FINITE ELEMENT SIMULATION OF COMPRESSION TESTS ON CELLULAR METALS

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Abstract*. Metal foams are materials of recent development and application that show interesting combinations of physical and mechanical properties. Many applications are envisaged for such materials, particularly in equipments of passive safety, because their high capacity of energy absorption under impact conditions. The damage analysis in metallic foams is a complex problem and must be performed in a finite strain context. Considering that compression is the dominant loading in impact situations, in this work a finite deformation simulation including damage effects of a compression test on a cellular metal sample is shown. A comparison with experimental results is also presented.*

Keywords: *Cellular metals, Metallic foams, Damage, Gurson model, Finite elements*

1. INTRODUCTION

This work continues the research on the simulation of metallic foams behavior that was presented in earlier papers (OLIVEIRA et al., 2006, CUNDA et al., 2005, ÖCHSNER e LAMPRECHT, 2003).

We understand by metal foam a material composed by a metallic matrix with internal voids (Fig. 1). Metallic foams are increasingly used by the automotive industry, particularly as recourse of passive safety. In that case, they act to absorb impact energy.

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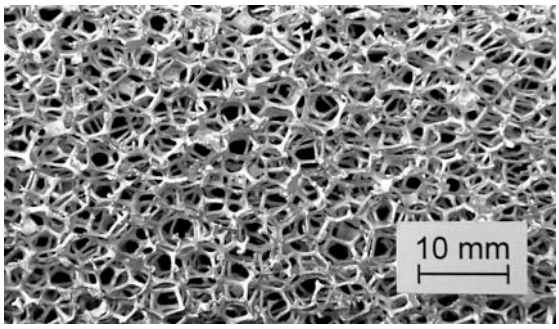


Figure 1 – Aluminum foam with open cell (DUOCEL®) (ÖCHSNER e LAMPRECHT, 2003).

Metallic foams show mechanical behavior and physical properties that strongly differ from those of solid materials and show interesting combinations of properties. For example, high stiffness combined with low specific weight, or permeability to gas flow combined with high thermal conductivity, offering possibilities of use in aerospace and automotive industries. The schematic stress-strain curve for a metallic foam in compression (Fig. 2), shows a large area in the plateau region corresponding to high energy absorption at constant stress.

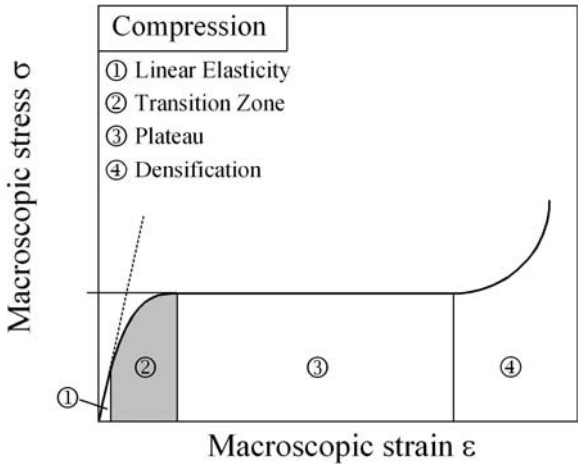


Figure 2 – Stress-strain curve for a metallic foam showing large capacity of energy absorption at constant stress (ÖCHSNER et al., 2003).

In order to employ these materials as a main component in protection structures, it is necessary to have reliable numerical methods and constitutive relations, developed and validated using experimental procedures that take into account the variety of mechanical, geometrical and physical properties of the foam and the base material.

2. GURSON DAMAGE MODEL

Gurson damage model was developed to describe the mechanical effect of high plastic deformations in ductile metals. The loss of resistance is governed by the porosity level. The (isotropic) damage variable employed is the volumetric void fraction, represented by f and defined by $f = V_v / V$, where V_v is the volume of voids in a representative small volume V, corrected for effects as stress concentration, etc.; f is defined at each point of the continuum.

The presence of voids alters the elastoplastic constitutive relations. The equations usually employed in computational damage analyses, the Gurson-Tvergaard model (GURSON, 1977, TVERGAARD, 1981), considers a yield surface defined by

$$\Phi = \sqrt{\frac{3}{2} s_{ij} s_{ij}} - \overline{\omega} \sigma_y = 0 \tag{1}$$

where

$$\overline{\omega} = \left[1 - 2\alpha_1 f \cosh\left(\frac{\alpha_2 3p}{2\sigma_y} \right) + \alpha_3 f^2 \right]^{1/2} \tag{2}$$

$$s_{ij} = \sigma_{ij} - p\delta_{ij} \qquad p = \tfrac{1}{3} \sigma_{ij} \delta_{ij} \tag{3}$$

$$\alpha_1 = \frac{1}{f_U} = 1.5 \qquad \alpha_2 = 1.0 \qquad \alpha_3 = \alpha_1^2 \tag{4}$$

and σ_{ij} are the Cauchy stresses, σ_y the yield stress in simple tension. α_i are material parameters. The parameter $f_U = 1/\alpha_1$ is the maximum volumetric void fraction admissible before rupture in the absence of pressure. Another possible interpretation for the α_1 and α_2 parameters is that they work as multipliers acting on porosity f and pressure p, respectively.

In Fig. 3, yield surfaces for different levels of void content are shown, in a plot of normalized deviatoric stress versus normalized pressure.

