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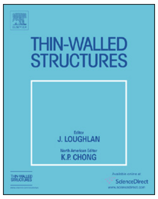

Full length article

Compressive and shear strengths of the ductile closed-cell Kelvin and Weaire-Phelan foams along the lattice direction [100]

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ABSTRACT

The compressive and shear responses of the closed-cell Kelvin and Weaire-Phelan foams along the lattice direction [100] were studied using explicit dynamic analyses in this work. Expressions describing the relationship of compressive and shear strengths to relative density were developed for these two foams. The compressive and shear strengths of the Kelvin and Weaire-Phelan foams are found to increase quadratically with relative density at low relative densities and linearly at high relative densities. This is because elastic buckling followed by material yielding cause the failure of low relative density foams, while large deformation and material yielding is the main cause of failure for high relative density foams. Cell wall buckling and local material yielding only cause reduction in global stiffness. Ductile foams fail globally when a certain amount of material has yielded, forming a plastic band across the foams. Shear buckling occurs in foams with very low relative density under shear.

1. Introduction

Foam materials have been increasingly used in a large number of applications such as packaging, heat insulation, acoustic isolation, impact energy absorbing, cores of sandwich structures, filters and flotation, due to their advantages of improved properties, such as lightweight, large impact and acoustic absorption and low thermal conductivity [1]. It is well recognized that the global properties of foams are dependent on the properties of materials from which the foams are made (base materials) and foam microstructures. Numerical modelling of foams has been extensively undertaken in the last decades [1–28] in order to investigate the property-microstructure relationship of foams, to understand foam deformation and failure mechanisms, and to provide a predictive tool for foams. Over the years, three types of foam micro-models have been developed, namely, idealized cell models (including the cubic unit model [1], the Kelvin model [29] and the Weaire-Phelan model [30]), tessellation models (including Voronoi tessellation [9,31] and Laguerre tessellation model [10,11,32]) and tomography image-based models [33–36]. Idealized foam cells have simple geometry, therefore often being utilised to study foam mechanics.

For instance, Gibson and Ashby [1] established the relationship between the global properties of open- and closed-cell foams and their relative density using the cubic model and scaling law. The Kelvin cell (truncated octahedron with the hexagonal faces slightly curved) was proposed by Lord Kelvin [29] in 1887 as a solution to the famous question posed by himself – how space can be partitioned into cells of equal volume with the least surface area. It has been widely used to study foam properties during the last decades. For example, Kyriakides, et al. [5,18,20,37,38] modelled the compressive responses of a polyester urethane open-cell foam and an aluminium open-cell foams using the Kelvin cell with measured general geometric characteristics. Zhu and Mills [39–41] analysed the responses of the open- and closed-cell Kelvin foam to high strain compression. Simone and Gibson [2,3] obtained the relationships of Young's modulus and collapse stress of the closed-cell Kelvin foam to its relative density and investigated the effects of solid distribution, cell face curvature and corrugations on the stiffness and strength of the Kelvin foam. Grenestedt [4,42] studied the effects of cell shape and cell wall thickness variations on the stiffness of closed-cell foams using the Kelvin model. Fischer and Handge [43] ascertained that the mechanical properties of polymeric foams can be adequately predicted using the Kelvin model incorporating the inhomogeneous feature of foam microstructures. Mills [44] and Nammi [12] predicted the compressive impact response of closed-cell foams using the Kelvin model. Mills [45] investigated the deformation mechanism and yield surface of low-density polymeric closed-cell foams

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based on the Kelvin model.

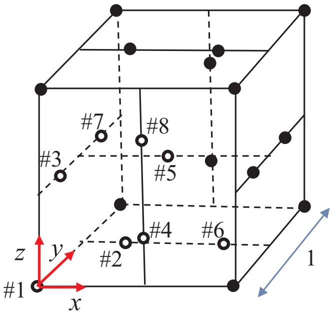
For more than a century the Kelvin cell was believed to be the solution to the Kelvin's problem. However, in 1994, Weaire and Phelan [30] published a new structure, known as the Weaire-Phelan structure, which is an aggregate of eight polyhedrons, one irregular dodecahedron with pentagonal faces and seven tetrakaidecahedrons with two hexagonal and twelve pentagonal faces. The Weaire-Phelan structure partitions space into cells of equal volume with a surface area approximately 0.3% less than the Kelvin cell. Additionally, the Weaire-Phelan structures are more consistent with Matzke's foam observations [46] than the Kelvin cell. Therefore, theoretically the Weaire-Phelan structure is more suited for modelling foams, at least from the perspective of geometrical similarity. However, in comparison to the Kelvin foam, research on the mechanical response of Weaire-Phelan foam is far less abundant. Daxner and Bitsche [47,48] investigated the relationship between elastic moduli and relative density of the closed-cell Weaire-Phelan foam, and compared the properties of the closed-cell Weaire-Phelan foam with the closed-cell Kelvin foam. They found that the average effective mechanical properties of the Kelvin and Weaire-Phelan foams are close, within a few percent of each other, and the Weaire-Phelan foam is more isotropic than the Kelvin foam.

