Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

Development of Mechanical Analysis Model for Two Layered Coating Cladding

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***Keywords :** Transfer Matrices, Accident Tolerant Fuel, Mechanical Analysis, Multilayer Cladding, Elastic-plasticity model

1. Introduction

It is desirable that improvements in accident tolerance are simultaneously accompanied by improvements to normal operations in terms of compatibility with current power plants and operations, economics, and impact on fuel cycles. For this reason, accident tolerant fuel (ATF) is being developed in several countries. In the case of accident tolerant fuel coated on the outer surface of the cladding to enhance the safety of the nuclear fuel, the characteristics of the coated layer shall be reflected in order to evaluate the performance.

FRAPCON [1], a typical nuclear fuel performance code, performs deformation analyses with formulas based on thick-wall theory for a single material, which is not suitable for analyzing cases where the base material and coating (Cr/CrAl) layer have different properties, such as ATF cladding. Numerical methods such as finite difference and finite element methods are more appropriate to analyze the elastic-plastic deformation of a cladding with two different properties than the thick-wall theory. A mechanical model exists to calculate the elastic-plastic deformation of nuclear fuel using the finite difference method. [2] It is difficult to properly implement the performance of accident tolerant fuel because the cladding is expressed only in a single layer in the existing mechanical model. The transfer matrices methodology [3] was used to develop an algorithm that could be applied to multi-layer cladding. A new model was developed by applying elastic-plastic properties and calculating boundary conditions with multilayer cladding. By modeling multilayered cladding, stress gradients in the thickness direction can be calculated.

2. Mechanical model for ATF

In the existing model [2], the pellet is calculated using multilayer elements as shown in Figure 1(a), but the cladding is calculated as a single layer. In the case of ATF, since the properties of the cladding and coating layers are different, the model is modified to reflect this, so that the cladding is also composed of multiple layers, as shown in Figure 1(b). This section presents the methodologies for the mechanical analysis of multilayer cladding.

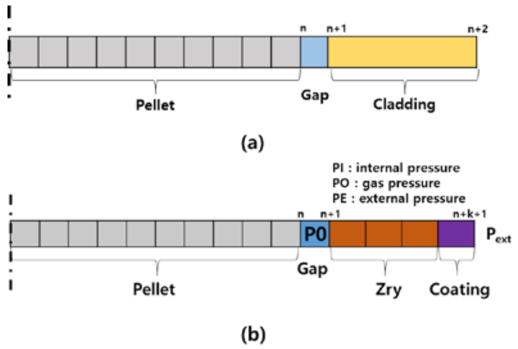


Fig. 1. Mechanical analysis model; (a) conventional concept, (b) modified concept for ATF.

2.1 Transfer Matrices

By performing a finite difference method for the governing equations of force equilibrium, compatibility, and constitutive equations for a single height layer, the stress components of all elements can be coupled and expressed as shown in Figure 2, which is called the transfer matrices method. Based on these relationships, once the initial stress values are known, the stresses in the rest of the entire region can be calculated.

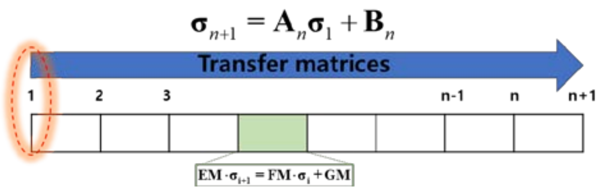


Fig. 2. Concept of transfer matrices.

2.2 Boundary condition according to contact condition

In order to find all the stress components in each region using the transfer matrices method, an initial stress value must be given. Depending on the contact conditions of the pellet and cladding, the boundary conditions will be different and therefore the initial stress values will be different. The initial stress condition was defined for three different contact conditions: no contact, contact with axial slip, and contact without axial slip.

2.2.1 No contact

In the case of no contact, the pellet and cladding are considered as separate continuums and the initial stress is calculated using their respective boundary conditions. Based on this, the stress components in the entire area of the pellet and cladding are calculated.

$$\begin{cases} \textbf{Pellet region} \\ \sigma_{r,n} = -P_o,\ \boldsymbol{\sigma}_{n+1} = \mathbf{A}_n\boldsymbol{\sigma}_1 + \mathbf{B}_n \\ \sigma_{r,1} = -P_i \ \ .or.\ \ \sigma_{r,1} = \sigma_{\theta,1} \\ \sum_{i=1}^{n-1}\left(\frac{\sigma_{z,i}+\sigma_{z,i+1}}{2}\right) dA_i = F_z,\ \boldsymbol{\sigma}_{n+1} = \mathbf{A}_n\boldsymbol{\sigma}_1 + \mathbf{B}_n \end{cases} \Rightarrow \sigma_{r,1},\ \sigma_{\theta,1},\ \sigma_{z,1}$$

$$\begin{cases} \textbf{Cladding region} \\ \sigma_{r,n+2} = -P_e,\ \boldsymbol{\sigma}_{n+1+k} = \mathbf{AA}_k\boldsymbol{\sigma}_{n+1} + \mathbf{BB}_k \\ \sigma_{r,n+1} = -P_o \\ \sum_{i=n+1}^{n+k}\left(\frac{\sigma_{z,i}+\sigma_{z,i+1}}{2}\right) dA_i = 0,\ \boldsymbol{\sigma}_{n+1+k} = \mathbf{AA}_k\boldsymbol{\sigma}_{n+1} + \mathbf{BB}_k \end{cases} \Rightarrow \sigma_{r,n+1}, \sigma_{\theta,n+1}, \sigma_{z,n+1}$$