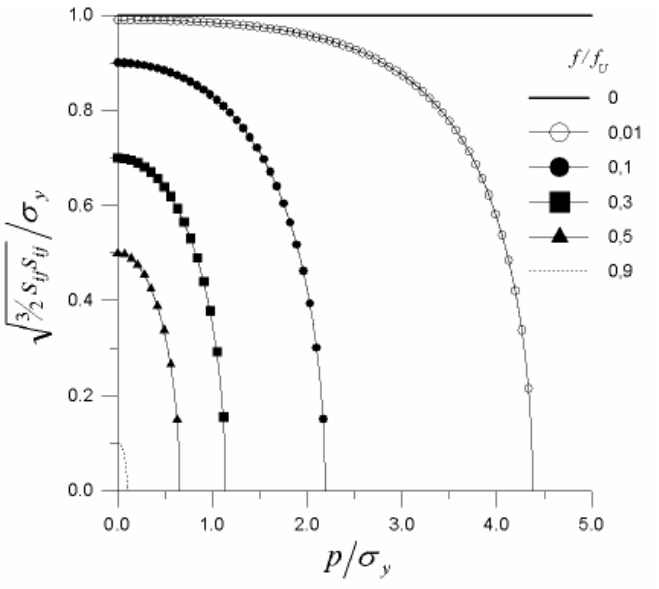


Figure 3 – Yield surface for a porous material: influence of volumetric void fraction.

It can be seen that the elastic domain depends on the hydrostatic pressure. When the volumetric void fraction f decreases, decreases the influence of pressure, leading to a larger elastic domain. For $f = 0$, the model reduces to the von Mises model, which is independent of

pressure. It should be noted here that in the absence of hydrostatic pressure, the coefficient $\overline{\omega}$ reduces to

$$\overline{\omega} = 1 - \alpha_1 f = 1 - \frac{f}{f_U} \tag{5}$$

The plastic strain rate tensor is given by,

$$D_{ij}^p = \dot{\lambda} \frac{\partial \Phi}{\partial \sigma_{ij}} \tag{6}$$

and the equivalent plastic strain rate is defined by

$$\dot{\varepsilon}^p = \sqrt{\tfrac{2}{3} D_{ij}^p D_{ij}^p} \tag{7}$$

The basic mechanisms of damage evolution are nucleation, growth and coalescence of voids. Nucleation occurs mainly due to material defects, in the presence of tension. Growth occurs when the voids (preexistent or nucleated) change their size according to the volume change in the continuum.

Coalescence is related to the fast rupture process that occurs after that the volumetric void fraction reaches a limit, indicated by f_C. Coalescence consists in the union of neighbor voids due to the rupture of a ligament.

The equations that govern damage evolution are modeled in a simplified form as follows. First, it is assumed that total void rate is given by

$$\dot{f} = \begin{cases} \dot{f}_n + \dot{f}_g & f \le f_C \\ \dot{f}_c & f > f_C \end{cases} \tag{8}$$

where $\dot{f}_n$ is the void nucleation rate, $\dot{f}_g$ is the void growth rate and $\dot{f}_c$ is the void coalescence rate. Thus, as long as f is smaller than a characteristic value f_C, only nucleation and growth develop. Above f_C, only coalescence takes place.

The nucleation rate is proportional to the rate of equivalent plastic strain

$$\dot{f}_n = A(\varepsilon^p)\dot{\varepsilon}^p \tag{9}$$

For $A(\varepsilon^p)$ Chu and Needleman (CHU e NEEDLEMAN, 1980) propose the statistical distribution

$$A(\varepsilon^p) = \frac{f_N}{s_N \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\varepsilon^p - \varepsilon_N}{s_N} \right)^2 \right] \tag{10}$$

where f_N, is the nucleation void volumetric fraction, ε_N is the plastic strain value for nucleation and s_N is the standard deviation for the distribution. Sometimes it is assumed that

nucleation takes place only in tension (ABAQUS, 1992, CUNDA e CREUS, 1999), what implies that

$$A(\varepsilon^p) = 0 \qquad \text{if} \qquad p < 0 \tag{11}$$

Growth rate of voids is controlled by mass conservation through the expression

$$\dot{f}_g = (1 - f) D_{ii}^p \tag{12}$$

Voids increase or decrease their volume according to the volume variation in the continuum. Coalescence is governed (TVERGAARD, 1982) by the relation

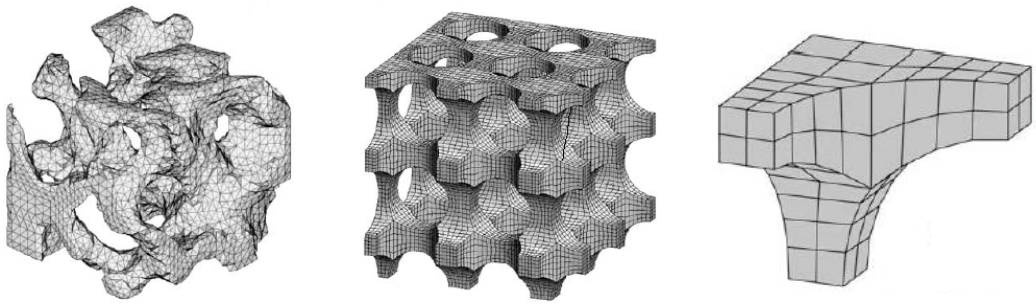
$$\dot{f}_c = \frac{f_U - f_C}{\Delta\varepsilon} \dot{\varepsilon}^p \tag{13}$$

3. MODELING CONSIDERATIONS FOR METTALIC FOAMS

Metal foam properties can change along the production process, particularly according to the cell being open or closed and the relative density of the foam in relation to the base material.

