FEM ANALYSIS AND EXPERIMENTAL VERIFICATION OF THE CONSTOR® STEEL-CONCRETE-SANDWICH CASK UNDER DROP TEST CONDITIONS

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ABSTRACT

The CONSTOR® steel-concrete-steel cask is a Type B(U)F package for transport and storage of spent fuel elements. Aspects of its design development will be presented in a separate paper at the PATRAM 01.

The cask body is a steel-concrete-steel sandwich construction. It consists of an outer and an inner steel liner, with the space in between filled with heavy concrete for additional shielding, within a reinforcement frame welded to the inner liner. The closure system consists of a bolted primary lid, a welded intermediate lid and a welded secondary lid.

As a final verification of the cask's integrity in 9m regulatory drops, finite element (hereafter FE) analysis have been carried out using the explicit non-linear code LS-DYNA.

The work had two objectives: 1) to verify the FE modelling technique and of the FE model in accurately predicting the drop behaviour of the cask; and 2) to evaluate the integrity of the cask in the 9m regulatory drop scenarios using the validated models.

To this end, two FE models of the CONSTOR® were built, one of the ½ scale model cask which had previously been 9m side drop tested, and the other of the full scale cask. The models differ only in dimensional details. All cask components were modelled explicitly, and the concrete was modelled using an anisotropic brittle damage model by Govinjee.

Analysis results compared well with test results. This sufficiently demonstrates the capability of FE analysis to simulate the behaviour of casks in impact, and forms a sufficient validation for the model.

Integrity of the full scale cask containment was then evaluated under the three drop orientations: side drop, bottom edge drop and lid edge drop. Maximum stresses in all scenarios were lower than the stress limits, hence demonstrating the integrity of the cask in the regulatory 9m drop scenarios.

INTRODUCTION

The CONSTOR® steel-concrete-steel cask is a Type B(U) package for the transport and storage of spent fuel elements. Aspects of its development and drop testing have been covered in a number of papers at PATRAM 98 and also in another paper at this conference.

Finite element (FE) analyses were performed to evaluate the CONSTOR® cask behaviour and to demonstrate the integrity of the cask's containment in three 9m regulatory drop test scenarios – side drop, bottom edge drop, lid edge drop.

In order to demonstrate the accuracy and reliability of the FE analysis results, it was also deemed necessary to verify the analysis methodology and the FE model against test.

EVALUATION STRATEGY

The ensuing work hence included two tasks. The first task was to verify the analysis methodology and the FE model in simulating the behaviour of the cask. The second task was to evaluate the behaviour of the cask and to assess its integrity in 9m drop scenarios.

Drop tests of the cask using a ½scale model were carried out in 1997. Among the scenarios tested, was 9m side drop. Acceleration and strain time histories were recorded during the test. This test was deemed a sufficient basis for the verification exercise.

Hence, two FE models were built. The first FE model was of the 1/2 scale model as used in the drop tests. And the second FE model was of the full scale cask. The geometry of the full scale cask differ from the 1/2 scale model cask only in scale and a few secondary details - including trunnion dimensions and method of trunnion attachment.

The FE model of the 1/2 scale model cask was analysed for a 9m side drop, and results verified with the corresponding drop test. Having verified the modelling methodology and the FE model, integrity of the cask in the side drop scenario was evaluated based on this analysis. Lid edge and base edge drops were then analysed using the FE model of the full scale cask. Cask behaviour and integrity were assessed based on these analyses.

The analyses were carried out using the explicit non-linear finite element code LS-DYNA version 950.d.

THE CONSTOR® CASK

The CONSTOR® cask is a Type B(U)F package for the transport and storage of spent fuel elements.

The cask body is a steel-concrete-steel sandwich construction. It consists of an outer and an inner steel liner, with the space in between filled with heavy concrete within a reinforcement frame which is welded to the inner liner. The heavy concrete represents together with the steel liners the cask's shielding material. At the top end of the cask, the liners are welded to a head ring made of forged steel. The trunnions are attached to this ring. The closure system consists of a bolted primary lid, a welded intermediate lid and a welded secondary lid. The bolted primary lid provides temporary sealing. The intermediate lid and the secondary lid are welded to the head ring after loading and servicing of the cask. The welded lids together with the inner and outer liners together represent the double barrier system.

