VALIDATION OF NUMERICAL SIMULATION METHOD USING A 1/3-SCALE MODEL DROP TEST OF KN-18 SNF TRANSPORT CASK

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ABSTRACT

The KN-18 SNF (spent nuclear fuel) transport cask is a newly developed cask intended for the dry or wet transportation of up to 18 PWR spent nuclear fuel assemblies in South Korea.

The structural performance of the KN-18 transport cask in normal and hypothetical accident conditions was demonstrated in the SAR(safety analysis report) by the analysis using state-of-the-art finite element methods, and that will be presented in another paper given during this PATRAM.

A series of actual drop tests using 1/3-scale model were carried out to verify the numerical simulation method used in the analyses and to confirm the impact characteristics of the cask. Total of five 9 m drop tests and two 1 m puncture tests were performed using one 1/3-scale cask model with four sets of impact limiters. Basically 1/3-scale model has same design with real cask except some inevitable differences in geometry between the scale model and the real cask for the reason of fabrication, operation, and etc. In order to provide a robust basis for verification, finite element analyses of the scale model cask in all the drop test conditions were carried out. The same numerical tool and analysis methodology used in the real cask analysis were used in the FE analyses of the scale model. To allow a robust comparison between test and analysis results, the analysis model represents the complete cask, and all of the components are explicitly modelled in three dimensions. This paper presents the dynamic impact characteristics of the cask from test and analysis results and the validation of numerical simulation method by showing the correlation between test and analysis results.

INTRODUCTION

According to the International Atomic Energy Agency (IAEA) and Korean regulations for the transportation of radioactive material, a SNF transport cask must withstand a free-drop impact of 9 m onto an unyielding surface, a free-drop impact of 1 m onto a mild steel bar, fire up to 800 ℃, and immersion to 200 m [1,2,3]. In particular, the safety of the cask under the 9 m free-drop and 1 m puncture conditions, which generally produce the maximum structural damage, is of primary concern. However, the structural performance of a transport cask is not easy to evaluate precisely because the dynamic impact characteristics of the cask, which includes impact limiters to absorb the impact energy, are so complex.

In general, two types of methods have been applied to evaluate the structural performance of transport casks. The first involves a numerical simulation using the FE method, and the second is an actual test using a prototype or scale model. Although actual testing is an accurate means of confirming the performance of the cask and verifying the numerical tools and modeling methodology used in the analysis, actual tests are often very expensive. Therefore, they can be performed only in limited cases and only as a supplementary method.

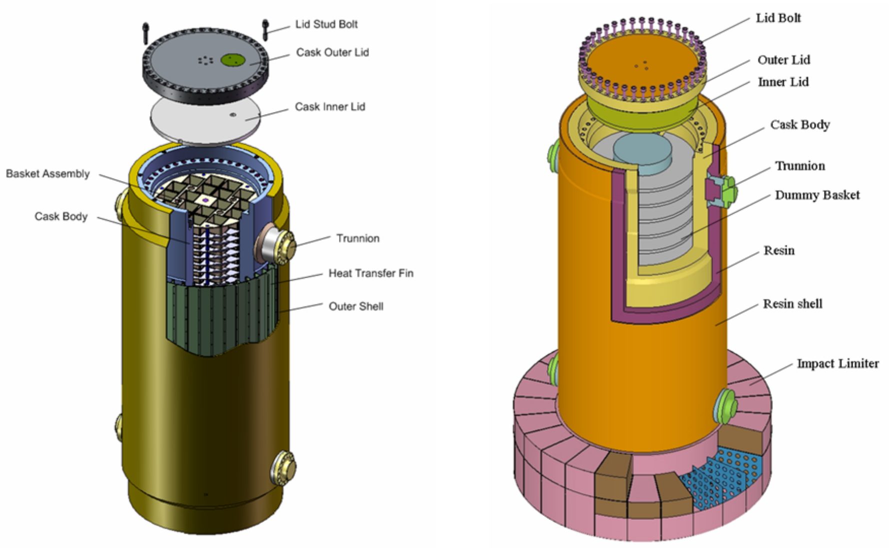
In this study, a more improved numerical simulation technique using the FE method via the commercial FE code LS-DYNA is introduced, and the detailed dynamic impact characteristics of the KN-18 transport cask under free-drop conditions are investigated using the suggested numerical simulation method. In addition, a series of actual drop tests is performed to confirm the impact characteristics of the cask and verify the proposed numerical simulation method using a 1/3-scale model of the KN-18 SNF transport cask, recently developed in Korea.

