ABSTRACT

The spent fuel from the Nuclear Power Plants (NPP) in India is transported to the re-processing plant using lead shielded shipping cask. The shipping cask used is rectangular in shape with lead used as a shielding material sandwiched between inner stainless steel and outer carbon steel plates forming the sides of the container. The weight of the empty cask is about 55 tonnes. The drop of the prototype cask from a height of 9 meter was simulated numerically using a non-linear explicit code. An actual drop test was also carried out on a 1:4.5 scale model of the cask. High-speed cameras were used to capture the impact behavior of the cask during the actual test. The results of the actual drop test of the scale model from 9 meter height were compared with the simulated drop using Finite Element (FE) analysis. Measured value of damage parameters viz. maximum deformation, stress and the slump in the lead core of the dropped cask were compared. The drop simulation was carried out for different orientations of the cask viz. flat drop on bottom face and corner drop. After validation of the FE model, the numerical analysis of the prototype cask was carried out to confirm the shielding integrity of the lead-filled cask. The paper brings out the details of the finite element model, actual drop tests on a scale model, its comparison with the simulated drop test and the results of the simulated drop test of the prototype cask.

Keywords: Cask, Flat drop, Corner drop, Simulation, drop test

1.0 Introduction

The spent fuel shipping cask used in the Nuclear power Plants (NPP) in India is a lead shielded rectangular vessel. The cask consists of a body and a lid, both of which have mild steel outer shell with stainless steel cladding. The inner shell, made up of stainless steel, forms the cavity in the cask body for keeping the cage carrying the trays with fuel bundles. Lead is filled between the inner and outer shell for the purpose of shielding. The overall cavity dimensions are 1600 mm x 1200 mm x 1220 mm. The overall outer dimensions of the cask are 2170 mm length x 2160 mm width x 2233 mm height. Four numbers of trunnions are provided on the body for handling purpose. The weights of empty and loaded cask are approx. 55 tonnes and 60 tonnes respectively. The details of cask are shown in Fig 1.
The spent fuel shipping cask is required to meet the requirements of Indian Atomic Energy Regulatory Board (AERB) Safety Code SC/TR-1 [1] for demonstrating the ability to withstand normal conditions of transport and accidental conditions during transport. The ability of the cask to withstand accident conditions of transport is verified by conducting a 9 meter drop test.

2.0 Methodology

As, the 9 meter drop test on the prototype cask is not feasible considering its huge weight of 60 tonnes, the drop test was simulated numerically using non-liner FEM analysis on a 1:4.5 scale model and the results were validated by actual drop test on a scale model. The validated FE model of the cask was then further used for numerical simulation of the full-scale prototype model.

3.0 Finite Element Modeling of the Cask

The finite element model of the cask is shown in Fig-2. The entire model is discretized with shell, brick and beam elements.

4.0 Drop Test on Scale Model

The 1:4.5 scale model was decided based on the practical consideration of fabrication and handling at the test facility which requires having a weight less than 1 tonne. The weight of the scale model was approx. 800 kg. For the purpose of validating the FE model, simulation of the drop tests were performed on the scale model for the following drop orientations.

1) Corner Drop
2) Flat Drop on bottom face

A total of 4 samples were drop tested – two each for corner drop and flat drop.

5.0 Test set-up

The test set-up used for conducting the drop test is shown in Fig-3. The test set-up consists of an unyielding surface and a chain-pulley arrangement for raising the cask. The design of the un-yielding surface was carried out to meet the requirements of IAEA safety series regulation-37, section-VII [2].

6.0 Drop test procedure

The scale model was suspended using a chain-pulley block with a hook. A quick release mechanism was devised to release the cask along with the hook instantaneously. The cask was pulled up with the help of the chain-pulley block and fixed to the test rig to achieve a height of 9 meters from the lowest portion of the cask to the un-yielding surface. The cask was balanced and aligned properly for vertical drop by providing additional weights at appropriate locations.
High-speed cameras (with speed of 500 frames/sec) were used to capture the impact behaviour of the cask during the actual drop test.

7.0 Comparison of Test Results and Validation of FE Model

7.1 The validation of the FE model was based on the comparison of deformation and stress levels obtained by analytical simulation and from the actual drop test at some selected locations. For comparison of deformation, internal and external critical dimensions at three different sections across the height and the corner-to-corner dimensions were measured before and after the drop test. These dimensions are shown in Fig-4 and Fig-5.

7.2 For comparison of stress levels, 10 strain gauges were pasted for the flat and the corner drops. The locations of these strain gauges are shown in Fig-6 and Fig-7. The strain gauge data was acquired at a 20 kHz sampling rate with a high-speed data acquisition system.

7.3 Comparison of deformation

7.3.1 Flat drop

The maximum deformations of the cask in the FE simulation and in the actual drop test (average value of two tests) were compared for the critical dimension selected for comparison as shown in Fig-4 and Fig-5. The deformation values for flat drops are given in Table-I. The comparison between the deformation of the inner shell of the cask during both simulated and actual drop test is shown in Fig-8. In either case, there was no visible deformation. The comparison between the deformation of the lid with simulated and actual drop test, which were 13.4 mm and 10 mm respectively is shown in Fig-9.

7.3.2 Corner drop

For the corner drop, the measured values of deformation were compared with those of the analytical simulation and are given in Table-2(a) & Table-2(b).

