2D AND 3D CREEP DAMAGE ANALYSES FOR LOCAL HEATED TUBE OF LIGHT WATER REACTOR

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ABSTRACT

The two and three dimensional FE analyses of the coolant tube which is heated locally under severe accident condition are performed in the present analysis. The local creep damage analysis of a creep constitutive equation based on the Kachanov-Ravotnov isotropic damage rule that considers the tertiary creep behavior is applied to the tube used the coolant system of light water reactor under severe accident condition. The creep constitutive equation including damage variables is added to a commercial FEM code.

In the present analysis of the coolant tube with graded temperature in both radial and tangential directions, the damage variable of both 2D and 3D model are confirmed further to be able to reproduce the observation in Japan Atomic Energy Research Institute (JAERI) creep piping failure tests; pipe failure from the wall outside.

1. INTRODUCTION

In a severe accident of a light water reactor (LWR), fission products (FPs) are released from damaged reactor core region into the reactor vessel and piping. The reactor coolant piping might be subjected to local heating resulting from decay heat of the FPs deposited on the inside surface of the piping. In addition to the local heating, the piping is subjected to internal pressure due to the high temperature gas generated in the reactor core region. In such conditions, large creep deformation is caused in the coolant piping by local creep damage due to the local heating and results in the creep failure of the piping. It is important to simulate such behaviors of piping in order to evaluate safety margin of the coolant piping in the LWR under the severe accident condition. In the severe accident, the coolant piping might be subjected to the temperature over about 1000°C and the internal pressure of about 10MPa. In such temperature and pressure conditions, the creep strain rate is so high that the material goes into the tertiary creep region very quickly. Thus, the tertiary creep behavior of piping material should be taken into account to simulate the creep behaviors of the reactor coolant piping under severe accident condition.

The WIND(Wide range piping INtegrity Demonstration) project was performed at JAERI(Japan Atomic Energy Research Institute) in order to prove the integrity of LWR piping under severe accident condition [1]. According to the experimental results of the piping at high pressure and high temperature, after the local expansion of radial direction of the tube was observed, the tube was failed due to creep. The reduction of thickness of the tube is also observed in the experiment when the tube was cut at cross section.

In the present paper, an isotropic damage rule of the Kachanov-Rabotnov type was used as the creep constitutive equation [2]. Then, the present creep constitutive equation is applied to calculate the local heated piping of the WIND project experiment. Although there are linear cumulative rule and etc. which are the life prediction methods, the damage mechanics is used for life prediction and failure criteria of a tube in this analysis. The creep damage of a tube was estimated by using the partly coupled approach of the local approach under severe accident condition [2][3][4].

2.METHOD OF ANALYSIS

2.1 Creep Constitutive Equation and Evolution Equation of Damage

The following creep constitutive equation based on the creep damage mechanics of Kachanov-Rabotnov[1] is employed in the present analysis . The creep strain rate and The evolution equation of the isotropic creep damage are expressed by a damage variable $D\ (0 \leq D \leq 1)$ as following equations respectively [3] [4] [5] [6].

$$\frac{d\bar{\varepsilon}^c}{dt} = B\left(\frac{\bar{\sigma}}{1-D}\right)^n + c\beta\bar{\sigma}^m \exp(-ct) \tag{1}$$

$$\frac{dD}{dt} = \frac{A}{q+1}\frac{\left[\alpha\sigma_1 + (1-\alpha)\bar{\sigma}\right]^p}{(1-D)^q} \tag{2}$$

where $\bar{\varepsilon}^c$, $\bar{\sigma}$, t and $D\ (0 \leq D \leq 1)$ denote creep strain, effective stress, time and the damage variable respectively and σ_1 denotes principal stress. The coefficients A , q p , α , B , n , c , β and m and are determined so as to agree with the creep-time curves obtained from uniaxial creep tests of nuclear-grade cold-drawn SUS316 material by JAERI [7]. The multiaxial description of the creep strain is expressed by the creep potential theory of Mises as follows:

$$\frac{d\varepsilon_{ij}^c}{dt} = \frac{3}{2}\cdot\frac{d\bar{\varepsilon}^c}{dt}\cdot\frac{s_{ij}}{\bar{\sigma}} \tag{3}$$

where, s_{ij} denotes deviatoric stress and $s_{ij} = \sigma_{ij} - \sigma_{kk}\delta_{ij}/3$.

2.2 Partly coupled approach

There are two methods for the relation between the damage variable D and Young's modulus, which are called fully coupled approach and partly coupled approach. Partly coupled approach is adopted in the present analysis. In the partly coupled approach, the elastic modulus taking account of the damage variable D is expressed as follows:

$$E(D) = \begin{cases} E_0 & D \leq D_{cr} \\ 0 & D \geq D_{cr} \end{cases} \tag{4}$$

where E_0 denotes the initial elastic modulus. D_{cr} denotes the critical value of the creep damage.

The partly coupled approach is programed to a user subroutine of the MSC/MARC which is a famous FEM analysis code.

