Methodology for Evaluation of Spent Nuclear Fuel Damage Ratio under Horizontal Drop Accident

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1. Introduction

The Spent Nuclear Fuel (SNF) cladding acts as the first barrier to prevent the release of radioactive materials. For storage safety evaluation, it is essential to evaluate the damage ratio of spent fuel rods loaded inside the cask. In horizontal drop, which is the most damaging during drop accident of SNF cask, the fuel rods receive the bending load and pinch load, as shown in Fig. 1 [1]. The fuel damage ratio is a very important intermediate variable for dry storage risk assessment which requires an interdisciplinary and comprehensive investigation. However, the complex properties and geometries of irradiated spent fuel, combined with the limited available data, necessitate a comprehensive study. Furthermore, the amount of computation involved makes it impractical to analyze every detail of the transport cask and the SNF rods. In this study, we present a methodology to quantitatively evaluate the fuel damage ratio under impact loads in various horizontal drop accident scenarios. A step-by-step simplified models were developed to quantify loading conditions applied to the spent fuel in various horizontal drop accident scenarios and to eventually evaluate the fuel damage ratio. Additionally, a simulation model was developed to evaluate the resistance to pinch loads, taking into consideration the hydride characteristics of the irradiated cladding. Although many studies have been carried out on the bending load failure criteria, the pinch load failure criteria have not been clearly studied. Therefore, the pinch load failure criteria have been presented using simulation models developed. The vulnerability of spent fuel rods to bending load and the failure criteria was considered during the fuel rod simplification process.

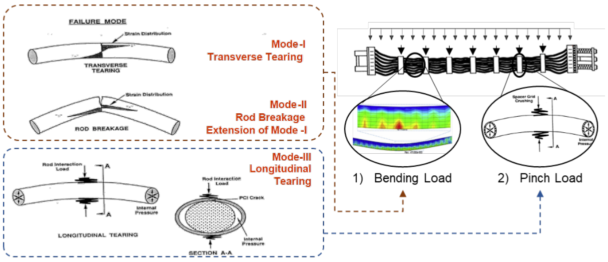


Fig. 1. Possible failure modes and impact loads under cask drop in horizontal orientation [1].

2. Methods and Results

2.1 Overall framework

The fuel damage ratio evaluation is performed in the following steps shown in Fig. 2. In the first stage, considering the failure criteria for bending load, a simplified model for a single spent fuel rod was developed. This model aimed to understand the influence of cladding-pellet interface conditions on the failure resistance of fuel rod. In the second stage, the simplified fuel assembly model for CE 16x16 fuel assembly was developed, utilizing simplified models of a single fuel rod, and extracted the position-specific impact accelerations within a cask during a horizontal drop. In the third stage, we apply each extracted impact acceleration to a detailed CE 16x16 fuel assembly model to quantify the maximum bending load and pinch load exerted on each fuel rod. In the next stage, a simulation model was developed to evaluate the failure resistance of the fuel rod under the pinch load that may cause longitudinal tearing of the cladding, and the quantified pinch load is used to establish the failure criterion of fuel rod under pinch load. Finally, the the fuel damage ratio is calculated by comparing the quantified maximum loads on the fuel rods against the failure criteria.

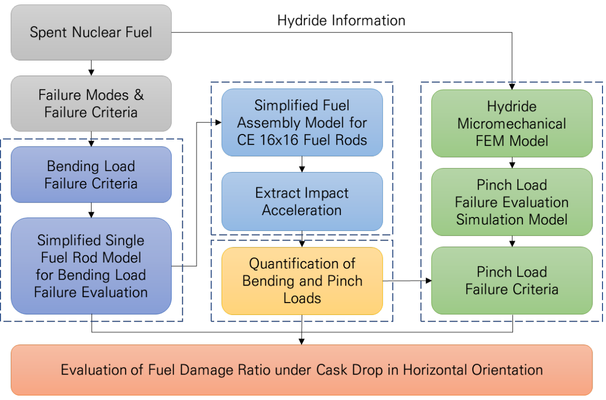


Fig. 2. Research flowchart for fuel damage ratio evaluation.

