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INFLUENCE OF CERAMIC FOAM PARAMETERS ON THE FRACTURE BEHAVIOUR UPON THE TENSILE TEST

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Abstract: *The contribution deals with numerical simulation of response of the open cell ceramic foam to tensile loading and attempts to predict experimental fracture-mechanics behaviour of the foams using numerical FE model composed of beam elements. Models of different structure irregularity (including regular one) are considered and generated using 3D Voronoi tessellation technique. Complete fracture of the model is simulated by iterative FE simulations where in each step, one strut with maximal tensile stress (higher than the material tensile strength) is removed – until complete separation of the model in two parts. Critical forces, leading to complete breakage of the foam structure, together with final fracture "surfaces", are investigated and compared for both regular and irregular structures. It is shown that the regular foam structure, composed of Kelvin cells, exhibit generally 10 – 20 % higher fracture resistance than the irregular foam structures and also that structures with smaller cells should be more fracture resistant than the structures with bigger cells.*

Keywords: Ceramic foam, Fracture, FEM, Voronoi tessellation, Tensile test.

1. Introduction

The growing exploitation of ceramic foams with open cell porosity in a great number of industrial branches and/or as bone replacement materials, has instigated experimental and theoretical studies of their mechanical behaviour. The main drawback still impairing the use of ceramic open foams in load-bearing applications is their intrinsic brittleness. Understanding and prediction of the fracture of such foams under various loading conditions is thus essential for employment of them in the mechanically loaded applications. Most authors employed perfectly periodic tetrakaidecahedron cells corresponding to the open-cell Kelvin foam, e.g. (Warren and Kraynik, 1997), (Zhu et al., 1997) or (Li et al., 2005). Real irregular foams were modelled by a random dispersion of the joint positions from that of the perfect lattice, see e.g. (Tekoglu et al., 2011), (Roberts and Garboczi, 2002). With regard to the overall elastic properties it was shown that the Kelvin foam based models very often provide a reasonably good approximation. However, with regard to strength prediction, irregular foam structure exhibit different behaviour comparing to regular one (usually lower resistance to fracture). Another parameters influencing the fracture resistance could be the cell and structure size and the foam porosity. Effect of these parameters is thus going to be investigated within this contribution using the simplified beam element based model, enabling modelling of larger foam structure volumes even with relatively low demands on the computation time. The main aim of the work is to understand how the tensile strength of the given ceramic foam depends on the foam (primarily geometrical) characteristics. The work will also extend recent pieces of knowledge of a previous work of authors, where a study of the influence of the structure irregularity on the apparent Young´s modulus of the foam structure has been carried out - see (Ševeček et al., 2017).

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2. Computational model

To investigate an influence of the ceramic foam parameters (such as foam porosity, cell irregularity or cell size) on the response of the foam to a tensile loading, a 3D-beam element based FE model was developed (with both regular and irregular structure – see Fig. 1a). First, as the reference case, the FE model of the foam composed of regular Kelvin cells was prepared using the 3D Voronoi tessellation in mathematical software Matlab, where the cores of the future cell were regularly distributed within the volume of a block. To create the irregular structure, each of these cores, were moved in the random direction (within a spherical volume) by random distance d (lying within interval 0-d_{max}) before running of the tessellation process. Value d_{max} is related to the size of the cell D_C using parameter δ - as shown in Fig. 1b). After modification of all cores positions within the whole model volume (for specific δ), the irregular structure of cells was created again using the Voronoi tessellation routine and subsequently exported using APDL (Ansys Parametric Design Language) text commands into FE system ANSYS 16.2 where simulations and post-processing were executed. Particular struts of the foam structure were meshed using quadratic 3D beam elements BEAM189. Each strut has been meshed using a single element to reduce number of elements in the model. Since the used element type is a quadratic one, even this simplification provides a sufficiently accurate solution to stresses within the struts, in comparison with a finer discretization. The struts were considered to be of circular cross-section and of the same thickness all along their length. This simplification does not correspond with a real state, but it is sufficient for qualitative comparison of various geometrical configurations of the foam structure. The dimensions of the model were designed to meet dimensions of a typical tensile test specimen – in our case 10 x 10 x 30 mm. The applied boundary conditions (simulating tensile test) are depicted in Fig.1a).

A pure stress criterion was employed to define failure of the particular struts. The model was subjected to stepwise displacement load (in z-direction) and in each loading sub-step the stress conditions in all struts were monitored. In case, when the tensile stress in the strut exceeded its critical value (in our case corresponding to the strength of the bulk ceramic σ_c = 60 MPa) the corresponding element of the strut was removed and a new FE solution step was performed. Such a simulation process was iterated until the whole cross-section of the foam structure was broken or at least until that moment when the reaction force at top fixture of the model started to drop (which indicates the achievement of the tensile strength of the foam structure). Young's modulus of the considered ceramic material was considered to be E_{bulk} = 90 GPa and Poisson ratio ν_{bulk} = 0.25 (corresponding to source material of "VUCOPOR®A" - Al_2O_3 based ceramic foam).