CASK MODEL DESCRIPTION

In this study, the cask model is designed by scaling down the original KN-18 SNF transport cask by a factor of three. Basically, this 1/3-scale model has the same design as a real cask, except for the inevitable differences in geometry between the scale model and the actual cask for reasons of fabrication, operation, etc. An overview of the recently developed actual KN-18 SNF transport cask and the configuration of the 1/3-scale model are shown in Figure 1.

A cylindrical thick-walled cask body made of forged carbon steel and closed by a bolted lid made of stainless steel constitutes the containment vessel. Neutron shielding is provided by NS-4-FR resin on the exterior of the body and the lid. The cask contents, which consist of a fuel basket, fuel assembly, support structure, and water, are replaced by a basket dummy structure of equivalent mass in the scale model. The scale model has two pairs of trunnions (lifting devices) as in the original cask. A pair of impact limiters is attached to the cask by bolts to absorb the impact energy during severe accident conditions. In a number of tests, the non-impacting impact limiters are not installed on the scale model in order to control the test model more easily.

The overall length of the 1/3-scale model with the top and bottom impact limiters is 2,101 mm, and the midsection outside diameter of the cask body is 782 mm. The total mass of the test model with both impact limiters is about 4.60 metric tons.



(a) (b)

Figure 1. Overview of the KN-18 SNF transport cask: (a) Real cask, (b) 1/3 Scale model

The mechanical properties of the steel used in manufacturing the scale model cask are used in the FE model so that the FE analysis results can be compared on an equal footing with the test results. The stress-strain behavior for all of the steel is modeled as bilinear elasto-plastic with strain hardening. The stress-strain behavior of the resin and polyethylene is modeled using elastic-perfectly plastic behavior without strain hardening. The stress-strain behavior of the wood blocks is modeled using MAT_HONEYCOMB in LS-DYNA [4]. The major use of this material model is for honeycomb and foam materials with real anisotropic behavior. A nonlinear elasto-plastic material behavior can be defined separately for all normal and shear stresses in this model.

OUTLINE OF NUMERICAL ANALYSIS

Numerical Analysis Method and Drop Cases

Numerous alternative methods are available for the transport cask free-drop analysis, ranging from the dynamic lumped mass method, to the quasi-static methods that use a static implicit FE code, or to the detailed dynamic analyses that use a nonlinear explicit FE code. In this study, the dynamic impact characteristics of the model are investigated using an explicit nonlinear dynamic FE simulation with a three-dimensional detailed model of the complete cask via the commercial FE code LS-DYNA. Drop analyses are performed for the various impact orientations to consider the worst orientations that could inflict the worst damage to the package. Five 9 m drop cases and two 1 m puncture cases are analyzed. The drop orientations of the cask at the beginning of the analysis are as follows.

(1) 9 m drop cases: top-down, base-down, side drop, lid edge (60.34°), slap-down (6°)
(2) 1 m puncture cases: side puncture, top puncture

Modeling Methodology

The analysis model represents the complete cask, and all of the components are explicitly modeled in three dimensions. Especially in comparison with conventional FE models, the bolt connections that include the bolt pre-torque, impact limiter components and trunnion components are modeled in detail, and a high level of mesh quality using only hexahedral solid and rectangular shell is applied in this refined FE model to simulate the realistic and accurate impact behavior of the cask. Figure 2 provides an overview of the FE model and mesh details.

