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THERMO-MECHANICAL COUPLED SIMULATION OF RUBBER O-RINGS FOR MOX FRESH FUEL TRANSPORT PACKAGES

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ABSTRACT

The containment performance of transport packages which apply rubber O-rings as their containment barrier depends on the stress relaxation and compression set of rubber O-rings.

In this paper, to establish a prediction method for compression set of the EP rubber O-rings, a thermo-mechanical finite element analysis code was proposed. The proposed simulation code considers the coupling problem of heat conduction and mechanical deformation of rubber materials, simultaneously. The nonlinear viscoelastic model which apply hyperelasticity to the elastic part and viscous-dashpots to the time-dependent parts, was applied to the simulation code to predict the mechanical behavior in finite deformation and thermal-dependent stress relaxation. For numerical modelling, the biaxial-loading tests for EP rubber sheet specimens were conducted to verify the material modulus for hyperelasticity. Stress relaxation tests for EP rubber O-rings were conducted to verify the relationships between relaxation times and temperature. Finally, the accelerated thermal aging tests of EP rubber O-rings were conducted and the compression sets of EP rubber O-rings were measured.

In this study, a concept of the accelerated thermal aging tests was applied to the experimental and numerical simulation method. The concept of the thermal accelerating test is that rather higher temperature than real one is applied to the specimen though the duration time is shorter the real situation. This cause is that progress of the plastic deformation and stress relaxation of rubber follows the Arrhenius equation. The compression sets of the EP rubber O-ring were simulated numerically, and simulated results shows good agreement with the experimental results.

INTRODUCTION

The prediction of the replacement period of rubber parts such as elastomer O-rings and sealing elements is an important issue for all mechanical devices used for electricity. Also, rubber O rings were applied to the lid of MOX fresh fuel transportation packages as containment barrier. Replacement and maintenance schedules for O-rings and sealing elements should be appropriately set. The Japanese Industry Standards (JIS K 6262) describe aging tests for O-rings. In the standard, compression set that defines the ratio of elastic and plastic deformation of O-rings is used to determine replacement time. The compression set is given by the following expression in the JIS K 6262:

$$\varepsilon_p = \frac{d_0 - d_1}{d_0 - d_2} \times 100(\%) \tag{1}$$

Here, d_0 and d_1 are the cross sectional diameter before and after deterioration, respectively. The depth of the O-ring ditch is d_2. Generally, O-rings are replaced when the compression set is larger than 80%.

In the proposed method, a thermo-mechanical viscoelastic model consists of hyperelastic spring and viscous-dampers, was applied to the material modeling of EP rubber O-rings (Fig. 1). The relaxation times of viscous-dampers were calculated in the finite element analysis simulation code by using the Arrhenius equation to be able to predict the compression set of rubber O-rings under various temperatures. The biaxial loading tests were conducted to define the elastic potential function of hyperelastic part. Test specimens for biaxial loading tests were made by same EP rubber which was used to the O-rings. The relaxation times of the material modeling were defined by the stress relaxation test results.

THEORY OF NUMERICAL SIMULATION

In this section, we introduce the volumetric and deviatoric multiplicative split [1]. The deviatoric part of the deformation gradient tensor is given as

$$\overline{\boldsymbol{F}} = J^{-\frac{1}{3}}\boldsymbol{F}, \tag{2}$$

where J is the determinant of the deformation gradient tensor $\boldsymbol{F}$. The second Piola-Kirchhoff stress tensor $\boldsymbol{S}$ of the viscoelastic material is given by[2][3]:

$$\boldsymbol{S} = 2\frac{\partial W(\overline{\boldsymbol{C}})}{\partial \boldsymbol{C}} - \frac{\partial \overline{\boldsymbol{C}}}{\partial \boldsymbol{C}}\sum_{i=1}^{N}\boldsymbol{Q}_i + Jp\boldsymbol{C}^{-1}, \tag{3}$$

where $\boldsymbol{C}$ and $\overline{\boldsymbol{C}}$ are the right Cauchy-Green tensor and volume-preserving of the right Cauchy-Green tensor, respectively. W and p are the strain energy function of elastic deformation and hydrostatic pressure, respectively. $\boldsymbol{Q}_i$ and N are the viscous stress tensor and the number of dashpots in Fig. 2, respectively. The viscoelastic stress $\boldsymbol{Q}_i$ satisfies the following evolution equation including material temperature $\theta\,(K)$ as follows:

$$\dot{\boldsymbol{Q}}_i(t) + \frac{1}{\tau_i(\theta)}\boldsymbol{Q}_i(t) = \frac{\gamma_i}{\tau_i(\theta)} DEV\left\{ 2\frac{\partial W}{\partial \boldsymbol{C}} \right\}, \tag{4}$$

where $\tau_i(\theta)$ is the relaxation time of a dashpot and the notation DEV is given by

$$DEV[\bullet] = (\bullet) - \frac{1}{3}[(\bullet):\boldsymbol{C}]\boldsymbol{C}^{-1}. \tag{5}$$

