Simplified Beam Model of Spent Nuclear Fuel Rod

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1. Introduction

Structural integrity of spent nuclear fuel assembly should be carefully examined under storage and normal condition of transportation. Due to the complicated shape and uncertainties in the mechanical properties, the structural evaluation of spent fuel assembly is a challenging task. During analyses for storage and transportation, the spent fuel assemblies are often simplified to reduce the computational burdens. In the simplified model, the spent fuel rods are replaced by beam elements with effective material properties calculated from the properties of cladding and fuel pellets. However, a well agreed procedure for the model degeneration has not been developed yet and the validity of the effective material properties have not been discussed in depth. In some approach, the stiffness of the pellets is ignored while their masses are lumped into cladding. In others, the average values of Young's modulus are used while no considerations are made on the plastic properties of cladding. In this work, a procedure for material property calibration for spent nuclear fuel rods is proposed based on the static analyses and optimization and the validity of the properties are checked using the dynamic impact simulations.

2. Material Properties

2.1 Storage condition and material properties

The material properties of spent fuel rods with Zircaloy cladding can be calculated from a sophisticated models proposed in [1]. They are given as functions of neutron fluence, temperature, cold work ratio, strain rate, hydrogen concentration, and oxide thickness.

2.2 Storage conditions

During the storage pool stage, the temperatures are roughly maintained at 30°C, while the initial temperature at the vacuum drying stage is around 400°C (the maximum fuel cladding temperature) which decreases gradually during the dry storage period. The temperature typically drops from 400°C to 250°C in the first ten years. The neutron fluence of HBF (45–60 GWd/MTU) in a light-water reactor roughly ranges from 7×10^{25} n/m^2 to 12×10^{25} n/m^2. For discharge burnup in the range of 45–60 GWd/MTU, the average hydrogen concentration ranges between 200–600 ppm. These variables are considered in the material properties calculation for cladding and fuels.

3. Simplified Beam Model

3.1 Overall procedure

A segment of fuel rod is considered in this work. A detailed model of the segment is constructed with enough details of cladding and pellets. Two separate models are built based on the interfacial conditions between the pellets and cladding. Then, static analyses are performed to capture important mechanical response of the model to external load, namely the maximum equivalent plastic stain which can be a measure for determining the fracture of cladding, the compliance of fuel rod which is important in determining the load exerted on the rod due to the interaction with other fuel rods and structural component within a cask. Then, a beam model with the same diameter of fuel rod is considered and its material properties are calibrated which generate the same equivalent plastic strain and displacement under the given load. The whole procedure is implemented using the optimization platform i-Sight integrating ABAQUS and MATLAB. The design variable of the calibration procedure is the Young's modulus, strength coefficient, and the hardening coefficient.

3.2 Results of material calibration

For two cases, the effective material propreties of beams which produces the same plastic strain and displacement at critical load is identified. The results are illustrated in the following figures.

Table 1. Effective material properties of beam

Cases	E	n	K
Bonded	235697	0.15	1682
De-bonded	83042	0.15	781

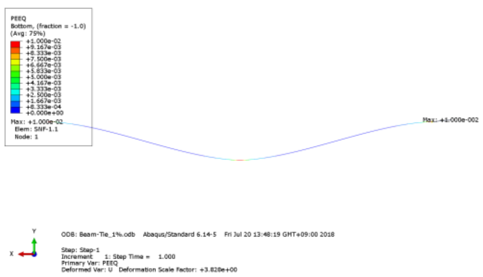

Fig. 1. Fully bonded case.

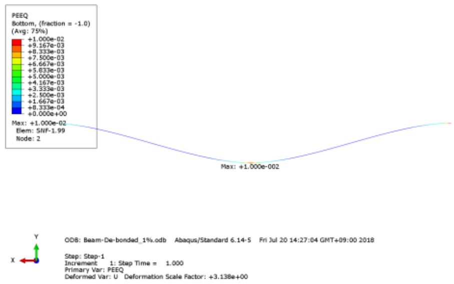

Fig. 2. Fully de-bonded case.

4. Conclusions

Using a sophisticated calibration procedure, the effective material properties of simplified beam model of spent fuel rods can be successfully determined. These material properties produce exactly same plastic strain and displacement at critical load. However, the validity of thus found properties should be carefully examined in dynamic simulations before using them in structural integrity assessment of spent nuclear fuel.

REFERENCES

[1] Adkins, H. et al. Used Nuclear Fuel Loading and Structural Performance under Normal Conditions of Transport— Demonstration of Approach and Results on Used Fuel Performance Characterization, US DOE, 2013.