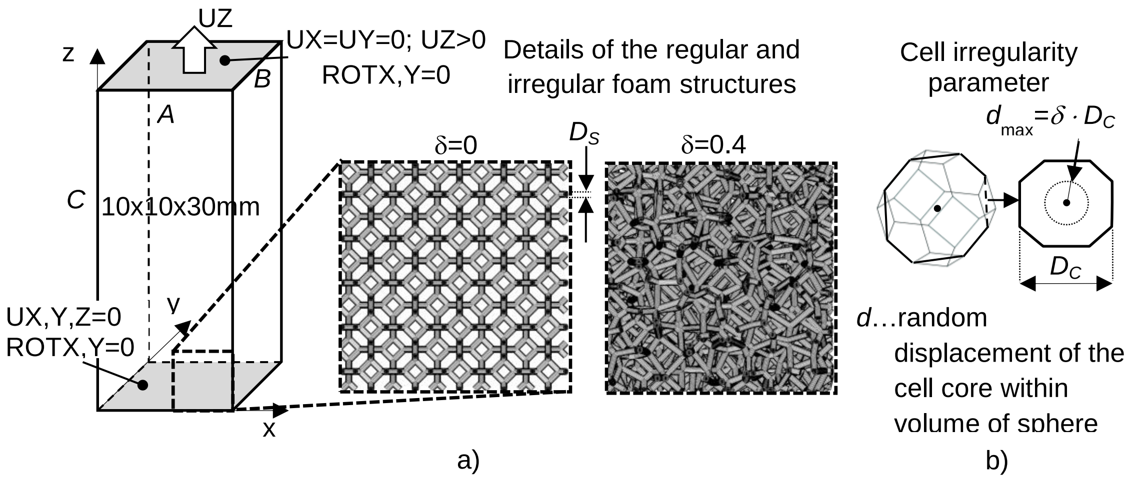

Fig. 1: a) Scheme of the boundary conditions applied to the FE model;
b) Definition of the cell irregularity parameter δ.

3. Results

Using the above described FE model a parametric study, investigating an influence of the cell size and foam porosity on the tensile strength of the foam (critical fracture force), has been performed. For three different cell dimensions D_C a set of foam structures with various strut diameter was generated – for more details about the geometrical combinations used within the study see Tab. 1. With these parameters both regular and irregular foam structure models were subjected to tensile test simulation. In case of the irregular structure, several different meshes with same parameters were always simulated (to involve into the study also a statistical factor of the mesh irregularity).

Tab. 1: Varied geometrical characteristics of the investigated foam structures.

Porosity [%]	**D_C=800μm**	**D_C=1200μm**	**D_C=1600μm**
	D_S [μm]	**D_S [μm]**	**D_S [μm]**
99	30	45	60
95	70	105	140
90	110	165	220
80	160	240	320
70	200	300	400

The results of the failure stresses and displacements for various geometrical configuration of the foam structure model of dimensions 10 x 10 x 30 mm are summarized in the plots of Fig. 2a and 2b.

