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Creep Characteristics in Thick Welded Joints and Their Improvements (Report I)†

−Development of A Simple Model for Creep Analysis of A Thick Welded Joint−

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Abstract

Reliable predictions of the creep behavior of thick welded joints are very important to secure the safety of elevated temperature vessels like nuclear reactors. Creep behavior is very complex, thus it is difficult to practice the experiment and conduct the theoretical analysis.

A simple accurate model for theoretical analysis was developed in this study. The simple model is constructed of several one-dimensional finite elements which can analyze not only one-dimensional creep behavior but also the three-dimensional case. The model is easy to treat, and needs only a little labor and computation time to predict the creep curve and the local strain for a thick welded joint. The simple model will be verified by comparing the analyzed results with the experimental ones in the next report.

KEY WORDS : (Thick Welded Joint) (Creep Test) (Three-Dimensional Creep Behavior) (Theoretical Analysis) (Simple Mathematical Model) (One-Dimensional FEM)

1. Introduction

Reliable predictions of the creep behavior of thick welded joints are very important to secure the safety of elevated temperature vessels like nuclear reactors. The thick welded joint experiences a complex thermal history. Its material properties including creep are very complicated and are largely different, depending on the location. So the creep behavior of a thick welded joint is very complex.

In this study, for the thick welded joint of a nuclear reactor, etc., the creep behavior to rupture, which is important as one of the limit capacities of the joint, is analyzed by theoretical calculation and by experiment. Based on the results, the desirable material properties and welding methods are investigated to improve the creep capacities (the creep strain rate, the life time, etc.) of the joint, considering the control of the metal structure. In the first stage, to progress these aims rationally and efficiently, a simple mathematical model based on FEM is developed, to be able to simulate accurately the creep behavior of the thick welded joint. The structure and the theory of the simple model are explained in this report.

2. A Simple Mathematical Model for Creep Analysis of A Thick Welded Joint

A simple mathematical model for the creep analysis of a thick welded joint is developed for the following purposes.

(1) It is very difficult to experiment on the creep behavior with the thick welded joints because they need large-capacity equipment and high-level techniques. Also it is hard to perform accurate theoretical analysis.

(2) For the development of the model, it is necessary to analyze and clarify the creep phenomena in a thick welded joint. Then some simplification of behavior is required. It is also a essential work to complete this serial study.

(3) When a simple model is completed, it becomes possible to test easily the calculations under various conditions with a personal computer, to improve of the creep property of thick welded joint.

2.1 Thick welded joint for analysis

The thick joint produced by multi-layer butt welding and the extracted test specimen, for this study, are shown in

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Fig. 1[1]. The materials of the base plate and the weld metal are SUS304HP and Y308 respectively. The narrow gap of 50 mm thickness was welded by submerged arc welding using 24 passes and 13 layers. The specimen with a 10 mm width was cut out from the joint. The load acts on the specimen in the direction of the perpendicular to the weld line (X-direction).

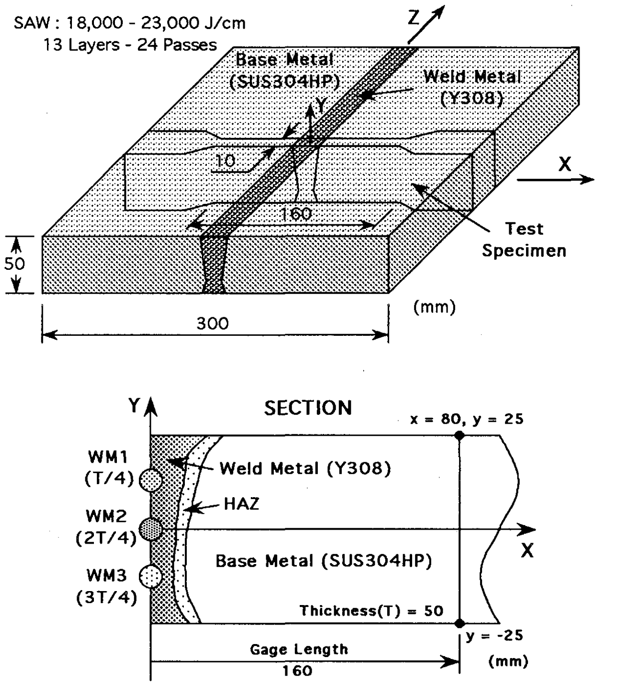

Fig. 1 Thick welded joint and its creep test specimen

2.2 Structure of a simple model

The creep properties of the weld metal and the base metal were determined in previous experiments[1]. The creep behaviors are largely different, depending upon the location. **Figure 2** shows the creep curves of the weld metals (WM1: a quarter of thickness inside from the top surface, WM2: half of thickness inside, WM3: three quarters of thickness inside, see Fig. 1) and the base metal, under the condition of 550 °C and 235 MPa of initial loading stress.