With the purpose of cushioning the cask against hypothetical drops during handling at the storage site, a special shock absorber made up of a ring of steel ribs is located at the cask bottom.

For energy absorption in hypothetical drop accidents during transport in the public domain, the cask is fitted with two impact limiters made from a steel casing, filled with wood.

MODELLING OF THE CASK AND ITS CONTENTS – THE MESH

The mesh of the full scale cask and the ½scale model cask were essentially identical except for scale. The mesh of the FE model for the lid edge drop analysis was also considerably refined in the top half of the cask. The top half of the cask body and the lids of the lid edge drop model is shown in Figures 1, with the lids "exploded" for ease of visualisation. For clarity, the concrete is not shown. Reinforcement bars are shown in Figure 2. The lower half of the model including the base shock absorbers are shown in Figure 3. The models were half models, taking advantage of symmetry.

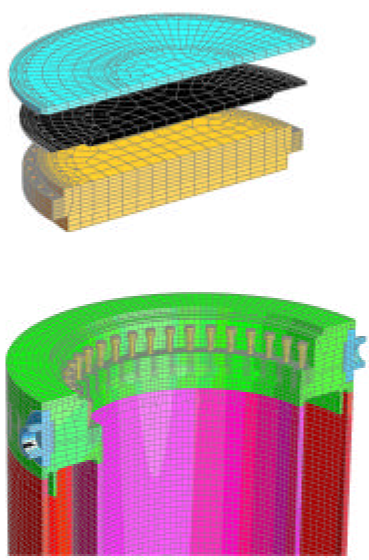
Figure 1, Model of cask body and lid – top half (steel structure only)

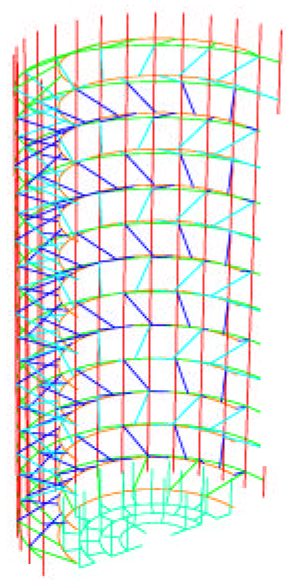
Figure 2, Model of reinforcement bars

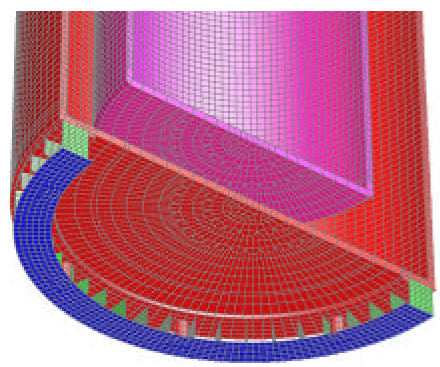
Figure 3, Model of lower half of cask body model (steel structure only)

The cask was modelled using solid elements, except for the reinforcement bars which were modelled using beam elements, and the base shock absorber were modelled using shells. Fully integrated solid elements were used extensively in the model - where large stress gradients are expected over a small number of elements where using large number of elements is not practical, or where large deformations are expected.

MODELLING OF THE CASK AND ITS CONTENTS – MODELLING OF STEEL

Stress strain properties of all the steel components were modelled as elastic-perfectly plastic.

The minimum 0.2% proof stress of the specified material was adopted as the "yield" value in constructing the stress strain curves for the FE model of the scale model cask and of the full scale cask. This is a conservative assumption as far as deformation and strain is concerned.
And of course, this assumption only affects those components which deforms plastically in reality – i.e. trunnions and base shock absorbers only.