One basic, common FE model with different initial conditions and boundary conditions is used for the analysis of all the 9 m free-drop scenarios. Taking advantage of the symmetry of the package in the drop scenarios, a half-model is used for each drop scenario. A basic half-model consists of 445,506 nodes and 369,182 elements.

The mesh is designed to be appropriate for the purpose of the analysis and for the expected behavior of the package. It is refined at areas of high stress gradients, areas of large deformation gradients, and where a high level of accuracy is required. Elsewhere, the mesh is coarse to keep the overall number of elements to a minimum, as the number of elements directly affects the analysis time and computing costs. Regardless of weld type, all welded connections are modeled using a continuous mesh across the weld, that is, as continuous full penetration butt welds.

Initial and Boundary Conditions

At the start of each analysis, the model is located close to the target and given an initial velocity of 13.3 m/s and 4.43 m/s perpendicular to the target, representing the initial impact velocity after a drop from 9 m and 1 m, respectively. All the interactions among the contact components are also modeled carefully using appropriate contact algorithms. The unyielding target is modeled using *RIGIDWALL [4], which allows no penetration and absorbs no energy during an impact; and the bottom of the puncture bar is fixed.

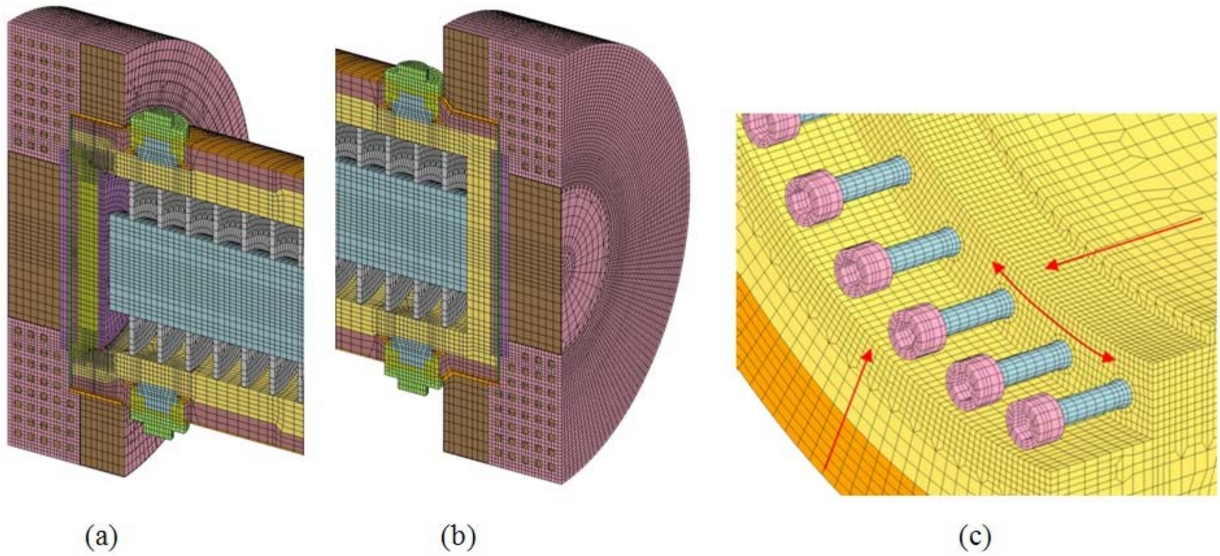


Figure 2. Overview of the FE Model: (a) Top end, (b) Bottom end, (c) Mesh detail.

1/3-SCALE MODEL TEST

The objectives of the actual drop test are to confirm the dynamic impact characteristics of the KN-18 SNF transport cask and to verify the proposed numerical simulation method used in the analyses. These objectives are achieved by comparing the numerical and physical test results. One 1/3-scale cask model with four sets of impact limiters is used in seven drop tests with various drop orientations. The drop orientations are the same as described in the drop analysis section of this paper; that is, five 9 m drop tests and two 1 m puncture tests are performed. Figure 3 illustrates the overall views of the test setup and the attached sensor locations for the drop tests.