A simple model is constructed with seven one-dimensional elastic-plastic creep elements[2] to simulate the creep behavior of the above thick welded joint, as shown in **Fig. 3**. Elements EWM1 - EWM3 correspond to the weld metal. Elements EBM1 - EBM4 correspond to the base metal. The heat-affected zone (HAZ) is divided into two regions of the weld metal and the base metal, because the elastic-plastic creep properties of the HAZ are between those of the weld metal and of the base metal, and the width of the HAZ is very small. So the region of the HAZ is separated in half, and they are included in the weld metal elements and the base metal elements. Each element has elastic-plastic creep properties depending on the temperature and the stress. For example, they have the properties shown in Fig. 2 at 550 °C and 235 MPa, depending on location. The details of the temperature and the stress dependencies of the properties at each location are shown in Ref. 1.

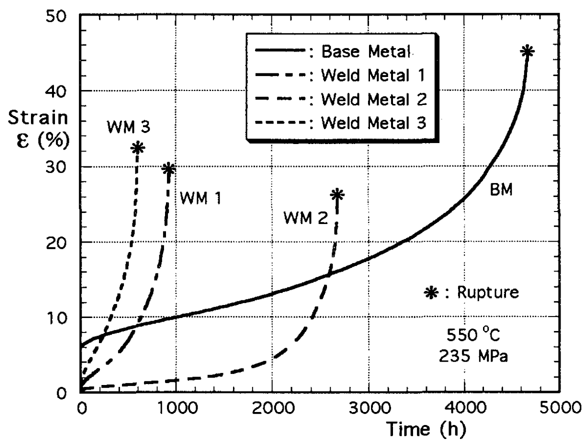

Fig. 2 Creep curves of weld metals and base metal

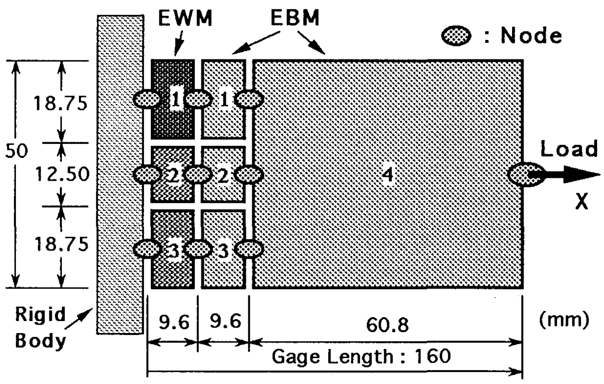

Fig. 3 A simple mathematical model for creep analysis of a thick welded joint

The creep property is the same in the base plate. Nevertheless the base plate is separated into four elements EBM1 - EBM4. The reason is as follows. The joint is a continuous solid body. The creep property of the weld metal is largely different, depending on the location. The interaction of the creep behaviors occurs in the joint, especially near the weld metal. The role of the base plate for the interaction is realized in one-dimensional analysis, by being divided into four elements, such as shown in Fig. 3. The elements EBM1 - EBM3 have the almost same length as the EWM1 - EWM3. Their nodes at the outer sides are connected to the element EBM4, and have the same displacement. The interaction among the EWM1 - EWM3 can be carried out through elements EBM1 - EBM4.

2.3 Sizes of elements

Here the sizes of each element will be decided. The dividing line is drawnat the mean location of the region of the HAZ, perpendicular to the surface. The region between Y axis (x=0) and this line is further divided into three parts by separating at two means (WM1-WM2, WM2-WM3) of the three positions where the creep property was investigated in the experiments. The three parts are named the weld metal elements EWM1 - EWM3. The depths (the dimensions of Y-direction) of the base plate elements EBM1 - EBM3 are assumed to be the same as the elements EWM1 - EWM3 described above. It may be appropriate that the length (the dimension of X-direction) of the elements EBM1 - EBM3 is about the length of the elements EWM1 - EWM3 from the consideration of the material mechanics, so they are assumed to have the same length as the elements EWM1 - EWM3. The model which has these sizes is called the basic model. The length of the elements EBM1 - EBM3 will be discussed again in the analysis for the verification of the model in the next report.

