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Rigorous Study of mechanical module in FRAPCON/FRAPTRAN

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1. Introduction

Nuclear fuel operates in an extreme environment that induces complex multiphysics phenomena, occurring over distances ranging from inter-atomic spacing to meters, and times scales ranging from microseconds to years. This multiphysics behavior is often tightly coupled, a well-known example being the thermomechanical behavior. Adding to this complexity, important aspects of fuel behavior are inherently multidimensional, examples include pellet-clad mechanical interaction (PCMI), fuel fracture, oxide formation, non-axisymmetric neutronics and cooling, and coupling to lower length scale models.

The most of fuel performance code systems own the mechanical module to analyze the stress and strain of fuel rod during operation. Based on the results of stress and strain with the given conditions, characteristics of fuel performance such as rod internal pressure, cladding deformation and so on can be calculated.

The FRAPCON/FRAPTRAN code system, which possesses world-wide source-code users, incorporates the mechanical module to calculate stress and strain of cladding, which is called 'FRACAS'. The FRACAS module calculates stress and strain of cladding with the prescribed conditions [1]. The module employs the analytical method with the assumptions that the most of traditional performance code uses. In order to improve prediction of Pellet Cladding Mechanical Interaction (PCMI) for the FRAPCON, a new model, the FRAPCON Radial-Axial Soft Pellet (FRASP) model, was developed with new assumptions [2].

On the other hands, the present state of the art in numerical simulation of FE-based fuel performance predominantly involves 2-D axisymmetric model and 3-D volumetric model. In 2-D simulation, the FALCON code, developed by EPRI, is a 2-D (R-Z and R-θ) fully thermal-mechanically coupled steady-state and transient FE-based fuel behavior code [3]. The French codes TOUTATIS and ALCYONE which are 3-D, and typically used to investigate localized behavior [4, 5]. In 2008, the Idaho National Laboratory (INL) has been developing multidimensional (2-D and 3-D) nuclear fuel performance code called BISON [6].

In this paper, the FRACAS module has been rigorously studied to investigate the scope of the method by comparison with numerical model. According to gap status, the FRACAS consists of subroutine 'cladf' for the open gap and subroutine 'couple' for the closed gap. To evaluate the modules, each method was analyzed and the equivalent numerical model using finite element method was established. Based on the comparison of the FRACAS and numerical model, the scope of the module can be defined and evaluated.

2. Mechanical module of FRAPCON/FRAPTRAN (FRACAS)

The FRAPCON/FRAPTRAN employs the identical mechanical module which is called by FRACAS (Fuel Rod and Cladding Analysis Subcode) except cladding ballooning model [7]. The FRACAS module is a computer code which performs the mechanical analysis in the FRAPCON/FRAPTRAN code system. At each time step, the module calculates a complete elastic-plastic-creep solution for the stresses, strains and displacements. To analyze the stress and strain of cladding efficiently, the assumptions are defined as follows; The cladding is modeled as a thin cylindrical shell with prescribed uniform temperature, pressures, and radial displacement of the inside surface (thin-walled cylindrical shell); The pellet is not deformable (Rigid pellet); When the contact occurs, slip of pellet against cladding is not allowed (no slip).

The FRACAS consists of a set of independent subroutines according to gap status. The 'cladf' module is for open gap. The 'couple' module is for the closed gap.

2.1 model for open gap (subroutine cladf)

Subroutine cladf considers a thin cylindrical shell loaded by both internal and external pressures. Axisymmetric loading and deformation are assumed. Loading is also restricted to be uniform in the axial direction and no bending is considered. The geometry and coordinates are shown in the Figure 1. According to thin-walled theory, hoop and axial stresses are obtained by the Eq.(1) and Eq.(2).

$$\sigma_\theta = \frac{r_i p_i - r_o p_o}{t} \quad \text{Eq. (1)}$$

$$\sigma_z = \frac{r_i^2 p_i - r_o^2 p_o}{r_o^2 - r_i^2} \quad \text{Eq. (2)}$$

With the known conditions, stresses and strains can be obtained by the stress-strain relation.

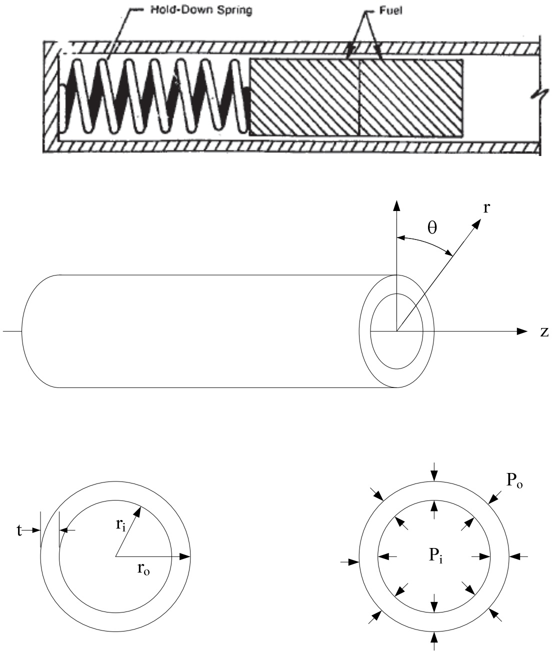

Figure 1. The simplified fuel rod geometry

2.2 model for the closed gap (couple)

For the closed gap, subroutine couple is called. The couple considers the problem of a cylinder shell for which the radial displacement of the inside surface and axial strain are prescribed. In the FRAPCON, the radial displacement is identical to displacement of pellet outer surface due to rigid pellet assumption. With the prescribed displacement, stress and strain can be obtained.

