Preliminary study for evaluation of spent nuclear fuel failure probability

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1. Introduction

The spent nuclear fuel cladding acts as a barrier to primarily preventing the outflow of radioactive materials, and maintaining the integrity of the cladding is very important for safe and economical spent nuclear fuel management. For storage safety evaluation, it is essential to evaluate the probability of failure of spent fuel rods loaded inside the cask. However, the amount of computation involved makes analyzing every detail of the transport cask and the spent nuclear fuel impractical. In this study, we present a methodology for performing cask-level analyses by sequentially simplifying spent fuel assemblies and fuel rods. The simplified single fuel rod model is assembled into CE 16 by 16 configuration, with 21 assemblies loaded in a cask. A methodology to replace the loaded assembly with a simplified model is presented for cask drop event analysis. The equivalence of the simplified model and the detailed model was verified in cask drop analyses by comparing critical structural responses such as impact deceleration. The impact acceleration obtained from the simplified assembly model is then applied to a detailed single assembly model to calculate the ratio of fuel rod failure in a horizontal drop accident. The vulnerability of spent fuel rods to impact and pinch loads and the failure criteria was considered during the fuel rod simplification process.

2. Methods and Results

2.1 Development of fuel rod simplification model

Simplified beam models of spent nuclear fuel rods were developed which can predict the displacement and failure state of a detailed fuel rod with a much smaller computational cost [1]. The physical properties of the parameters were calibrated through optimization, and horizontal drop impact analysis was performed to check the correlation between the simplified model and the detailed model. The developed simplified beam model well simulated the behavior of the detailed model at the critical drop height according to the cladding failure criteria, and it was confirmed that the failure prediction showed high accuracy as it approached the critical drop height. Fig. 1 is the process of calibrating the physical properties and beam section properties to minimize the discrepancy in the behavior of simplified and detailed models. Fig. 2 is the finite element model of CE 16 by 16 assembly made of simplified beam models created for cask drop event analysis.

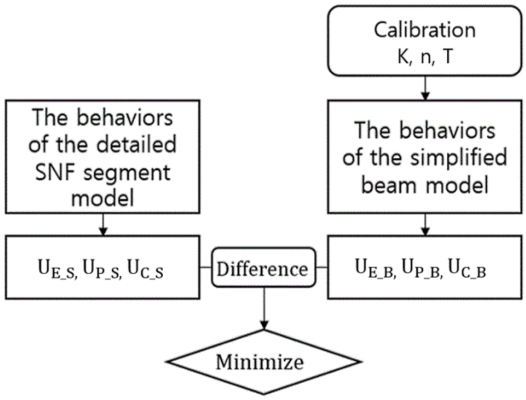

Fig. 1. Process of optimizing the beam material and section properties

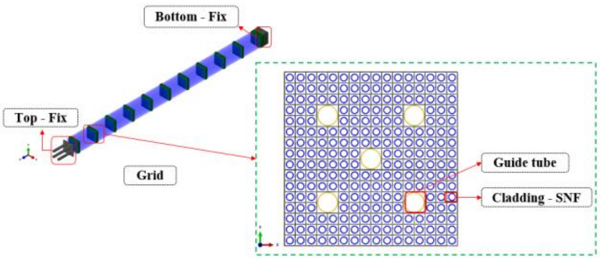

Fig. 2. Finite element model of CE 16 by 16 assembly is made of the simplified beam model.

2.2 Finite element model of transport cask

To evaluate the probability of fuel rod failure in a horizontal drop accident, a finite element model of a transport cask with 21 fuel assemblies loaded was created. The cask has 21 basket cells to accommodate fuel assemblies and space disks with two thicknesses that support the basket inside the cask.

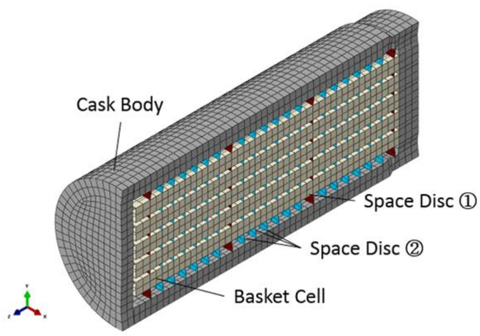

Fig. 3. Finite element model of transport cask

2.3 Methodology of fuel rod failure probability calculation

In the event of a horizontal drop accident, the loaded fuel rod assemblies receive shock acceleration due to the impact of the cask. Because the magnitude of the impact acceleration applied to each assembly is different according to its loaded position inside the cask, the probability of fuel rod failure for the 21 assemblies is also different [2]. Therefore, in this study, the impact acceleration was extracted to calculate the probability of fuel rod failure of each fuel rod assembly according to the loaded position. An equivalent model development methodology that can replace the behavior of an assembly model composed of 16 by 16 simplified fuel rods was proposed to extract the impact acceleration for individual assemblies. The equivalent model developed based on the proposed methodology greatly reduced the computational analysis time and at the same time showed similar behavior to the detailed fuel assembly model, eventually producing accurate fuel rod failure probability.

