DEVELOPMENT OF FINITE ELEMENT MODELS FOR EVALUATING MECHANICAL INTEGRITY OF SPENT NUCLEAR FUEL DURING HANDLING AND TRANSPORTATION

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ABSTRACT: *There are a lot of spent nuclear fuels (SNFs) and various kinds of SNFs in spent fuel pools and they all have different loading histories. To assure the mechanical integrity during handling and transportation, it is not efficient way that the mechanical tests regarding all types of SNFs are performed. SNF evaluation candidates were selected using the classical calculation method considering fresh fuel data in the previous study. In this study, computer simulation techniques have been taken and finite element models are developed for evaluating several spent nuclear fuels using commercial finite element analysis code (ANSYS). 16x16 Korean Standard Nuclear Power Plant type (16x16 KSNP type), 17x17 Westinghouse type (17x17 WH type), and 14x14 Westinghouse type (14x14 WH type) SNF models are developed. The length of SNFs are a far longer than width so the SNFs are assumed and are described as single beam. The masses of SNFs are distributed at several points and the lumped mass modeling method is applied for effective analysis. The developed three types of SNFs are compared with and benchmarked to the fresh fuel tested data. Modal analysis, lateral impact analysis, and axial drop analysis are performed and the results are directly compared with results of lateral vibration test, lateral impact test, axial drop test. The analysis results are well matched with test results so the dynamic characteristics, lateral impact characteristics, and axial impact characteristics of FE models are valid. Using the developed three types of FE models, axial drop analysis and side drop analysis will be performed in accordance with 10CFR71 and representative-SNF(R-SNF) will be selected through the results of SNF evaluations in the following studies. Then the more detailed computer simulation models applied to depletion effect will be generated and tested thoroughly for the mechanical integrity evaluation.*

KEYWORDS: *Spent Nuclear Fuel, Handling and Transportation, Mechanical Integrity, SNF finite element Model*

I. Introduction

There are 21 pressurized water reactors (PWRs) in Korea and approximately 8 hundred tons of spent nuclear fuels(SNFs) are unloaded every year. Various kinds of SNFs, 13,000 tons, have been temporally stored in spent fuel pool in each nuclear power plant. The SNF on-site storage capability in Korea is expected to be saturated, and Kori unit 1 will be shutdown permanently in 2017. Therefore, the management of SNF is one of the upcoming issues in the nuclear industry. The interim dry storage and the permanent disposal will be possibly taken for the SNF management options. So Korean government issues the management plan for high level nuclear wastes in 2016. The geological survey for 12 years before selecting the interim dry storage and permanent disposal site is performed for the nuclear waste disposal program in around 2028. The low burn-up SNFs are going to be transferred to selected storage sites in priority order. Handling and transportation of SNF are inevitable processes for its interim dry storage, final disposal, recycling, and the others. One of the top tier requirements of SNF during handling and transportation is that the SNF has to maintain the mechanical integrity because the SNFs are stored in spent fuel pool for a long time.

There are various kids of SNFs in spent fuel pools and they all have different loading histories as shown in Fig. 1 and Fig. 2 (Ref. 1). The tests for all kinds of SNFs are not efficient way, thus a selection and concentration strategy has been taken. Most of the international leading institutes, such as Electric Power Research Institute(EPRI) and SANDIA, have approached this matter from a selection of representative-SNF(R-SNF) at the first stage for more effective evaluation(Ref. 2 and 3). In order to select the R-SNF, computer simulations with a few kinds of fresh fuels such as an axial drop analysis and a side drop analysis are performed in EPRI and SANDIA in accordance with 10CFR71, and it was reported that the side drop is the most severe case for the mechanical integrity. Moreover, in the previous study (Ref. 4), three types of target fuels which are 16x16 KSNP type, 17x17 WH type, and 14x14 WH type were chosen for R-SNF selection evaluation considering fresh fuel data. The fuel rod buckling load, grid stiffness, grid buckling load etc. are evaluated based on geometrical data, component weight, and materials using hand calculation techniques and 14x14 WH fuel was assessed as the weakest SNF in the previous study (Ref. 4). They need to be evaluated in more detail with computer simulation technique in order to select R-SNF.