Moreover, foams show (see Fig. 1) a fairly random structure. It is possible to determine the exact geometry using CT-scan (computed tomography) and model it with a dense mesh of finite elements, as in Fig 4a. A different approach towards the understanding and modeling of these materials, adopted in this work, is an idealization as a cellular material with regular structure, as in Fig. 4b. In this case, modeling a RVE (representative volume element, Fig. 4c) and still considering the existent symmetries, good results can be obtained with fewer elements. Then, specimens with regular structure may be tested to validate results and determine material parameters. These homogenization procedures have been used with success in other areas of continuum mechanics.

Figure 5 shows a specimen of a cellular metal made to represent a foam.



(a) (b) (c)

Figure 4 – Meshes used to represent a cellular metal (ÖCHSNER e LAMPRECHT, 2003).

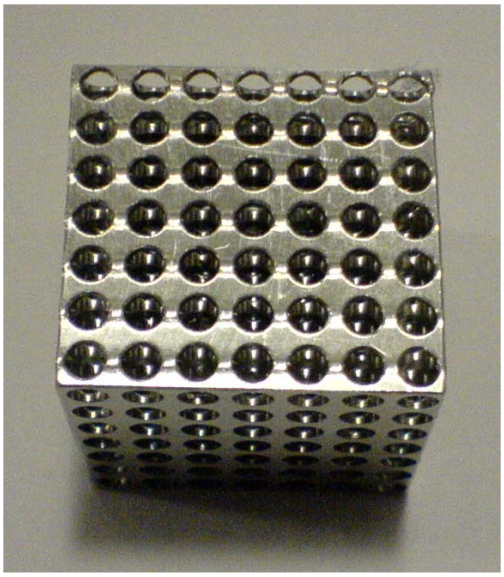


Figure 5 – Cube of cellular metal.

3.1. Application of boundary conditions

One important aspect to take into account when modeling cells as those described above are the boundary conditions, that must represent the average behavior of the foam. When a vertical displacement is applied to the top side (see Fig. 6) the vertical faces must continue vertical while the distance between them may change.

This behavior can be computationally imposed using multiple point constraints (MPC). The used FE code (ABAQUS) offers the possibility to realize such a boundary condition where all nodes on a certain surface have the same x-displacement: $u_{xi} = \ldots = u_{xj}$. The effect of differing boundary conditions on the deformation is shown in Fig. 6

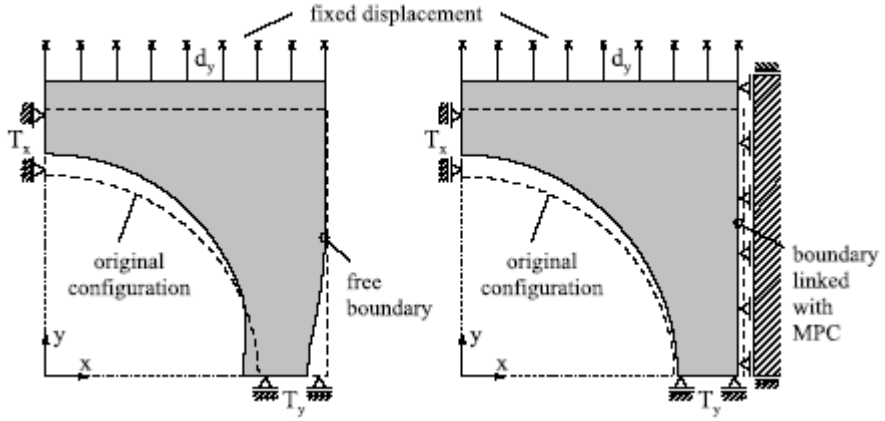


Figure 6 – Results of different boundary conditions applied to the right face (Öchsner and Lamprecht, 2003).

4. SIMULATION OF A COMPRESSION TEST ON A CUBE OF CELLULAR METAL

A cube of a cellular metal as shown in Fig. 5 is considered in the following. The cube contains 3 mm diameter holes with distance of 4 mm among them. The presence of holes simulates a cellular metal with relative density of 0.2712.

