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ANALYSES TO DEMONSTRATE THE STRUCTURAL PERFORMANCE OF THE KN18 IN HYPOTHETICAL DROP ACCIDENT SCENARIOS

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ABSTRACT

The KN18 is a new cask design by KONES for KHNP for the dry or wet transportation of up to 18 PWR spent nuclear fuel assemblies in South Korea.

The containment vessel consists of a cylindrical thick-walled forged steel body, closed by a stainless steel lid with bolts. Spent fuel assemblies are located in a basket which consists of a tube disc system. Two pairs of trunnions are attached for lifting, manoeuvring and tie-down. A pair of impact limiters manufactured from wood and encased in steel cladding provide impact energy absorption during the hypothetical accident conditions.

The package complies with the requirements of 10 CFR Part 71 for Type B(U)F packages. It received its transport license from the Korean Competent Authority KINS in early 2010 and is expect to enter service in 2011.

Structural performance of the package in the normal and accident conditions were demonstrated against the requirements of 10 CFR Part 71 by analysis including extensive calculations by state-of-the-art finite element methods, and confirmed by tests carried out on a 1/3 scale test model which were also used to verify the numerical tool and methods used in the analyses.

For the analyses of the hypothetical accident drop conditions, the models consisted of the complete package - including the impact limiters, the containment structure and the basket – which was modelled explicitly in detail and in three dimensions, to take into account the complex interaction between the components and the non-linearities in the geometry, the material behaviour and overall behaviour. The analyses were carried out using the explicit transient finite element method so that the transient behaviour could be robustly simulated.

This paper presents two of the analyses from the suite of analyses for demonstrating the performance of the package in the hypothetical accident drop scenarios, discussing the analyses methodology, modelling technique and evaluation methodology, as well as analyses results and package response.

1/3 scale model drop testing and benchmarking of the model to the scale model tests are the subject of a separate paper.

INTRODUCTION

The KN18 is a new cask design by KONES for KHNP for the dry or wet transportation of up to 18 PWR spent nuclear fuel assemblies in South Korea. It received its transport license from the Korean Competent Authority KINS in early 2010 and is expect to enter service in 2011.

It has been designed to satisfy the regulatory requirements of the 10 CFR 71 [1] for Type B(U)F packages. Its structural performance was demonstrated against the load cases and boundary conditions as defined in 10 CFR 71 and NRC's Regulatory Guide 7.8 [2], and further explained in NUREG 1617 [3]. This included normal conditions of transport load cases - including Hot Environment, Cold Environment, Increased External Pressure (140MPa), Minimum External Pressure (24.5kPa), Vibration and shock, and 0.3m free drop – and the hypothetical accident conditions load cases – including the 9m Free Drop, Puncture, Thermal Fire Accident, 200m Water Immersion and 1.5x MNOP Internal Pressure.

Structural performance of the package in the normal and accident conditions were demonstrated against the requirements of 10 CFR Part 71 by analysis including extensive calculations by state-of-the-art finite element methods, and confirmed by tests carried out on a 1/3 scale test model which were also used to verify the numerical tool and methods used in the analyses. Structural analyses and calculations including demonstration of performance against requirements were carried out by Arup, validation against drop tests was carried out by KONES, , and drop tests were carried out by KAERI.

This paper concentrates on the analysis carried out to demonstrate performance in the hypothetical accident 9m free drop scenarios, and results from two scenarios.

DESCRIPTION OF THE CASK

The containment vessel consists of a cylindrical thick-walled forged carbon steel body, closed by a stainless steel lid with 37 stud-nut assemblies with M48 threaded interfaces and shaft diameters of 41mm, plus three M48 cap screws and sealed by an elastomer O-ring.

A vent and drain valve is installed on the lid. It is closed by a closure plug with an elastomer O-ring seal and covered by a bolted closure lid sealed with an elastomer O-ring.

The inside cask cavity surfaces, the O-ring seating surfaces and the outer cask region of the lid and bottom side are covered by a welded stainless steel cladding for corrosion protection.

For neutron absorption, a thick layer of NS-4-FR resin, encased within a 16mm thick casing on the outside, covers the external surface of the body over the entire height. A disc of resin is also installed in a recess at the bottom end of the body and encased by a steel plate for the same purpose. Forty heat dissipation fins each spanning the thickness of the resin layer is installed to facilitate dissipation of decay heat to the atmosphere. A layer of resin is also installed in a recess on the upper side of the lid, encased within a steel plate which is welded to the lid.

