Simulation of Bending Behavior of High Burnup Spent Fuel Rod Considering Breakage of Interfacial Bonding

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1. Introduction

In spent fuel management, such as transportation and storage, maintaining the integrity of nuclear fuel is an essential requirement for safety and economics. Many previous studies have evaluated the mechanical properties of nuclear fuel cladding and nuclear fuel rods to assess their resistance to external loads and to develop computational models to evaluate fuel integrity under transportation or storage conditions. The CIRFT(Cyclic Integrated Reversible-Bending Fatigue Tester) test data of Oak Ridge National Laboratory showed that the interfacial bonding condition between the fuel pellets and cladding have significant impact on the load resistance of fuel rod [1]. Kim [2] proposed a method of building simplified model of a high burnup spent fuel rod assuming fully bonded and de-bonded interfacial conditions between the fuel pellets and cladding.

The behavior of a spent fuel rod subjected to external load is generally affected by the following factors. (1) cladding properties, (2) the bonding of the interface between the cladding and the pellet, and (3) bonding of the interface between the pellets. The static CIRFT data for high burnup fuel rod showed that the bonding of the interfaces breaks during the loading and the stiffness of the fuel rod varies accordingly. Therefore, assuming the condition of the interface to be fully bonded or fully de-bonded is not realistic and can lead to overly conservative or unsafe solutions.

In this work, a finite element model of high burnup spent nuclear fuel rod is developed that can simulate the sequential breakage of interfacial bond between the pellets and pellet-cladding under bending load. The parameters necessary for the simulation of damage behavior of interfaces are calibrated against the static CIRFT data using optimization. This research will enable more realistic simulation of spent nuclear fuel rod under various loading condition.

2. Test Development Methods and Analysis Results

This section describes the CIRFT test data presented in NUREG-2224 and the finite element model of a nuclear fuel rod to simulate the test using ABAQUS. The damage parameters are derived using the Moment-Curvature curve of the CIRFT test.

2.1 Static CIRFT test method and data

CIRFT has a loadcells and three Linear Variable Differential Transformers (LVDTs) to measure the real-time curvature of the tested fuel rod. The applied Displacement was applied up to 12.0 mm at a rate of 0.1 mm/s to generate pure bending of 80 N·m in the specimen. As a result of the test, a moment-curvature curve was obtained as shown in Fig.1. The curve can be divided into two linear sections and the last one non-linear section.

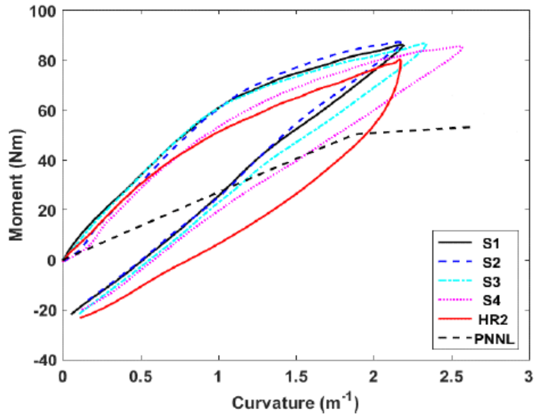
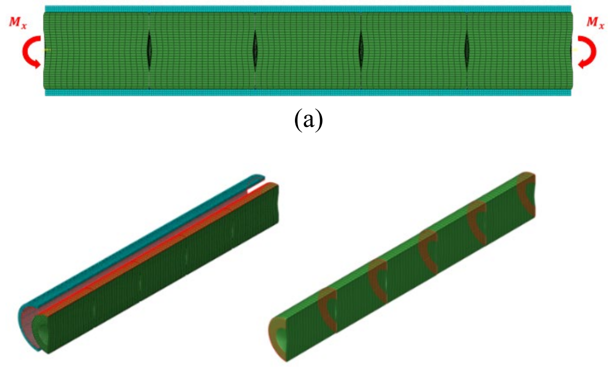


Fig. 1. Moment – Curvature curve from static CIRFT test[1]

2.2 Fuel rod finite element model

A finite element model was created using Abaqus to simulate static CIRFT test. The model consists of nuclear fuel pellets and Zircaloy-4 cladding as shown in Fig. 2(a). The properties of the cladding and pellet are obtained from the formula of the PNNL-17700 and listed in Table 1. Bending moment of up to about 80 N·m is applied to both ends of the fuel rod model.