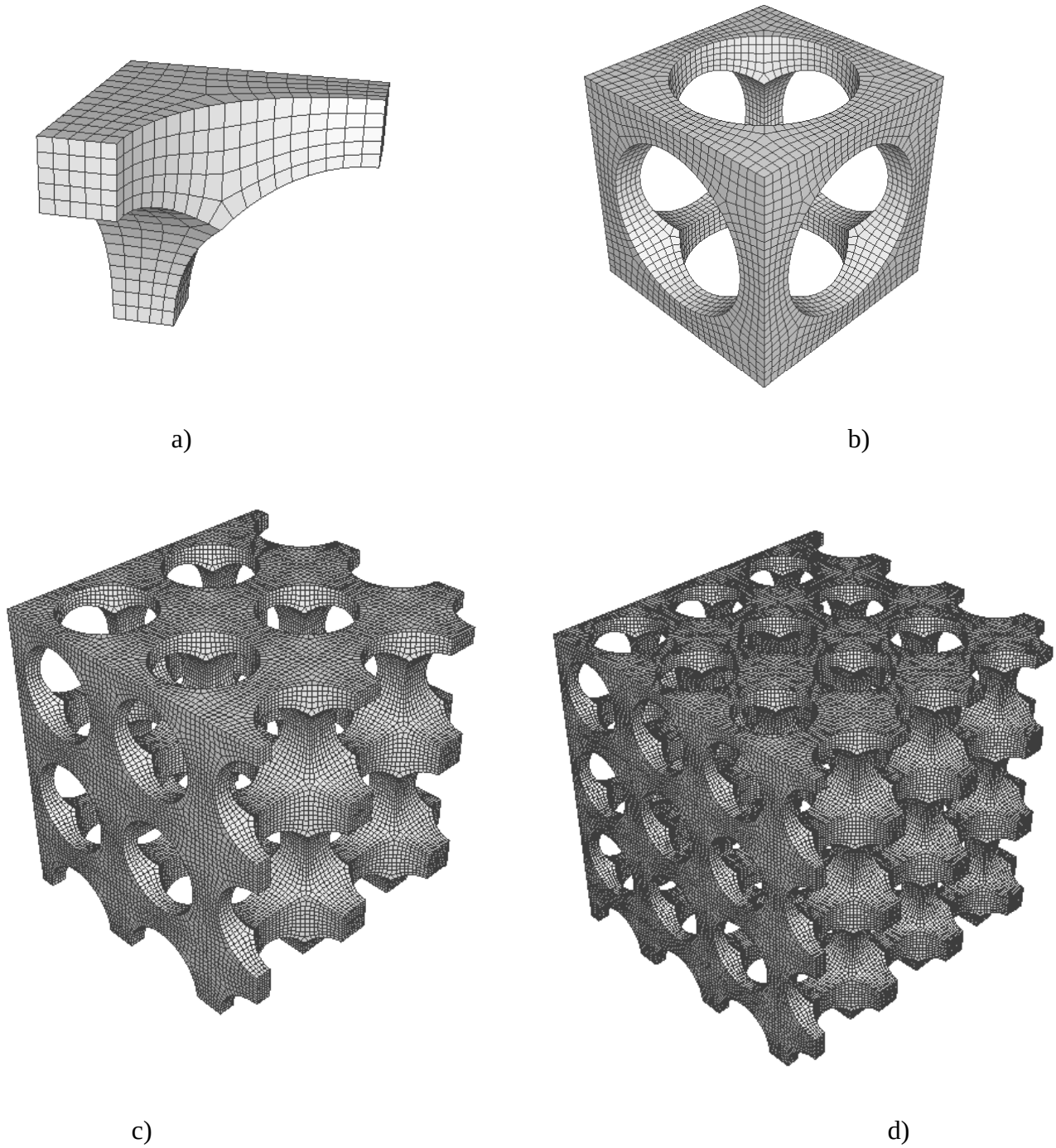


Figure 7 – Meshes used to study the cube. a)unit cell b)2-cells c)5-cells d)7-cells.

The matrix material properties are E = 72.7 GPa, ν = 0.34, initial yield value $\sigma_y^0 = 250$ MPa and final yield value $\sigma_y^\infty = 410$ MPa. Hardening is taken into account by the relation $\sigma_y = \sigma_y^0 + (\sigma_y^\infty - \sigma_y^0)[1 - \exp(-k\varepsilon^P)]$, with $k = 25$. Gurson model parameters considered are 5% of initial porosity, α_1 = 1.5 and α_2 = 1.0.

Load is applied as a vertical displacement on the top surface of the cube.

The objective of this analysis is to compare numerical results with experimental results available from a cellular metal cube compression tests, and to check if MPC boundary condition works properly in compression as in tension situations (OLIVEIRA et al., 2006, ÖCHSNER e LAMPRECHT, 2003).

Five models are used to simulate the problem, beginning with a single cell as shown in Fig. 7a, and varying the number of cells in each direction and the boundary conditions. The single cell model of Fig. 7a is studied with and without MPC boundary condition (see Fig. 6). With 2 cells in each direction the model called 2-cells (Fig. 7b) is obtained, representing a cube with a hole. Employing 5 or 7 cells in each direction the models called 5-cells (Fig. 7c) and 7-cells (Fig. 7d) are obtained.

Figure 8 shows a comparison among results for the five models used in the analysis. It can be seen that a unit cell (Fig. 7a) with MPC overestimates the stiffness of the model. Using MPC, due the nature of the restriction (see section 3.1), the walls remain vertical. This effect is more significant after 2.5% macroscopic strain, when buckling occurs in the walls between the holes (see Fig. 9). Figure 10 shows the von Mises stress distribution for the unit cell with MPC at an applied macroscopic strain of 22.73%.