3. Evaluation of the mechanical module

To study the 'cladf' and 'couple' model, the equivalent numerical models have been built using finite element method. To build the FE model, ANSYS 15.0 was employed.

3.1 Equivalent FE model for the open gap and closed gap

In the case of the subroutine 'cladf' for the open gap, the equivalent FE model can be built as shown in Figure 2 (left). In the FRACAS, the module calculates stress and strain of the given axial node that was determined by the user. However, the FE model shows that the semi-infinite long cylinder shape is designed because of the boundary conditions. Load conditions are pressure at the inner side and outer side like analytical model. It is axisymmetric model and the bottom of model is symmetric as a boundary condition.

On the other hands, the equivalent FE model of subroutine 'couple' shows Figure 2 (right). It is also axisymmetric model of axial node. As the boundary conditions, bottom line of cladding is symmetric. As load conditions of the FE model, the prescribed displacement loads at the inner side as well as the upper side of model. In the 'couple' module, upper displacement represents axial displacement of pellet because of no-slip assumption.

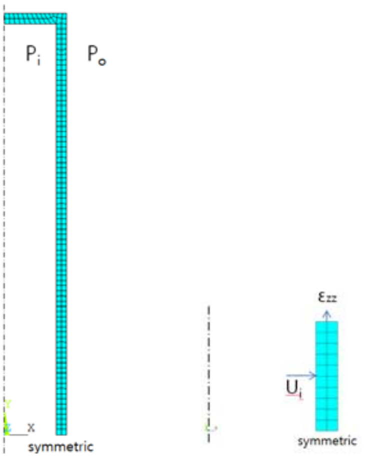

Figure 2. The equivalent FE model for the open gap (left) and the closed gap(right)

To simplify the material properties, Young's modulus of cladding is 90 GPa and poission ratio is 0.3. In the case of 'cladf', loading conditions are as follows; inner pressure is 2MPa, outer pressure is 15MPa. In the case of 'couple', loading conditions are as follows; the prescribed displacement is 0.04 mm, the prescribed strain is 0.004 in the axial direction. Only elastic behavior is considered.

3.2 Comparison stress components of FRACAS module with those of equivalent FE model

Figure 3 shows the radial(σ_{rr}), hoop($\sigma_{\theta\theta}$) and axial (σ_{zz}) stresses with respect to radius at the bottom node of model. In comparison with the results from analytical model, axial and hoop stress at the middle position of cladding are identical within numerical error whereas radial stress is not same. Due to thin-walled assumption, radial stress of is defined as zero.

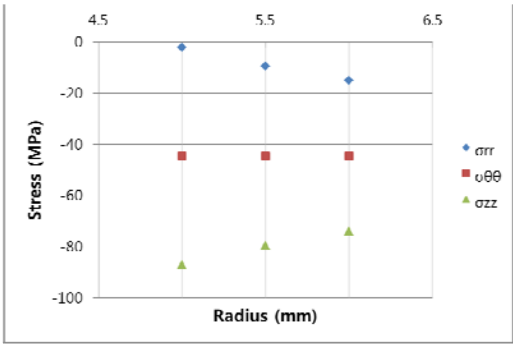

Figure 3. Stress components of FE model for the open gap

Therefore, hoop and axial stresses in the subroutine ‘cladf’ can be acceptable whereas radial stress should be considered because it is not negligibly.

Figure 4 shows stress components of the equivalent FE model for the closed gap. Compared with analytical results as shown in Table 1, the stress components in the middle of cladding are approximately identical with those of numerical method except radial stress. In the ‘couple’ model, interfacial pressure can be obtained because pellet and cladding contact occurs. In comparison with the FE model, the radial stress at the outer surface is zero like analytical model whereas the stress at the inner surface approximately identical with interfacial stress.

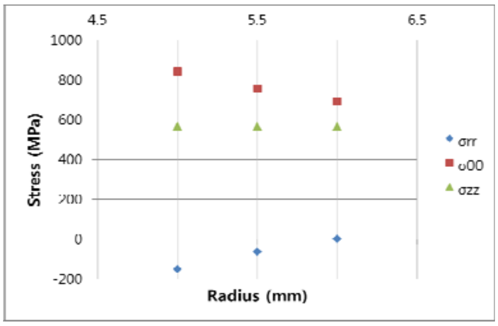

Figure 4. Stress components of FE model for the closed gap

Table 1. Stress components of analytical model

subroutine	Hoop stress (MPa)	Axial stress (MPa)	Radial stress (MPa)	Interfacial stress (MPa)
cladf	-80.0	-44.545	0.0	
couple	796.15	598.85	0.0	159.2

According to the ‘couple’ model, interfacial pressure is computed from Eq. (3).

$$P_{\mathrm{int}} = \frac{t\sigma_\theta + r_o p_o}{r_i} \qquad \text{Eq. (3)}$$

The equation means that interfacial pressure is treated as inner pressure in the same manner as ‘cladf’ if hoop stress is known. As a result, hoop and axial stresses can be acceptable. In the case of radial stress, the stress of the model represents the stress of outer region as well as interfacial stress stands for the stress of inner region.

4. Conclusions

The FRACAS module has been rigorously studied to investigate the scope of the method. According to gap status, subroutine ‘cladf’ or ‘couple’ was called in the FRACAS module. To evaluate the modules, each method was analyzed and the equivalent numerical model using finite element method was established. Based on the comparison of the FRACAS and FE model, the scope of the module can be defined and evaluated. Compared with results from numerical model, hoop and axial stresses of analytical model with assumptions are identical. However, radial stress should be considered because value of the radial stress is not negligibly.

As a further study, the stress components of analytical model for the PCMI behavior will be compared with those of numerical model, which is similar to practical model.

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