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MODELLING MECHANICAL BEHAVIOR OF ALUMINIUM FOAM UNDER COMPRESSIVE LOADING USING REPRESENTATIVE VOLUME ELEMENT METHOD

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Abstract:
In this paper, a numerical study is conducted to model the mechanical behaviour of aluminium foam under compressive loading using the representative volume element (RVE) method. Tetrakaidecahedrons are selected as cells to form the RVE model for modelling the mechanical properties of the aluminium foam. The study is conducted via the commercial finite element code Ansys-LS Dyna. The three-dimensional solid element 164 is used to mesh the RVE model.This micro-structured RVE model is used to model the mechanical behaviour of aluminium foam of density of 230 kg/m^3 under quasi-static compressive loading. A convergence test is firstly conducted to decide the mesh density. The stress-strain relationship obtained from the numerical modelling is compared to that from experimental study and the agreements of the results demonstrate the efficiency of the RVE model. The deformation process of the RVE under the compressive loading obtained from the numerical simulation is also presented.

Introduction

Close cell aluminium foams are very competitive materials for application in engineering structures where weight and impact resistance are the main concerns, due to their superior mechanical characteristics such as light weight and energy absorption. Typical application of aluminium foams include aircraft wing structures [1],engine fan propeller blades [2], telescope lifting systems[3], trucks and trains [3] and space structures [4].

To facilitate the structural application of the aluminium foams with effective and optimal structural design, it is essential to gain an insightful understanding of the mechanical behaviour of the materials. Finite element modelling have been employed to study the mechanical behaviour of metal foams and demonstrated to be an effective method [5-9]. These models were mainly generated based on the Voronoi random method, which results in unstable mechanical properties due to the randomness. Utilising repeating cells such as

tetrakaidecahedrons is a possible way overcome this flaw and can guarantee stable mechanical properties. Researchers have developed some aluminium foam models based on tetrakaidecahedron cells. Simone and Gibson [10] proposed a model and analytically analysed the effect on stiffness and strength of closed-cell tetrakaidecahedral foam. Song et al.[11] developed a model of 686 tetrakaidecahedron cells to model the dynamic crushing behaviour of aluminium foam. Nonetheless, modelling the mechanical properties, especially the hardening stage of aluminium foam based on tetrakaidecahedron cells is still rare.

In this paper, a numerical model is proposed to model the mechanical behaviour of aluminium foam under compressive loading using Representative Volume Element (RVE) method. Tetrakaidecahedrons are selected as cells and trimmed to form the RVE model for modelling the mechanical properties of the aluminium foam. The study is conducted via the commercial code Ansys-LS Dyna. 3D solid element 164 is used to mesh the RVE model. This micro-structured RVE model is first used to model the mechanical behaviour of the aluminium foam of the density of 230 kg/m3 under quasi-static compressive loading (2 mm/min). The numerical results are compared to experimental data from literature.

Geometric model of the RVE

This geometric model of the RVE is cut from 9 tetrakaidecahedrons (see Figure 1) formed volumes, including one intact tetrakaidecahedronwraped in the centre and eight (each with one eighth left) surrounding the one in the center. Tetrakaidecahedrons can be used to fill spaces to the full. As tetrakaidecahedral foam can be accounted as a number of repeated proposed RVEs in the structure, this RVE is considered to represent aluminium foam with uniform close tetrakaidecahedron cells. D is used to define the cell size of tetrakaidecahedron. Specifically D is fixed to 2.88 mm in this paper while the thickness of the cell is slightly more than 0.04 mm to guarantee the relative density of the foam is at approximately 8.52%, which is equivalent to the density of aluminium foam of 230 kg/m^3.

This model is used to model the stress-strain relationship of the Alporas® aluminium foam of densityof 230 kg/m^3 under quasi-static loading subjected to compression at a rate of 2 mm/min using uniform close tetrakaidecahedroncells. The geometric model is shown in Figure 2 withthe RVE defined as Part 1, and the upper steel plate and bottom steel plate defined as Part 2 and Part 3. Part 3 is defined to support the RVE, while Part 2 is the structure acting compression on RVE. The computed stress-strain relationship is compared to that from the experiment [12].

