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Development of simplified beam model of a spent nuclear fuel rod

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1. Introduction

The integrity of spent nuclear fuel during handling operations or transportation became an important issue as the storage period extends due to the failure of timely installation of final disposal site. This is an issue especially for the high burn up fuels with burnup higher than 45,000 GWd/MTU which is more fragile than the low burn-up fuel to many degradation mechanisms such as hydride reorientation and so on. A lot of efforts have been made to quantify and model the degradation of fuel cladding as a function of relevant parameters including time and to evaluate the integrity of fuel assemblies during transportation accidents [1]. In many references, it is deemed impractical to model the whole fuel assembly with solid finite elements and many of them use a simplified beam element to represent a single fuel rod. However, the procedure to find an appropriate set of properties of the beam element has not been investigate much. In this paper, a procedure to find the material properties of a beam element which considers the interfacial bonding between the fuel pellets and cladding. During the reactor operation, there occur complicated mechanical and chemical interaction between the pellets and cladding, and it is known that a chemical bond can form between them. The effect of such bonding is investigated in this paper with the aim of building an equivalent beam model of single, irradiated fuel rod.

2. Single Fuel Rod Detailed Model Analyses

In this section, a detailed explanation on the finite element model development of single, irradiated fuel rod considering the pellet-cladding bonding status.

2.1 Finite element model of single fuel rod

Fig. 1 illustrates the 89.22 mm gauge section model with the pellets, in which there are seven full-length and two partial-length pellets. Bending moments were applied on both ends of the fuel rod rotating along the X axis as shown. This model is comprised of pellets, cladding and thin interfacial layer between the pellets and cladding to mimic the oxide layer between them.

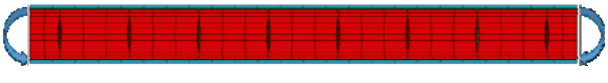


Fig. 1. Finite element of single fuel rod section

The pellets are modeled with solid elements, C3D8 in ABAQUS/explicit while the interfacial layer and the cladding are modeled with C3D8I to capture the bending behavior effectively with small number of element layers through the thickness.

The material properties of each component are borrowed from reference [2] which corresponds to those of high burnup fuel as listed in Table 1.

2.2 Boundary conditions and loading

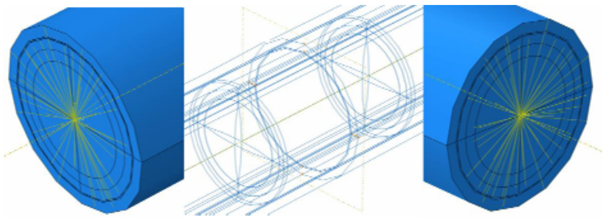


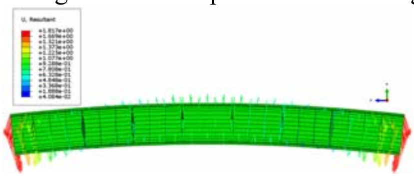
Fig. 2. Loading and boundary condition imposed on fuel rod section model

At the ends of the fuel rod section model, reference points were generated with rigid connection to the surfaces of pellets and cladding as shown in Fig. 2. Moments are imposed on those two points to bend the fuel rod section accordingly. The lateral direction displacements and out-of-bending plane rotations are restricted to get more stable results.

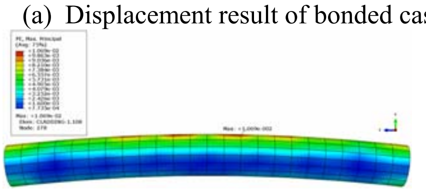
The interfaces between the pellets are modeled as frictionless hard contact surfaces while the interface between the pellets and cladding are models either a frictionless hard contact (de-bonded condition) or tied surfaces (bonded condition). The de-bonded condition mimic the original status of fuel rod where there is no chemical and mechanical bonding between the pellets and cladding while the bonded condition represents a status where all the pellets are chemically bonded to the cladding with reactor operation. Actually, the properties of this bonding has not been investigated much and the parameters like bonding strength, failure criteria have not been known exactly. In this work, the properties of the oxide layer are borrowed from those of epoxy as shown in [3].

2.3 Analysis results and implications

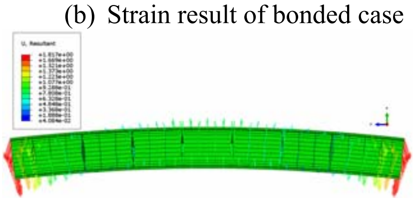
In this work, a various values of bending moments are tried to find the value which yield 1 % of plastic strain in cladding which is the assumed threshold value for cladding failure. The strain and displacement results for both the de-bonded condition and bonded conditions are depicted in Fig. 3. The critical bending moments are found to be 4.65 N·m and 1.85 N·m for bonded case and de-bonded case, respectively. It is shown that the resistance of fuel rod against bending fracture is about 2.5 time greater when there exists strong bonding between the pellets and cladding.



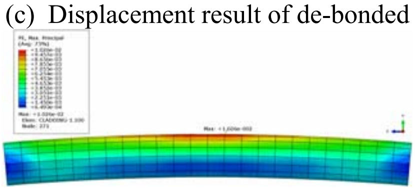
(a) Displacement result of bonded case



(b) Strain result of bonded case



(c) Displacement result of de-bonded case



(d) Strain result of de-bonded case

Fig. 3 Analysis results using detailed fuel rod model

The relative displacement of fuel rod due to bending is calculated as 0.844 mm and 0.646 mm for bonded and de-bonded case, respectively. It is seen that the pinch stress exerted by the pellet to cladding contributes to the strain of cladding.

3. Development of Equivalent Beam Model

3.1 Method and logic

The logic to find the section or material properties of equivalent beam model of single fuel rod is as follows.

(1) The two model, the detailed solid model and the simplified beam model should have the same threshold moment that corresponds to the failure of fuel rod.

(2) They should have the same in-plane displacement for given bending moment so that the interaction between fuel rods in an assembly model can be well simulated.

(3) The simplified beam model should account for the interfacial bonding efficiency.

In this work, only the material properties of the equivalent beam elements are considered for the parameters to be calibrated since the cross section of beam are fixed to solid circular one so that the rod to rod interactions are accurately simulated in the future research.

3.2 Results and discussion

Table I illustrates the results of material properties calibration for equivalent beam model.

Table I: Problem Description

	Detailed model	Simplified model
Bonded	Zircaloy cladding E: 77.64 GPa σ_Y: 828 MPa Fuel Pellets E: 168 GPa σ_Y: 2146 MPa Epoxy E: 3.5 GPa σ_Y: 69 MPa	E: 168.3 GPa σ_Y: 2574 MPa
De-bonded		E: 153.8 GPa σ_Y: 825 MPa

When the critical bending moments 4.65 N·m and 1.85 N·m are exerted, the plastic strain and displacement of the beam model are calculated as 1 %, 1.2 mm and 0.95 % and 0.66 mm for bonded and de-bonded cases, respectively. The error is less than 5 % compared to the results using the detailed fuel rod model.

4. Conclusions

A simple and robust procedure to find the equivalent properties of simplified beam model that simulates the behavior of complicated spent fuel rod. The interfacial bonding status can be accounted for by appropriately modeling the interfaces and the found model predicts almost same strain and displacement for given bending moments. In our future work, a detailed fuel assembly model will be built using the developed simplified beam to calculate the fuel damage ratio in transportation accidents within a framework of risk assessment.

REFERENCES

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