The interfaces between the pellets and the pellet-cladding are modeled with the cohesive element which can simulate the progressive damage accumulation in the interfaces due to normal and shear stress. The traction-separation law is used to describe the behavior and the parameters of the model is calibrated against the moment-curvature curve of CIRFT test.



(a)

(b)

Fig. 2. (a) Loaded moment of SNF, (b) Cohesive behavior section

Table I: CIRFT test model materials

	Parameter	Value
Zircaloy cladding (SRA Zry-4)	Mass density	$6.95 \times 10^{-9}\ ton/mm^3$
	Modulus of elasticity	75226 MPa
	Poisson's ratio	0.3377
Fuel (Uranium dioxide, UO_2)	Mass density	$1.04 \times 10^{-8}\ ton/mm^3$
	Modulus of elasticity	171067
	Poisson's ratio	0.32

2.3 CIRFT Test Model Analysis Result

2.3 Finite element analysis Result

The analysis results are shown in Fig. 4, and it is confirmed that the contact surface between the cladding and the pellet receives relatively large stress. In addition, a large local stress is generated at the edge of the pellet which contacts the cladding inner surface. This is consistent with the test results, which show that cladding failure occurs at a location corresponding to the pellet-pellet interface. Before the bonding breaks, large shear stress is generated at the interface of pellet-cladding and as the deformation progresses, normal stress is generated at the pellet-pellet interface. The breakage of bonding is observed in the results and the detailed parameter calibration will be conducted in our future research. The curvature of fuel rod was calculated as follows:

$$R = \sqrt{(x_0 - d_2)^2 + {y_0}^2} \quad (1)$$

$$x_0 = \frac{-2m_a m_b h - m_a(d_2 + d_3) + m_b(d_1 + d_2)}{2(m_a - m_b)} \quad (2)$$

$$y_0 = -\frac{1}{m_a}\left(x_0 - \frac{d_1 + d_2}{2}\right) - \frac{h}{2} \quad (3)$$

Where

$$m_a = \frac{h}{d_2 - d_1} \quad (4)$$

$$m_b = \frac{h}{d_3 - d_2} \quad (5)$$

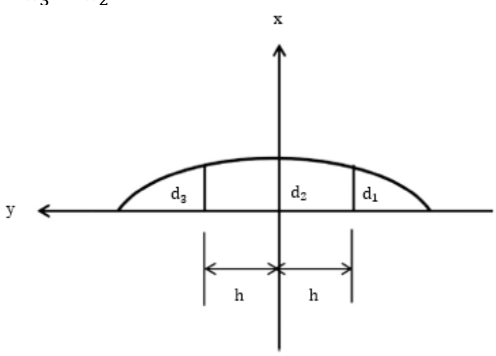


Fig. 3. Determination of the curvature of the bending rod by use of deflections measured at three points.

When comparing the moment-curvature curve with the test result using the calculated curvature, they show good correlation. However, three characteristic intervals in Fig. 2 could not be identified in the analysis results since the fine tuning of damage model of cohesive element has not been completed yet.

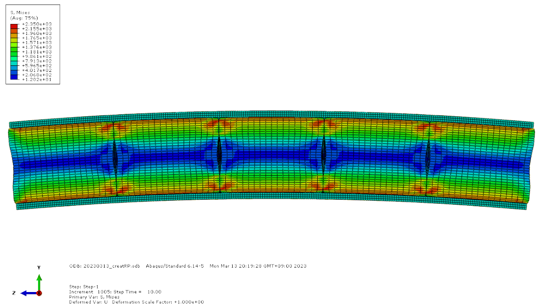


Fig. 4. Longitudinal section view of curvature and von Mises stress

3. Conclusions

In this study, a simulation method of adhesive behavior between cladding and pellets and between pellet and pellet of SNF were presented. Important parameters of cohesive damage model are calibrated using the CIRFT test data. It is envisioned that using this method more realistic simulation of fuel rods behavior under impact condition would be possible and calculation of fuel damage ratio would be more accurate.

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