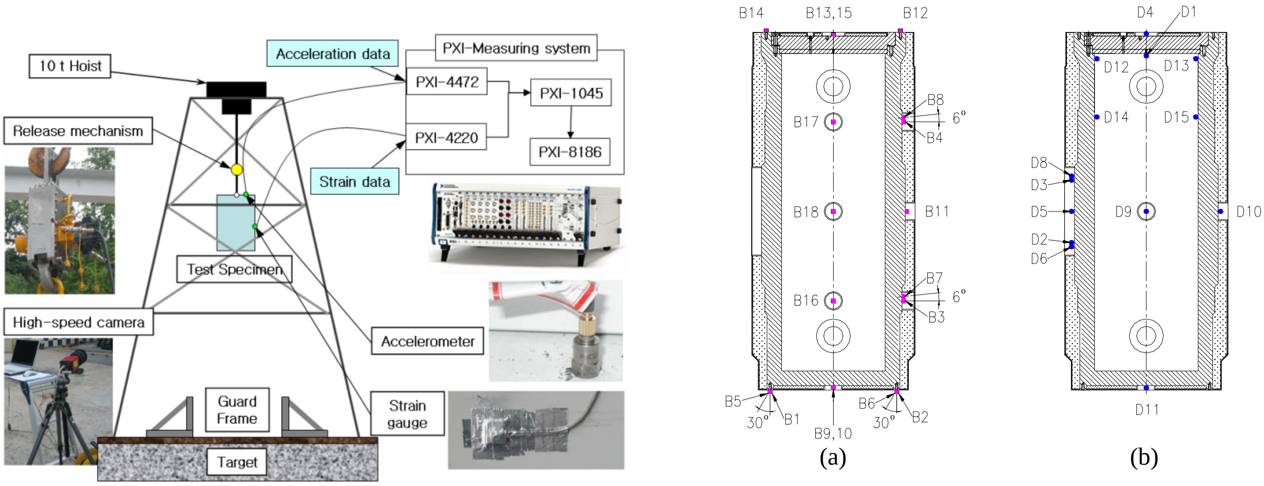


Figure 3. Test setup and Measurement locations: (a) Accelerometer, (b) Strain gauge.

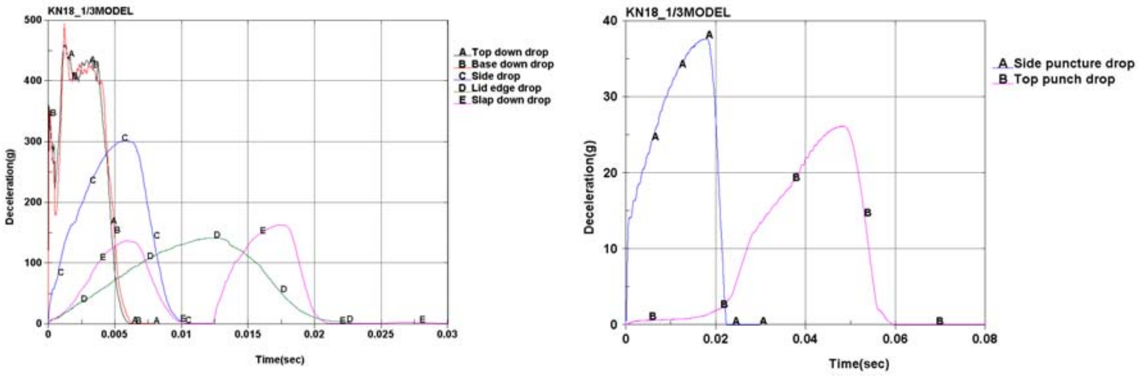
NUMERICAL AND EXPERIMENTAL RESULTS

Energy Balance

For all of the analyses performed, the energy value at the start of each analysis agrees with the expected value. The time history curves for all the drop cases are smooth; i.e., no indication of any significant numerical instability is present. The loss of energy for the hourglass, sliding interface and stonewall types of energy amounts to less than 10% of the total energy in each case. No loss in total energy also indicates that the analyses were performed well. In summary, the energy balances obtained from the analyses demonstrate that all the analyses were performed successfully.