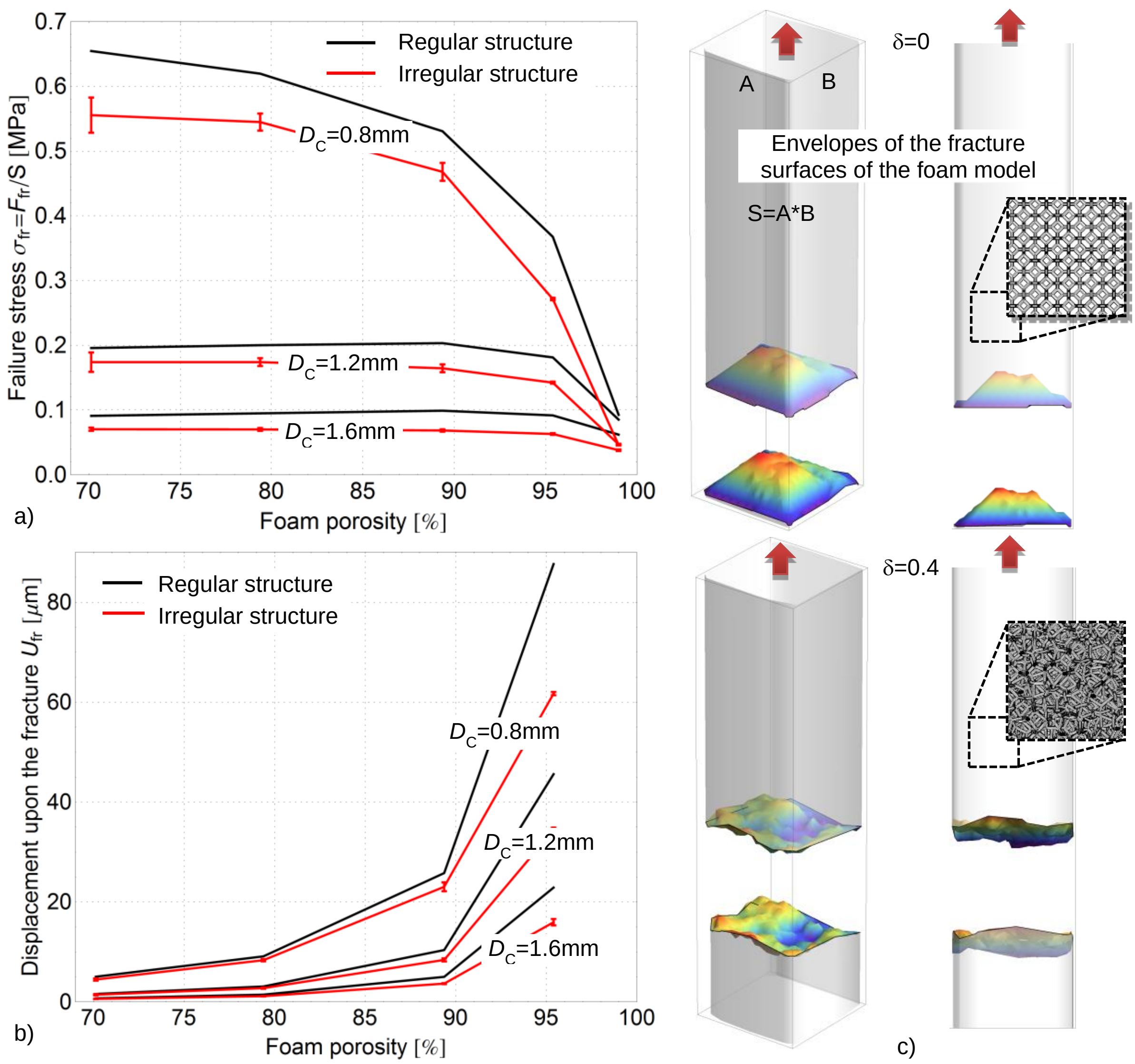

Fig. 2: Dependence of: a) Fracture stress, b) Displacement of top of the specimen upon the fracture, on the foam porosity and cell size D_C for a specimen of dimensions 10 x 10 x 30 mm; c) Demonstration of the simulated fracture surfaces in case of the regular (δ = 0) and irregular mesh (δ = 0.4).

Based upon the performed simulations the tensile strength of the regular structure is about 10 – 20 % higher than of the irregular one. This fact can be explained by different orientation of the struts to loading direction in both models. While in case of the regular structure, most (2/3) of the struts are oriented under 45 ° to loading direction, in case of the irregular structure, most of the struts are oriented with angle higher than 50 ° to loading direction so these struts have higher bending stress components resulting in increase of tensile stresses on the strut surface. Since the bending of struts leads to higher stresses in comparison with a pure tension (upon same external loading conditions), the struts are broken under lower applied loads and the structure thus globally exhibit lower resistance to fracture. The plots also shows that the tensile strength of the foams is higher for structures composed of smaller cells than of the bigger ones. This can be explained by the bending theory of beams. The bending moment at the end of the strut depends on the length of the strut, so the longer the strut is, the higher bending moment is achieved and the higher stress is induced at the strut end. The longer strut will thus fail earlier than the shorter one.

To demonstrate how the final fracture of the foam structure model can look like, envelopes of the separated model surfaces were created, see Fig. 2c). In case of the regular structure, the fracture usually starts at the site of the supports and extends under the angle of 45 ° towards the centre of the specimen. On the other hand in case of the irregular structure, the fracture can occur at arbitrary place along the specimen length and the fracture “surface” is of irregular shape.

4. Conclusions

Fracture mechanics response of the ceramic foam structure of various porosity and cell size on the applied mechanical load was studied using the FE analysis and beam element based models. Based upon the performed simulations it can be concluded that the tensile strength of the regular structure is about 10 – 20 % higher than the strength of the irregular structure. The results also show that foam structures with smaller cells should exhibit higher resistance to fracture than structures with bigger cells (under consideration of the same porosity of both structures). The smaller the cell (and correspondingly strut length) is, the lower stresses are generated on them and the foam structure thus sustain higher applied loads before reaching the critical failure stress on particular struts. It must be pointed out yet, that the beam element based model of the foam structure, used in this work, is a strong simplification of the real state of the foam structure which should be primarily used for qualitative comparison of various geometrical configurations, but quantitatively can produce different results in comparison with the realistic 3D (solid element based) models. On the other hand, with realistic 3D models it would be very difficult to study failure of bigger foam structure volumes, because of necessity of the very fine discretization of particular struts which in combination with iterative simulation process (described above) would lead to very long computation times. A solution of this problem could be a utilization of the sub-modelling technique, where just critical part of the foam structure is modelled using the realistic 3D mesh. This is planned to be done in the future studies.

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