Fuel assemblies are located within a stainless steel fuel basket of a tube-disc type, consisting of eighteen basket cells, forty circular support discs, connected by seven steel bar columns. For neutron absorption, Metamic plates, encased in stainless steel casing, are installed on each face of each cell along the entire length of the cell.

Two pairs of trunnions are attached for lifting, handling and also tie-down during transportation.

Energy absorption and control of deceleration during hypothetical accident 9m drop scenarios are provided by a pair of impact limiters, one at each end of the cask, attached to the cask by bolts during transportation. They are manufactured from a carbon steel plate inner structure and a stainless steel outer structure, and filled with spruce and beech. The outer steel shell is welded water tight to protect the wood against humidity. The steel structure was designed to fully utilise the energy absorbing capacity of the wood.

ANALYSIS AND EVALUATION METHODOLOGY

The structural performance of the KN18 in the hypothetical accident conditions was analysed using explicit FE simulation using a three-dimensional detailed model of the complete package, with the FE code LS-DYNA. Stresses in the containment and the basket were evaluated against the requirements of ASME Boiler and Pressure Vessel Code.

DROP SCENARIOS

10 CFR 71 requires the structural adequacy be demonstrated for a free drop through a height of 9m onto a flat, unyielding, horizontal surface, striking the surface in a position for which maximum damage is expected.

The cask was analysed in all the centre of gravity (CG) over initial point/plane of impact orientations:

- Corner - lid edge and base edge drops
- Axis vertical – lid down and base down drops
- Axis horizontal – side drop

For the side drop, it was analysed with three hoop orientations, 0°, 45° and 90°, and the lid edge and base edge drops were analysed with the worst hoop orientation.

In addition, its behaviour in the oblique drops, with the CG not directly over the initial point of impact, was also analysed.

These drop orientations bound the behaviour of the cask in the 9m free drop scenario.

MODELLING

One basic detailed FE model, in combination with different initial and boundary conditions, was used for the analysis of all the CG over point of impact drops and the oblique drop at the worst oblique angle. Taking advantage of symmetry of the package in the drop scenarios, half models (representing a 180° segment of the package) was used in all but the 45° hoop orientation side drop in which a full model was used.

The full model consists of 1 060 000 elements. The half model is shown in Figure 1. Details at the top end of the model around the lid-body interface is shown in Figure 2.

The mesh was designed to be appropriate for the purpose of the analysis and for the expected behaviour of the package. It was refined at areas of higher stress gradients, areas of larger deformation gradients, and where a higher level of accuracy was required. It was coarsened elsewhere to keep the overall number of elements to a minimum, as the number of elements directly affects the analysis time. Identical mesh was employed for all the lid bolts, so that the same accuracy can be attributed to the results for all bolts. Identical mesh was employed for each repeating geometry in the body flange between adjacent lid bolts, and in the lid flange between adjacent bolt holes, for the same reason. Identical mesh was employed for similar components that undergo similar deformation or experience similar stresses.

The lid-body bolts were modelled using solids with 32 elements in the cross section. The threaded interfaces between the bolt and the cap nut, between the bolt and the bushing, and between the bushing and the body were modelled with continuous meshes across the interfaces.

The basket was modelled with a combination of solids and shell elements. The perimeter of the basket was modelled with a similar mesh as the cavity of the interface has a significant influence on the behaviour of the basket.

The steel housing and the wood in the impact limiters were modelled separately. The housing was modelling using a combination of shells and solids. The wood in each compartment of the steel housing was modelled as a single “block” of continuous solids. This made best use of the wood crush data that was available. Crush behaviour was modelled using MAT_HONEYCOMB, based on test data.

Water was modelled using solid elements, with bulk modulus of water but with no shear stiffness. Instead of modelling the water to occupy all the gaps and spaces in the cask cavity between the many components of the basket and fuel assemblies, the whole volume was modelled as a single continuous block of solids, but with no interaction with the basket or the fuel assemblies. For components submerged in water, this is a conservative assumption, as far as loading on them is concerned.