The major deformation in corner drop was the deformation of the corner on which the cask was dropped. The average value of the deformation of the dropped corner was 81.0 mm and the predicted value from the FE simulation was 76.3 mm, which compare very well. The deformation of the dropped corner in both the cases is shown in Fig 10. The photograph of dropped corner of the cask inside the cavity is shown in Fig 11. Visually there is no significant deformation observed inside the cavity in both cases. The deformation of the trunnion in the simulation and drop test is shown in Fig 12. The measured deformation of 58.00 mm of the trunnion from drop test compares very well with the simulated deformation of 60.68 mm. The deformation of the outer shell for both simulated and drop test is shown in Fig 13. The deformation of the corner is essentially due to the deformation of the supporting legs. There was no significant deformation of outer shell. The maximum deformation of the outer shell at the corner was about 6 mm.
7.4 Comparison of stress levels

The stress level computed from the strain gauge data obtained during both the flat drop and corner drop were compared with the finite element simulation results and are given in Table 3 and Table 4 respectively.

The stress level (Ref Table-3 and Table-4) were computed for the elements in a zone within a radius of 10mm around the location of strain gauges. This was done to understand the stress variation due to the positional variations in the placement of strain gauges and dimensional variations due to manufacturing. The large variation in stress range at some locations is attributed to the following reasons.

- Although the two components used for the two drop tests were identical, there could be likelihood of slight variation in the dimensions of the components during manufacturing.

- Even though, visually, the drops were perfectly flat, there could be variations within a couple of degrees, which can result in large variation in stress patterns. Similar studies carried out elsewhere have shown the stress variation of approximately 25-30\% for 1 degree change in drop angle.

- The variation in placement of strain gauge even within ± 5mm is likely to cause large variation in stress values.

It can be observed from Table-3 and Table-4 that the simulated stress levels at 7 locations out of 10 for flat drop and all locations for corner drop were below the yield stress of 326.5 N/mm² for the material. However, at 3 locations viz. guage1, 3 and 5 for flat drop, the stresses were exceeding the yield stress. The stress plots as shown in Fig-14 and Fig-15 for these locations clearly indicate that these are very localized high stresses, which may be due to local vibrations. It was seen that these stresses lasted only for a very short duration.

8.0 Study of Prototype Model from Simulation

After validating the FE model for 9 meter drop on a scale model, the simulation of the 9 meter drop was carried out on a prototype model.

The deformation and the percentage deformation of the main cask at some critical locations (Ref Fig-4 and Fig-5) were computed for flat drop and are given in Table-5. The results for the case of corner drop are given in Table-6. From the tables, it can be observed that for flat drop case, the maximum deformation was 43.8 mm of the outer cladding. In case of corner drop, the maximum deformation of the dropped corner was 356.2 mm which is about 9.7\% of the original dimension. However, this deformation was essentially due to deformation of the supporting legs which have a height of about 310 mm. The maximum slump in the lead was 127 mm in case of flat drop and 74 mm in case of corner drop.
9.0 Conclusion

1) The deformation results predicted by the simulation correlate very well with the drop test results in case of both flat as well as corner drop.
2) The overall deformation at almost all locations concerned with the lead shielding was within 1-2%.
3) No significant failure or damage to outer or inner shell was observed carrying concern was observed either experimentally or analytically in both the drops.

10.0 References

1.0 AERB Safety Code SC/TR-1, 1986

Table -1 Comparison of Deformation of Cask Flat Drop Tests and Simulation Results (Scale Model)

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<th>Eo</th>
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<td>TEST (mm)</td>
<td>FEM (mm)</td>
<td>TEST (mm)</td>
<td>FEM (mm)</td>
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Table -2(A) Comparison of Deformation of Flask Corner Drop Tests and Simulation Results (Scale Model)

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### Table-2(B) Comparison of Deformation of Flask Corner Drop Tests and Simulation Results (Scale Model)

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### Table-3
Comparison of Stresses at Strain Gauge Locations for Flat Drop Test and Simulation Results

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### Table-4 Comparison of Stresses at Strain Gauge Locations from Corner Drop Test and Simulation Results

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### Table 5: Deformation Results of main cask after flat drop by simulation

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#### Internal Dimensions

### Table 6: Deformation Results of main cask after corner drop by simulation

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#### Internal Dimensions
Fig 1: Details of the cask

Fig 2: FE model of the Cask

A: Un-Yielding Target  
B: Chain-Pulley and Release Mechanism

Fig 3: Test set-up
Fig 4: External Dimensions of the Scale Down Cask

Fig 5: Internal Dimensions of the Scale Down Cask
Fig 6: Strain Gauge Locations for Flat Drop

'X' SHOWS STRAIN GAUGE LOCATIONS, '—' SHOWS STRAIN GAUGE DIRECTION.
Fig 7: Strain Gauge Locations for Corner Drop

'\times' SHOWS STRAIN GAUGE LOCATIONS, '---' SHOWS STRAIN GAUGE DIRECTION.

Fig 8: Comparison of deformation of the inner shell
Fig 9: Comparison of deformation of the lid

Fig 10: Comparison of deformation of dropped corner

Fig 11: Comparison of deformation of inner shell
Fig 12: Comparison of deformation of trunnion

Fig 13: Comparison of deformation of outer shell
Fig 14: Stress Plot for Lid (Strain Gauge No. 5)

Fig 15: Stress Plot for Outer Cladding (Strain Gauge No. 1 and 3)