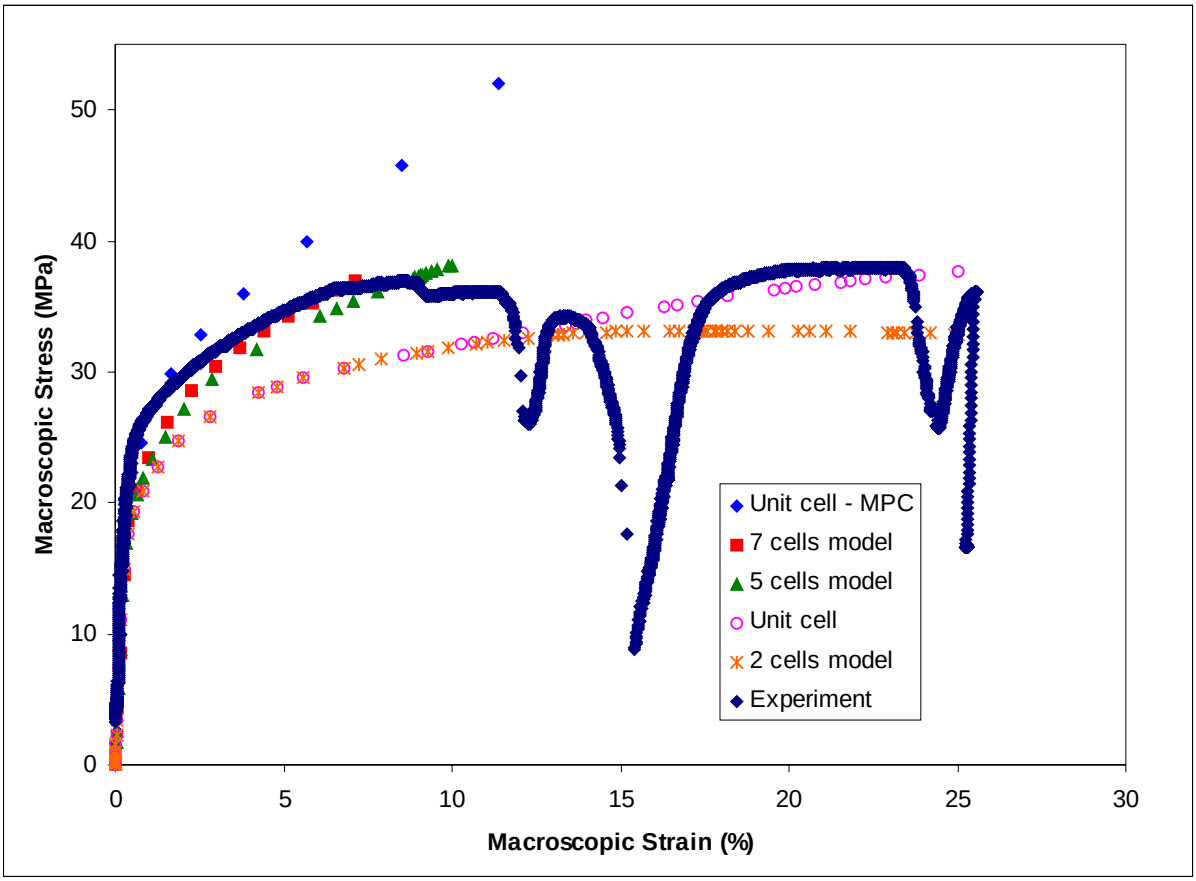


Figure 8 – Stress strain plots for the five models used in the analyses.

The 2-cells model (Fig. 7b) and a unit cell without MPC that represents an eighth of the 2-cells model, underestimate the stiffness of the cube because in this case all the walls suffer strong buckling effects, that in the actual behavior of the real specimen (Fig. 5) is restricted (at this loading level) to the slenderer external walls. Figures 11 and 12 show the von Mises stress distribution for the unit cell without MPC and for the 2-cells model for an applied macroscopic strain of 25%, respectively.

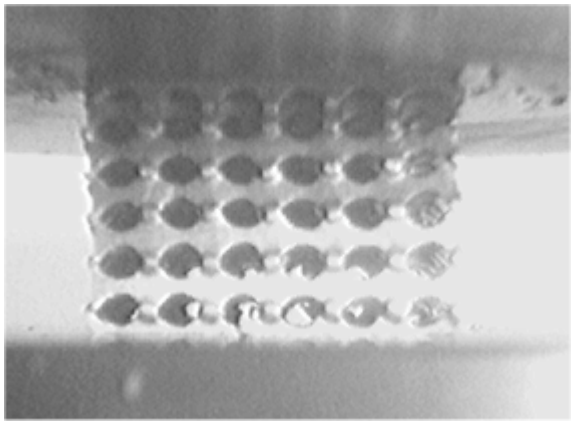


Figure 9 – Picture showing buckling process at the walls between holes.