3. Theory of the Simple Model

The model described in the previous section is a simple model constructed of seven one-dimensional elastic-plastic creep elements, and can be used easily. In the actual thick welded joint, complex three-dimensional welding residual stresses exist in the initial state, and the creep behavior may be different from the one-dimensional stress state. So a new theory was developed, which can incorporate the effect of the three-dimensional stress state, when using the one-dimensional stress element. This theory is expressed for displacement, strain, and stress in only one direction, which are important and are given attention, but the effect of the existence of components in the other directions is included in the equations, with some assumption.

The main equations are shown below. They are expressed for the condition of constant temperature because the creep test is performed in that condition. The isotropic rule was assumed to govern both plastic property and creep property, based on the material tests, in Ref. 1. In the rule, the centers of the plastic potential and the creep potential are at the origin in the stress space and do not move at all time. This rule was applied to develop the theory of the model, too, because it is necessary to use the above properties in the analysis.

3.1 Basic equations in uni-axial (one-dimensional) stress state (X-direction)

(1) Creep strain rate

$$^{r}\varepsilon_x^c = f_x^c\left(c_1, c_2, -, c_n, \varepsilon_x^c, \sigma_x\right) \qquad (1)$$

where

$c_1, c_2, -, c_n$ = creep constants

ε_x^c = creep strain in X-direction

σ_x = stress in X-direction

(2) Constitutive equation (Relation between stress and total strain)

$$d\sigma_x = M^U \cdot \left(d\varepsilon_x - d\varepsilon_x^c\right) \qquad (2)$$

where

$d\varepsilon_x$ = total strain increment in X-direction

M^U = stiffness coefficient in uni-axial stress state

Elastic element :

$$d\varepsilon_x = d\varepsilon_x^e \qquad (3)$$

$$M^U = M^{Ue} = E \qquad (4)$$

$d\varepsilon_x^e$ = elastic strain increment in X-direction

E = Young's modulus

Elastic-plastic element :

$$d\varepsilon_x = d\varepsilon_x^e + d\varepsilon_x^p \qquad (5)$$

$$M^U = M^{Up} = \left(E\,W\left(\varepsilon_x^p\right)\right) / \left(E + W\left(\varepsilon_x^p\right)\right) \qquad (6)$$

$d\varepsilon_x^p$ = plastic strain increment in X-direction

$W\left(\varepsilon_x^p\right)$ = strain-hardening modulus

$$W\left(\varepsilon_x^p\right) = d\sigma_x / d\varepsilon_x^p = d\sigma_{YI}\left(\varepsilon_x^p\right) / d\varepsilon_x^p$$

$\sigma_{YI}\left(\varepsilon_x^p\right)$ = yield stress

(3) Yield condition

$$\sigma_{YI}\left(\varepsilon_x^p\right) - \sigma_x = 0 \qquad (7)$$

3.2 Basic equations in multi-axial (three-dimensional) stress state

(1) Elastic strain increment, plastic strain increment, and creep strain rate (For all components)

$$\left\{d\varepsilon^e\right\} = \left[RD^e\right]\left\{d\sigma\right\} \qquad (8)$$

$$\left\{d\varepsilon^p\right\} = (3/2)\left(d\sigma^{EQ} / W\left(\varepsilon^{pEQ}\right)\right) \cdot \left\{\sigma^{de}\right\}\left(1/\sigma^{EQ}\right) \qquad (9)$$

$$\left\{^{r}\varepsilon^c\right\} = (3/2)\ {}^{r}\varepsilon^{cEQ}\ \left\{\sigma^{de}\right\}\left(1/\sigma^{EQ}\right) \qquad (10)$$

where

$\left[RD^e\right]$ = strain-stress matrix

σ^{EQ} = equivalent stress

$\left\{\sigma^{de}\right\}$ = deviatoric stresses

$W\left(\varepsilon^{pEQ}\right)$ = strain-hardening modulus

$$W\left(\varepsilon^{pEQ}\right) = d\sigma^{EQ} / d\varepsilon^{pEQ} = d\sigma_{YI}\left(\varepsilon^{pEQ}\right) / d\varepsilon^{pEQ}$$

$\sigma_{YI}\left(\varepsilon^{pEQ}\right)$ = yield stress

ε^{pEQ} = equivalent plastic strain

${}^{r}\varepsilon^{cEQ}$ = equivalent creep strain rate

$${}^{r}\varepsilon^{cEQ} = f^{cEQ}\left(c_1, c_2, -, c_n, \varepsilon^{cEQ}, \sigma^{EQ}\right)$$

ε^{cEQ} = equivalent creep strain

In uni-axial stress state, X component in Eq. (10) corresponds with Eq. (1).