With this modelling method, the volume of water in the model was larger than in reality, because the presence of the components it submerged were ignored. To compensate for this increased volume, the density of the water should be reduced to achieve the correct mass of water. But since water pressure on the cavity walls is proportional to the density of water, reducing the density would lead to a water pressure smaller than that in reality. Hence, the real density of water (1000kg/m3) was used, achieving the correct water pressure on the cask walls, and conservatively overloading the cask with a heavier than reality mass of water, and similarly, inertia.

Contact surfaces were defined extensively to simulate components which were in contact at the start of the analysis and components that would come into contact during the impacts.

The components of the containment were modelled with linear elastic stress-strain properties in accordance with the requirement for stress evaluation to ASME Boiler and Pressure Vessel Code [4] Section III Division 3.

The basket was analysed using the plastic analysis method as allowed by ASME Boiler and Pressure Vessel Code Section 3 App F, to obtain a correct or conservative prediction of displacements. Basket components were modelled using elastic-plastic properties with strain hardening. The input properties were derived from the "minimum" properties of the materials specified in ASME Boiler and Pressure Vessel Code Section 2 Part D and Part A. “Minimum” properties were used in order to obtain conservative estimates of deformation.

The unyielding target was modelled using *RIGIDWALL, which allows no penetration and absorbs no energy in impact.

INITIAL CONDITIONS

Each analysis consisted of two phases. Phase 1 was the “dynamic relaxation” phase during which bolt prestresses due to bolt torque were applied to the lid bolts and the closure lid bolts by “dynamic relaxation” to obtain the correct bolt stresses and stresses in the adjacent components. Phase 2 was the transient phase during which the impact was analysed.

At the start of transient phase, for the CG over point of impact drops, the whole cask model was given an initial velocity of 13.3m/s perpendicular to the target, corresponding to the impact velocity after a drop from 9m.

For the oblique drop, instead of prescribing an initial velocity of 13.3m/s to the model and analysing the model at a range of drop orientations, a staged approach was adopted. Using a simplified model which was identical to the detailed model except that the whole cask and its contents were modelled as undeformable, a range of drop angles from 2.5° to 15° was analysed in order to obtain a drop angle at which the velocity at second impact is highest. From the analysis of the simplified model at the worst drop angle, the velocity profile and cask orientation at second impact were obtained. They were then applied to the detailed model as initial conditions. The detailed model was analysed only for the second impact.

The advantage of this approach was that a larger range of impact angles could be analysed to determine the worst impact angle, hence determining it with greater accuracy than is possible with either hand calculations or with the detailed model.

BEHAVIOUR IN THE SIDE DROP

The impact limiters contacted the target first and 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. Deformation of the impact limiters is shown in Figure 3.

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 contents, while supported at the top and base ends. This caused the tensile stresses on its side closest to the target, compressive stresses on the side away from the target, and localised stress in the vicinity of the interfaces with the impact limiters.

The loading at the interface with the impact limiter at the top end of the cask body caused the body to deflect inwards radially, in an ovalising manner, to bear onto the lid, then pushing the lid to bear onto body at the opposite end. As part of the ovalisation, the open end of the cask body widened in the direction lateral to the impact, causing it to stretch away from the inner lid on the sides.

These are best illustrated by way of direct stress in the lengthwise direction (Z-direct stress) of the cask body as in Figure 4, and direct stress in the radial direction in the direction of impact (X-direct stress) of the lid in Figure 5.

Inside the cask, the basket bore onto the decelerating cask. If the cask were rigid, the basket would be supported uniformly along its length. However, because the cask body deflected, the basket was more supported towards the top and bottom ends, causing the basket itself to deflect to contact the cavity along its length. In each disc, stresses increased towards where it was supported on the cask cavity due to the inertia loading of itself and the inertia loading of the basket cells and the fuel assemblies. There were also higher local stresses where there were change in plate thickness and at sharp changes in geometry, e.g. at corners of cut-outs. As the basket cells were only welded to the base disc, there were local bending stresses in the basket cells and in the base plate where they were connected, as the basket cells tried to drop onto the support in their cut-out in the intermediate discs.

Behaviour of the basket in the 0° hoop orientation drop is shown in terms of Von Mises stress in Figure 6. Stress flow of compressive stresses in the second highest disc in this hoop orientation is shown in Figure 7. Compressive stresses in the discs in the 45° hoop orientation drop and the stress flow in the second highest disc is shown in Figures 8 and 9.

BEHAVIOUR IN THE BASE DOWN DROP

The cask compressed the bottom impact limiter against the target.

