected to compression in some areas of the cross section while bending, the continuum damage in these areas will be held constant. Crack closure effects are not taken into account. The plastic strain rate \(D^p\) in the struts is assumed to be normal to the flow potential:

\[
D_{ij}^p = \lambda \frac{\partial \Phi}{\partial \sigma_{ij}} .
\]  

(3)

2.3 Finite element model

The finite element model makes use of layered Timoshenko beam elements. The cross section of the struts is assumed to have a constant diameter and a circular
shape. The diameter is based on the geometry of the considered Duocel foam with a relative density of 8% and an average of 20 pores per inch.

At large deformations geometric nonlinearities occur. An incremental, updated Lagrangean approach is used to calculate the tangential stiffness against tension and bending in the integration points of the cross section of the struts. The integration is carried out numerically by dividing the cross section into a number of segments as shown in figure 3 [11]. The local axial strain in each segment depends on the average axial strain of the strut and its bending curvature. The tangential material stiffness in each segment is a function of the local strain. It is evaluated with the help of the constitutive material laws above.

All of the struts are divided into a number of finite elements according to their length. This allows a rather uniform distribution of the element length throughout the unit cell. The shorter struts which buckle at high compressive loads contain less elements than the longer struts which buckle first. During large deformations contact between the struts may occur and is taken into account by fixing the relative normal displacement between the struts [12].

The boundaries of the unit-cell are assumed to remain straight and even during the deformation process. On the boundaries either a pre-described force or displacement can be applied. Since a metal foam is a typical filler material, the macroscopic stresses $\Sigma$ and strains $E$ acting on the boundaries of the unit-cell are evaluated. This defines the effective or homogenized material properties of the unit-cell.

### 3 Results

The response of a unit-cell of the artificial foam to various triaxial loading situations has been calculated. To reflect the random cell geometry around 500 seed points are used to generate the foam structure of a three dimensional unit-cell. This leads to a finite element model consisting of around 10000 beam elements. The used material parameters for the struts are based on generic Aluminium. Due to the lack of realistic parameters for the strut material the performed calculations describe effects in the foam only qualitatively.

The calculations show that the random arrangement of the cell struts in foam structures results in an irregular deformation pattern. Figure 4 shows the maximum von Mises stress in a slice of the unit-cell. The high stresses occur in a small number of randomly distributed struts. For tension they lead to large void volume fractions in a few struts. In compression the collapse of the cells is the dominating failure mechanism. It is initiated by the larger cells of the foam structure. The strains and therefore the observed void volume fractions are limited by the bending radius of the struts while buckling.

Within the struts the deformation is often localized in a small region. Figure 5 shows the equivalent von Mises stress and the void volume fraction in an average strut of a three dimensional unit-cell which is deformed by a tension force and a bending moment. This loading condition leads to the formation of a plastic hinge. The ductile damage grows progressively from the extreme fibers towards
Figure 4: Maximum von Mises stress in the struts.

Figure 5: Local distribution of stress (left) and void volume fraction (right).

the neutral axis in the elongated sections of the strut.

4 Conclusions

A model for the microstructure of a low-density open-cell metal foam has been presented to describe the behaviour of metal foams based on a geometrical description of the foam and the behaviour of the solid material. With the help of the developed model the basic deformation mechanisms and the evolution of the ductile damage within the struts can be explained. The calculations show the necessity of a rea-
sonable large unit-cell to reflect the randomness of the foam structure. Due to the efficiency of the used beam formulation the developed model can also be evaluated in each integration point of a macroscopic finite element model.

References