Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(8) (2020) 529-532
DOI: 10.22060/mej.2019.15661.6176

Metallic Closed-Cell Foam Filled Tube Uniaxial Crushing Behavior Analysis Using Voronoi Approach

Y. T. Jamshidi[1], A. Pourkamali Anaraki[1*], M. Sadighi[2], J. Kadkhodapour[1], S. M. H. Mirbagheri[3], Behnaz Akhavan[4]

[1] Department of Mechanical Engineering, Shahid Rajaee University, Tehran, Iran.
[2] Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran.
[3] Department of Mining and Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran.
[4] Department of Industrial Engineering, IAU Tehran north branch, Tehran, Iran.

ABSTRACT: Porous materials especially metallic foams are novel materials with high energy absorption and strength to weight ratio capability. In the present paper, we investigate quasi-static uniaxial compression and crushing behavior of closed-cell graded aluminum foams and foam-filled tubes, both numerically and experimentally. To model the mentioned specimens, we place cubes with several densities and strengths to generate functionally graded specimens. Specimens are considered to be graded with two and three layers and non-graded single layer, with and without tubes. Various standard uniaxial compression experiences are conducted for numerical model calibration and validation and also for non-linear mechanical properties and hardening characterization. To enhance strength and energy absorption capability and also tailoring purpose, we layout the cubic foams in tubes with square profile. The 3D Voronoi diagrams approach is manipulated to model stochastic foam microstructure. Also Novel unit cell is proposed based upon Kelvin cell. We implement the hybrid finite element analysis and Voronoi diagram using Python script and Abaqus 2017 commercial finite element method based code for more convenient modeling and efficient analysis. Finally, and after numerical model calibrations, numerical and experimental results showed good agreement.

Review History:

Received: 2019/01/17
Revised: 2019/03/30
Accepted: 2019/04/14
Available Online: 2019/05/07

Keywords:

Foam-filled tube
Alporas closed-cell foam
Voronoi diagram
Micro-structure
Finite element method

1- Introduction

Cellular solids and closed-cell foams have complex microstructure with a random distribution of voids and cells [1] . Therefore, microstructural modeling is essential for mechanical behavior analysis using Finite Element Method (FEM). There are different methods for cellular structures modeling. Kelvin and other unit cells, Voronoi diagrams, Computerized Tomography (CT) scan images geometric reconstruction, stochastic placement of voids and soap froth are some of these methods. Furthermore, there are standard methodologies for material identification such as uniaxial loading, and Nano-indentation. Microstructural damage investigation using electron microscopes and optical methods have conducted by Yuan [2]. They model microstructure using Kelvin cell with thin faces and simulate uniaxial loading and effect of material properties by finite element method and experiments. Kadkhodapour et. al. [3] presented an approach connecting micro-scale displacement to macro-mechanical behavior in closed cell metallic foams using numerical methods and experiments.

In the present paper, firstly several geometrical models of cubic closed-cell foam specimen are generated and then graded foam filled tubes with these foam layers are modeled within square tubes. The specimens are 2 and 3 layered graded arrangements of foam specimens in tube and without tube. Furthermore, simple 1 layer specimens with and without tubes are also investigated. Numerical models are verified using uniaxial compression tests. Hence, analyzing several graded structures yield to tailoring ability and also micro-macro crashworthiness properties prediction of closed-cell foam filled tubes. Finally, good agreement between test and simulation results are shown.

2- Methodology

The focus of present work is on modeling concept. In other words, the Voronoi based Finite Element (FE) models are generated to enhance the homogeneous model's accuracy. So, several tetrakaidecaheron or Kelvin cells with controlled irregularities are modeled and their relative error with experimental results are minimized. Finally using computed tomography images, and optimization procedures, morphological parameters such as edge and face thicknesses and solid material volume fractions are obtained. The calibrated FE models are used in mechanical behavior investigations. Furthermore, Kelvin cells are modified using beam elements on their edges to increase accuracy. Cubic specimen with 20% irregularity is shown in Fig. 1. Abaqus FE code is used for simulation purpose and the S4R and B31 elements are used for modeling faces and edges of microstructures respectively [4, 5].