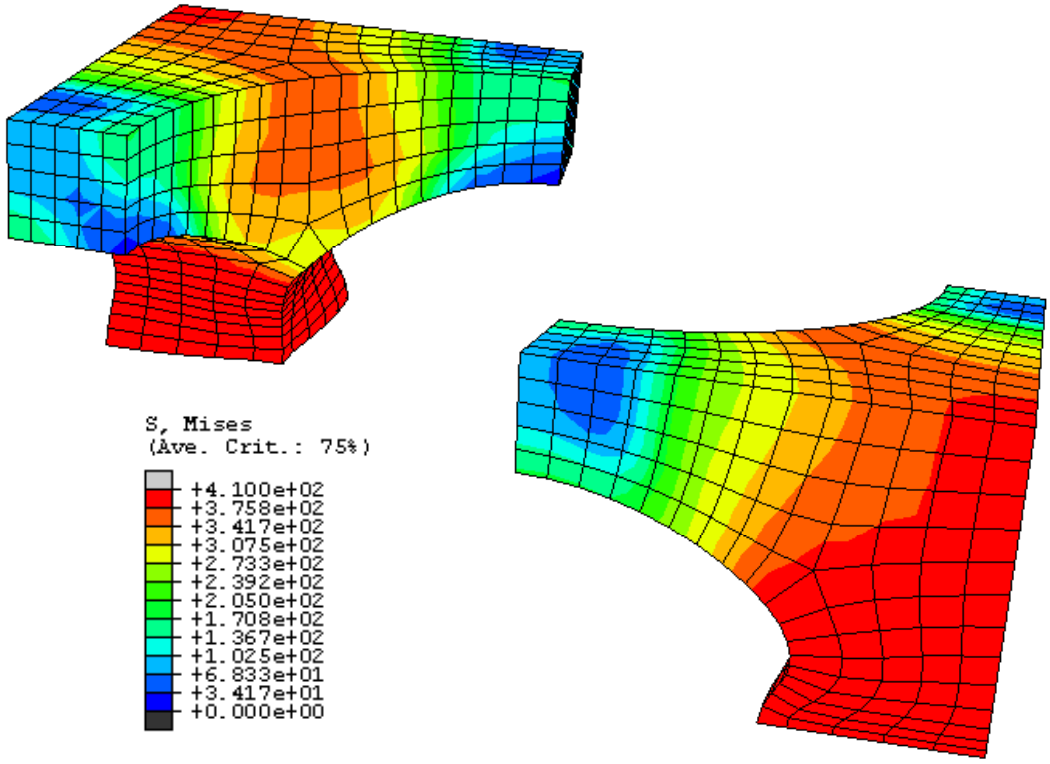


Figure 10 – Distribution of von Mises stress (MPa) for a unit cell with MPC for an applied macroscopic strain of 22.726%.

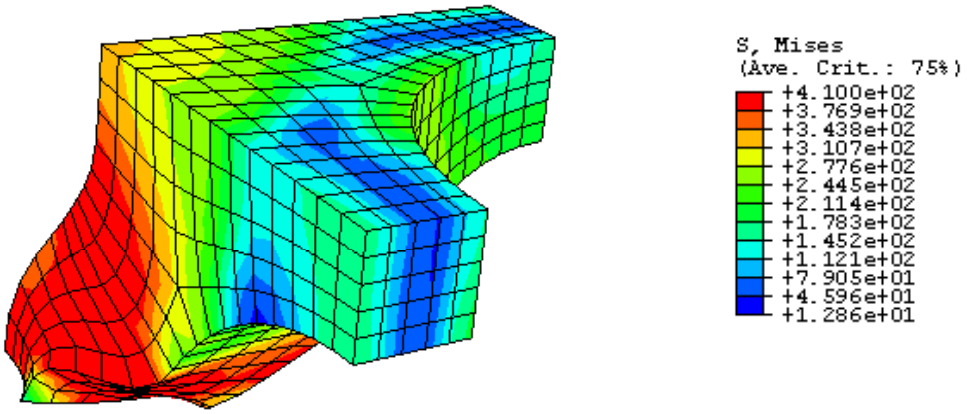


Figure 11 – Distribution of von Mises stress (MPa) for a unit cell without MPC for an applied macroscopic strain of 25%.

