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Development of the coupled 3D Finite element module with FRAPCON3.4 for Simulation of pellet-cladding mechanical interaction

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1. Introduction

In nuclear power plant, the fuel rod continuously comes to the fore in aspect of the nuclear safety because of the exposure of radioactive matter. The fuel rod is composed of the pellet made of UO_2 and the cladding made of zircaloy which covers the pellet and transfers the heat from the pellet to the coolant. In particular, pellet-cladding mechanical interaction(PCMI) causes the failure of the cladding. Therefore, PCMI simulation code is necessary to access this phenomenon. METEOR[1] and TOUTATIS[2] have been developed by CEA in France. These codes analyze the multi-physics behavior using axisymmetric, axially-stacked, one-dimensional representation. As these calculate the global rod shape, there is a weak point to represent local behavior. For this purpose, CAST3M[3], which is 3D-FE code, has been developed for TOUTATIS. Recently, ALCYONE[4] has been developed from METEOR and TOUTATIS in order to analyze chemical-physics and thermo-mechanical aspects. In USA, INL also has developed BISON code with multi-dimensional capability[5] .

In this paper, NUFORM3D, which is able to calculate elasto-plastic and contact behavior as three-dimensional finite element (FE) module, has been developed by KAERI and KAIST. To evaluate PCMI behavior of fuel rod, NUFORM3D has been linked with FRAPCON-3.4. The power ramp database (REGATE) in the test reactor was employed. The linked NUFORM3D module is able to show bamboo-shape deformation of cladding and maximum stress due to its deformation that FRAPCON-3.4 is unable to obtain. As well as, 3D effect such as radial crack of the pellet can be studied.

2. Development of the coupled NUFORM3D module

2.1 Description of NUFORM3D

The NUFORM3D has been developed to calculate the contact behavior for simulation of Pellet to Cladding Mechanical Interaction. In this module, the deformation of the fuel rod includes the elastic, plastic and thermal strain

$$\sigma_{ij} = C^{ep}_{ijkl}(\varepsilon - \varepsilon^{th} - \varepsilon^{pl}) \quad (1)$$

The stress components are calculated from eq (1) in the NUFORM3D module. In aspect of elasto-plasticity, it is assumed that isotropic hardening von-mises yield condition(J-2 flow) applies to the cladding and the deformation of the pellet is elastic behavior.

2.2 Development of the coupled NUFORM3D with FRAPCON-3.4

FRAPCON-3.4 is the NRC's fuel performance code for the calculation of steady-state thermal-mechanical behavior of light-water reactor (LWR) oxide fuel rods for long-term and high burn-up. The code calculates the temperature, pressure, and deformation of a fuel rod as functions of time-dependent fuel rod power and coolant boundary conditions. The phenomena modeled by the code includes 1) heat conduction through the fuel and cladding to the coolant; 2) cladding elastic and plastic deformation; 3) fuel-cladding mechanical interaction; 4) fission gas release from the fuel and rod internal pressure; and 5) cladding oxidation. The code contains necessary material properties, water properties, and heat-transfer correlations. The NUFORM3D has made the weak point of the transient analysis in FRAPCON-3.4 compensating mechanical dimension

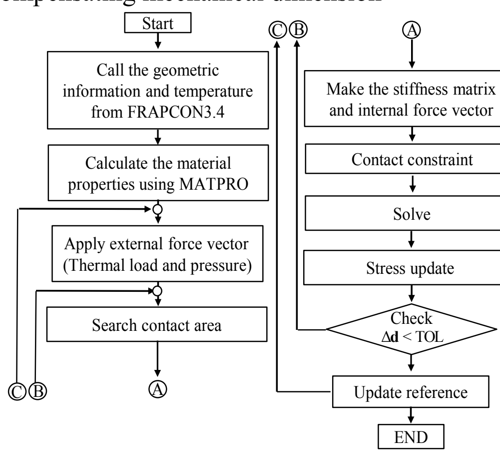

Fig.1 The coupled NUFORM3D algorithm

NUFORM3D calculates thermal strain and the contact between the pellet and the cladding considering plastic deformation. In this reason, NUFORM3D could show the effect of thermal strain and plastic deformation of the cladding as three-dimensional description instead of FRAPCON-3.4(1.5D). Therefore, the NUFORM3D module calls the geometric information from FRAPCON-3.4 code except plastic strain and thermal strain in eq (2) to calculate the thermal expansion and elasto-plastic deformation.

$$\varepsilon = \varepsilon^{total} - \varepsilon^{th} - \varepsilon^{el} - \varepsilon^{pl} \quad (2)$$

The temperature of FRAPCON-3.4 has applied to NUFORM3D using third-degree polynomial curve fitting using least square fitting method. The material properties are computed by using MATPRO [7].