2.2.2 Contact with axial slippage

For the contact condition with axial slip, the radial stress must be the same at the point where the pellet and cladding are in contact, so the initial stress of each is calculated at once based on these boundary conditions as shown below. Based on this, the stress components of the entire area of the pellet and cladding are calculated.

$$\begin{cases} \sigma_{r,n+k+1} = -P_e,\ \sigma_{r,n} = \sigma_{r,n+1} \\ \sum_{i=1}^{k}\left(\frac{\sigma_{z,n+i}+\sigma_{z,n+i+1}}{2}\right) dA_{n+i} = 0,\ \boldsymbol{\sigma}_{n+i+1} = \mathbf{AA}_i\boldsymbol{\sigma}_{n+1} + \mathbf{BB}_i \\ \sum_{i=1}^{n-1}\left(\frac{\sigma_{z,i}+\sigma_{z,i+1}}{2}\right) Area_i = F_z,\ \boldsymbol{\sigma}_n = \mathbf{A}_{n-1}\boldsymbol{\sigma}_1 + \mathbf{B}_{n-1} \\ Gap_{ini} = U_{r,n} - U_{r,n+1} = \varepsilon_{\theta,n}r_n - \varepsilon_{\theta,n+1}r_{n+1} \end{cases} \Rightarrow \begin{matrix} \sigma_{r,1}, \sigma_{\theta,1}, \sigma_{z,1} \\ \sigma_{r,n+1}, \sigma_{\theta,n+1}, \sigma_{z,n+1} \end{matrix}$$

2.2.3 Contact without axial slippage

For the contact condition without axial slip, the gap element is considered as a virtual structure and new transfer matrices (EM', FM', GM') are generated using the boundary conditions at the gap.

$$\begin{cases} \sigma_{r,n} = \sigma_{r,n+1} \\ d\varepsilon_{z,n+1} = d\varepsilon_{z,n} \\ Gap_{ini} = U_{r,n} - U_{r,n+1} \end{cases} \Rightarrow \ \mathbf{EM}'\cdot\boldsymbol{\sigma}_{n+1} = \mathbf{FM}'\cdot\boldsymbol{\sigma}_n + \mathbf{GM}'$$

By applying a new virtual element and assuming that the pellet and cladding are one continuum, the initial stress is calculated using the following boundary conditions, which are then used to calculate the total stress.

$$\begin{cases} \textbf{Considering virtual gap element} \\ \sigma_{r,n+k+1} = -P_e \\ \sigma_{r,1} = -P_i \ \ .or.\ \ \sigma_{r,1} = \sigma_{\theta,1} \\ \sum_{i=1}^{n+k}\left(\frac{\sigma_{z,i}+\sigma_{z,i+1}}{2}\right) dA_i = F_z \end{cases} \Rightarrow \ \sigma_{r,1},\ \sigma_{\theta,1},\ \sigma_{z,1}$$

2.2.3 Plastic model

To calculate the plasticity, the algorithm in Figure 3 is applied. The plasticity algorithm here is based on the relationship between plastic strain increment and modified total strain. It is defined to be faster and more convergent than the traditional Prandtl-Reuss method. [4]

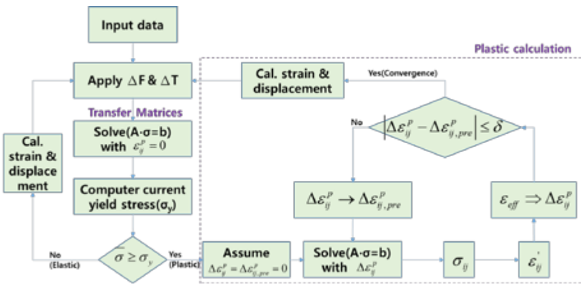


Fig. 3. Flow chart for Elastic-plastic calculation

3. Comparison with conventional mechanical model

In order to validate the developed code, the results from the existing model [2] are compared with the results from the modified model, as shown in Figure 4. The same material properties and boundary conditions are given, only the element of the cladding is defined as a single element in the conventional model and four elements in the developed model. Comparisons were made for elastic and elastic-plastic material properties.