There are three kinds of methods which are possibly taken for developing the finite element models of SNFs and they are full scale modeling, detail modeling, and single beam modeling. To apply the first and second modeling techniques, all of the fuel components including joint and connection parts are modeled. The fuel components and fuel assemblies also need to be tested to verify the finite element models. Moreover, it takes lots of time to perform the static and dynamic analyses, and they require extensive computation. The purposes of the analyses are the relative comparison of the target fuels and the full scale and 2-D modeling techniques are not appropriate for those relative evaluation. However, the 1-D beam modeling technique has a lot of advantages comparing to the full scale modeling and 2-D detail modeling for those analyses. The relative comparisons of the target fuels with proper computation time are performed and all the components are modeled as 1-D beam. Moreover, the mechanical test data are applicable to verify the analysis model. In this study, the 1-D beam model is apposite to the purpose of the analyses. Three types of finite element models for R-SNF candidates are developed. They are compared with and benchmarked to the tested data that generated when the fuel assemblies were developed. Modal analysis, lateral impact analysis, and axial drop analysis are performed and the results are directly compared with results of lateral vibration test, lateral impact test, and axial drop test of fresh fuels for the verification and validation of the developed finite element models.

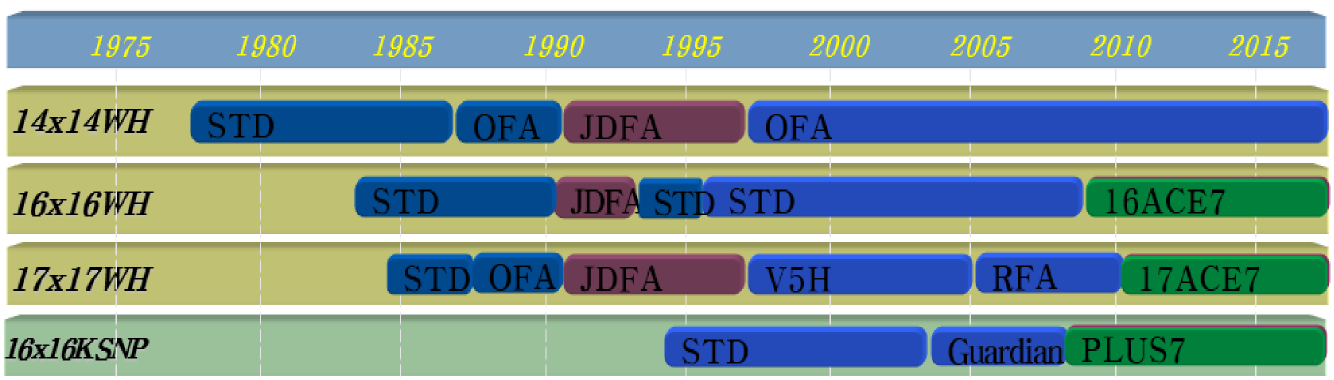


Fig. 1 SNF loading histories in Korean nuclear power plants

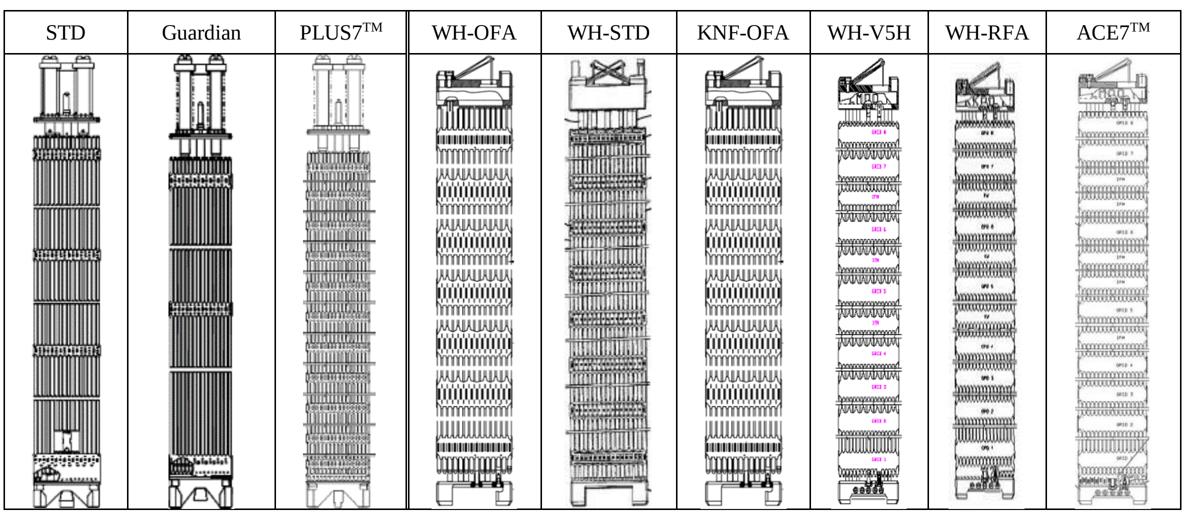
