BRITTLE FRACTURE OF OPEN-CELL KELVIN FOAM

Michael Ryvkin [a)] & Leonid Kucherov
School of Mechanical Engineering, Faculty of Engineering, Tel Aviv University, Ramat Aviv, Tel Aviv, 69978, Israel

Summary The flaw propagation in a spatially periodic brittle elastic lattice subjected to a uniaxial tension is considered. The initial defect is introduced by removing a strut, and sequent break of the struts resulting from the stress redistribution is observed. The dependence of the obtained fracture pattern upon the loading direction is investigated.

Fracture behavior of 2D cellular materials is a well documented topic (e.g., [1]). Failure of foams which are modelled by spatial lattices is less investigated, the published results deal mainly with compressive loading [2]. In the present paper fracture of an open-cell foam subjected to a uniaxial tension is considered. The perfect Kelvin foam is addressed with the periodic microstructure produced by straight-linear elastic struts rigidly connected at the nodal points (Fig. 1). Each node has six degrees of freedom and struts undergo stretching, bending and twisting deformations. The fracture analysis of such a material is complicated by the fact that its microstructure defines several possible crack propagation planes. Therefore, similar to the 2D case, it is of interest to investigate the crack nucleation phenomenon [3] prior to the fracture toughness analysis.

The problem is formulated as follows. The lattice is subjected to a remote uniaxial tensile loading, and the generated periodic stress state is then violated by removing (breaking) a strut. The analysis of the lattice with one missing strut shows, which of its neighbors is the most stressed one and, consequently, will fail next. Then the lattice with two missing struts is considered and this procedure is repeated until a cluster of broken struts produces a clear fracture pattern (flaw). The adopted criterion for the strut failure is that the skin stress evaluated in the framework of the beam theory reaches the tensile strength of the parent solid material.

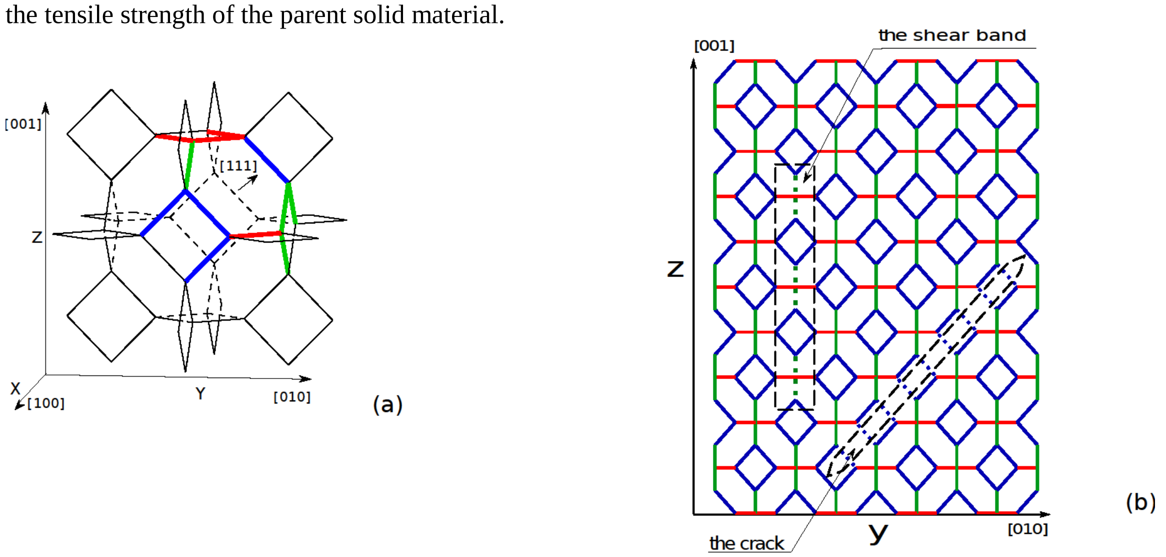

Fig. 1. Part of the spatial lattice modelling the open-cell Kelvin foam with the representative cell emphasized by colour (a), and two possible flaw types which may appear, colours indicate the elements parallel to the respective coordinate planes (b).