Overall Deceleration

The overall deceleration values of the packages were obtained by dividing the stonewall force of the *RIGIDWALL target (i.e., the reaction force at the target in response to the impact) by the mass of the model. These results are shown in Figure 4. The maximum deceleration values for the 9 m drop cases vary from 141 g in the lid edge drop to 494 g in the base-down drop. The peak value in the deceleration trace of the slap-down drop occurs twice, because the center of gravity was not directly above the point of initial impact. The peak value of the second impact is higher than that of the first impact due to the added rotational velocity. The maximum deceleration values of the 1 m puncture cases are significantly lower than those of the 9 m drop cases due to the differences in drop height and the local shearing of the wood or resin layer.



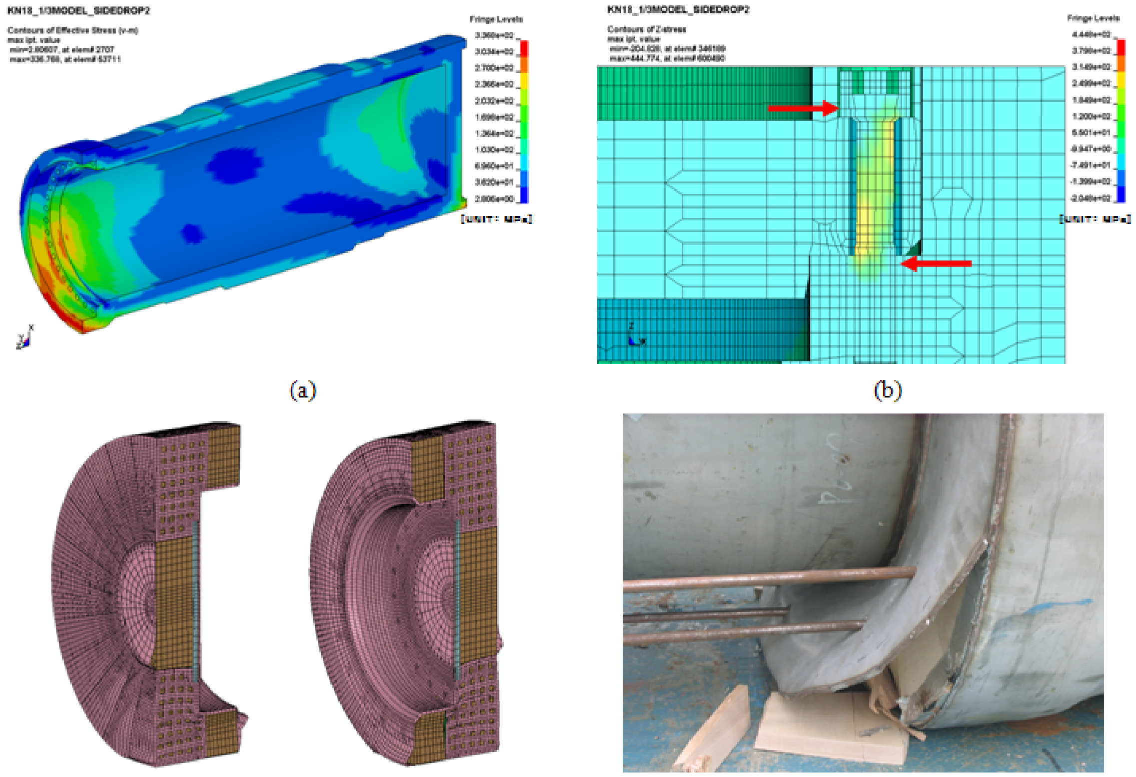
(a) (b)

Figure 4. Overall deceleration time histories: (a) 9 m drop case, (b) 1 m puncture case.