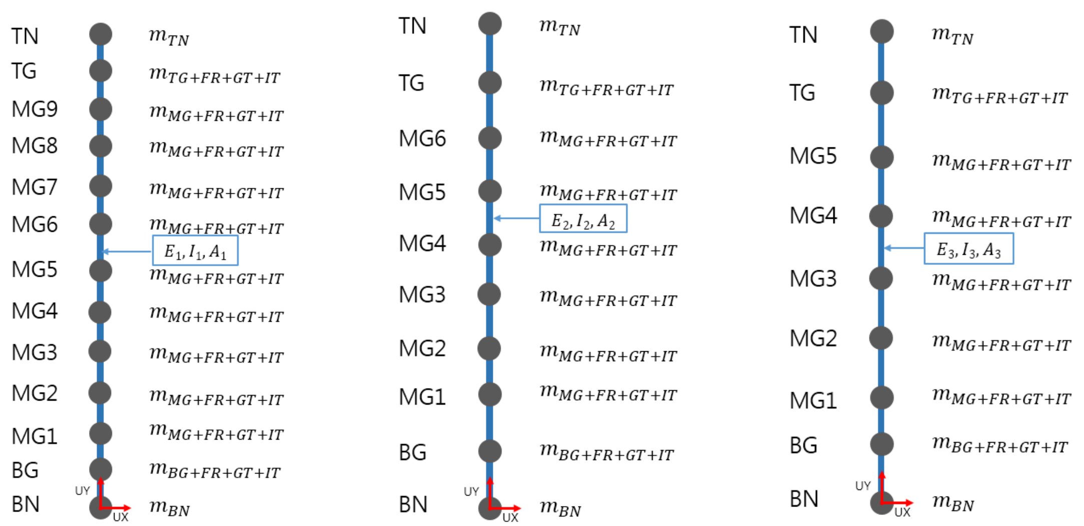


Fig. 2 Stored SNFs in Korean nuclear power plants

II. Development of Finite Element Models

The target SNFs are 16x16 KSNP type, 17x17 WH type, and 14x14 WH type. The 16x16 KSNP type fuel consists a top nozzle(TN), a bottom nozzle(BN), a top grid(TG), a bottom grid(BG), 9 mid grids(MG), 4 guide tubes(GT), an instrumentation tube(IT), and 236 fuel rods(FRs). 17x17 WH type fuel consists a top nozzle, a bottom nozzle, a top grid, a bottom grid, 6 mid grids, 3 IFM grid, 24 guide tubes, an instrumentation tube, and 264 fuel rods. 14x14 WH type fuel consists a top nozzle, a bottom nozzle, a top grid, a bottom grid, 5 mid grids, 16 guide tubes, an instrumentation tube, and 179 fuel rods.

Three types of finite element models which are 16x16 KSNP type, 17x17 WH type, and 14x14 WH type for target SNFs are developed using ANSYS. To develop finite element models, a single Euler-Bernoulli beam element and several mass elements are used. As shown in Fig. 3, the SNF finite element models are single lumped mass models. The single beam element represents geometric characteristics of guide tubes and fuel rods, and material property. Several mass elements represent mass of grids, fuel rods, top/bottom nozzles, and guide tubes in accordance with span length. The centers of the masses are the same as the grid center elevation. It is assumed that the mass of fuel rods, guide tubes, and an instrumentation tube are uniformly distributed from top of bottom nozzle to bottom of top nozzle and the span lengths are a half of two consecutive nodes. It is also assumed that the material property along those length of each SNF models is uniform as of zirconium alloy. Although the SNFs are different a little, the modeling techniques are the same.