2.2 Development of simplified single fuel rod model

In a horizontal drop, the bending stress in the cladding caused by the inertial load has a significant effect on the integrity of the fuel rod and it is exaggerated by the pellet-cladding mechanical interaction. A simplified model for a single fuel rod of CE 16x16 was devised to predict displacement and failure state under bending load, as shown in Fig. 3. Fig. 4 is the process of calibrating the physical properties and beam section properties to minimize the discrepancy in the behavior of simplified and detailed models. The failure criterion for SNF was selected as the membrane plus bending stress through stress linearization in the cross-sections through the thickness of the cladding. Because the stress concentration in the cladding around the vicinity of the pellet–pellet interface cannot be simulated in a simplified beam model, a stress correction factor is derived through a comparison of the simplified model and detailed model. The resulting simplified fuel rod model effectively replicated the behavior of the detailed model when considering cladding failure criteria at the critical drop height while sustaining nearly identical flexural rigidity to that of the detailed model.

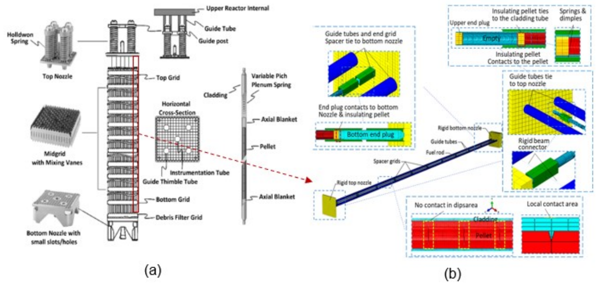
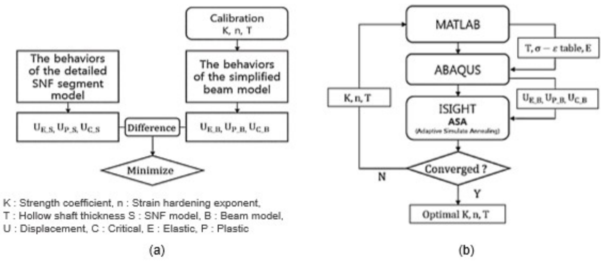


Fig. 3. (a) CE 16x16 fuel assembly design of the PLUS7 and (b) detailed single fuel rod finite element model [3].



K : Strength coefficient, n : Strain hardening exponent,
T : Hollow shaft thickness S : SNF model, B : Beam model,
U : Displacement, C : Critical, E : Elastic, P : Plastic

Fig. 4. (a) Strategy and (b) process of the simplified single fuel rod model under bending load.

2.3 Development of simplified fuel assembly model

In the event of a horizontal drop accident, the fuel assemblies loaded in a cask receive shock acceleration due to the impact. Because the magnitude of the impact acceleration applied to each assembly is different depending on its loaded position inside the cask, the fuel damage ratio for the 21 assemblies is also different [4]. In this section, a simplified fuel assembly model that can replace the detailed assembly model composed of 16 by 16 simplified fuel rods was developed to extract the impact acceleration exerted on individual assemblies. Isotropic material property obtained by performing compression analysis on the CE 16 by 16 assembly model were applied to the simplified assembly model. The material properties in the lateral direction were obtained from the results of static compression analysis on two parts of the grid part and the fuel rod assembly part of the entire assembly model. The simplified assembly model developed based on the proposed methodology significantly reduced the computational time and at the same time showed a similar behavior to the detailed assembly model under the static analyses performed.

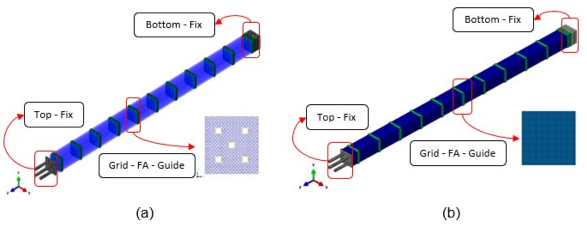


Fig. 5. (a) Fuel assembly model with simplified single fuel rod model and (b) simplified fuel assembly model for CE 16x16.

2.4 Quantification of bending and pinch load during horizontal impact

To calculate the fuel damage ratio during horizontal drop accidents, it is necessary to extract the impact acceleration that depends on the location of the assembly inside the cask [1, 4]. This stage aims to extract the impact acceleration for each loaded position in the cask using a simplified fuel assembly model and apply each extracted impact acceleration to the detailed CE 16x16 fuel assembly model in Fig. 5 (a) to quantify the bending load and pinch load exerted on each fuel rod. To evaluate the fuel damage ratio in horizontal drop accidents, finite element model of a transport cask loading 21 fuel assemblies was created. The impact acceleration was extracted using the simplified fuel assembly model developed in Section 2.3. The extracted acceleration for each loaded position was applied to the CE 16x16 fuel assembly model to quantify the bending load and pinch load. The maximum membrane plus bending stress in each fuel rod is calculated and compared with the failure criteria introduced in Section 2.2 to assess the failure of fuel rod. The pinch loads caused by the fuel rod interaction with the other rods, the grid spring, and the basket under impact acceleration were quantified by using ABAQUS script. The quantified pinch load is compared against the failure criterion introduced in next section.

