Optical strain measurement techniques for soft cellular structures

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Abstract. Soft cellular structures are found extensively throughout nature and can be used to inspire the design of structures for a wide range of engineering applications. For many applications, such as soft tissue scaffolds, structure stiffness and density need to be optimised. This study aimed to investigate the effect of cell density for a constant material volume on structure behaviour and stiffness. An Imetrum video strain gauge system and a Dantec digital image correlation (DIC) system were used to capture structure deformation under tensile uniaxial loading. Results demonstrated that with an increase in cell density there was an increase in structure stiffness, with experimental results validating those found through Finite Element models (FEM).

Introduction

Naturally occurring soft cellular structures are widespread, such as the natural supporting structures of plant stems, the structure of bone tissue, and forming the periodic structures of honeycomb within a beehive. Cellular structures possess many interesting and desirable properties, and by taking influence from these natural structures, new materials and structures can be designed for many engineering applications [1]. For many such applications, such as soft tissue scaffolds, the density and stiffness of the structures need to be optimised. This study aims to investigate the effect of varying the number of cells for a constant material volume for cellular bodies of non-linear materials through the use of optical strain measurement techniques. These results will be used to validate FEM results.

Experimental Methods

Specimen Manufacture. 3x3, 5x5 and 9x9 cellular structures were designed and manufactured with a constant material volume within the area of interest. Each structure has a constant thickness to length ratio, a parameter known to affect structure performance [1]. Specimens were made by casting Tech-Sil 25 silicone in aluminium moulds.

Uniaxial Tensile Testing. A bespoke fixture was designed for tensile testing of the specimens (Figure 1). This fixture allowed a uniaxial tensile load to be applied to the structures in the vertical y-direction, whilst using needle roller bearings such that the structure was unconstrained in the horizontal x-direction and the out-of-plane z-direction. The fixture had a low co-efficient of friction (<0.02) on the surface contacting the bearings, meaning the effect of friction would be minimal when testing. Structures were loaded at a rate of 2mm/s and to a maximum load of 100N.

Figure 1. Test fixture for tensile testing of specimen.

Optical Strain Measurement Techniques. An Imetrum video strain gauge was used to capture the displacement of the structure and test fixture throughout the tensile loading. In addition, a Dantec dynamics two camera DIC system [2] was also used to investigate the behaviour of the cellular structures at the cellular level, focusing on the deformation and strains within the cell walls. Both techniques were used simultaneously to provide a complete picture of the structure's behaviour, validate that the correct approach was used for testing and to validate the FEM results.

For both optical measurement techniques a high contrast pattern was required. For the DIC, white and black Snazaroo face paints and a sponge were used to create the random speckle pattern required (Figure 2). This was applied over a small area of interest in the centre of each of the structures. For the video strain gauge system, a marker pen was used to apply black dots to the surface of the specimen, with dots applied to the intersections and mid wall of the cells.

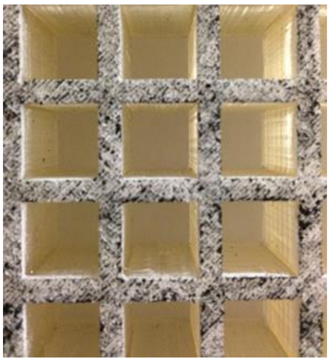

Figure 2. Face-paint speckle pattern on cellular structure.

Finite Element Modelling. The FEBio software suite was used to produce and analyse the FEM. The structure design and boundary conditions replicated the conditions used for the experimental testing of the structures, however the models used symmetry conditions to reduce computational time. For each structure a mesh convergence study was conducted. The silicone was modelled as a neo-Hookean material, with an elastic modulus of 0.74 MPa, and a Poisson's ratio of 0.48.

Results and Discussion

When comparing the performance of the three different structures, structure stiffness was found to increase with an increase in the number of cells (Figure 3). This trend was found experimentally and within FEM. The behaviour of each of the structures experimentally was compared to the FEM (Figure 4). Each structure had a mean relative error of 10-12% when comparing FEM engineering strain to experimental engineering strain up to around 80% strain. The accuracy of the models can be improved through improved characterisation of silicone behaviour and material parameters for use within the FEM. This is the goal for future work and would be expected to result in a lower relative error, especially at strains below 50%.