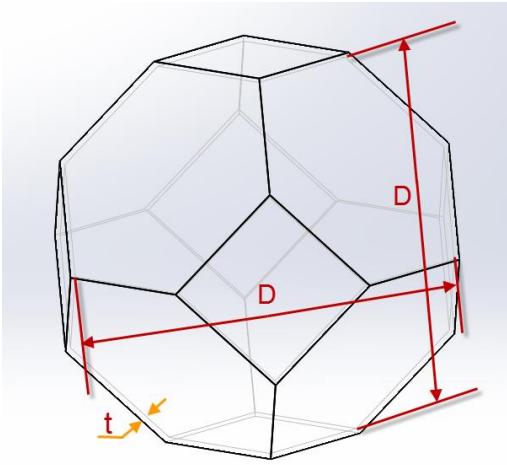


Figure 1.Tetrakaidecahedron with wall thickness

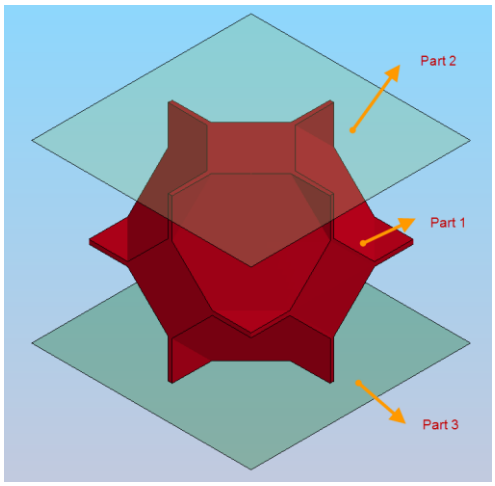
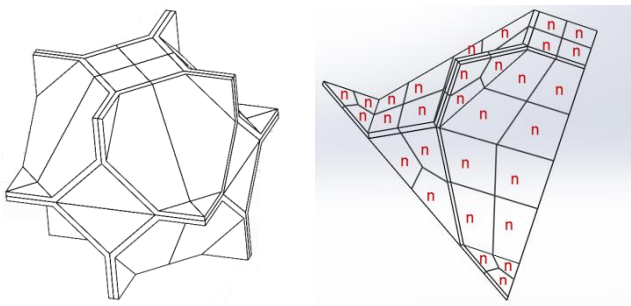


Figure 2.Geometric model of the RVE

Finite element analysis of the RVE model

This numerical modelling is conducted via the commercial finite element analysis software Ansys LS DYNA. The Part 1 and part 2 of the RVE model are meshed using the Belytschko-Tsay shell elements. Corresponding shear factor which scales the transverse shear stress is set tobe 5/6, and the number of through shell thickness integration points is set to be 1. The RVE is meshed using 3D solid element 164, which is a fully integrated quadratic 8 node element with nodal rotations.

To better mesh the model using solid hexahedron elements 164, the RVE is divided into eight equal parts as shown in figure 3a), andeach part is divided into many hexahedrons(see figure 3b))and each hexahedron can be meshed using n×n solid elements, where n =1,2,3,4, ...



a) b)

Figure 3Meshing of the RVE

To find out the best value of 'n', a convergence test is conducted. The compressive force-time curve is computed from the finite element model with different mesh density with n ranging from 1 to 6. The computed results and the computation time for each modelling are shown in figure 4 and Table 1 respectively. From Figure 4 it can be seen that the curves converged with the refinement of the mesh,and that the curve obtained from the mesh density of n=4 is very close to those obtained from the mesh density of n=5 and n=6, and that the curves from the mesh density of n=5 and 6 are nearly the same. This means the converged results are achieved with the mesh density reaches n=5. From Table 1 it can be seen that the computation cost

increases significantly with the increase of the mesh density. When n=4, the computation time is 9 hours. When n=5, the computation time is 16 hours while it took 21 hours for the computation when n=6. Therefore n=5 is adopted to mesh the RVE model for both accuracy and time efficiency.

Table 1 Computation time at different mesh densities

Mesh density	Computation time
n=1	0 hrs 44 min. 26 sec.
n=2	2 hrs 21 min. 6 sec.
n=3	6 hrs 6 min. 31 sec.
n=4	9 hrs 5 min. 44 sec.
n=5	16 hrs 17 min. 1 sec.
n=6	21 hrs 15 min. 24 sec.

