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Evaluation of Cladding Stress Effect According to Pellet MPS Type and Size using Finite Element Analysis

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1. Introduction

Missing Pellet Surface (MPS) defects in nuclear fuel pellets can significantly affect the stress distribution in fuel rod cladding, potentially increasing the risk of Pellet-Cladding Interaction (PCI) failure[1,2]. This study presents a comprehensive evaluation of MPS-induced stress effects using three-dimensional finite element analysis combining the ROPER fuel performance code[3] with the ABAQUS finite element software[4].

2. Methods

This section describes the ROPER fuel rod performance code input and output conditions, the finite element model, the analysis conditions, and the material and performance models used to evaluate stress as a function of MPS size. First, the core and thermal-hydraulic conditions, pellet and cladding specifications, material properties, and performance models are selected and calculated using ROPER. Based on the ROPER input and calculation results, ABAQUS inputs for three-dimensional finite element analysis are generated, and the MPS finite element model (FEM) is constructed. The respective roles of ROPER and ABAQUS are shown in Fig. 1.

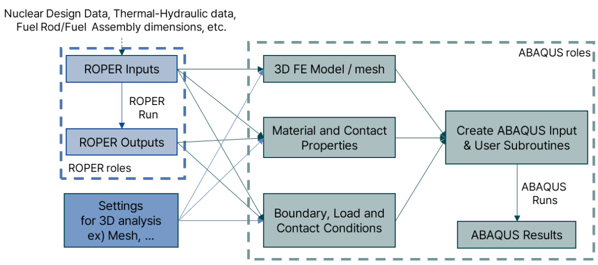

Fig. 1. Roles of ROPER and ABAQUS

2.1. Power Conditions

The MPS stress impact evaluation was performed using a conservative burnup history and power ramp rate as shown in Fig. 2. The conservative burnup history was set to slowly decrease power at the end of cycle N-1, so that the pellet and cladding contact earlier at the beginning of the next cycle (cycle N), resulting in higher hoop stress. At the startup of cycle N, power was immediately increased to 50%, and then ramped to 100% at 3% per hour.

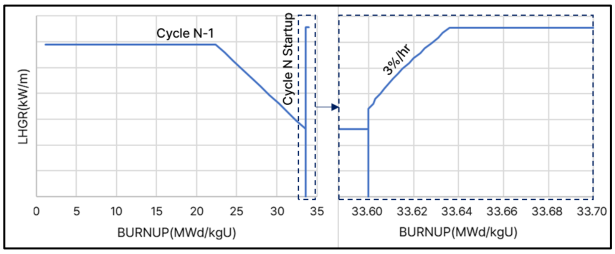

Fig. 2. Fuel Rod Power History

2.2. Finite Element Model for Normal Pellet and MPS

The finite element model incorporated 1.5 pellets with 45-degree circumferential symmetry to simulate 8 radial cracks[5]. Four MPS types were modeled as shown in Fig. 3: side chip, column-type, mid-pellet side chip, and end chip.

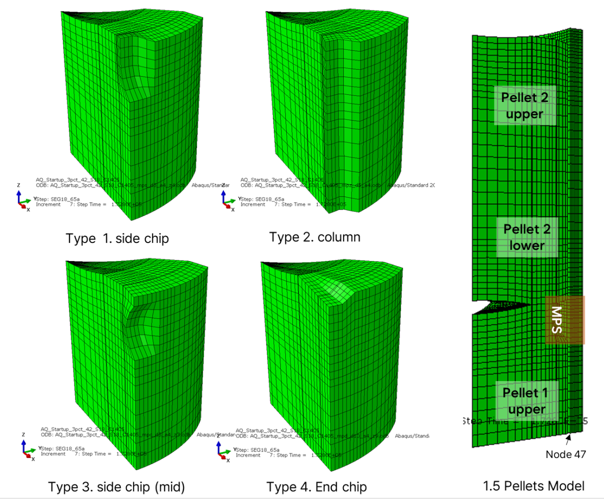

Fig. 3. Finite Element Model for MPS

2.3. Conditions and Properties

The boundary conditions, loads, and contact conditions used for the 3D ABAQUS analyses of both the normal-pellet and MPS models are as follows:

▪ Thermal Analysis Conditions

- Heat generation per unit volume for 16 radial pellet rings is input from ROPER calculation results.