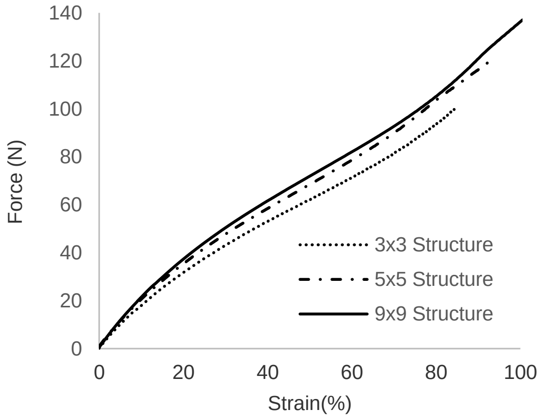

Figure 3. Experimental results for structures with varying cell density with the figure showing force versus engineering strain for the entire structure,.

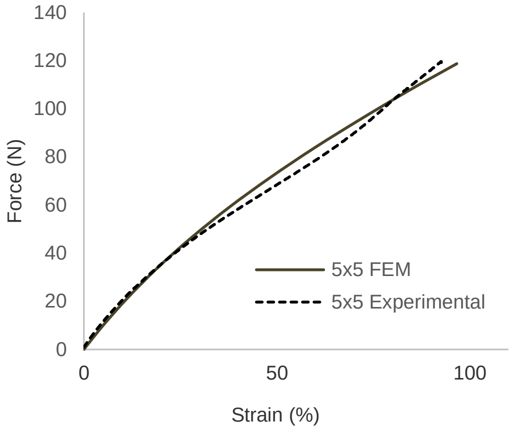

Figure 4. Force versus engineering strain for the entire 5x5 structure, comparing FEM and experimental data.

DIC investigated the behaviour of the structure wall at a cellular level, demonstrating how the strain varies due to the complex behaviour of the structures. At the intersections of the cell walls complex behaviour can be seen (Figure 5). The strain distribution seen within Figure 5 is similar to that seen within the FEM. The strain distribution seen at the intersection is due to the vertical struts being in tension and the horizontal struts being in compression.

Video strain gauge data was used to measure displacement across the entire structure, and thus compute strains across the various regions. Both the horizontal-x and the vertical-y strains were analysed, and the Poisson's ratio of the structures computed. The Poisson's ratio was a parameter of interest due to the decreasing behaviour that can theoretically be achieved with these structures [3]. When considering the global behaviour of the structure, video gauge data demonstrated a small reduction in the apparent Poisson's ratio of the structure as the tensile load increased, additionally the apparent Poisson's ratio for the individual cells within the structure were found to differ to that of the overall structure. Further analysis of this data is required to fully understand the effect of cell density on Poisson's ratio.

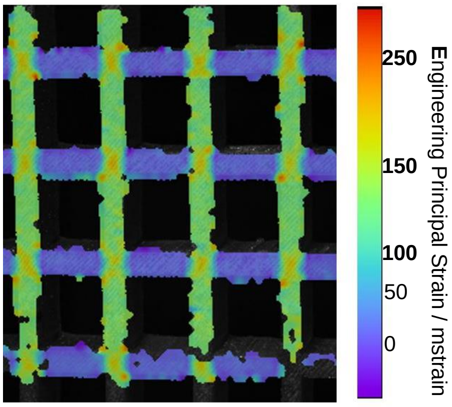

Figure 5. Image from DIC showing the maximum engineering principal strain for a non-linear cellular structure.

Conclusion

Uniaxial tensile testing of non-linear cellular structures was conducted, and a good comparison was found between the experimental and FEM data. Two optical strain measurement techniques were used within this study, with DIC providing information on a cellular level and demonstrating the complex strain distributions within the cell walls, and the video gauge being used to investigate the global behaviour of the structure, including a reduction in the Poisson's ratio of the overall structure with increasing tensile load.

Acknowledgements The support for L.A.M. and H.W. by the Engineering and Physical Sciences Research Council of Great Britain under research grant EP/M011992/1 is gratefully acknowledged.

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