3. RESULTS AND DISCUSSION

3.1 2 D Analysis of Creep Damage for Tube Subjected to Internal Pressure

We performed the two dimensional creep damage analysis for the internally pressured tube at 9.8MPa using the creep constitutive equation and the evolution equation of damage. The boundary condition of the tube in this analyses is described in Fig. 1. A half of the tube of cross section is divided into 800 elements. The material properties of the both material at 950°C are used in the present analysis.

Young's modulus : $E = 108.750\ GPa$

Poisson's ratio : $\nu = 0.3$

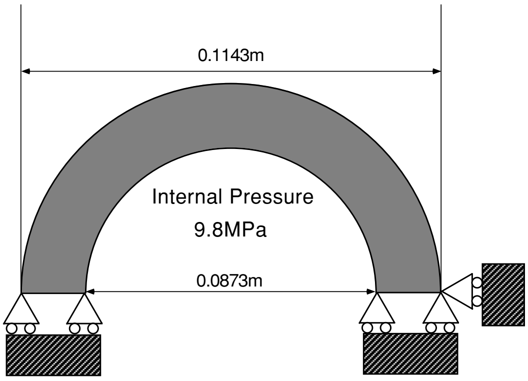

Fig.1 Dimensions and boundary conditions of half model of coolant piping for FEM analysis.

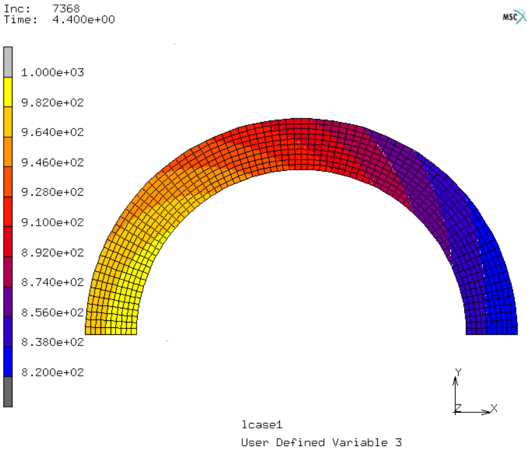

Fig.2 Temperature gradient of the tube for 2D analyses of non-isothermal condition.

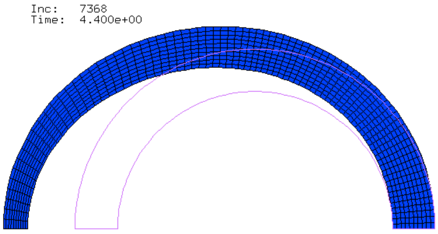

Fig.3 Deformation of coolant piping obtained from FE analyses of graded temperature condition after 4.40 hours.

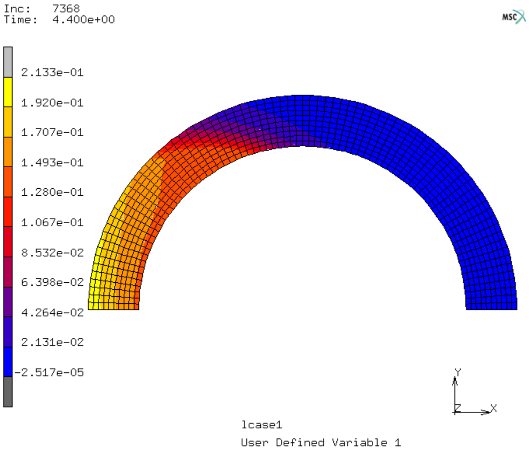

Fig.4 Distribution of damage variables of tube with graded temperature condition after 4.40 hours.

The plane strain condition and the generalized plain strain on are assumed in the 2D analysis. The distribution of graded temperature shown in Fig. 2 is the same as a experimental condition of the JAERI. The creep deformation of the tube after 4.40 hours and the initial shape of the tube in the analysis are depicted in Fig. 3. The thin thickness in high temperature region can be seen in Fig.3. The creep damage variable in the creep damage after 4.40 hours are also depicted in Fig. 4. The larger deformation of the tube due to creep strain is calculated in higher temperature area of the tube. In the distribution of creep damage shown as Fig. 4, the higher damage is accumulated in the outside of the wall of the tube than the inside of the wall. In the present analysis, the coefficients of Eq. (1) are interpolated between the coefficients of the temperatures obtained from creep tensile tests. It can be understood that the area of high temperature is the easiest area to cause failure. The damage variables at the outside of the wall are higher than the damage variables at inside wall in higher temperature area. This results are similar to the experimental results of the tube performed by JAERI [1].

