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2-Dimensional Homogenization FEM Analysis of Hyperelastic Foamed Rubber

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Abstract

Foamed rubbers are widely used for the shoe-soles, shin-guards, protectors and so on. The complex microstructure of foamed rubber consists of rubber matrix and pores. Therefore, foamed rubbers show good shock-absorbing properties in addition to good formability and lightweight. The mechanical characteristics of foamed rubber are determined by the mechanical characteristics of rubber matrix and its microstructure.

In this study, a homogenization numerical analysis of mechanical characteristics of foamed rubber considering the rubber matrix and microstructure was shown. In order to develop the evaluation method, the microstructure of the foamed rubber was assumed to have the periodical holes, and a homogenization FEM code for formed rubber was developed based on homogenization theory with hyperelasticity. To verify the applicability of our developed code, rectangular rubber specimens with periodically holes were prepared to observe stress distributions of periodical inner structure. Incompressible hyperelasticity was applied to the rubber matrix. The material parameters of hyperelasticity for rubber matrix were identified by the biaxial tensile test results. Compression test of the rubber specimen reproducing FEM model was conducted to verify the applicability of the analysis code. The analysis result showed good agreement with the compression test result in the low strain region.

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Keywords: Foamed rubber; Microstructurre; Relative density; Homogenization; Finite element analysis;

1. Introduction

The complex microstructure of foamed rubber which was made by rubber matrix and microscopic pores has a great effect on its mechanical characteristics. When foamed rubber is compressed, the rubber matrix bends, thereafter occurs buckling. Therefore, foamed rubber has good shock-absorbing characteristics in addition to good formability and lightweight. For these reason, foamed rubber has been widely applied to shoe-soles, shin-guards and protectors as shock-absorbing materials in the sports field.

The mechanical characteristics of foamed rubber is determined by the mechanical characteristics of rubber matrix and its microstructure, in particular, depends on relative density. The relative density represents the ratio of rubber matrix in foamed rubber. While suitable design of foamed rubber used for each engineering products is required, mechanical characteristics of foamed rubber has been evaluated with material tests using prototypes under the assumption to be homogeneous material. Thus, an evaluation method using a numerical analysis considering the microstructure would be an effective method to improve quality, performance and productivity of foamed rubber. Previous studies have analyzed mechanical characteristics of the carbon foams using a detailed model with the research of Kirca et al. (2007). The detailed FEM mesh model required approximately 400,000 finite elements and one million degrees of freedom with quadratic 10-noded tetrahedron elements. However, it is high computational cost.

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In order to establish the evaluation method, 2-dimensional homogenization finite element analysis code were developed in this study. The microstructure of the foamed rubber was assumed to the periodic structure with hole. Therefore, homogenization theory was applied to the developed code. The rubber matrix was assumed to have incompressible hyperelasticity which was represented by the Mooney-Rivlin model. The material parameters of rubber matrix were identified from the biaxial tensile test results. Compression tests of the rubber specimen reproducing homogenization model were conducted to verify the validity of analysis code. Relative density of the rubber specimen was reproduced by adjusting the diameter of the holes. By comparing the compression test and 2-dimensional homogenization FEM analysis, the mechanical characteristics of foamed rubber considering microstructure were evaluated.

2. Homogenization analysis model and material model

In this study, the microstructure of foamed rubber was assumed to have the equally-sized periodic holes, homogenization model for numerical analysis was prepared using analysis code programmed all in house shown in Fig. 1. The gray area in Fig. 1 represents the rubber matrix and the white holes represent the inner holes. Relative density was reproduced by adjusting the diameter of the holes. Homogenization analysis was conducted by using the unit cell which is a part of microscopic structure. The uniform deformation and periodic boundary condition were applied to the unit cell. From this reason, homogenization analysis reproduced the infinite periodic structure of holes by conducting analysis only for the unit cell. Homogenization model required 1,024 finite elements and 2,200 nodes with quadratic 4-noded quadrilateral elements. Therefore, this analysis enables relatively low computational cost.

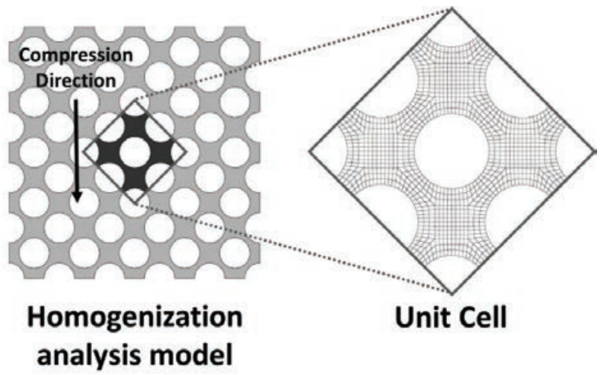

Fig. 1. Homogenization model and its unit cell.

The formulation for the large deformation problem of porous polymers was described using $\boldsymbol{X}$ and $\boldsymbol{Y}$-coordinates. The macroscopic behavior is described with the $\boldsymbol{X}$-coordinate, and the microscopic behavior is described with the $\boldsymbol{Y}$-coordinate. The two coordinates are related using a scale ratio ε as follows:

$$\boldsymbol{Y} = \boldsymbol{X} / \varepsilon \tag{1}$$

When the scale of the microscopic structure is much smaller than the scale of the whole structure, the scale ratio ε is a very small value. In that case, the macroscopic characteristics, such as stiffness, stress and strain, are calculated from the volume average of microscopic characteristics using the homogenization theory. The deformation of microscopic structure is uniform, and microscopic periodicity is kept under finite deformation.

The total deformation of microscopic structure is divided into macroscopic deformation $\boldsymbol{Y}$ and microscopic periodical deformation $\boldsymbol{w}$.

$$\boldsymbol{y} = \tilde{\boldsymbol{F}}\boldsymbol{Y} + \boldsymbol{w} \tag{2}$$

Here, $\tilde{\boldsymbol{F}}$ is the macroscopic deformation gradient tensor. The gradient tensor $\tilde{\boldsymbol{F}}$ is applied to the numerical simulation as the deformation condition. The microscopic deformation gradient tensor is calculated from Equation 2 as follows:

$$\boldsymbol{F} = \nabla \boldsymbol{y} = \tilde{\boldsymbol{F}} + \frac{\partial \boldsymbol{w}}{\partial \boldsymbol{Y}} \tag{3}$$

The rate of displacement is also described by