(2) Elastic strain increment, plastic strain increment, and creep strain rate (For X component which is given attention)

$$d\varepsilon_x^e = d\sigma_x^{el}/E \tag{11}$$

$$d\varepsilon_x^p = (3/2)\left(d\sigma^{EQ} / W\left(\varepsilon^{pEQ}\right)\right) \cdot \sigma_x^{de}\left(1/\sigma^{EQ}\right) \tag{12}$$

$${}^{r}\varepsilon_x^c = (3/2)\ {}^{r}\varepsilon^{cEQ}\ \sigma_x^{de}\left(1/\sigma^{EQ}\right) \tag{13}$$

where

$$d\sigma_x^{el} \equiv d\sigma_x - \nu\left(d\sigma_y + d\sigma_z\right)$$

ν = Poisson's ratio

(3) Influence coefficients of multi-axial stress state (hereinafter called multi-axial stress coefficients)

Multi-axial stress coefficients are defined as follows.

$$\sigma_x^{el} = m_x^{el} \cdot \sigma_x \tag{14}$$

$$\sigma^{EQ} = m_x^{EQ} \cdot \sigma_x \tag{15}$$

$$\sigma_x^{de} = m_x^{de} \cdot \sigma_x \tag{16}$$

where

$m_x^{el}, m_x^{EQ}, m_x^{de}$ = multi-axial stress coefficients

Here it is assumed that the ratio of stress components does not change when the stresses change. Then the multi-axial stress coefficients $m_x^{el}, m_x^{EQ}, m_x^{de}$ hold the constant values, and the incremental forms of Eq. (14) - Eq. (16) are satisfied.

$$d\sigma_x^{el} = m_x^{el} \cdot d\sigma_x \tag{17}$$

$$d\sigma^{EQ} = m_x^{EQ} \cdot d\sigma_x \tag{18}$$

$$d\sigma_x^{de} = m_x^{de} \cdot d\sigma_x \tag{19}$$

(4) Relations between X-directional strains (rate) and X-directional stress or equivalent strains, using multi-axial stress coefficients

Equation (11) - Eq. (13) are represented as follows, using multi-axial stress coefficients.

$$d\varepsilon_x^e = \left(m_x^{el}/E\right) \cdot d\sigma_x \tag{20}$$

$$d\varepsilon_x^p = (3/2)\left(m_x^{de} / W\left(\varepsilon^{pEQ}\right)\right) \cdot d\sigma_x \tag{21}$$

$${}^{r}\varepsilon_x^c = (3/2)\left(m_x^{de} / m_x^{EQ}\right) \cdot {}^{r}\varepsilon^{cEQ} \tag{22}$$

When the ratio of stress components does not change every time(increment),

$$\varepsilon_x^p = (3/2)\left(m_x^{de} / m_x^{EQ}\right) \cdot \varepsilon^{pEQ} \tag{23}$$

$$\varepsilon_x^c = (3/2)\left(m_x^{de} / m_x^{EQ}\right) \cdot \varepsilon^{cEQ} \tag{24}$$

(5) Constitutive equation (Relation between stress and total strain)

From the above equations, the constitutive equation is obtained for X components.

(5-1) Elastic state

$$d\varepsilon_x^e = \left(m_x^{el}/E\right) \cdot d\sigma_x \equiv \left(1/C^e\right) \cdot d\sigma_x \tag{25}$$

$$d\sigma_x = C^e \cdot d\varepsilon_x^e \equiv M^{Me} \cdot d\varepsilon_x^e \equiv M^{Me} \cdot \left(d\varepsilon_x - d\varepsilon_x^c\right) \tag{26}$$