3.2 3 D Analysis of Creep Damage for Tube Subjected to Internal Pressure

The three dimensional creep damage analysis is performed for the same problem as the two dimensional analysis. A half of the tube is divided into 16000 elements. Internal pressure is $9.8MPa$. The symmetric condition of tube is given to the cross section under high temperature. The material properties of the 3D analysis are the same as those of 2D analysis. The graded temperature of the 3D tube which is given is described in Fig. 5. The maximum and the minimum temperature of cross section of high temperature region which is graded in the radial direction are 1000°C and 820°C. The minimum temperature of the other side is set to 672°C. The distribution of damage

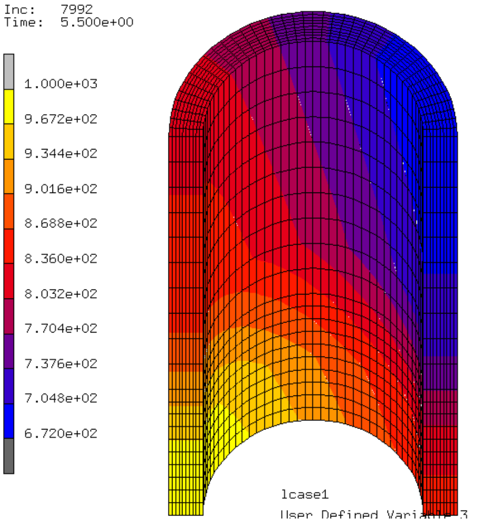

Fig.5 Temperature gradient of the tube for 3D analyses of non-isothermal condition.

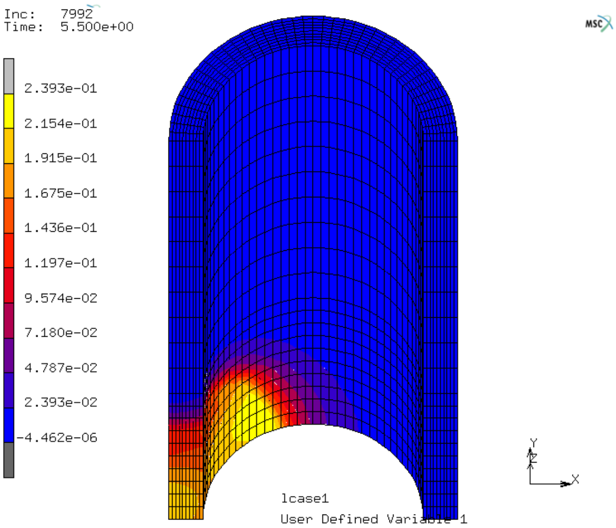

Fig.6 Distribution of damage variables of 3D tube model with graded temperature condition after 5.50 hours.

variable is described in Fig. 6. The damage variables at the outside of the wall are higher than the damage variables at inside wall in higher temperature area, which is similar to the results of the 2D analysis. Althogh the failure time of the experiment is 2.7 hours after temperature is kept, the maximum value of the damage variable is about 0.24 after 5.5 hours. It can be seen the defference between the result of the experiment and that of the 3D FE analysis. The critical value of damage variable have to be determined to vicinity of lower value than 0.24. The creep deformation of the 3D analysis are depicted in Fig. 7. The deformation of the 3D analysis is less than that of the 2D analysis because the constraints are effect to the creep deformation. But large deformation is calculated at the higher temperature region.

4. CONCLUSIONS

In the present study, we applied the creep constitutive equation including creep damage to the 2D and 3D finite element analysis for the creep deformation of coolant piping in severe accident. An isotropic damage rule of the Kachanov-Rabotnov type is also applied to the creep constitutive equation for tertiary creep region. The graded temperature is given to the 2D and 3D model of the tube, which is the same as the condition of the creep piping failure test performed by JAERI.

In both the 2D and 3D analyses, the value of the damage variables can indicate the state of the damage distribution of the tube. The damage variables are confirmed to be able to reproduce the failure from wall outside of the tube in the experimental results. There is small difference between the 2D and the 3D analyses. The deformation and damage variable of the tube of the 3D analysis are smaller than those of the 2D analysis because low temperature region of the 3D model is larger than that of the 2D model.

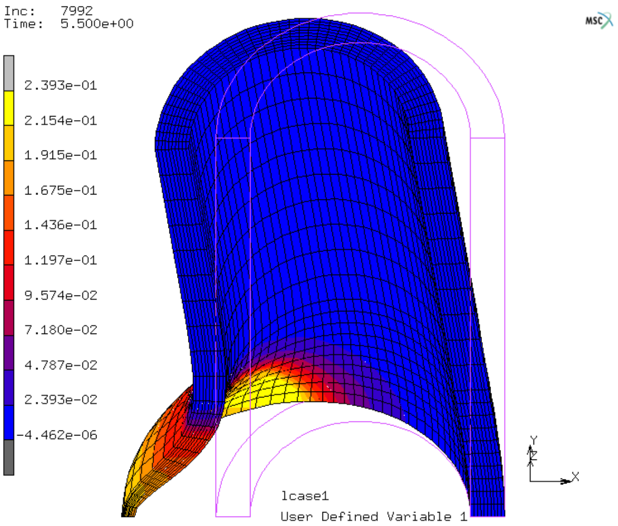

Fig.7 Deformation of coolant piping obtained from 3D FE analyses of graded temperature condition after 5.50 hours.

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