The direct numerical modeling (e.g., by the finite element method) of a large portion of lattice material, which is required to achieve a universal result for a flaw in an unbounded lattice is a non-trivial computational task due to a large number of degrees of freedom. Therefore an analytical approach based on the discrete Fourier transform is employed. The solution $\boldsymbol{U}$ for the lattice with $\boldsymbol{J}$ missing struts is sought in the form of superposition of the solutions for the undamaged lattice

$$U = U_0 + \sum_{j=1}^{6J} C_j U_j$$

where $\boldsymbol{U_0}$ is the periodic solution corresponding to the remote tensile loading, $\boldsymbol{U_j}$ are the solutions produced by the unit forces applied to the struts to be removed, and $\boldsymbol{C_j}$ are the unknown coefficients, which are adjusted in order to cancel six generalized internal forces at the extremities of these struts. The solution $\boldsymbol{U_0}$ is derived from the results obtained in [4] and the solutions, $\boldsymbol{U_j}$ are found similar to [3] by the representative cell method hinged on the discrete Fourier transform. To this end the lattice is viewed as an assemblage of identical cells consisting of 12 struts (struts of one cell are shown in

[a)] Corresponding author. Email: arikr@eng.tau.ac.il

colour in Fig. 1a) and, consequently, the analysis of the entire lattice is reduced to multiple analyses of the representative cell in the transform space.

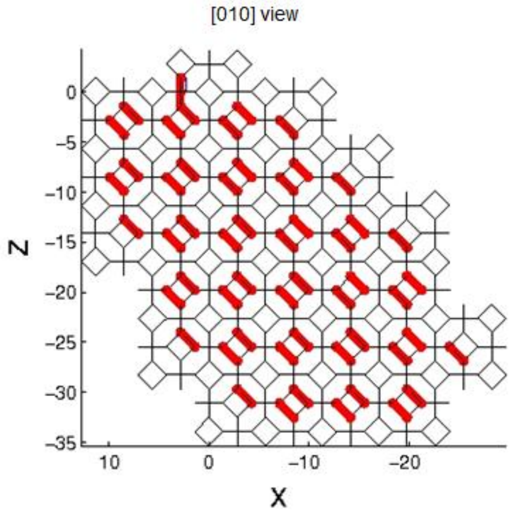

Fig. 2. Fracture pattern obtained for the tension in the [111] direction, the broken struts shown in red.

As expected, the structure of a nucleated flaw depends upon the applied loading direction. The general trends observed for different loadings and strut aspect ratios varying within the limits (0.01, 0.1) are as follows. The damaged region produced by broken struts is found to be a planar penny-shaped like spot. The flaw propagates along the "weak" planes, which are never orthogonal to the loading direction. The only crystallographic planes where the flaw obtained can be treated as a crack with complete separation of the material are the {101} ones. An example of a crack-like flaw of this type is shown in Fig. 1b. This phenomenon can be explained by the fact that all the struts crossing these planes are perpendicular to them and, consequently, provide a poor resistance to the shift between the corresponding half-spaces. Flaw of another non-crack type was observed, e.g., for the tension in the {111} directions. It develops in the {001} planes and may be baptised as shear band since the parts of material at the opposite sides of the flaw remain connected. Only part of the struts in the flaw plane is broken and on a macroscale this region will be characterised by an increased shear deformation. An example of the obtained fracture patterns is shown in detail in Fig. 2 and indicated in Fig. 1b. The question either the shear band flaw at some stage will convert to a crack or not is a subject for further investigation.

CONCLUSIONS

The numerical experiments were carried out for the flaw nucleation in the spatial lattice modelling open-cell Kelvin foam subjected to a uniaxial tension. It was found that broken lattice struts form a planar flaw the type of which depends upon the remote loading direction. Two competing failure mechanisms are detected. The crack-like flaw appears at one of the {101} “weak” planes characterized by low resistance to shear deformation, and never perpendicular to the tensile loading direction. The second flaw type at {001} planes is similar to shear band without complete separation of the material in the flaw region. The obtained results provide a necessary information for the study of crack resistance of the Kelvin foam and can be used in design of new energy absorbing materials with shear band dominating failure.

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References

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