From the results of the stress relaxation tests of EP rubber O-rings, we propose the following relationships to the temperature-dependent stress relaxation behavior of rubber materials using the Arrhenius equation[4].

$$\tau_i(\theta) = \frac{\tau_i(\theta_0)}{\alpha} = \frac{\tau_i(\theta_0)}{A\exp\left(\dfrac{-E}{R\theta}\right)}, \tag{6}$$

where α is the rate constant of the chemical reaction depending on the temperature of the rubber, *R* is the gas constant (=8.31447J/K/mol), θ_0 is the referenced temperature, *E* is the activation energy. Equation (6) means that the relaxation time $\tau_i(\theta)$ of all dashpots shortens uniformly with an increasing temperature.

EXPERIMENTS AND MODELING

The biaxial tensile tests to determine the strain energy function of hyperelasticity and the stress relaxation tests to determine the viscous parameters were conducted for EP rubber which applied to O-rings. Biaxial tensile deformations were applied to the sheet specimen (2mm thickness) in biaxial loading tests (Fig. 3). From the biaxial loading test results, the strain energy function of the EP rubber *W* were approximated as following equation:

$$\frac{\partial W(\bar{I}_A)}{\partial \bar{I}_A} = C_{A1} + C_{A2}(\bar{I}_A - 3) + C_{A3}(\bar{I}_A - 3)^2 \tag{7}$$

Where $\bar{I}_1$ and $\bar{I}_2$ are the first and second invariants of the volume-preserved right Cauchy-Green tensor. To evaluate the applicability of above function, the simple uniaxial tensile loading test of same EP rubber was conducted (Fig. 4). Comparison of stress-strain curves by uniaxial loading test and theoretical calculation with equation (7) are shown in Fig. 5.

The stress relaxation tests for EP rubber O-rings (diameter of cross-section was 6.0mm) were conducted in a thermal chamber under three constant temperatures. The test specimens were kept at 373K, 393K and 423K constantly after applying compressional deformation of 2.4mm in test jig (Fig. 6). The surface temperature of a specimen was measured with a thermocouple, and the vertical load was measured using the heat-resistant load cell. Fig. 7 shows 2000 hour results under 423K, and Fig. 8 shows 10-day results under 373K and 393K, respectively. Here, stress of stress relaxation test results are normalized by dividing the maximum load. The viscoelastic stress reduction under a constant temperature and deformation is given as the following relationship when the deformation is applied at t = 0:

$$\frac{\sigma(t)}{\sigma(0)} = \sum_{i=1}^{N} \gamma_i \exp(-t/\tau_i(\theta)) \tag{8}$$

We introduced 7 hyperelastic spring and dashpot connections in parallel to approximate the relaxation times $\tau_i(\theta_0)$ and material parameters γ_i from the 2000 hour test results under the referenced temperature θ_0 (423K). Here the relaxation times $\tau_i(\theta_0)$ were assumed as follows:

$$\sum_{i=1}^{7} \tau_i(\theta_0) = 10^{(i+2)}\ [s] \tag{9}$$

It was then possible to calculate the acceleration rate α as 0.09 under 373K, and 0.20 under 393K. In Fig. 9, the logarithm of α and the reciprocal of absolute temperature ($1/\theta$) were plotted on the vertical and horizontal axes, respectively. The relationship between the logarithm of α and the reciprocal of absolute temperature shows good linearity. This indicates that the stress relaxation of EP rubber follows the Arrhenius equation.

FEM SIMULATION OF COMPRESSION SET OF EP RUBBER O-RINGS

Material parameters given by biaxial loading tests and stress relaxation tests were introduced to the FEM simulation code and numerical simulations of stress relaxation tests were conducted. The FEM code was developed originally and it was coded by the FORTRAN. For FEM modeling, upper half of cross section of O-ring was applied considering symmetry deformation. FEM model of O-ring and boundary condition of simulation were shown in Fig. 10.