- Time-dependent cladding outer surface temperature from ROPER is applied as boundary condition.
- Thermal contact between pellet outer surface and cladding inner surface uses ROPER's GAPCON model implemented in ABAQUS user subroutine.
- Thermal contact between pellets uses He gas thermal conduction model.

▪ Mechanical Analysis Conditions
- Circumferential symmetry conditions applied to pellet and cladding surfaces.
- For 45-degree symmetry model with 8 pellet cracks, symmetry conditions applied only to partial areas on both circumferential surfaces.
- Vertical symmetry conditions applied to pellet bottom surface and cladding bottom surface.
- Time-dependent fuel rod internal pressure applied between pellet outer and cladding inner surfaces.
- Reactor coolant pressure applied to cladding outer surface.

For the MPS models, the same boundary, loads, and contact conditions were applied as in normal-pellet model. However, the total heat generation decreases due to the reduced pellet volume caused by the MPS.

2.4. Material Properties

Material properties were taken from the models implemented in the ROPER code[3]. The pellet material property models applied include thermal conductivity, specific heat, elastic modulus, Poisson's ratio, thermal expansion, swelling, and densification. The cladding material property models include thermal conductivity, specific heat, elastic modulus, Poisson's ratio, thermal expansion, plasticity, creep, and irradiation growth.

3. Results

Fig. 4 shows the peak hoop stress and temperature reduction as functions of MPS type, size, and volume reduction. Fig. 5 shows the relationship between peak hoop stress and the temperature reduction relative to node 47 on the cladding inner surface as shown in Fig. 1.

As shown in Fig. 4(a), the maximum hoop stress generally increases with MPS size. Even at the same MPS size, hoop stress increases as MPS depth increases (d1 → d6). Among the types, the highest stress was observed for Type 2 (column), which has the largest MPS size. In addition, when comparing cases where the MPS is located at the pellet end (Type 1) and (Type 3), higher stress was observed for Type 1. For Type 4, the stress increase was relatively large compared to the MPS size.

In Fig. 4(b), the peak hoop stress increases with MPS volume reduction, but above approximately 0.1 mm³, the rate of increase decreases and shows a converging trend.

In Fig. 5, the relationship between temperature reduction and peak hoop stress shows a linear trend for each MPS type.

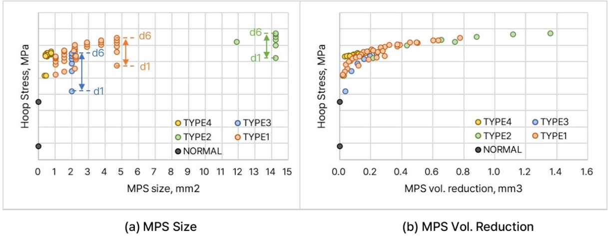

Fig. 4. Peak Hoop Stress vs. MPS Size / Volume Reduction

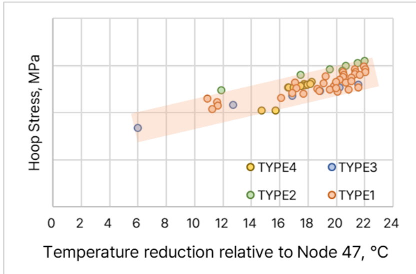

Fig. 5. Peak Hoop Stress vs. Temperature Reduction

4. Conclusions

In this study, the stress effects induced by various MPS types and sizes were evaluated using 3D finite element analysis, and the stress effects of MPS were confirmed in the PCI risk assessment. In the future, MPS evaluations will be performed under various power histories and conditions, and the results will be incorporated into establishing a PCI evaluation system required for flexible operation.

Acknowledgement

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