Impact Behavior of a Cask : 9m side drop

Figure 5 illustrates the behavior of the package obtained from the analysis and experiment. The analysis results were all taken at t = 0.0065 s, at which point the overall deceleration was at its peak. The impact limiters first contacted the target and then started to decelerate. The cask then dropped onto the impact limiters and also started to decelerate, crushing the impact limiters from the inside and the outside. The cask deflected like a simply supported beam, as it was loaded along its length by its own inertia and the inertial loading of the basket dummy, while supported at the top and base ends. This deflection caused tensile stress on the side closest to the target, compressive stress on the side away from the target, and localized stress in the vicinity of the interfaces with the impact limiters.

Figure 5(d) shows that the welds along the inner and outer edges of the limiters fail partially during the drop event.



(a) (b)

(c) (d)

Figure 5. Drop behavior – 9 m side drop: (a) Stress distribution, (b) Shear behavior on the lid bolts, (c) Deformation in the impact limiter, (d) Weld failure in the impact limiter.

VALIDATION OF NUMERICAL PROCESS

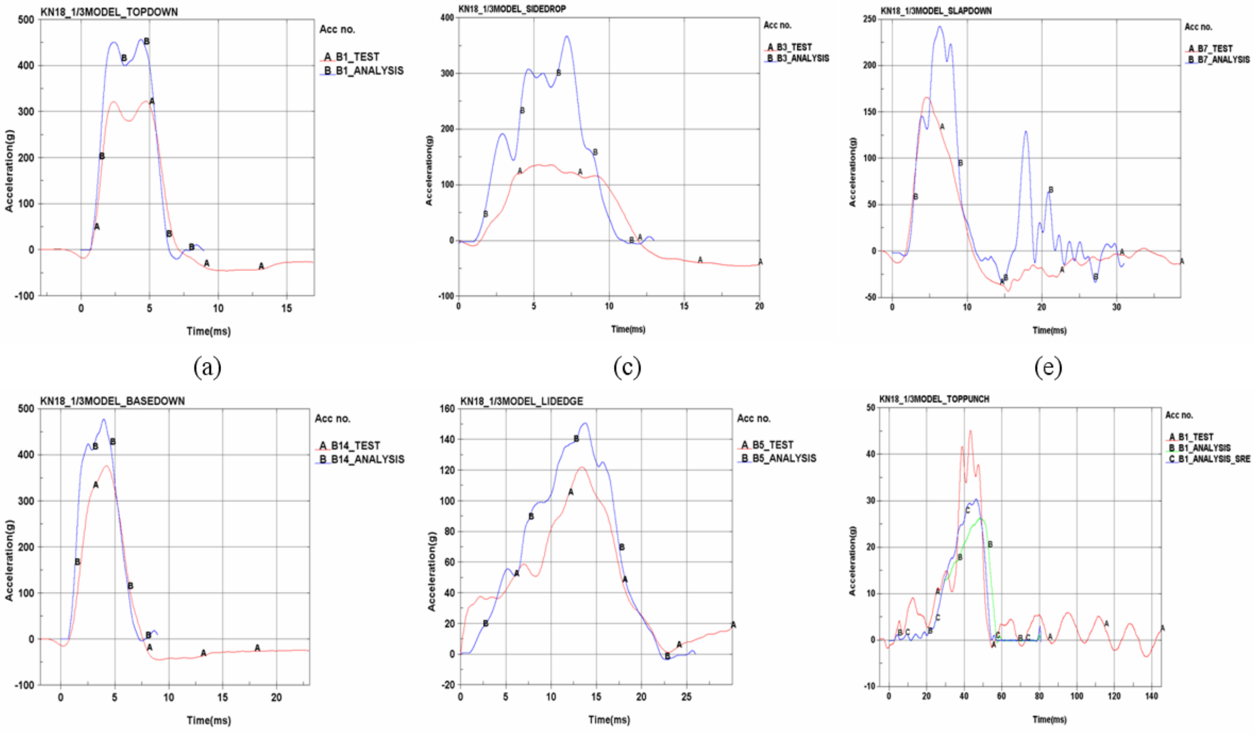
The numerical results were compared with the physical test results to verify the numerical tools and the methodology used in the analyses. The strain and acceleration measurements provide the essential components for the validation of the numerical methods. Acceleration time histories were extracted from the FE model at the nodes nearest the accelerometers in the test, and strain time histories were calculated from the relative distance between the nodes nearest the strain gauges in the test. Both time history data were obtained at 1.0E-6s interval from the numerical results to ensure that the transient data could be accurately recorded.