(5-2) Elastic-plastic state

$$d\varepsilon_x^e = \left(m_x^{el}/E\right) \cdot d\sigma_x \equiv \left(1/C^e\right) \cdot d\sigma_x \tag{27}$$

$$d\varepsilon_x^p = (3/2)\left(m_x^{de} / w\left(\varepsilon^{pEQ}\right)\right) \cdot d\sigma_x \equiv \left(1/C^p\right) \cdot d\sigma_x \tag{28}$$

$$d\varepsilon_x^{ep} \equiv d\varepsilon_x^e + d\varepsilon_x^p = \left(1/C^e\right) \cdot d\sigma_x + \left(1/C^p\right) \cdot d\sigma_x = \left(\left(C^e + C^p\right) / \left(C^e C^p\right)\right) \cdot d\sigma_x \tag{29}$$

$$d\sigma_x = \left(\left(C^e C^p\right) / \left(C^e + C^p\right)\right) \cdot d\varepsilon_x^{ep} \equiv M^{Mp} \cdot d\varepsilon_x^{ep} = M^{Mp} \cdot \left(d\varepsilon_x - d\varepsilon_x^c\right) \tag{30}$$

(5-3) General form

$$d\sigma_x = M^M \cdot \left(d\varepsilon_x - d\varepsilon_x^c\right) \tag{31}$$

where

$d\varepsilon_x$ = total strain increment in X-direction

M^M = stiffness coefficient in multi-axial stress state

Elastic element :

$$d\varepsilon_x = d\varepsilon_x^e \tag{32}$$

$$M^M = M^{Me} = C^e \tag{33}$$

$$C^e = E/m_x^{el}$$

Elastic-plastic element :

$$d\varepsilon_x = d\varepsilon_x^e + d\varepsilon_x^p \tag{34}$$

$$M^M = M^{Mp} = \left(C^e C^p\right)/\left(C^e + C^p\right) \tag{35}$$

$$C^p = (2/3)\left(W\left(\varepsilon^{pEQ}\right)/m_x^{de}\right)$$

(6) Yield condition

$$\sigma_{YI}\left(\varepsilon^{pEQ}\right) - \sigma^{EQ} = \sigma_{YI}\left(\varepsilon^{pEQ}\right) - m_x^{EQ} \cdot \sigma_x = 0 \tag{36}$$

3.3 Stiffness equation of element

$$\begin{Bmatrix} dP_i \\ dP_j \end{Bmatrix} = k \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} du_i \\ du_j \end{Bmatrix} \tag{37}$$

where

dP_i, dP_j = nodal force increment

du_i, du_j = nodal displacement increment

$$k = \begin{cases} k^{Ue} = AM^{Ue}/L & \text{: uni-axial elastic element} \quad (38) \\ k^{Up} = AM^{Up}/L & \text{: uni-axial elastic-plastic element} \quad (39) \\ k^{Me} = AM^{Me}/L & \text{: multi-axial elastic element} \quad (40) \\ k^{Mp} = AM^{Mp}/L & \text{: multi-axial elastic-plastic element} \quad (41) \end{cases}$$

A = sectional area of element

L = length of element

3.4 Consideration of change of sectional area due to loading

The magnitude of the tensile load acting on the specimen is constant, but the magnitude of the stress in the specimen increases with the decrease of the sectional area due to the elongation of the specimen. The increase of the stress is very small in each increment, but the creep strain rate changes, dependingon the magnitudeof the stress, very sensitively. The analysis has to considerthese behaviors, in the one-dimensional element, exactly. In the incremental method, the changeof the sectional area, new magnitudeof the stress for newsectional area, andthe creep strain rate for newstress have to be calculatedaccuratelyin each increment, satisfying the equilibrium condition between the load and the stresses of the elements.

4. Conclusion

In this study, for the thick welded joints of nuclear reactors, etc., the creep behavior to rupture, which is important as one of the limit capacities of the joint, is analyzed by theoretical calculation and by experiment. Based on the results, desirable material properties and welding methods are investigatedto improve the creepcapacities (the creep strain rate, the life time, etc.) of the joint.

In this first report, to accomplish these purposes rationally andefficiently, a simple mathematicalmodel based on FEM has been developed. The simple model is constructed of seven one-dimensional elastic-plastic creep elements, and can be used easily. In the actual thick welded joint, complex three-dimensional welding residual stresses exist in the initial state, then the creep behavior may be different from in one-dimensional stress state. So a new theory has been developed.

The theory is expressed for displacement, strain, and stress in only one direction, but the effectof the existence of components in the other directions is included in the equations, with some assumption. Then the model cananalyze creep behavior in the three-dimensional stress state, using the one-dimensional stress element with the multi-axial stress coefficients.

The model is easy to treat, and needs only a little labor and computation time with the common personal computer to predict the creep curve and the local strain of a thick welded joint. The simple model will be verified by comparing the analyzed results with the experimental ones in the next report.

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