In the numerical analysis of stress relaxation, the heat transfer was calculated at the same times and temperatures at each integration points were used for calculation of viscosity. The initial compressional deformation was applied to the top surface and the specimen's viscosity and thermal conductivity were calculated while maintaining the deformation. Stress distributions of O-rings were shown in Fig. 11. In Fig.12, compression set resulting from the relaxation test and the numerical simulation were plotted. The compression set of EP rubber O-rings were calculated by using equation (1). Simulated results show good agreement with experimental results.

CONCLUSIONS

To estimate the compression set of EP rubber O-rings which depend on the environmental temperature, a nonlinear viscoelastic model for rubber-like material was proposed. In this model, the relaxation time of a dashpot was calculated using the Arrhenius equation with temperatures of each FEM element.
The viscous parameters were obtained using a relaxation test of EP rubber O-rings. The relaxation tests were simulated numerically and the compression set resulting from the relaxation tests and numerical simulation shows good agreement.

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Fig. 1 EP rubber O-ring
(Diameter of cross section is 6mm)

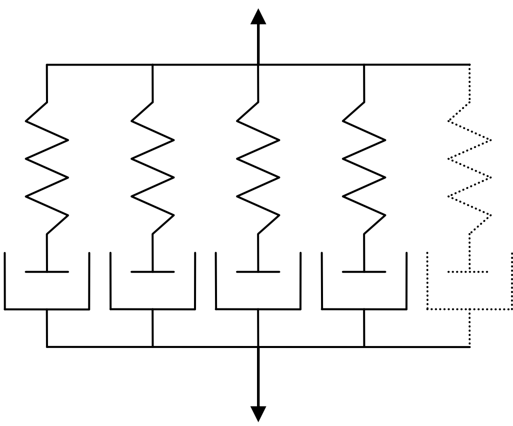

Fig. 2 Visco-elastic model for EP rubber

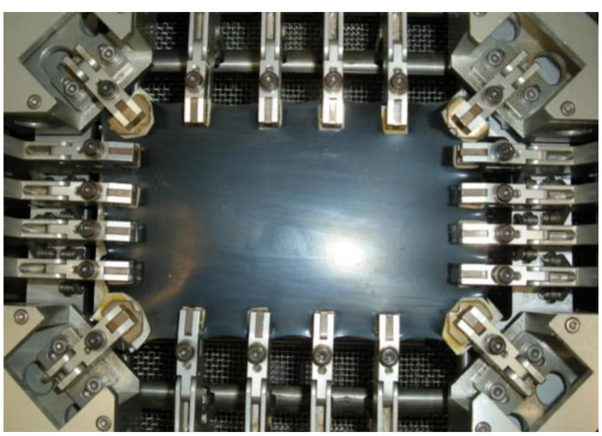

Fig. 3 Bi-axial loading test

Fig. 4 Uniaxial loading test specimen

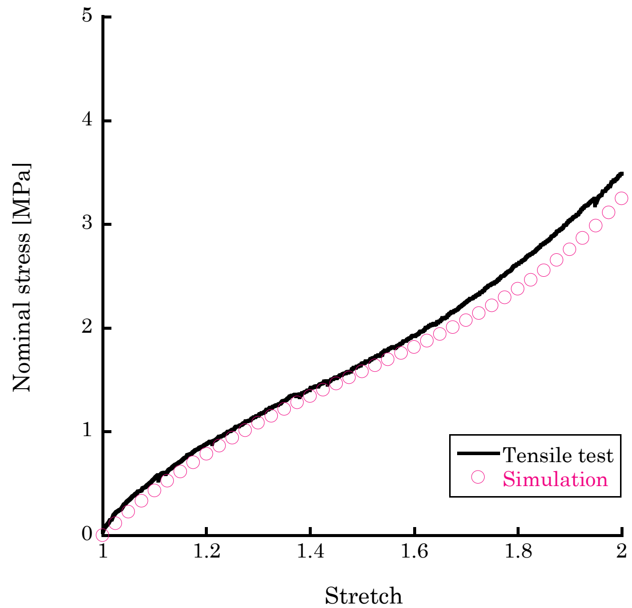