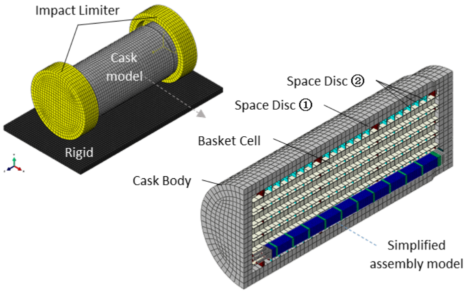


Fig. 6. Finite element model of transport cask.

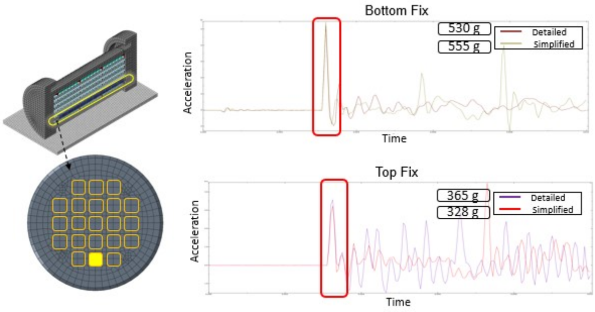


Fig. 7. Impact acceleration-time curve of simplified fuel assembly model under 30 cm horizontal drop.

2.5 Simulation model for failure evaluation under pinch load

The pinch load generated during a horizontal drop accident can have a decisive effect on the structural integrity and performance of the SNF rod. The pinch load applied to the cladding can lead to Mode-3 failure and the cladding becomes more vulnerable to this failure mode with the existence of radial hydrides and other forms of mechanical defects [5-7]. The resistance of the cladding under pinch loads can be evaluated with the Ring Compression Test (RCT) [6]. In this section, a pixel-based simulation model of RCT for microstructural and fracture behavior considering the effect of irradiated cladding under the pinch load is developed, as shown in Fig. 8. The developed pixel-based finite element model can simulate crack propagation through the cladding with hydrides of various configurations. Therefore, the developed simulation model can be used to evaluate the fracture resistance of the irradiated cladding under the quantified pinch load and to establish the pinch load failure criterion. Although many studies have been carried out on the bending load failure criteria, the pinch load failure criteria have not been clearly studied. Therefore, the pinch load failure criteria have been presented using simulation models developed for various hydride arrangements of the irradiated cladding.

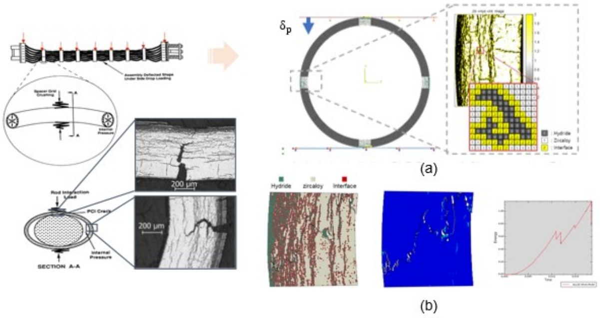


Fig. 8. Failure resistance evaluation simulation model under pinch load (a) pixel-based finite element model and (b) simulation results of RCT.

3. Conclusions

In this study, the step-by-step procedures to facilitate the evaluation of the fuel damage ratio were presented. In the horizontal drop, nuclear fuel rods are subjected to bending and pinch loads. Simplified models of the fuel rod and fuel assembly were developed for the evaluation of fuel damage ratio. The applicability of the simplified models was confirmed through static and dynamic analysis, and the impact acceleration was extracted for each fuel rod assembly according to the loaded position using the simplified assembly models. In addition, a simulation model was developed to evaluate the resistance of SNF cladding to pinch load through a continuum fracture mechanics approach considering the microscopic configuration of the hydrides and to establish the pinch load failure criterion. The fuel damage ratio was calculated using the bending load failure criteria and the proposed pinch load failure criteria. It is expected that the fuel damage ratio of each fuel rod assembly according to the loaded position can be quantitatively evaluated in various horizontal drop accident scenarios using the methodology developed in this work.

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