(a) 16x16 KSNP type (b) 17x17 WH type (c) 14x14 WH type

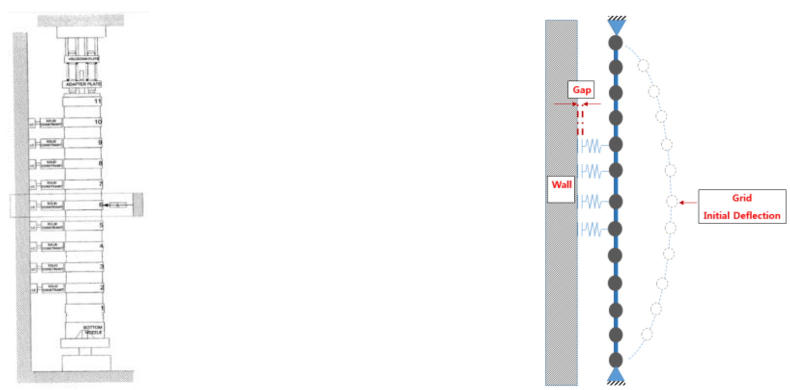
Fig. 3 Scheme of SNF models

III. Model Verification

Three different analyses with the developed models are performed securing the model validity and effectiveness. First of all, the modal analysis results are compared to lateral vibration test results. Those analyses and tests show the natural frequencies and mode shapes that represent dynamic characteristics. Secondly, the lateral impact analysis results are compared to lateral impact test results. The purpose of the test is to identify the impact characteristics between a grid and a wall or the other structures so the grid impact stiffness and damping are acquired from the test. The grid impact characteristics are used for the side drop analysis in order to determine the FR bending stresses. Lastly, the axial drop analysis results are compared to axial drop test results. The test simulates accident condition during handling and transportation. The bottom nozzle impact force and impact stiffness are determined from the test and analysis comparison. The impact characteristics of the models are used for the axial drop analysis to determine the weakest one. Fig. 4 to 6 show the test setup and simulation model constitution example of lateral vibration, lateral impact, and axial drop.

(a) Test (b) Simulation

Fig. 4 Lateral vibration test setup and simulation model constitution



(a) Test (b) Simulation

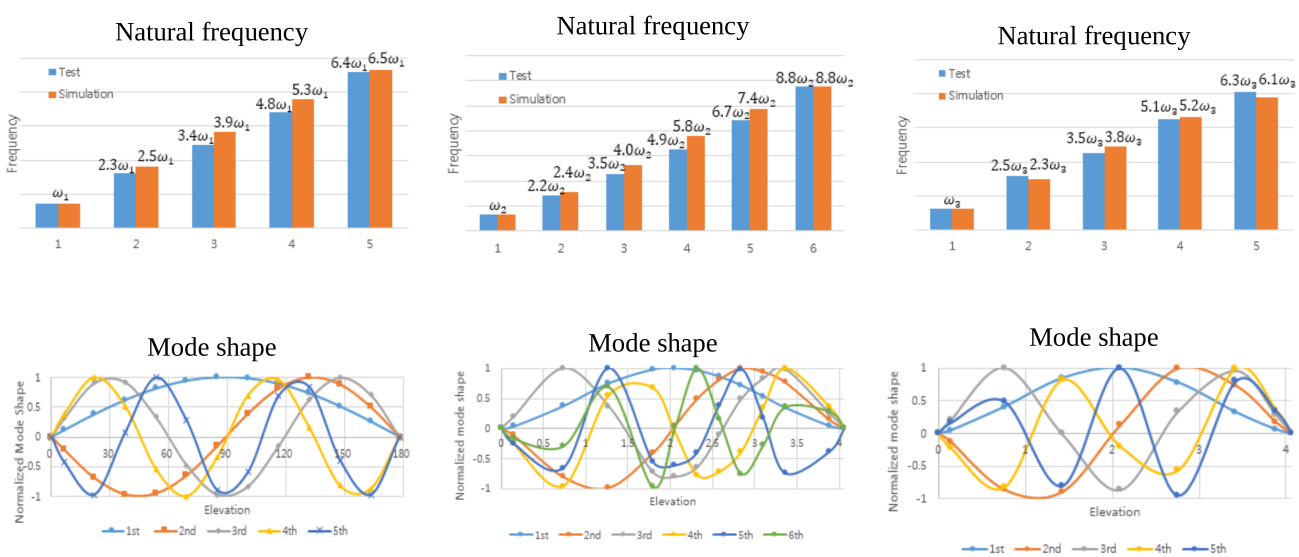
Fig. 5 Lateral impact test setup and simulation model constitution

(a) Test (b) Simulation

Fig. 6 Axial drop test setup and simulation model constitution

III.A. Modal Analysis

In order to perform modal analysis, the fixed constraints are added at the top/bottom nozzle nodes of finite element models. Natural frequencies and mode shapes of the models are acquired and compared with test results. The cross section area and 2nd area moment of the beam are determined with those simulations. Fig. 7 shows the analysis results of the three different types of models. The data is normalized based on the fundamental frequencies. The fundamental frequencies of the models are exactly coincided with test results and the other frequencies are very similar. The normalized frequency error ranges are 0 ~ 0.9ω. The mode shapes are almost same across the fuels. The generated three types of model dynamic characteristics are valid.



