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AN EXPERIMENTAL AND MODELLING EVALUATION OF THE DEFORMATION AND FRACTURE OF QUASI-BRITTLE RETICULATED VITREOUS CARBON FOAM

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Abstract: In quasi-brittle materials the addition of specific microstructural features such as porosity can lead to departure from linear elastic behaviour prior to maximum force, followed by graceful failure. A simple but extreme example is reticulated vitreous carbon foam, with its open-cell structure of brittle ligaments connected in a three-dimensional array. Tensile testing has been made on foams with various pore and ligament dimensions to provide a measure of force-displacement, combined with acoustic monitoring, and evaluation of the associated elastic moduli and fracture strengths. These tests provide insights into the mechanisms of quasi-brittle failure. The results are explored by comparing with predictions from a microstructure-based finite beam element model. Inputs to the model are the elastic modulus and fracture strength of the individual ligaments of the foam measured at the micro length-scale. Results are discussed with respect to the energy of fracture, the distribution and progression of fracture for individual ligaments.

1. Introduction

Quasi-brittle materials are those where the addition of specific microstructural features such as porosity can lead to departure from linear elastic behaviour prior to maximum force, followed by graceful failure. A simple but extreme example of a quasi-brittle material is reticulated vitreous carbon foam. The composition is simply carbon, but being vitreous there is little order on the atomic scale in contrast to graphite; the individual ligaments would be expected to have linear elastic brittle fracture characteristics like a glass. The ligaments are assembled in a random three-dimensional array with four ligaments emanating from each node, to form an open-celled foam [1].

2. Results

Samples of reticulated vitreous carbon foam, obtained from Ultramet (Pacoima, USA) with three pore sizes, 10 pores per inch (ppi), 45 ppi and 100 ppi (density 0.047, 0.054 and 0.057 $g.cm^{-3}$ respectively), were cut to produce cylindrical specimens of two sizes: 12 mm diameter x 12 mm long; and 25 mm diameter x 25 mm long. Cutting was undertaken using either a slow speed diamond wheel saw for flat surfaces or a trepan tool for the cylindrical surfaces. The ends of the cylindrical specimens were glued to aluminium plates using a stiff, fast-curing adhesive (5 minute epoxy). One plate was glued to a cylinder end initially and the assembly was mounted in the tensile tester. A second plate was then glued to the other end of

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the cylinder while the specimen was in the tester so as to minimise mounting strain on the specimen. After the glue had dried and cured for at least an hour, tensile testing commenced. A Zwick/Roell tensile tester was used in these experiments. Force and displacement were measured during the tests, which were displacement controlled. A displacement rate of 0.1 mm.min^{-1} was used throughout. An Olympus LS-10 sound recorder was placed approximately 2 cm from the specimen during testing in order to record any acoustic emissions. A simple USB camera was used to record images of the specimen at 1 s intervals during testing. In addition to these macro-length scale tests, micro-length scale tests were undertaken to determine representative mechanical properties for individual ligaments. Cantilever beam test specimens, typically 2 μm x 2 μm x 10 μm, were prepared by gallium ion milling in an FEI Helios Nanolab 600i dualbeam workstation [2]. Each test was undertaken within the workstation using a customised loading arrangement based on a system provided by Kleindek Nanotechnik. This gave a measure of the elastic modulus 29 ± 4.5 GPa and the fracture strength 350 ± 50 MPa for the vitreous carbon ligaments that were input to the computer modelling.

A microstructurally based finite beam element model was used to simulate the force-displacement response, elastic modulus and fracture strength obtained from the various reticulated carbon foam tensile tests [3]. The simulated specimens had a cylindrical geometry and were of the same dimension as those experimentally tested. In the model, pores were positioned at the centres of regular 14-hedra (eight hexagonal faces and six square faces) with the edges of the polyhedra defining the ligaments and the vertices representing nodes for the foam; the centres were positioned on a body centred cubic lattice arrangement. This regular cellular arrangement was modified by shifting each of the nodes by a small distance randomly to be more representative of the foam material. In addition, the cross-sectional areas of the ligaments were compensated to accommodate the changing thickness adjacent to each node. The mesh created was subjected to a simulated uni-axial tensile load in the vertical direction. To mimic the experimental conditions, all nodes at the top and the bottom surface were fully constrained and a vertical displacement was applied at the top. In the simulation, all elements were assigned linear elastic brittle behaviour, as observed in the micro-length scale mechanical tests.

3. Conclusions

The results of the tensile tests demonstrate that with their open pore skeletal structure, reticulated vitreous carbon foams deform and fracture with quasi-brittle characteristics. The predictions from computer modelling are compared with experimental data and provide insights into the mechanisms of quasi-brittle failure. In particular, the experimental and modelling results are discussed with respect to the distribution and progression of fracture for individual ligaments of the foam and the energy to initiate ligament failure.

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References

[1] P.J. Heard, P.E.J. Flewitt. Study of reticulated vitreous carbon foam as a quasi-brittle material, *Key Eng. Mat.* 2016:665:229-232.

[2] J. Darnbrough, D. Liu, P.E.J. Flewitt. Micro-scale testing of ductile and brittle cantilever beam specimens in situ with a dual beam workstation, *Meas. Sci. Technol.* 2013;24:055010(9pp).

[3] B. Šavija, D. Liu, G. Smith, K.R. Hallam, E. Schlangen, P.E.J. Flewitt. Experimentally informed multi-scale modelling of mechanical properties of quasi-brittle nuclear graphite, *Eng. Fract. Mech.* 2016;(in press).