Structural Integrity Assessment of Spent Nuclear Fuel Rod Under Drop Accident Condition

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1. Introduction

Wet and dry storages are widely used technologies to safely store the spent nuclear fuel (SNF) for several decades. Nonetheless, transfer SNF from wet to other types of longer term storage may occur multiple times before reprocessing or final disposal, due to accumulation problem or to enhance the safety and security level. This activity would probably make abrupt changes to the environment around the SNF assemblies and may lead to undesirable consequences on the fuel integrity. Moreover, the major requirements of SNF for long-term storage under normal storage conditions are to maintain fuel cladding integrity by complying the regulatory requirements of transportability and retrievability, and to provide adequate cooling and environmental control to prevent fuel degradation as stated by Liu (2015). Thus, technical issues on retrievability and cladding integrity with the concern of storage conditions and the aging effects should be investigated as major obstacles for safe handling, safe transportation operations, and economic management of SNF.

The present research is limited to a single fuel rod elastic-plastic deformations dynamics under vertical (end) and horizontal (side) drop orientations. The sensitivity analysis is performed to determine the relative impact of various parameters relevant to design safety on fuel rod strength/stiffness based on impact loads and resulting strains on fuel cladding, since it is considered as the first barrier against the release of radioactive materials. The parameters for the sensitivity study include material's mechanical properties of the fuel rod, pellet-to-cladding mechanical interaction (PCMI), spacer grid (SG) spring and dimple stiffness, and rod internal pressure (RIP). High burnup fuel with burnup higher than 45 GWd/MTU is considered for this study together with reported storage conditions.

2. FE Model and Storage Condition

2.1 Finite element model of single fuel rod

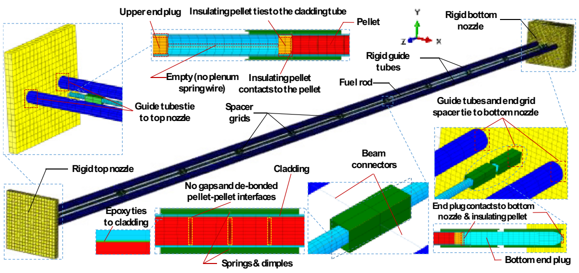

Fig. 1. Fuel rod model-finite element details.

The FE model of a single fuel rod has been developed, including all the structural features, to study the individual behavior of fuel rod under drop condition. The fuel rod was modelled with the actual dimensions of 350 fuel pellets in a 4.094-m-long fuel cladding referred to CE16x16 Plus 7 fuel type, as well as 2 end plugs, 2 insulating pellets, 2 guide tubes, top/bottom nozzles, and 12 SGs (see Fig. 1) were all modelled to investigate the interaction of fuel rod against the supporting components. This model is designed in a way to provide useful results that can be transferred to fuel assembly level model in a cask-loaded condition.

2.2 Storage conditions

The temperature history is an important variable for evaluating SNF behavior during storage and post-storage transportation accidents. The initial temperature, at vacuum drying stage, is somewhat around 400°C but decreases gradually influenced by the radioactive/heat decay. The temperature drops typically from 400°C to 250°C in the first ten years. The neutron fluence (or burnup) is also considered as a significant variable that affects the mechanical properties and failure criteria; particularly fracture toughness of irradiated Zircaloy. The cladding fluence associated with high burnup fuel (HBF) of 45~60 GWd/MTU in a pressurized water reactor

(PWR) is roughly ranged from 7 to 12 $\times 10^{25}$ n/m^2. For discharge burnup in the range of 45-60 GWd/MTU, the average hydrogen concentration is ranged between 200-600 ppm. These variables make a momentous influence on the structural integrity of spent nuclear fuel associated with the material degradation and failure criteria. Therefore, the effect of lower and upper bounds storage conditions within the first ten years has been studied in the sensitivity analysis.

3. Sensitivity Analysis

3.1 Test matrix

The sensitivity analyses are performed for high degree uncertain parameters such as material properties of cladding, pellet-cladding mechanical interaction(PCMI), spacer grid stiffness, and rod internal pressure to demonstrate the impact of each parameter on the resulting stress and strain predictions.

3.2 Cladding material properties

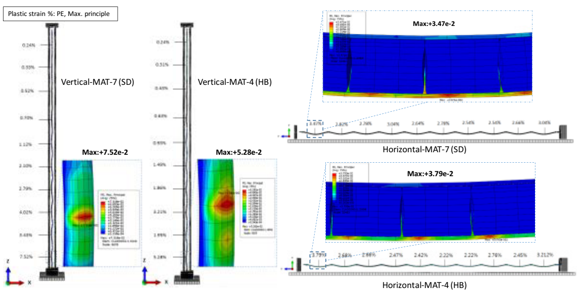

Fig. 2. Plastic strain at vertical and horizontal drop.

In the vertical drop, it appears that the largest lateral displacements occurred between the bottom SGs that near to the impact end. For the horizontal drop, the bending moments along the fuel rod are almost equivalent in both cases. The PE max. principal in the cladding for SD material is 37% higher than the HB material in the vertical drop and 5.1% higher in the horizontal drop.

3.3 PCMI

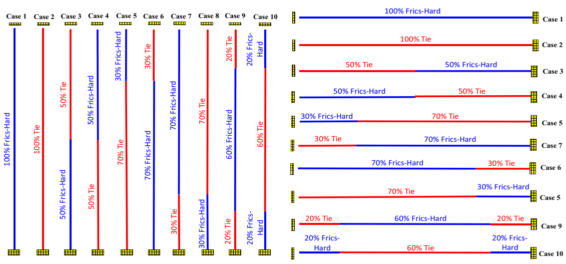

Fig. 3. Detailed fuel assembly analysis model.

Ten generalized interface bonding and de-bonding conditions have been implemented using frictionless hard contact property and surface-based tie constraint (permanently glued surfaces) to provide a fundamental understanding of the interface bonding efficiency for the fuel rod composite system as shown in Fig. 3. It is concluded that the PCMI can highly alter the location and magnitude of maximum plastic strain with a significant effect on fuel rod response under drop condition and thus affects the probability of fuel rod failure.

3.4 SG stiffness and RIP

Three stiffness reduction percentages (25%, 50%, 75%) of fresh springs and dimples have been examined representing the radiation-induced changes. RIP of the lower limit is 6 MPa at temperature 250°C and the upper limit is 7.72 MPa at temperature 400°C was examined.

The PE max. principal difference decreased 14.4%, 35%, and 70% in vertical drop, and decreased 4%, 2.2%, 1.9% in the horizontal drop when the springs and dimples stiffness decreased 25%, 50%, and 75%, respectively. PE max. principal difference decreased 13% in vertical drop, and 1.4% in the horizontal drop when the RIP increased from 6 MPa to 7.72 MPa.

4. Conclusions

This work establishes the basis of an intensive parametric study of uncertain parameters that highly affect the cladding integrity. Sensitivity analysis has been defined to evaluate the impact of fuel rod material properties, PCMI, RIP and SGs stiffness within the first ten years of dry storage period. Through this study, it is revealed that the PCMI bonding condition showed a high influence on the fuel rod behavior and in altering the strain deformation results comparing to other parameters.

REFERENCES

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