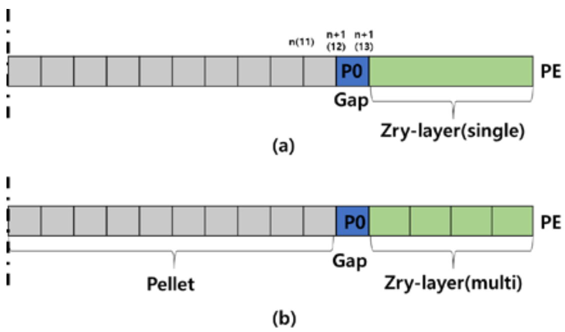
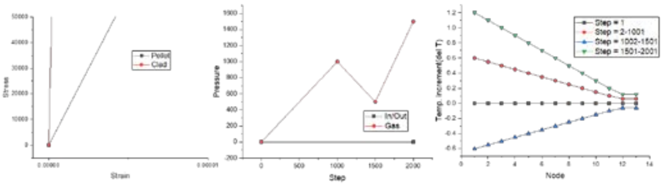


Fig. 4. Analysis model for comparison; (a) conventional model, (b) developed model

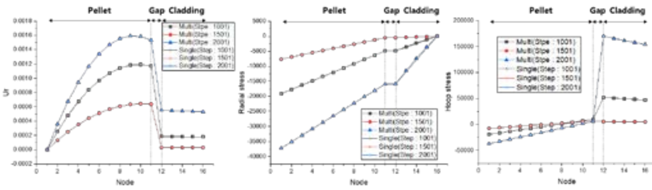
3.1 Elastic material property

In the case of elasticity, a constant elastic modulus was assigned as shown in Figure 5, and it was assumed that there was no external pressure acting on the pellet and the sheath tube, only internal pressure, and the input conditions were set to change the temperature according to the time step. A total of 2001 steps were analyzed. The results of the existing model and the developed model analyzed with the above input conditions are shown in Figure 6. Figure 6 shows the strain in the radial direction and the radial and hoop stresses. These results show good agreement between the two models. In the developed model, the presence of additional elements inside the cladding results in an additional representation of the values inside the cladding and shows that the internal stress distribution is not a perfectly linear relationship.



(a) (b) (c)

Fig. 5. Parameters used in elastic problem for comparison; (a) strain-stress curve, (b) inner/gap/outer pressure, (c) temperature increment.

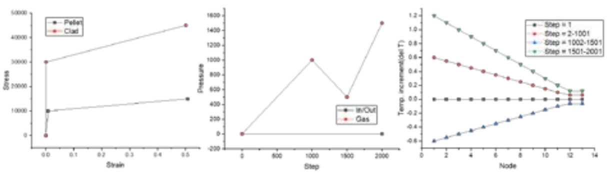


(a) (b) (c)

Fig. 6. Results of elastic problem; (a) radial displacement, (b) radial stress, (c) hoop stress

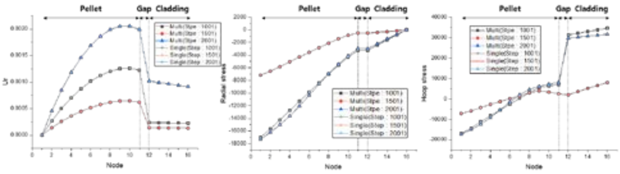
3.2 Elastic-Plastic material properties

In the case of elastic-plastic model, the input conditions are defined as shown in Figure 7, and the hardening characteristics due to plasticity are defined as a bilinear form, and the strain-stress components are visualized. In addition, the pressure and temperature changes were equivalent to the conditions imposed by elasticity. The results of the existing model and the developed model analyzed based on carbon properties are shown in Figure 8. Figure 8 shows the strain in the radial direction and the radial and hoop. As with the elastic analysis, the elastic-plastic problem analysis shows that the results of the two models are in good agreement.



(a) (b) (c)

Fig. 7. Parameters used in elastic-plastic problem for comparison; (a) strain-stress curve, (b) inner/gap/outer pressure, (c) temperature increment.



(a) (b) (c)

Fig. 8. Results of elastic-plastic problem; (a) radial displacement, (b) radial stress, (c) hoop stress

4. Conclusions

A new mechanical analysis model was developed for application in ATF. The model is capable of elastic, plastic, and thermal deformation calculations and allows the cladding to be divided into multiple layers and each element to have its own zircaloy and coating layer properties. The plasticity calculation algorithm is based on modified Prandtl-Reuss methods. The developed model was verified by comparison with a conventional model with a single cladding element. It was found that for the same properties, the two model gave identical results. In the future, the model will be further validated using the finite element code ABAQUS for problems with different conditions. After the verification calculation is completed, we plan to perform mechanical analysis on a cladding with an Cr/CrAl coating layer to analyze how the coating affects the behavior of ATF cladding. The stress distribution along the thickness direction inside the cladding will also be calculated, which will allow us to better predict the material's tendency to continuously change from elastic to plastic.

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government(MOTIE) (20217810100050, Development of Safety Enhanced Nuclear Core Technology for APR)

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