(a) 16x16 KSNP type (b) 17x17 WH type (c) 14x14 WH type

Fig. 7 Modal analysis results and test results comparison

III.B. Lateral Impact Analysis

The fixed constraint conditions are identical to those of modal analysis. Some of the nodes are added at the left side of SNF model nodes with the same elevations for representing impact wall and the wall nodes are fixed. Several gap, impact stiffness, and impact damping elements are added representing the impact characteristics. The impact stiffness is determined by comparing with test results. The model impact damping is calculated by Eq. (1) and Rayleigh damping is calculated by Eq. (2) for transient analysis.

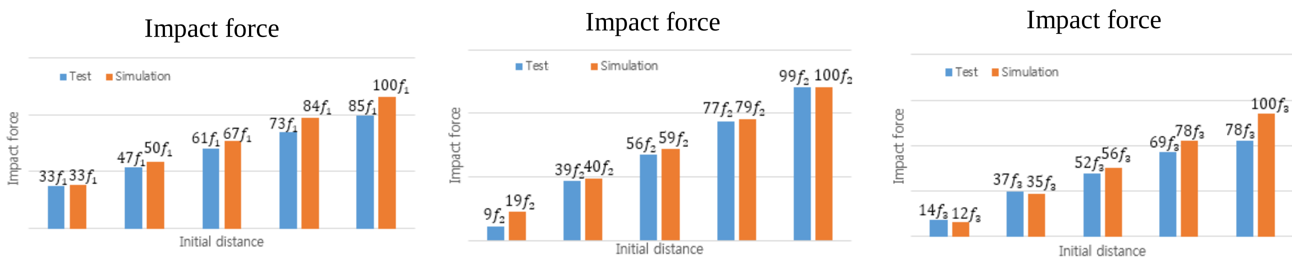
$$C_{impact} = \zeta * \sqrt{4KM} \qquad (1)$$

where, C_{impact} = Impact damping value
ζ = Damping ratio
K = Impact stiffness
M = Mass

$$\alpha = \frac{4\pi f_r f_s(\zeta_s f_r - \zeta_r f_s)}{f_r^2 - f_s^2}, \qquad \beta = \frac{\zeta_r f_r - \zeta_s f_s}{\pi(f_r^2 - f_s^2)} \qquad (2)$$

where, f_r = Fundamental natural frequency
f_s = The highest natural frequency
ζ_r = Fundamental frequency damping ratio
ζ_s = The highest frequency damping ratio

The SNFs need to be deflected initially to perform the lateral impact analysis and the SNFs are suddenly released. The grids are impacted to the wall and the impact forces are acquired. The initial deflection distances for impact simulation are determined based on the test condition. 16x16 KSNP type is deflected from 0.4 inch to 0.8 inch by 0.1 inch increment. 17x17 WH type is deflected from 0.2 inch to 1.0 inch by 0.2 inch increment. 14x14 WH type is deflected from 0.1 inch to 0.9 inch by 0.2 inch increment. All the fuels are tested 5 times by initial deflected distance condition. Fig. 8 shows the analysis results and test results. The data is normalized based on maximum simulation result and the normalized error ranges are 0 ~ 22f. The impact regions to the wall are the mid grids in the middle of SNFs. The simulation results are conservatively matched to test results. So, the developed three types of models are valid for the lateral impact characteristics.