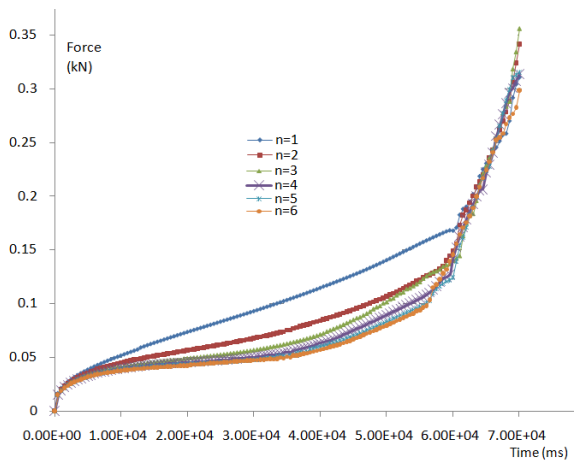


Figure 4 Convergence testing

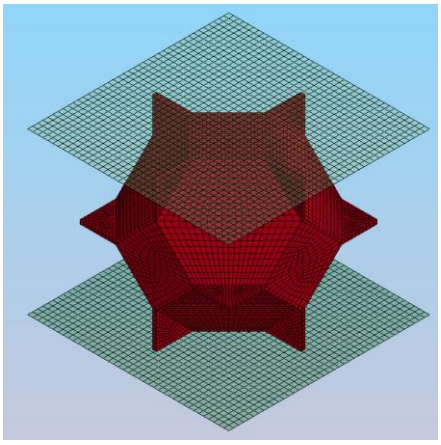


Figure 5 Finite element model

The aluminium foam RVE model is simulated using the low cost isotropic plasticity model Material Type 12, which is exclusively for solid element computation. In this model, strain rate is considered using Cowper-Symonds model which scales the yield stress via a strain rate dependent factor [13]. The steel plate Part 1 and Part 2 are treated as rigid body in the model. According material parameters are respectively given in Table 2 and Table 3.

Table 2 material parameters of aluminium foam material [14, 15]

Density	Shear modulus	Yield stress	Plastic hardening modulus	Bulk modulus
2700 kg/m3	23.73GPa	100 MPa	1.36 GPa	51.42 GPa

Table 3 Material parameters of steel plates [16]

Density	Young's Modulus	Poisson's ratio
7850 kg/m3	210 GPa	0.33

Two kinds of contact are defined in this model. One is the mutual contact between different parts, specifically between the RVE and Part 2 or Part 3. The other one is a sort of self-contact inside the RVE model resulted from large deformation.

Model validation and results

Figure 6 compares the compressive stress strain curve of the aluminium foam obtained from the finite element modelling of the RVE subjected to compressive loading at a loading rate of 2 mm/min and the experimental study [12]. It is clear that the curve obtained from numerical modelling of the RVE presents a trend close to that from the experiments [12] especially at the stage before hardening. The model can also model the hardening stage of the material but discrepancy exists between the numerical result and experimental data at this stage. The employing of the uniform cell and cell size to represent the aluminium foam may be the main reason for the discrepancy in the results. But at the same time it also shows that the aluminium foam with uniform cell can present better mechanical properties than aluminium foam with random pore sizes. Overall, the RVE model and the finite element model can reflect the mechanical properties of close cell aluminium foam well.