Fig. 5 Uniaxial stress-stretch curve by loading test and theoretical calculation

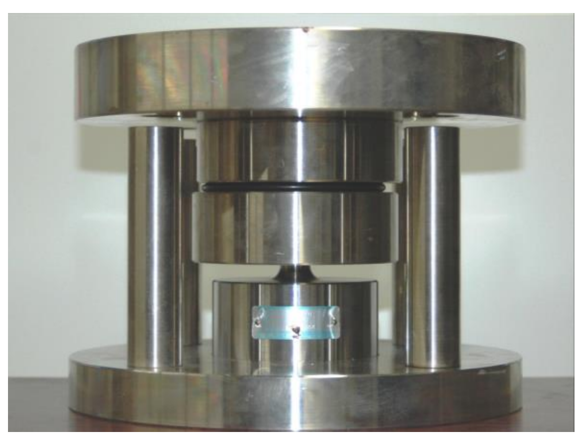

Fig. 6 Stress relaxation test jig

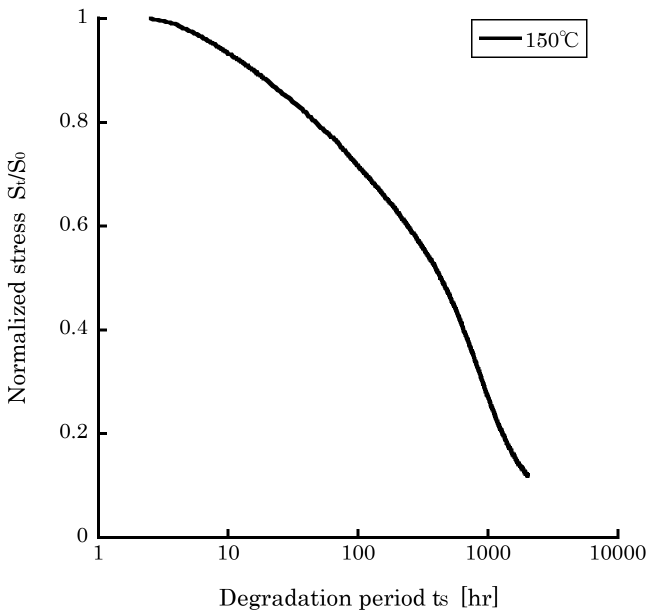

Fig. 7 Stress relaxation test results of EP rubber O-rings under 423K

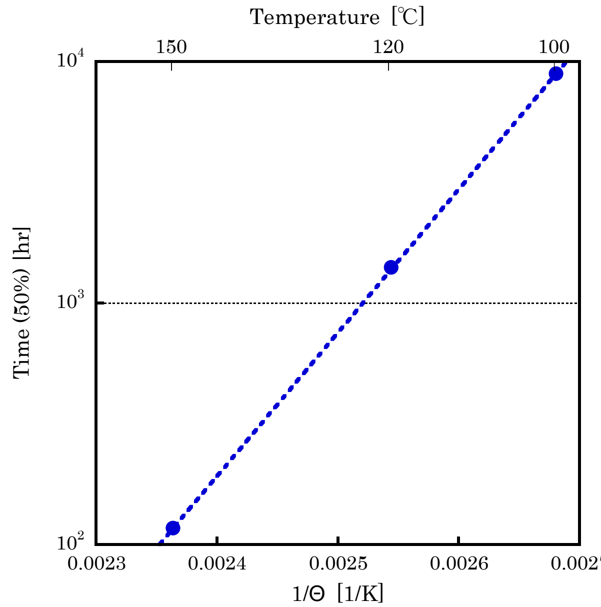

Fig. 9 The Arrhenius plot for stress relaxation

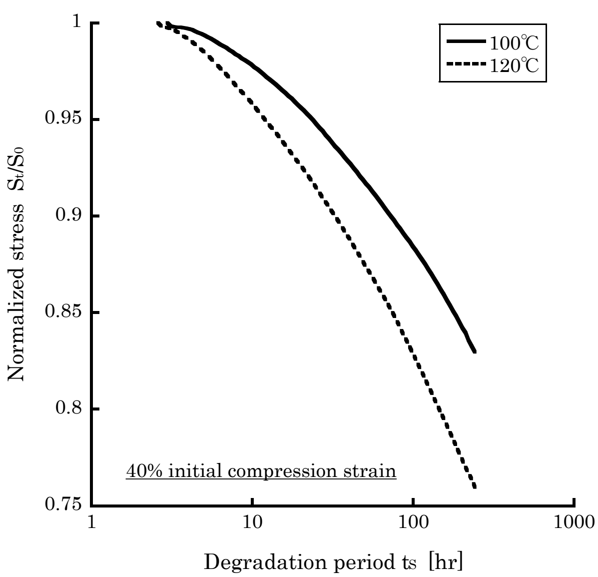

Fig. 8 Stress relaxation test results of EP rubber O-rings under 373K and 393K

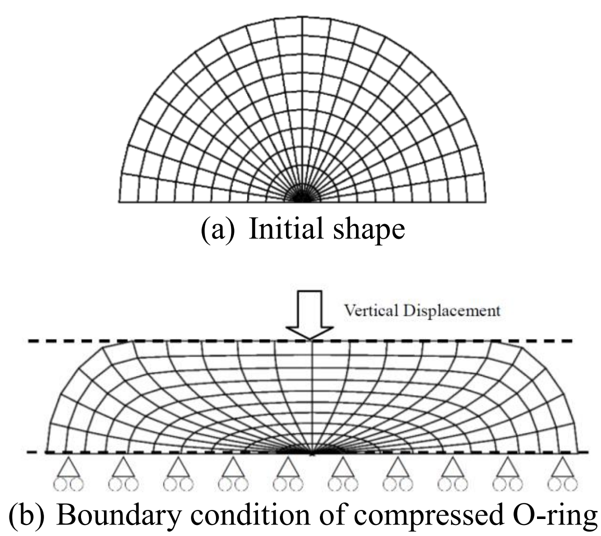

Fig. 10 Boundary condition of FEM simulation

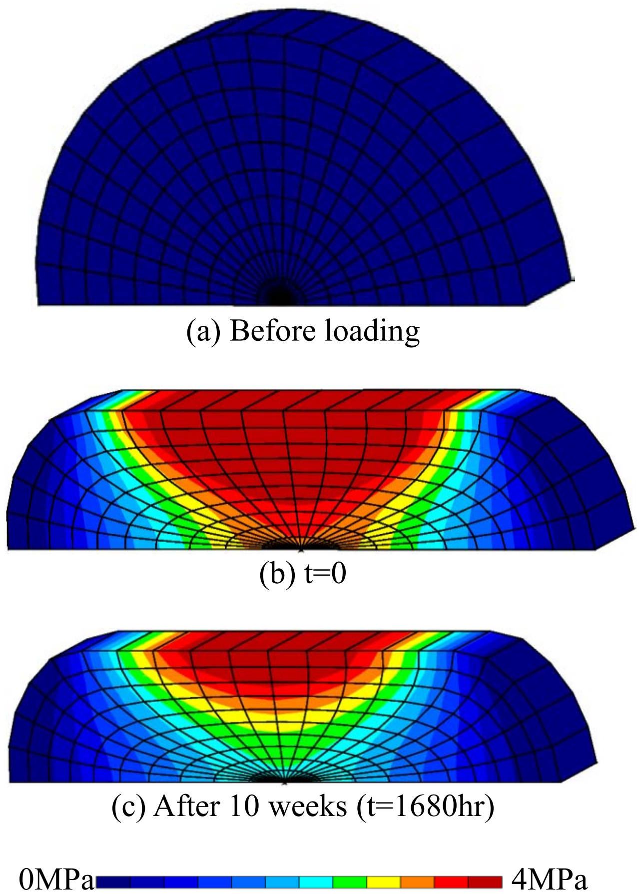

Fig. 11 Mean stress distribution of stress relaxation analysis (373K)

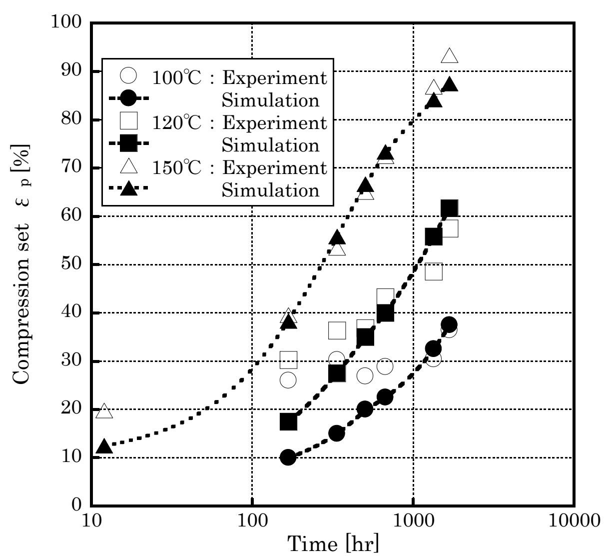

Fig.12 Compression set given by thermal-acceleration tests and FEM simulations