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Representative Volume Element Modeling of Flexible Polyurethane Foam under Compression with Periodic Boundary Conditions

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INTRODUCTION

Flexible polyurethane foam is widely used as a functional material for vibration damping, thermal insulation, and sound absorption in the automotive and aerospace industries. The mechanical properties of porous foams are specific for foam density, wall thickness, and the mean of cell size. Stochastic modeling based on the manufacturing mechanism of the foam's microstructure is considered important to investigate the impact of the structure on compressive behavior.

MATERIALS AND EXPERIMENT

- The cells were formed as they interpenetrated upon contact with adjacent cells, and a near-spherical morphology was observed.

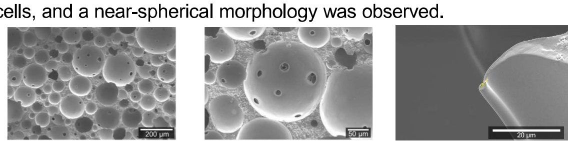
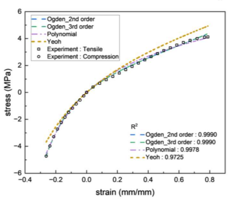


Fig 1. The SEM images of the 400 kg/m³ density polyurethane foam morphology

- The uniaxial compression and uniaxial tensile tests were conducted to characterize the material properties of the matrix.



* Polynomial 1st order Equation

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \qquad I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2$$

Parameter	Value
C_{10}	0.89633
C_{01}	0.86056

Fig 2. The fitting of hyperelastic models with uniaxial tension and compression test data

CHARACTERIZATION

- The nano-CT scanning (YXLON FF35CT) was performed to quantify the foam microstructure, and the internal cell size was quantified using the following five-step procedure.

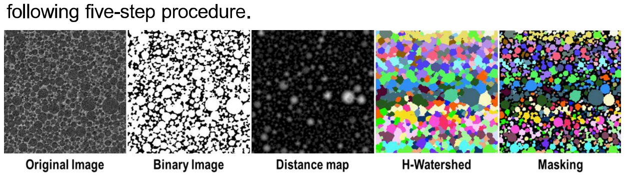


Fig 3. Image-processing sequence used to quantify cell size distribution from nano-CT data.

- The images were analyzed on a voxel unit using Fiji software, and the voxel size was 10 μm X 10 μm X 10 μm.

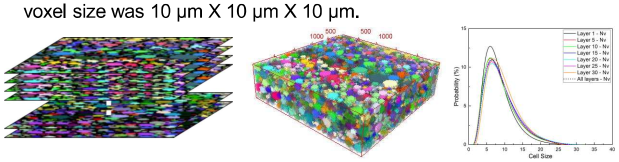
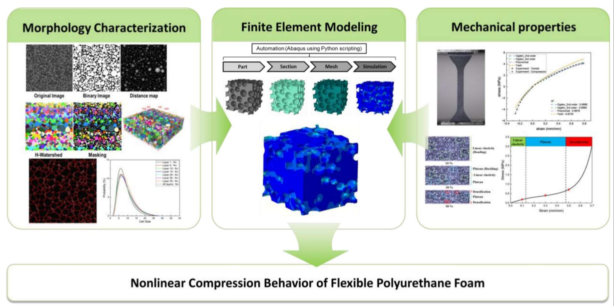


Fig 4. Cell size probability distribution extracted from segmented nano-CT images

ABSTRACT

In this study, the finite element analysis was conducted using Abaqus/Explicit, and the cell structures were generated based on probabilistic distribution parameters. To model the foam structure, preprocessing in element size by mitigating boundary effects.

GRAPHICAL ABSTRACT



FINITE ELEMENT ANALYSIS : GEOMETRY and ELEMENTS

- Spheres were generated such that their radii followed the cell size probability distribution and packed within unit cell.
- The geometry was constructed such that opposing boundary faces were symmetric to enable the application of periodic boundary conditions.

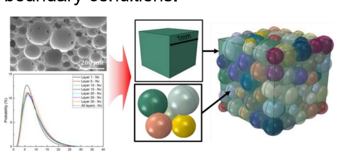


Fig 4. The method of foam geometry modeling

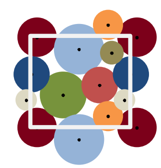
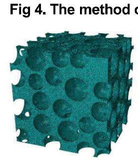


Fig 5. Geometry symmetry

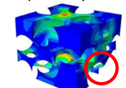


Element information	
Element type	C3D4H
Number of elements	299,063
Element size (approximate global)	0.01 mm

Fig 6. The element information of a representative model

FINITE ELEMENT ANALYSIS : BOUNDARY CONDITIONS

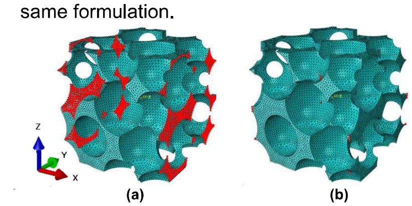
- The micro-structure of flexible polyurethane foam was modeled using Representative Volume Element (RVE) with periodic boundary conditions (PBCs) which reduces unit cell size dependency.



- When PBCs are not applied in the case of flexible foam, excessive buckling occurs at the boundaries, making PBCs essential of flexible polyurethane foam modeling.

Fig 7. Unexpected boundary buckling in flexible foam

- Only the x-direction is presented in Figure 8; y and z directions follow the same formulation.



* Surface nodeSet

$$u_1^{x+} - u_1^{x-} = u_1^{RP}$$
$$u_2^{x+} - u_2^{x-} = 0$$
$$u_3^{x+} - u_3^{x-} = 0$$

* Edge nodeSet

$$u_1^{x+y+} - u_1^{x-y+} = u_1^{RP}$$
$$u_2^{x+y+} - u_2^{x-y+} = 0$$
$$u_3^{x+y+} - u_3^{x-y+} = 0$$
$$u_1^{x+y-} - u_1^{x-y-} = u_1^{RP}$$
$$u_2^{x+y-} - u_2^{x-y-} = 0$$
$$u_2^{x+y-} - u_2^{x-y-} = 0$$

Fig 8. Definition of node sets for PBCs : (a) surface and (b) edge node set

RESULTS

- The RVE results show von Mises stress localization around open pores and buckling-induced collapse of the cell walls.

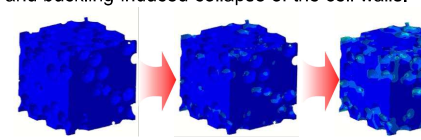


Fig 9. Stress field with increasing compression deformation

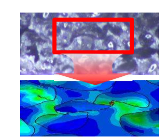


Fig 10. Buckling collapse in adjacent cells

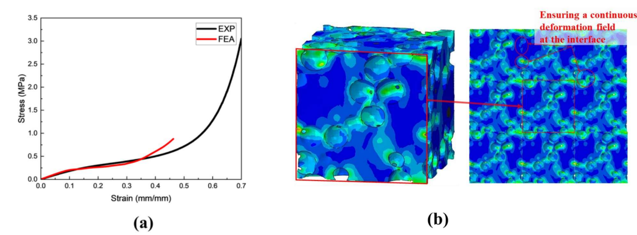


Fig 11. Numerical results of (a) stress–strain curves comparing simulation and experiment and (b) continuous deformation field obtained using PBCs

CONCLUSION

- The model was validated via simulation–experiment comparison of the stress–strain response, and PBC was shown to be essential for obtaining a continuous deformation field in highly compliant cell-wall structures.
- Nano-CT image analysis was used to quantify the cell-size probability distribution, which was incorporated into an RVE-based finite element model.

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