As the cask was decelerated, the contents in the cavity bore onto the base of the cavity. The base, supported around the perimeter deflected outwards under its own inertia loads plus the inertia loads from the contents.

Although the lid was not directly involved in the impact, its inertia caused it to deflect downwards in the middle while the bolts acted like rotational springs applying a restoring moment around the perimeter.

As the base deflected, the basket was “more supported” around the edges. The most significant loading in the basket were found in the steel columns which connect the basket discs. They were loaded by the inertia of the discs and this is obvious in the axial stresses, smallest at the top but increased towards the bottom. The inertia of the fuel assemblies were reacted directly by the thickened square areas of the base disc. The inertia of the basket cells caused bending of the base disc between where the basket cells were connected and the thicker square sections which rested on the cavity base.

Deformation of the base impact limiter is shown in Figure 10. The bending behaviour of the base of the cask body and the lid as discussed above are illustrated in Figures 11 and 12. Von Mises stresses in the basket structure is shown in Figure 13.

EVALUATION OF PERFORMANCE

Stresses in the containment and the basket from all the analysis were evaluated against the stress limits specified in ASME Boiler and Pressure Vessel Code. In all drop scenarios, the stresses were below the limits with sufficient margin in all cases.

Displacements between adjacent fuel assemblies were obtained from the analyses and provided for criticality evaluation. Criticality performance was shown to be satisfactory in all the drop scenarios.

CONCLUSIONS

The work has demonstrated the benefit of employing detailed three-dimensional modelling by explicit FE simulation in demonstrating the performance of the KN18 and its compliance with regulatory requirements in hypothetical accident drop scenarios.

REFERENCES

[1] Title 10 of the Code of Federal Regulations Part 71 (10 CFR Part 71), Packaging and Transportation of Radioactive Materials, April 1996
[2] U.S. Nuclear Regulatory Commission, Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material, Regulatory Guide 7.8, Rev 1, March 1989
[3] U.S. Nuclear Regulatory Commission, Standard Review Plan for Transportation Packages for Spent Nuclear Fuel, March 2000, NUREG-1617, March 2000
[4] American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, 2004.