*Corresponding author's email: ali_pourkamali@sru.ac.ir

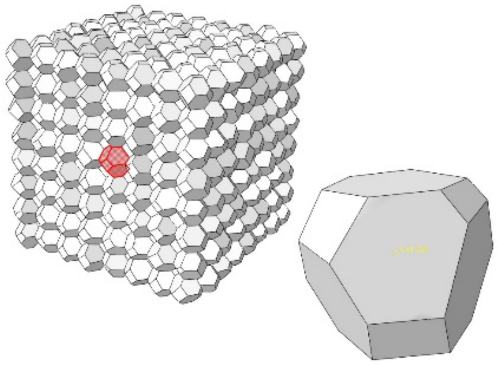

Fig. 1. FE model of cubic foam specimen using the Voronoi approach with 20% irregularity

To determine the mechanical properties such as plateau stress , densification strain and energy absorption, the stress-strain curve is analyzed. In which energy absorption efficiency is defined as the energy absorbed from initial yielding to corresponding strain normalized to stress . Initial yielding is defined as the first peak in the stress-strain curve. Densification strain could be determined by maximizing energy absorption efficiency.

$$E(\sigma_a) = \int_{\varepsilon_\sigma}^{\varepsilon_a} \sigma(\varepsilon)d\varepsilon \Big/ \sigma(\varepsilon_a) \quad (1)$$

Furthermore, plateau stress under compression loading is determined as below.

$$\sigma_p = \int_{\varepsilon_\sigma}^{\varepsilon_d} \sigma(\varepsilon)d\varepsilon \Big/ \{\varepsilon_d - \varepsilon_c\} \quad (2)$$

3- Results and Discussion

Several uniaxial compression experiments are conducted for numerical model calibration and also material properties characterization. These experiments are uniaxial compression of foam specimens and tubes. Foams experiments are conducted using 322 kg/cubic meter pure aluminum and 435 kg/cubic meter A356 foam specimens with 40 mm dimensions. These experiments are named B1 and B2 respectively. All the tests are continued until full densification and sudden rise in stress. Comparison between experiment and Finite Element Analysis (FEA) for B1 specimen is shown in Fig. 2. As depicted, good accordance in value of plateau stress and densification strain is obtained. Generally, experiments are repeated several times for each specimen to ensure results accuracy. Experimental values of plateau stress and densification strain 1.6 MPa and 70%. These results are 1.9 MPa and 75% for simulation. Hence, there are 18 % and 7% error in numerical simulation. In Fig. 3 experimental and numerical results for A356 alloy is shown. Plateau stress and densification strain for A356 foam are 2.6 MPa and 63% for experiment and 3.1 MPa and 71% for FEA. There are 19% and 13% error. Therefore, good agreement with maximum 20% error is obtained.

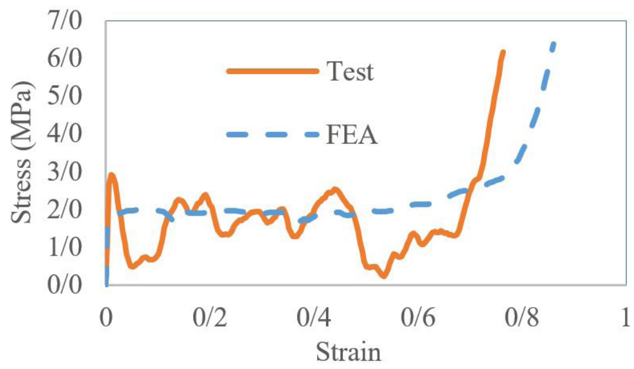

Fig. 2. FEA and experimental results comparison for B1 test of Al bare foam (322 kg/cubic meter)