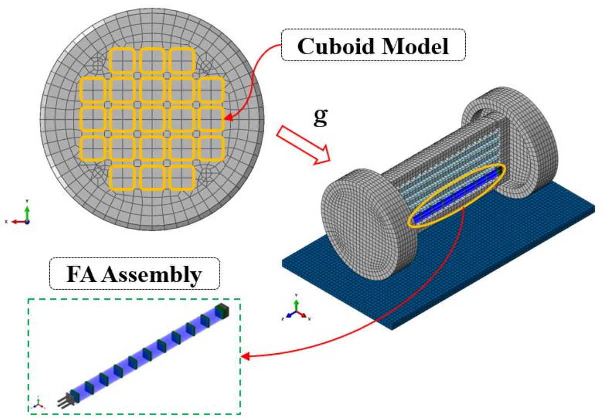

Fig. 4. Development of dummy fuel assembly model and review of its applicability.

2.4 Development of fuel assembly equivalent model and review of applicability

The properties of the fuel assembly equivalent model developed for the extraction of impact acceleration were generated based on the property data of the CE 16 by 16 assembly model. Anisotropic property data in the horizontal and vertical directions obtained by performing compression analysis on the CE 16 by 16 assembly model were applied to the fuel assembly equivalent model. The material properties in the horizontal direction were obtained from the results of static compression analysis on two fragmentary parts of the grid part and the fuel rod assembly part of the entire assembly model. Compression analysis in the vertical direction was performed on the grid and the fuel rod assembly section between the grids. The physical property data obtained through the analysis were assigned to each section of the simplified assembly model. The developed equivalent model was reviewed for applicability through bending analysis. The stress and strain generated under the same moment as the simplified assembly model were observed, and the similarity with the detailed model was confirmed. Fig. 5. is the result of compression analysis in the vertical and horizontal directions, and Fig. 6 shows the replacement of the CE 16 by 16 model with an equivalent model in the form of a cuboid.

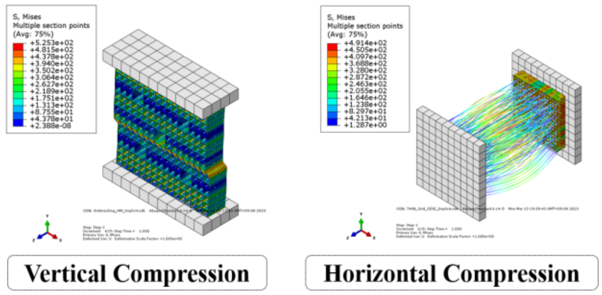

Fig. 5. Development of fuel assembly equivalent model and review of applicability.

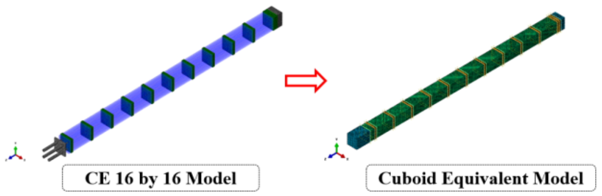

Fig. 6. Simplified to a cuboid equivalent model

3. Conclusions

In this study, a simplified model for spent fuel rods was developed for a cask-level analysis to calculate the fuel failure probability. In addition, a finite element model of cask was created for drop event analysis. A methodology for facilitating the evaluation of the fuel rod failure probability was presented, and the equivalent assembly model developed through the proposed methodology and the CE 16 by 16 assembly model were compared through bending analysis. The similarity between the two models was confirmed in a static bending analysis. In future studies, we plan to calculate the probability of spent nuclear fuel rod failure based on the results obtained in this study in dynamic impact situations.

REFERENCES

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[2] N. A. Klymyshyn, K. Kadooka, P. Ivanusa, C. Spitz, and J. F. Fitzpartrick, 30 cm Drop Modeling, U.S. Department of Energy Spent Fuel and Waste Science and Technology, PNNL-30495