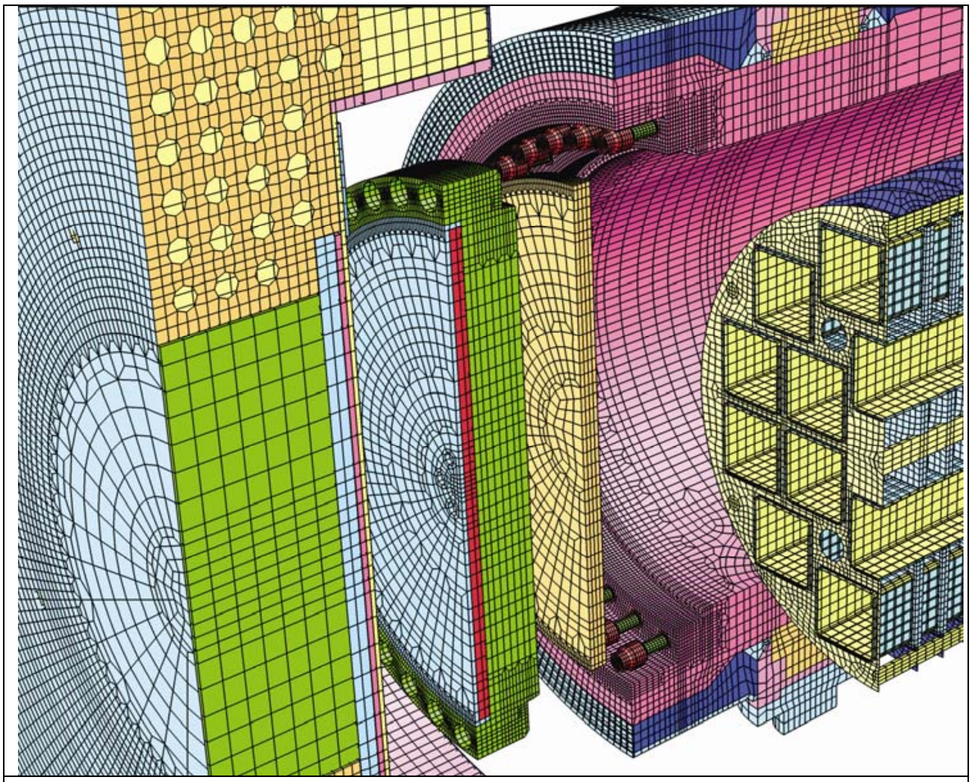

Figure 1 The finite element model

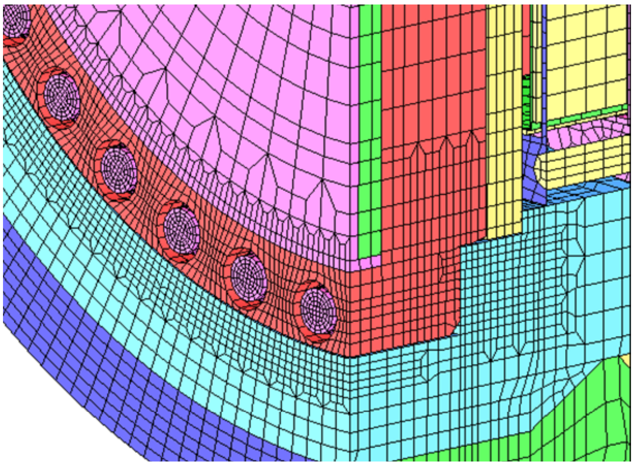

Figure 2 Details of the model at the top end of the cask around the lid-body interface