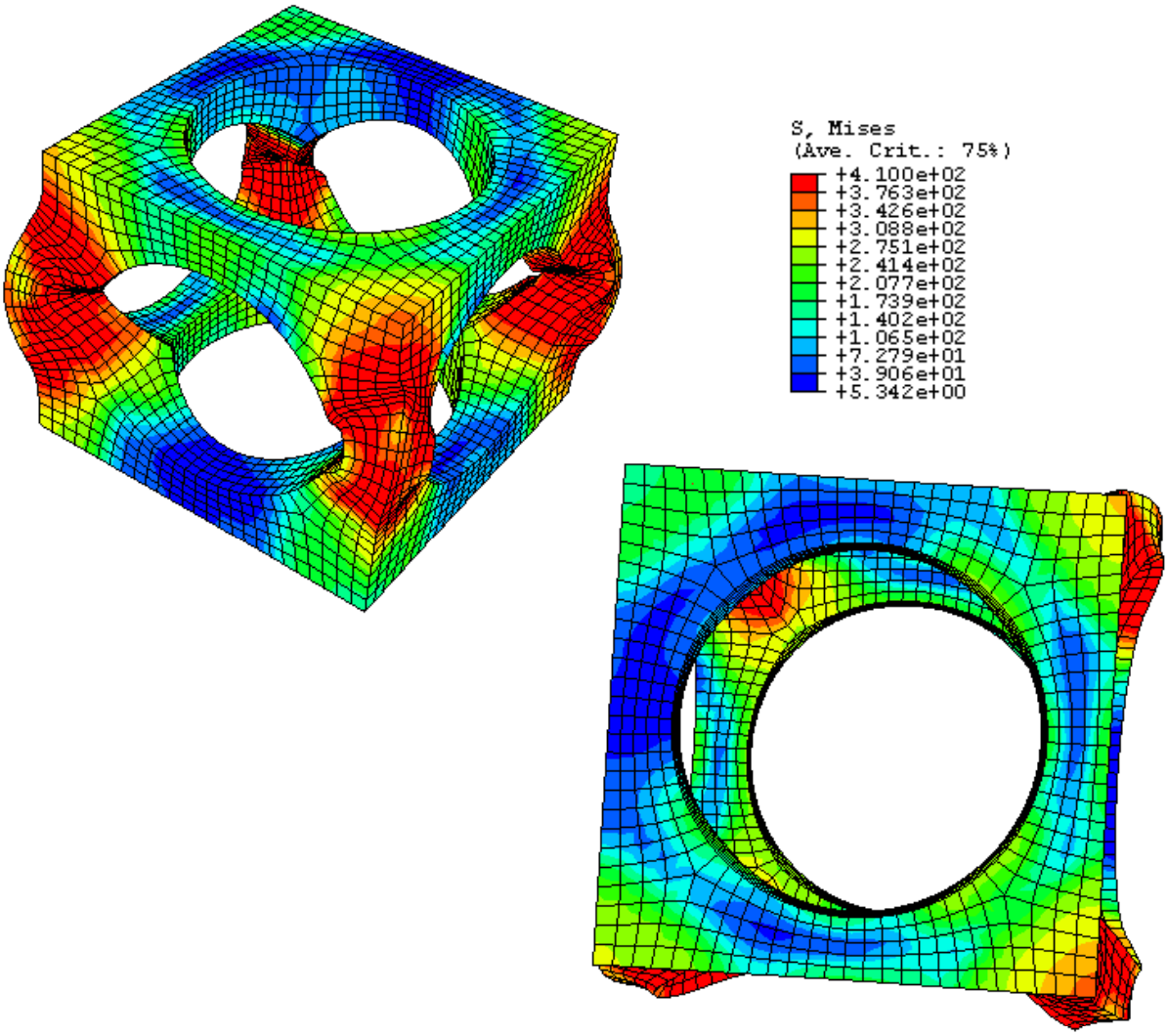


Figure 12 – Distribution of von Mises stress (MPa) for the 2-cells model for an applied macroscopic strain of 25%.

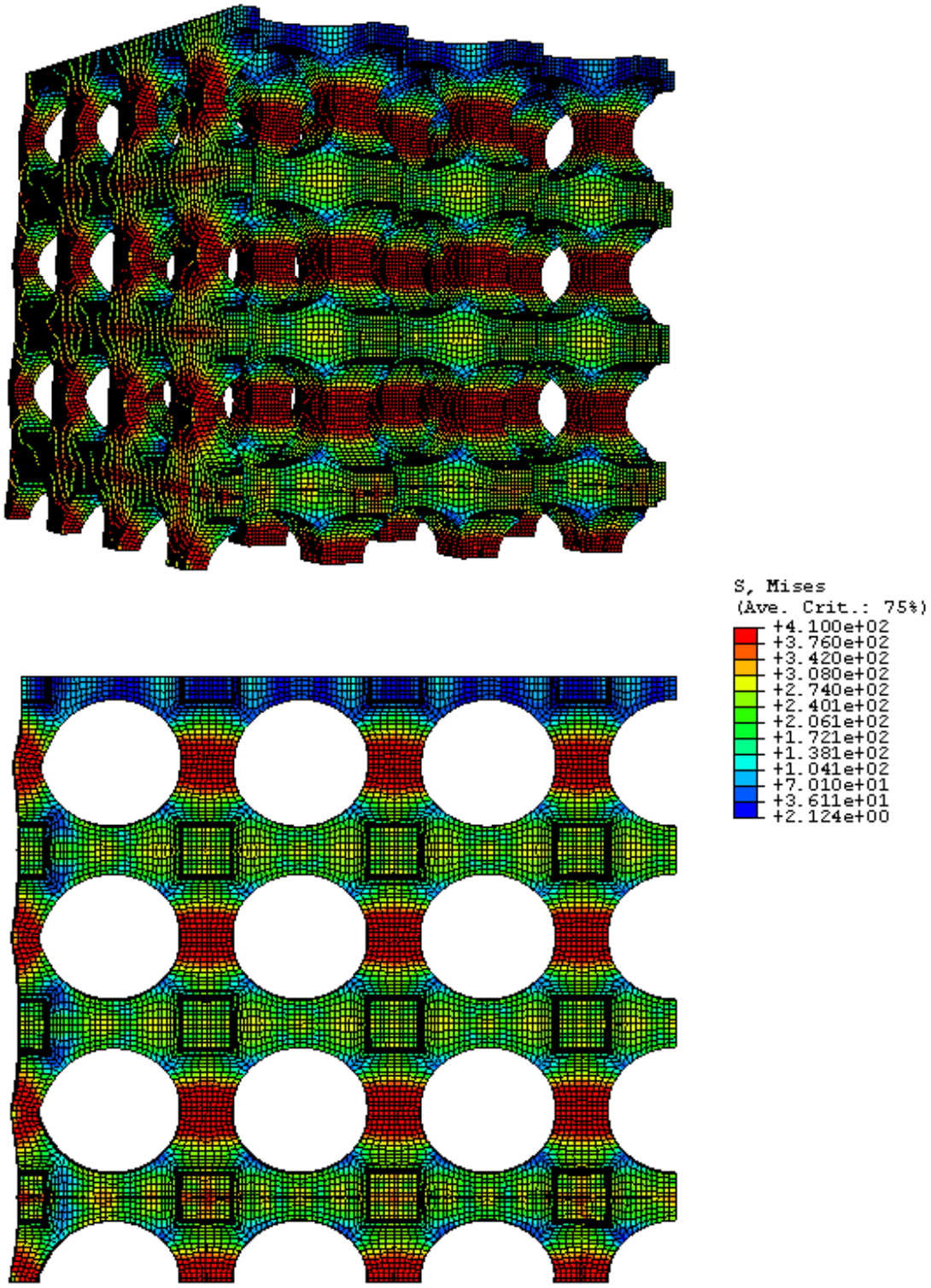


Figure 13 – Distribution of von Mises stress (MPa) for the 7-cells model for an applied macroscopic strain of 7.143%.