So far, the relationship of the compressive and shear strengths with the relative density and failure mechanisms of the closed-cell Weaire-Phelan foam have not been understood. The shear response of foams is important for their application as cores in sandwich structures. However, the modelling of foams to date has mostly focused on the aspects of compressive response and linear elastic shear response [4,9,10,42,47,49]. The nonlinear shear response of closed-cell foams has not been investigated much. In the present study, the nonlinear compressive and shear responses of the closed-cell Weaire-Phelan foam along the lattice direction [100] were explored. The compressive and shear strengths of the closed-cell Weaire-Phelan foam were determined and compared to those of the closed-cell Kelvin foam and Laguerre tessellation foams with uniform cell size and cell wall thickness. The deformation and failure mechanisms in the closed-cell Weaire-Phelan foam under compression and shear were subsequently investigated.

2. Methodology

2.1. Construction of the Kelvin and Weaire-Phelan models

In this work, all the cell faces in the Kelvin and Weaire-Phelan structures are assumed to be flat. Therefore, the Kelvin cell is approximated by a regular tetrakaidecahedron and was directly generated in Abaqus by constructing cell vertices, edges and faces. Nine Kelvin cells were built and fitted together. Then, a representative unit cell, as shown in Fig. 1a, was extracted from the assembly of Kelvin cells. The Weaire-Phelan structure cannot be created in the same way as the Kelvin cell due to the complexity of geometry. But the Weaire-Phelan structure is a special Voronoi tessellation, with seed points spatially positioned as shown in Fig. 2. The table in Fig. 2 lists the relative coordinates of the representative seed points. Hence, the Weaire-Phelan foam was built in the manner of generating Voronoi tessellations. Firstly, the topological information about each cell, such as the coordinates of vertices, which vertices constructs a line and which lines form a face, was determined and saved hierarchically in Matlab. Then, each cell was constructed from vertices, edges to faces in Abaqus using python scripts. Finally, a representative cubic unit cell of the Weaire-Phelan foam was cut out, as shown in Fig. 1b.



	x	y	z
#1	0.00	0.00	0.00
#2	0.25	0.50	0.00
#3	0.00	0.25	0.50
#4	0.50	0.00	0.25
#5	0.50	0.50	0.50
#6	0.75	0.50	0.00
#7	0.00	0.75	0.50
#8	0.50	0.00	0.75

Fig. 2. Cubic unit lattices of seed points of the Weaire-Phelan structure [30].

To investigate the accuracy of shell elements in modelling the response of closed-cell foams, models with solid elements (see Fig. 3) were generated. Compressive and shear tests were performed on the shell and solid element Kelvin models at relative densities of 11.16%. Fig. 4 presents the compressive and shear stress-strain curves predicted by the solid and shell element models. It can be seen that results predicted by shell elements and solid elements are in very good agreement.

2.2. Relative density calculation

When cell walls are discretised by shell elements, there is an overlap of material at cell wall junctions, as shown in Fig. 5, which should be taken into account while calculating the relative density of foam models. The relationship of relative density to cell wall thickness and cell edge length for the closed-cell Kelvin foam can be approximated by Eq.(10) in [2]. In the closed-cell Weaire-Phelan foam, three cell walls join together at approximately 120°. Hence, the cross-sectional area of overlapping material at cell wall junctions is

$$\Delta S = \frac{\sqrt{3}}{4}t^2 \tag{1}$$

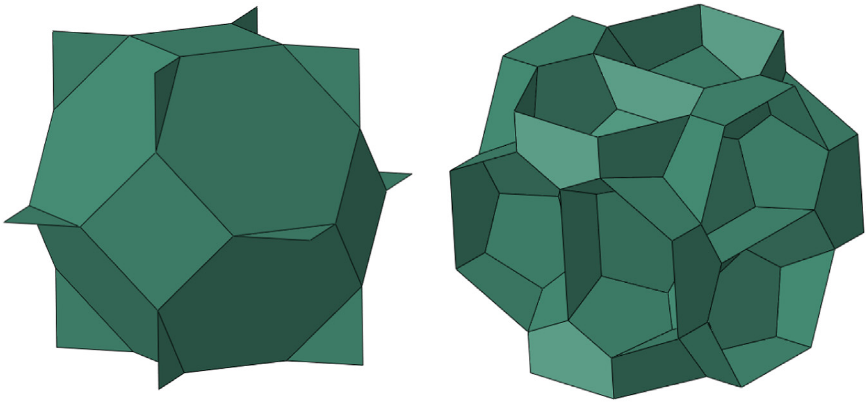

(a) (b)

Fig. 1. Representative unit cells of (a) the Kelvin foam and (b) the Weaire-Phelan foam.

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