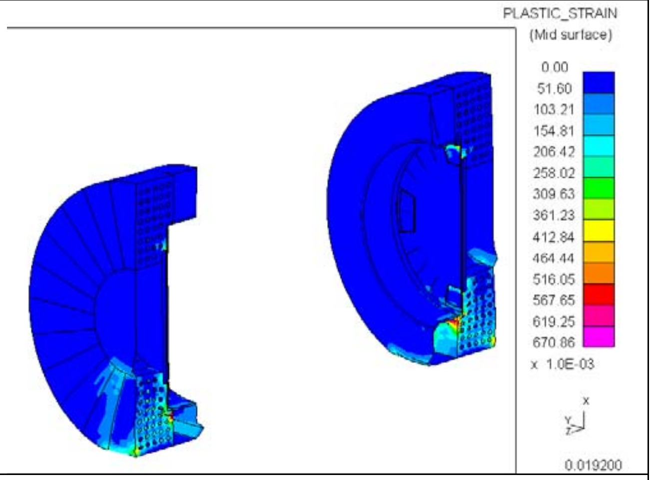

Figure 3 Deformation of the impact limiters in the 9m side drop

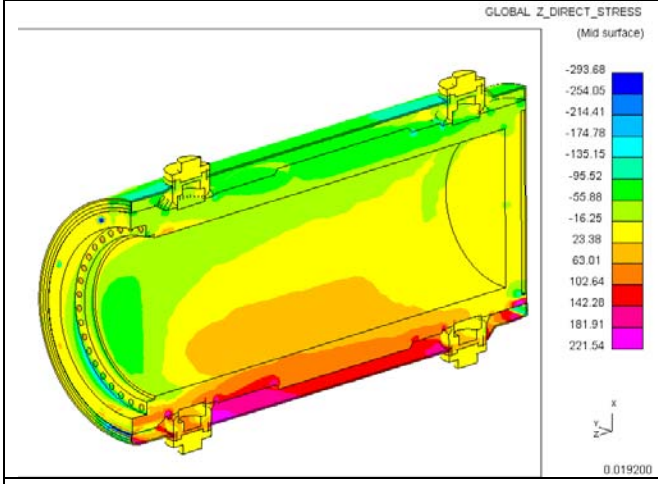

Figure 4 Bending stresses in the cask body in the 9m side drop

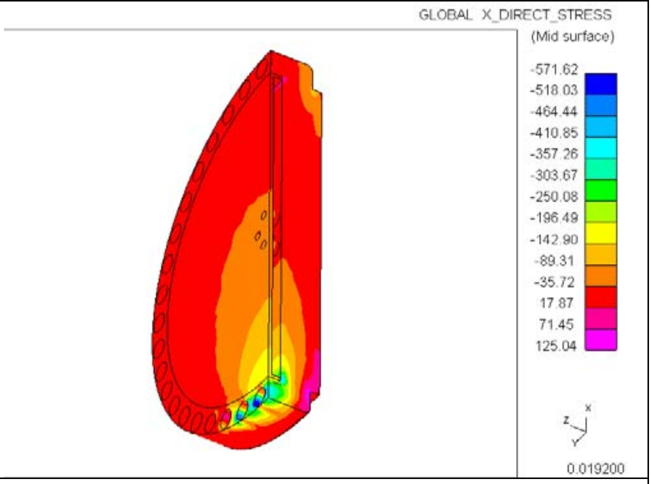

Figure 5 Radial compressive stresses of the lid in the 9m side drop

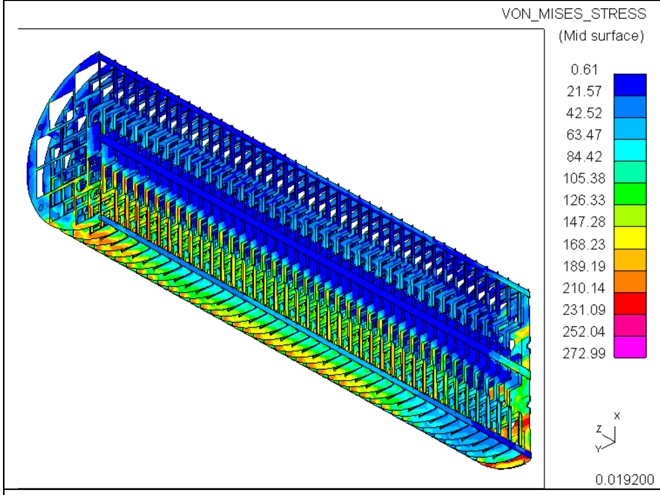

Figure 6 Von Mises stresses in the discs and columns in the 0° hoop orientation in the 9m side drop

Figure 7 Stress flow in the second highest disc in the 0° hoop orientation in the 9m side drop

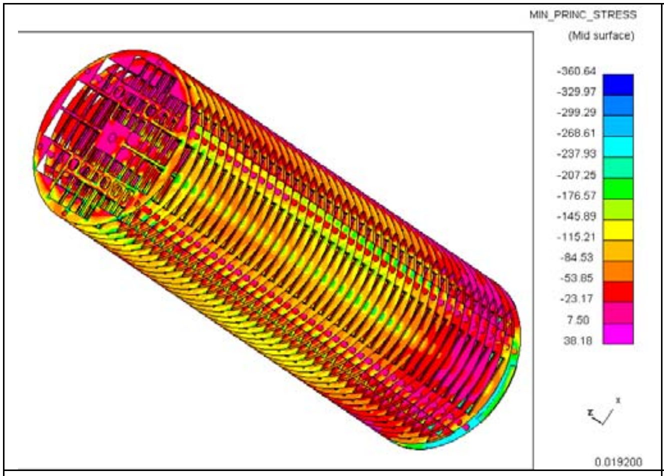

Figure 8 Compressive stresses in the discs and columns in the 45° hoop orientation in the 9m side drop

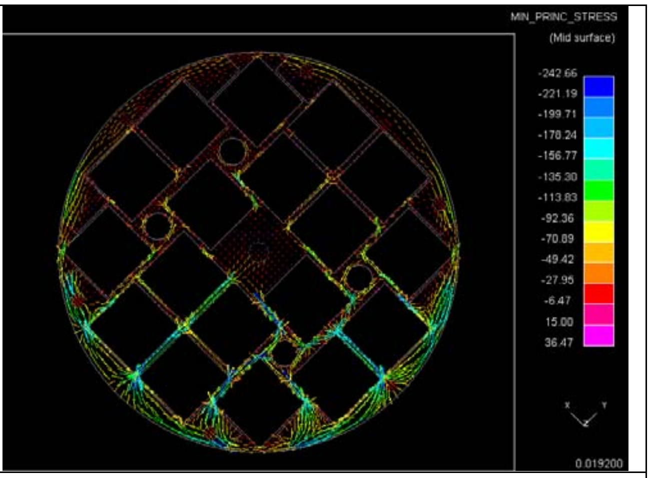

Figure 9 Stress flow in the second highest disc in the 45° hoop orientation in the 9m side drop