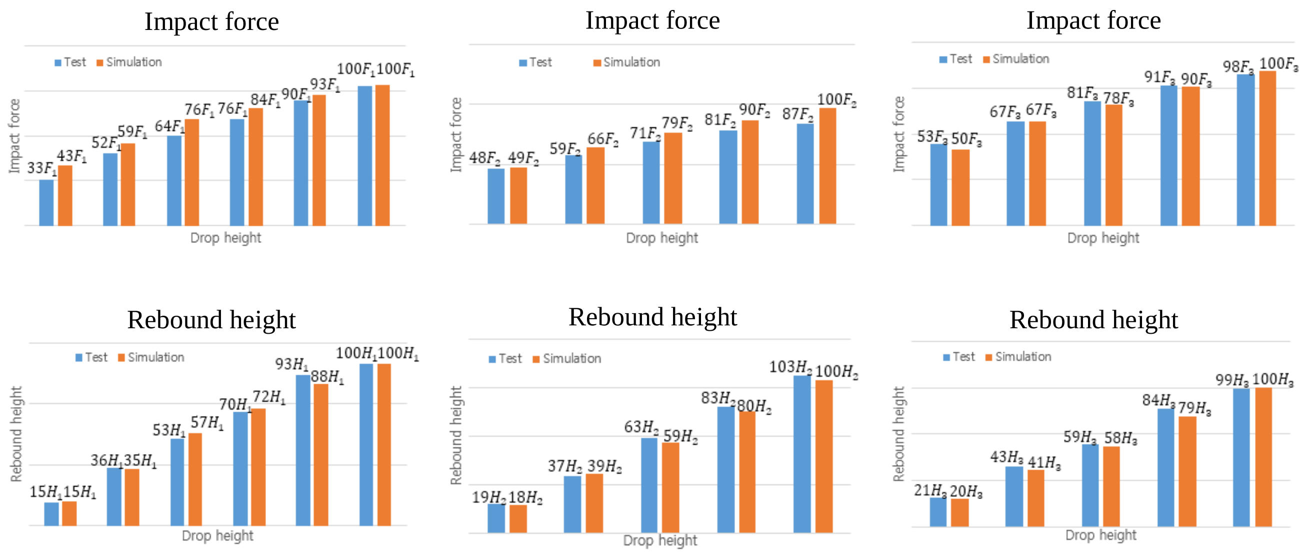
(a) 16x16 KSNP type (b) 17x17 WH type (c) 14x14 WH type

Fig. 8 Lateral impact analysis results and test results comparison

III.C. Axial Drop Analysis

In order to perform axial drop analysis, the three types of finite element models have the free constraint conditions. A ground node is added below the bottom nozzle element and the bottom nozzle node and the ground node are connected with gap, impact stiffness, and impact damping element to represent drop characteristics. The ground node is fixed and the SNF nodes are coupled vertically. The impact stiffness is determined by comparing with test results. The impact damping is calculated by Eq. (1) and the same value of lateral impact analysis is used for Rayleigh damping.

The impact behavior of axial drop is related to the impact force and the rebound height, thus the impact force and the rebound height are compared to test results in order to verify the axial drop models. The drop height of the SNFs are determined based on the test conditions. 16x16 KSNP type is dropped from 0.25 inch to 1.5 inch by 0.25 inch increment. 17x17 WH type is dropped from 0.2 inch to 1.0 inch by 0.2 inch increment. 14x14 WH type is dropped from 0.21 inch to 1.03 inch by around 0.2 inch increment. Fig. 9 shows the analysis results and test results comparison. The data is normalized based on the maximum simulation results. The normalized error ranges are 0 ~ 13F and 0 ~ 5H. The simulation results are well matched to test results. So, the developed three types of models are valid for the axial impact characteristics.



(a) 16x16 KSNP type (b) 17x17 WH type (c) 14x14 WH type

Fig. 9 Axial drop analysis results and test results comparison

IV. Conclusions

16x16 KSNP type, 17x17 WH type, and 14x14 WH type are selected as the target SNFs in the previous study and those of finite element models for SNFs are developed using commercial analysis code. Single lumped mass beam modeling techniques have been taken to develop three types of finite element models. The generated models have different types and shapes but the modeling methods are the same each other.

The modal analysis, the lateral impact analysis, and the axial impact analysis were performed and compared to test data in order to verify the generated models. The dynamic characteristics of the models are verified comparing to the lateral vibration test. The lateral impact characteristics of the models are verified comparing lateral impact test and lateral impact stiffness are determined. The axial impact characteristics of the models are verified comparing axial drop test and axial impact stiffness are determined. The simulation results of the modal, lateral impact, and axial drop analyses are well matched to test data. Thus, the models are valid for axial drop simulation and side drop simulation.

In further study, the axial drop simulation and side drop simulation in accordance with 10CFR71 will be performed with the developed three finite element models, and the weakest SNFs will be evaluated. From those of the simulation and the other evaluated data, the R-SNF will be selected, and more detail model of R-SNF will be generated to thoroughly investigate SNF mechanical integrity.

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