The deformed shapes of the impact limiters for the representative drop cases from the tests and analyses are compared in Figure 6. In general, the deformed shapes simulated by the analysis correspond well with those from the test, except that some fillet welds of the impact limiter housing failed in the actual test.

The acceleration time-histories obtained from the tests and analyses are compared in Figure 7. Generally, the acceleration traces from the analysis compare very well with those from the test in terms of shape, magnitude, and time scale, and conservatively over-predict them from the test. The reason for this over-prediction should be due to the conservative assumptions in the modeling methodology, such as no failure welds, glued wood blocks and the differences in the wood properties used in the analysis and those in the scale model cask. However, these assumptions are considered to be conservative for the evaluation of stress in the cask; therefore, from a design point of view such assumptions are not problematic.

(a) (b) (c)

Figure 6. Comparison of deformation behavior (Analysis vs. Test): (a) 9 m base down drop, (b) 9 m side drop, (c) 9 m lid edge drop.



(a) (c) (e)

(b) (d) (f)

Figure 7. Comparison of acceleration traces -300 Hz filtered (Analysis vs. Test): (a) 9 m top down, (b) 9 m base down, (c) 9 m side, (d) 9 m lid edge, (e) 9 m slap down, (f) 1 m top puncture.

For the top puncture case, this good agreement with the test is especially true for the analysis in which strain rate effects (SRE) were modeled as shown in Figure 7(f).
From the above, the modeling methodology and the analysis assumptions used in the numerical analysis are verified to be sufficient for predicting the dynamic impact response of a SNF transport cask.

SUMMARY AND CONCLUSIONS

The conclusions of this study drawn from the combined numerical and experimental studies are given below.

1. Drop analyses for various drop orientations using a more improved numerical simulation technique have been performed, and the dynamic impact characteristics of the KN-18 SNF transport cask under free-drop conditions have been investigated in detail.

2. A series of experimental studies on the free-drop and puncture behavior of a SNF transport cask has been performed using a 1/3-scale model, and the actual dynamic impact characteristics of the cask have been confirmed.

3. The numerical tool and the methodology used in the analyses have been validated through a comparison of the scale model test and the numerical results. In general, the numerical results are in good agreement with the test results in terms of the deformed shapes, acceleration traces, and strain traces. Moreover, the numerical results consistently and conservatively somewhat over-predicted the test results for most of the evaluated cases. In addition, the dynamic behavior of the model cask simulated by the analysis was also consistent with the behavior observed in the tests. These good correlations with the drop test results demonstrate that the numerical simulation method used in the analyses of KN-18 SNF cask is robust and reliable in simulating and predicting the dynamic impact behavior.

REFERENCES

[1] International Atomic Energy Agency (IAEA), 2005. IAEA Safety Standards Series No. ST-1, Regulations for the Safe Transport of Radioactive Material.
[2] Korean Ministry of Education, Science and Technology (MEST), 2008. MEST Notice No. 2008-69, Regulation for Packaging and Transport of Radioactive Material.
[3] US Title 10 of the Code of Federal Regulations, Part 71 (10CFR Part 71), 2006. Parking and Transportation of Radioactive Material.
[4] Livermore Software Technology Corp. (LSTC), 2007. LS-DYNA Keyword User’s Manual: Version 971. (January).