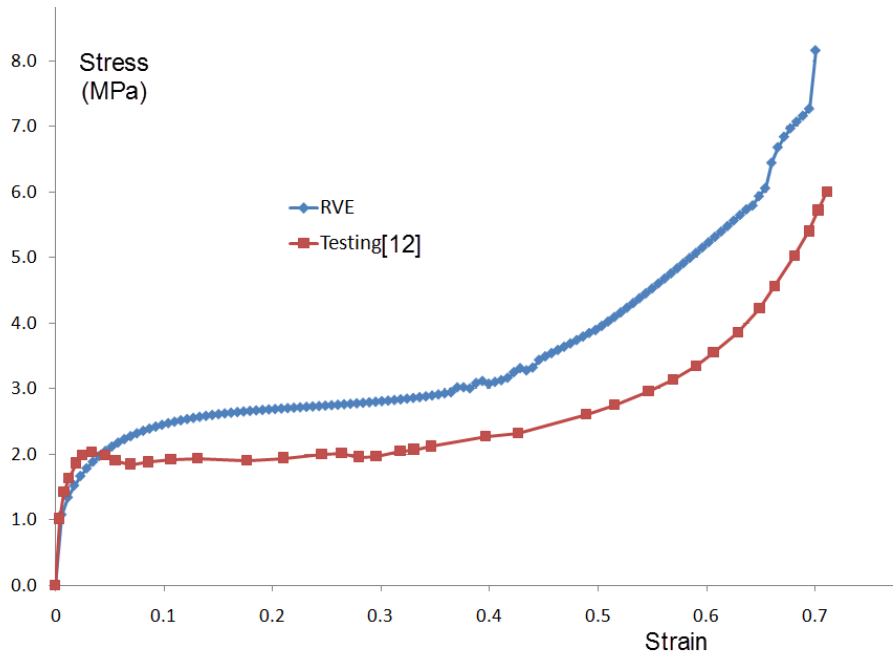
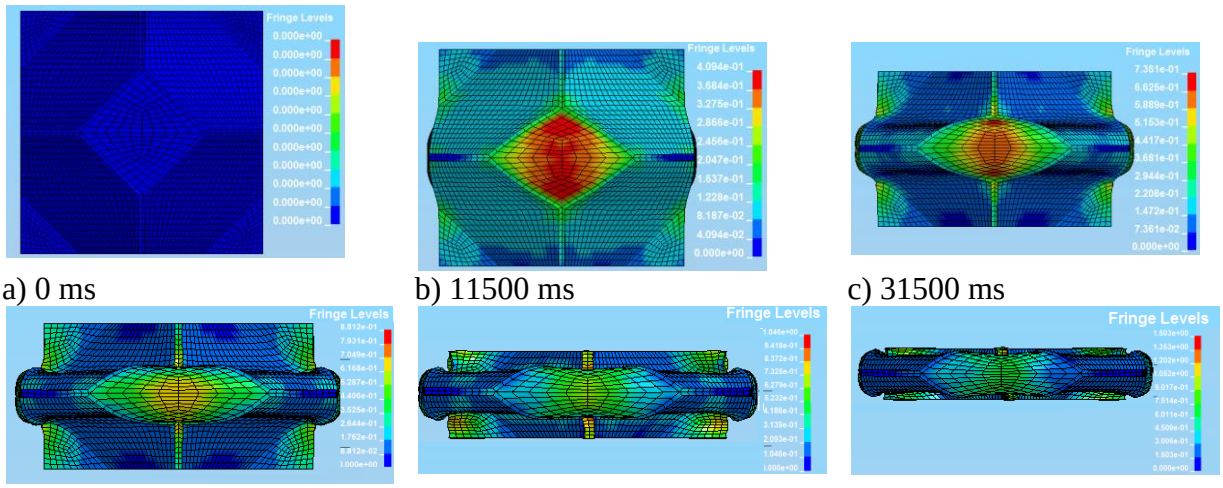


Figure 6 Comparison of compressive stress-strain curve

The modelled deformation process of the RVE during the process of applying the compressive loading is shown in Figure 7, in which the Von Mises stress contour is given. Several failure modes can be observed during the deformation process. One is stretching, which can be observed from the front view of the deformation in the square central area. The second sort of failure is bending, which can be seen on both left and right side of the model. Another failure mode is upsetting as presented in the middle of the model, where the vertical cell walls become wide and short.



a) 0 ms b) 11500 ms c) 31500 ms

d) 41000 ms e)55000 ms f) 71040 ms

Figure 7 Front view of Von Mises stress contour of the RVE during deformation process

Conclusion

A RVE model based on repeated tetrakaidecahedrons and its finite element are developed in this paper to model the mechanical behaviour of the close cell aluminium foam numerically.1/8 of the RVE is meshed using 3D solid element 164 with varying mesh density.Numerical analysis demonstrates that the finite element model converges well. Compressive stress versus strain curve of the Alporas® aluminium foam is obtained from the numerical modelling and the computed results are compared to experimental data. Overall, theRVE and the finite element model can model the compressive mechanical properties of close cell aluminium foam well. The deformation process and the failure modes of the RVE during the loading process from the numerical modelling are also presented.

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