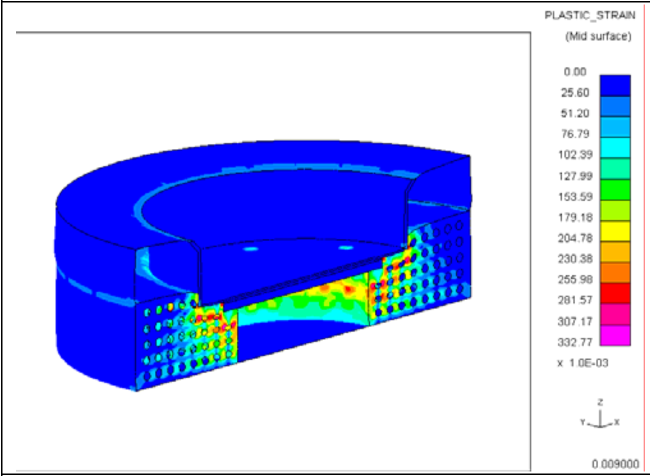

Figure 10 Plastic strains in the base impact limiter in the 9m base down drop

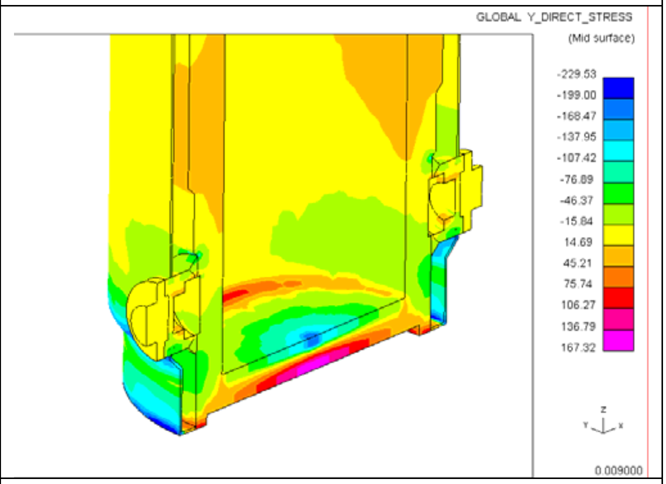

Figure 11 Bending stresses in the cask base in the 9m base down drop

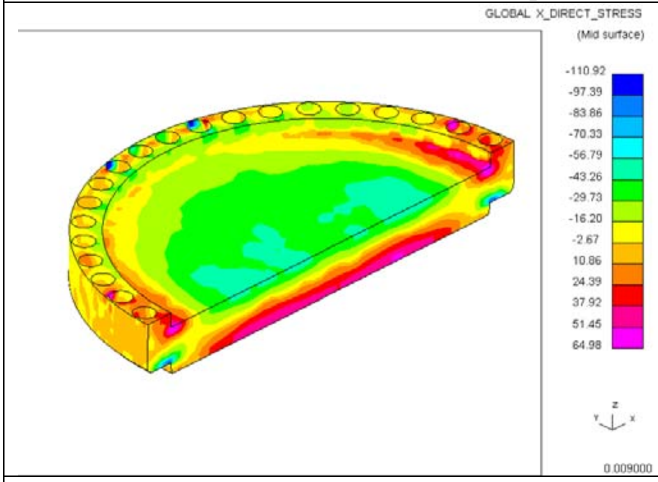

Figure 12 Bending stresses in the lid to show lid deflection in the 9m base down drop

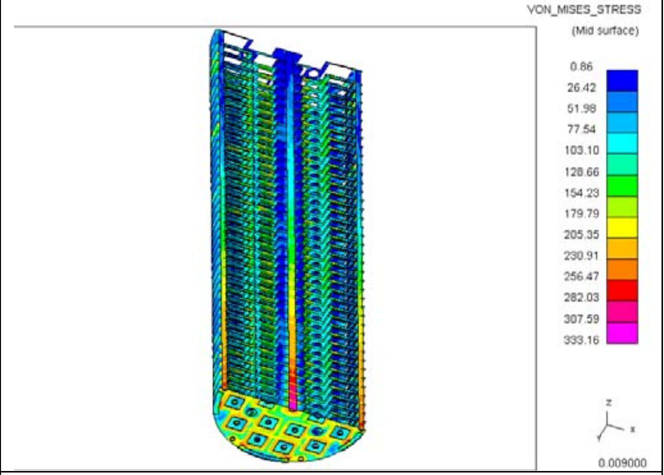

Figure 13 Von Mises stresses in the discs and columns in the 9m base down drop