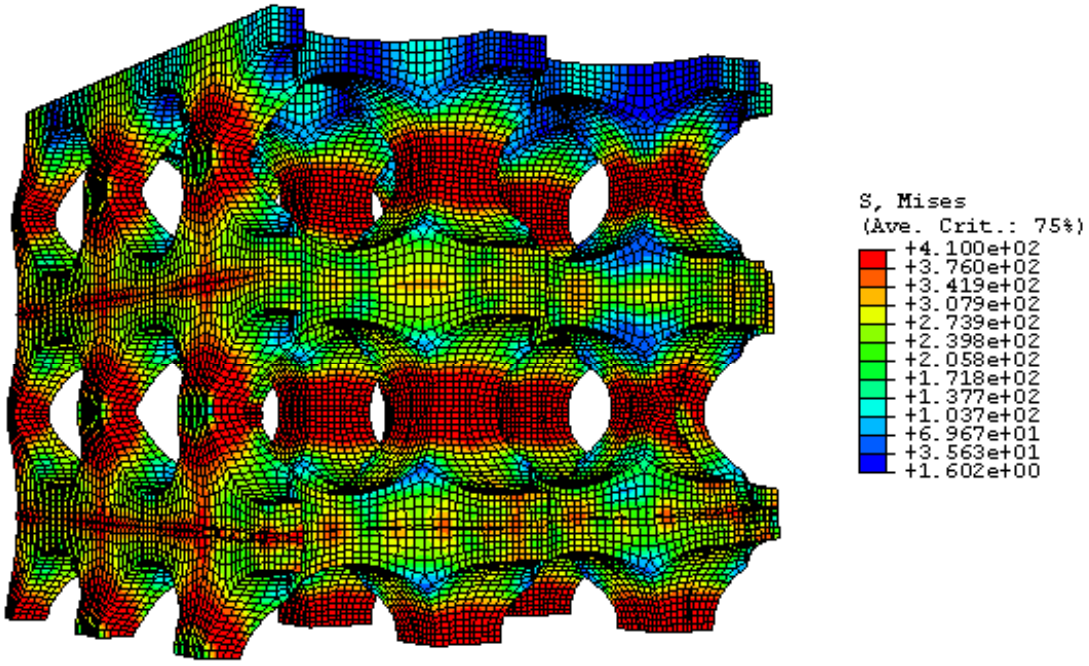


Figure 14 – Distribution of von Mises stress (MPa) for the 5-cells model for an applied macroscopic strain of 10%.

It can be observed in Fig. 8 that for macroscopic strains larger than 12% there is a divergence in the unit cell and the 2-cells model plots, that can be explained by the fact that the 2-cells model present a shear strain global effect (see Fig. 12) not found in the one eighth model (unit cell without MPC).

For the 7-cells and the 5-cells models, that represent more appropriately the effect of the buckling at the walls between holes, numerical results are closer to experimental results. The 7-cells model results are obtained only until an applied strain of 7.143% due time limitations. The mesh for this model has 253820 elements. The 5-cells model with a 92500 elements mesh present a similar problem and so, the results are obtained until an applied strain of 10% (see Fig. 8).

Figures 13 and 14 show von Mises stress distribution for the 7-cells model at an applied strain of 7.143% and for the 5-cells model at an applied strain of 10%, respectively. It is possible to observe there, the buckling of the external walls properly represented.

The experimental curve in Fig. 8 indicates how complex is the real behavior. After 12,8% of the macroscopic strain there is a partial rupture with stiff decrease in load until a new equilibrium situation achieved by contact of the fragmented parts. This process repeats itself until the final failure.

5. FINAL COMMENTS

This paper presents some new results from a research in development (see OLIVEIRA et al., 2006, CUNDA et al., 2005).

It is shown that MPC fails to represent the real behavior of the specimen in compression for large macroscopic strains (larger than 2.5% in the present case), mainly due to buckling

effects that are important at this strain level. The use of more complex models gives a good approximation of experimental results, up to a point close to postcritical softening (12.8% in the present case). To represent the real behavior at much larger deformations, the introduction of self contact effects should be needed. The research will continue looking for better models and damage parameters adjustment.

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SIMULAÇÃO DE TESTES DE COMPRESSÃO EM METAIS CELULARES POR ELEMENTOS FINITOS

Resumo. *Espumas metálicas são uma nova, e ainda não perfeitamente caracterizada, classe de materiais que apresentam interessantes combinações de propriedades físicas e mecânicas, como por exemplo alta rigidez combinada à peso específico muito baixo, ou permeabilidade à gases combinada com condutividade térmica alta, o que oferece amplas possibilidades de emprego, como por exemplo na indústria aeroespacial. Existem várias aplicações em desenvolvimento para estes materiais, particularmente como segurança passiva devido a sua alta capacidade de absorção de energia em situações de impacto. A análise de dano nas espumas metálicas é um problema complexo que deve ser analisado no contexto de grandes deformações. Considerando que a compressão é a carga dominante em situações de impacto, neste trabalho é mostrada a simulação de um teste de compressão em uma amostra de metal celular incluindo efeitos de dano. São apresentadas comparações com dados experimentais.*

Palavras-Chave: *Metais celulares, Espumas metálicas, Dano, Modelo de Gurson,, Elementos Finitos*