2.3 FE model of NUFORM3D

NUFORM3D uses 3-dimentional 8-node element using selective reduced integration that protects the locking problem.

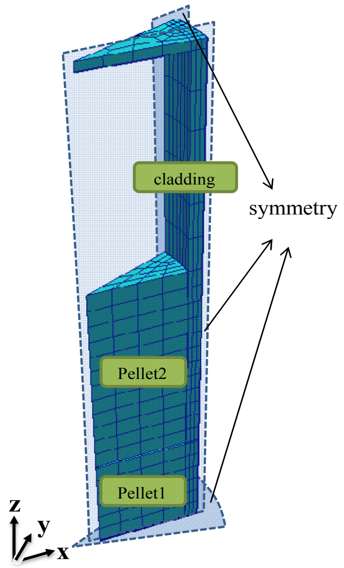

Fig.2 FE model of fuel rod

In fig.2, the eight-cracked pellet model has been employed. Also, the upper section of the fuel rod has been considered[8].

3. Validation of the coupled NUFORM3D module against in-pile test

The NUFORM3D has been developed to simulate the PCMI considering contact and thermal, elasto-plastic deformation. We have made a comparison between the results of the NUFORM3D module, which the FRACON-3.4 employs, and the power ramp database. As In-pile test data, REGATE experiment was used.

3.1 REGATE experiment

To evaluate the coupled NUFORM3D with FRAPCON-3.4, the in-pile test database REGATE experiment was employed. This experiment deals with the study of fission gas release and fuel swelling during power transient at medium burn-up. The rod was base irradiated in Gravlines 5 PWR up to 47.415 MWd/kgM and then re-irradiated in the test reactor SILOE for experimental power ramp in Grenoble France. Since the rod is initially a segmented rod (L10: 4.5 w/o UO_2 pellets, Zy4 stress relieved cladding, and 17x17 design). The re-fabrication process prior to loading in the test is light. In particular, the rod is not purged of its fission gases following re-fabrication.

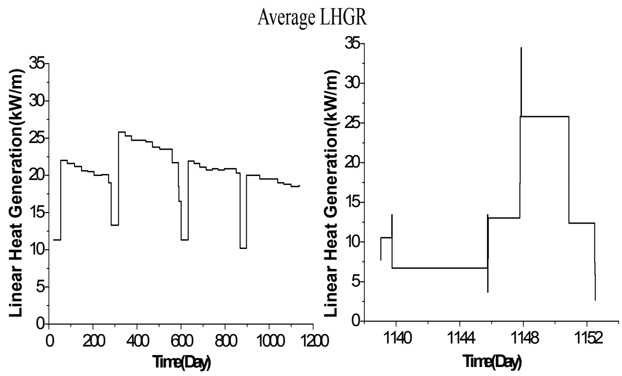

Fig.3 Power history of REGATE

In Fig.5-(b), PCMI considerably arises in the most linear heat generation rate which appeared on near 1147.86 day after the irradiation. At the height of ramp, the linear heat generation has been 38.0kW/m in the node that we analyzed in fig.4 for 1.5 hours. NUFORM3D has calculated PCMI at this time step with FRAPCON-3.4. In the test reactor, the temperature of the coolant was 526K and the pressure was 13MPa.

3.2 Comparison Results

The diameter of the cladding after power ramp test has been compared to the result of FE simulation result with FRAPCON-3.4.