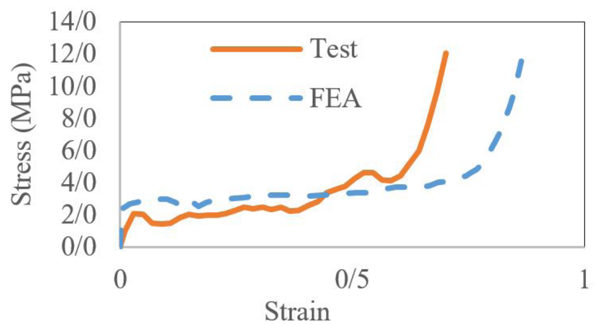

Fig. 3. FEA and experimental results comparison for B2 test of A356 bare foam (435 kg/cubic meter)

In Figs. 4 and 5 comparison between deformation modes for foam and tubes are shown. Because the importance of mesh independency investigation in FEA, comprehensive study is done with various finite element models. Finally, the fine mesh with 1 mm global approximate element size is chosen due to the high computational efficiency and accuracy. Relative error corresponding to fine, medium and coarse mesh is 20%, 33%, and 57%. Using finer mesh increases computational cost while error decreases slightly.

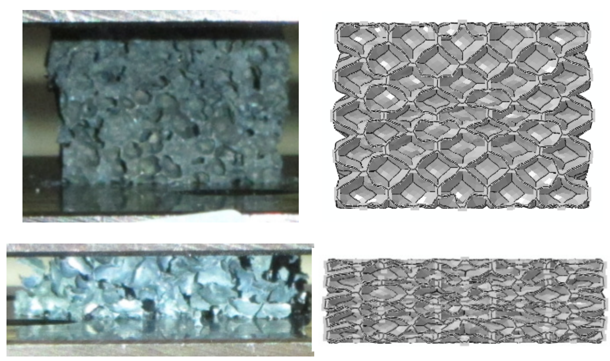

Fig. 4. Experiment and FEA comparison of deformation mode of foam specimen

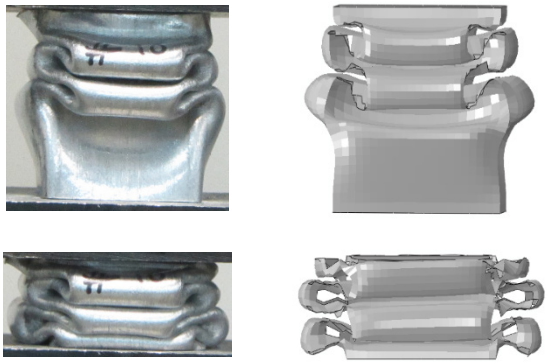

Fig. 5. Experiment and FEA comparison of deformation mode of the empty tube

4- Conclusions

the present research focused on designing mechanical properties and crashworthiness of Foam Filled Tube (FFT) and bare foam structures based on experimentally calibrated micro-structural finite element model both for quasi-static and low-velocity impact loading conditions. So the main achievements are summarized below.

• Micro-structural geometric and finite element model is obtained based on a modified Kelvin cell with beam elements on the edges and 3D Voronoi approach.

• A numerical model is calibrated using static uni-axial compression experimental results and modeling errors and limitations are determined e.g. densification strain and region prediction.

• Macro and micromechanical properties and crashworthiness index could be predicted in static loading conditions.

• The wide variety of graded structures in the form of bare foam and FFT with 15 to 435 J and maximum 20% variation increment in energy absorption capacity is obtained.

5- References

[1] A.E. M. Ashby, N. Fleck , L. J. Gibson, Metal Foams: A Design Guide, Butterworth-Heinemann publications, 2000.

[2] Y.X.L. J. y. YUAN Effects of cell wall property on compressive performance of aluminum foams, Transactions of Nonferrous Metals Society of China, 25(5) (2015) 1619-1625.

[3] S.R. J. Kadkhodapour Micro–macro investigation of deformation and failure in closed-cell aluminum foams, Computational Materials Science, 83(1) (2014) 137-148.

[4] Y.T. Jamshidi, Comprehensive Guide to Mechanical Analysis with ABAQUS, 4 ed., Tehran: Afrang Pub., Orange Triangle Series, 2017 (In Persian).

[5] M.S. Y. Taraz Jamshidi Engineering Elasticity, Applications and Problems, Tehran: Amirkabir University Press, 2017 (In Persian).