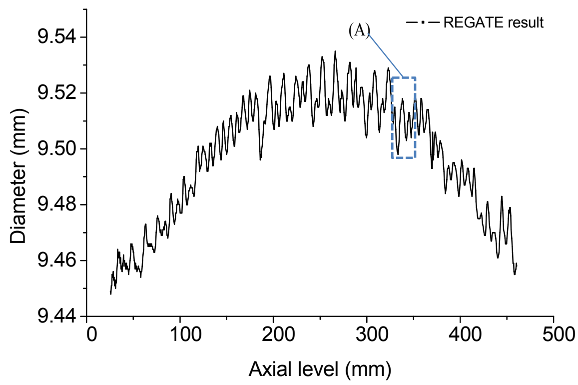

Fig.4 Diameter of the cladding after power ramp test (REGATE PIE result)

In fig.4, the residual diameter of the cladding has been measured by non-destructive PIE at room temperature after the test rod was re-irradiated. FE result of the diameter of the cladding has been compared to REGATE on (A) of the test rod. In fig.5 and fig.6, the results are described and it was found that the application of NUFORM3D to FRAPCON-3 was able to supplement the weak point of FRAPCON-3 because this could show the primary ridge which FRAPCON-3 can't show as well as the radial crack of the pellet. On the center of the cladding, FE module hasn't calculated the secondary ridge shown in the REGATE result. In order to show secondary ridge, visco-plasticity module in the pellet model has to be developed for NUFORM3D[9].

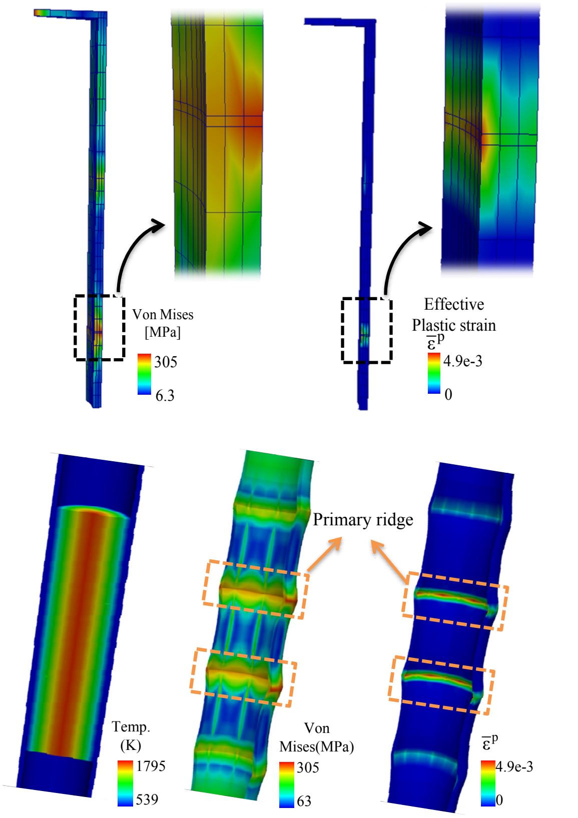

Fig.5 Temperature of the fuel rod, von-mises and effective plastic strain of the cladding

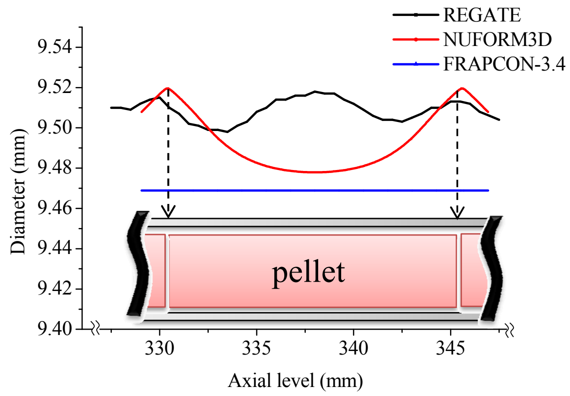

Fig.6 Comparison of the results of the diameter after power ramp test

4. Conclusions

The NUFORM3D, which is able to calculate elasto-plastic and contact behavior as three-dimensional finite element (FE) module, has been developed by KAERI and KAIST. To evaluate PCMI behavior of fuel rod, NUFORM3D has been linked with FRAPCON-3.4. The power ramp database (REGATE) in the test reactor was employed. The linked NUFORM3D module is able to show bamboo-shape deformation of cladding and maximum stress due to its deformation that FRAPCON3.4 cannot obtain. Comparison of results between NUFORM3D and FRAPCON3.4 shows that 3D mechanical module should be required to simulate PCMI behavior. As a further study, the pellet should include the visco-plasticity module to represent the secondary ridge in the center of the pellet that appears after power ramp.

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