MODELLING OF THE CASK AND ITS CONTENTS – MODELLING OF CONCRETE

It was assumed that the concrete was completely cracked in all directions, i.e. it can take compression, but it has no tensile capacity in any direction. This assumption commensurate with the design philosophy of the CONSTOR that the concrete is basically non-structural, and it is intended primarily for shielding. Although this may be a conservative assumption, the concrete in the ½ scale model cask at the time of the drop tests was certainly not cracked to this extent.

The MAT_BRITTLE_DAMAGE material model was used, to describe the assumed behaviour. This material model is an anisotropic brittle damage model designed for concrete based on the work by Govinjee, Kay and Simo [2]. It allows specification of a tensile limit. Once a principal stress exceeds this tensile limit, a crack plane is initiated perpendicular to this principal direction. Once initiated, the crack is fixed at that direction with respect to the element. As loading progresses, the allowed tensile traction normal to the crack plane is progressive degraded. Compressive failure is governed by a simplistic J2 flow.

The major drawback of this material is that it only allows formation of one crack, i.e. it can only crack in one direction, but not in all directions. However, for the loading scenarios in which the tensile component is found predominantly in a single principal direction as in the drop scenarios analysed (instead of, for example, tensile loading simultaneously in two or three principal directions), the effect of this drawback is acceptable.

MODELLING OF THE IMPACT LIMITERS

Different from similar recent analyses of CASTORs, the claddings and the wood were not modelled separately. As the strategy of the work, if correlation between analysis and test for the side drop is not sufficient, crush properties of the limiters were to be adjusted to improve correlation. A detailed model of the limiter was not deemed necessary.

MAT_HONEYCOMB was used to model the stress strain behaviour of the impact limiters. This model allows modelling of anisotropic behaviour and has been used extensively for modelling of honeycomb, foam, and wood crush behaviour. It allows definition of non-linear stress strain behaviour in all the normal and shear directions. These stress strain behaviours can be defined as fully uncoupled. The orientation of material axis is user-defined and this model allows non-volume conservation behaviour.

The layers of wood were not modelled as individual layers. Instead, they were modelled using a continuous mesh of solids. The material axes were oriented such that one of them is aligned with the direction of impact – i.e. direction of crush. Only the properties in the crush direction is of significance. The crush properties of the wood were used from a standard set of GNB data, from a series of generic tests [1] carried out by GNB in 1990. Cylindrical specimens of a variety of wood species with different grain orientations and with or without a thin steel casing were tested quasi-statically and dynamically by a guided falling mass with a strain rate typical of real regulatory impacts.

MODELLING OF CONNECTIONS AND CONTACTS

All the welded connections were modelled as continuous. Integrity of these connections were assessed by assessing the stress in the solid elements at the connection.

The concrete was modelled as continuous with the liners and the head block. The justification being that the reinforcement bars which are welded to the inner liners effectively key the concrete to the inner liner preventing any slippage between the concrete and the inner liner. At the concrete/outer liner interface, there may be relative movement between the concrete and the outer liner in the absence of any positive connection between them. However, the near-zero tensile strength prescribed for the concrete in the model effectively allowed uncoupling of the concrete from the outer liner.

The beams modelling the reinforcement bars were modelled as continuous with the solid elements which represented the concrete. This modelling assumed no slippage at the bar/concrete interfaces. This is a sufficient assumption considering that 1) the deformation in the reinforcement bars and the concrete are expected to be small and elastic, and 2) the concrete is well confined by the liners, the re-bars and the head block.

All other contacts - between contents and cask, between lids and body, between bolts and lid, between impact limiters and cask - were modelled using contact surfaces.

9M SIDE DROP – CASK BEHAVIOUR

The cask behaved like a simply supported beam under a combination of distributed and point loads, creating a tensile axial stress on the face nearest the target, and compressive stress at the opposite face. with localised compressive stresses at the supports (i.e. interface with the impact limiters) and at the interface with the ribs of the dummy basket - largest towards the ends, and "ovaling" of the section. This behaviour can be seen clearly in the containment structure in Figure 4, and in the concrete in Figure 5, by means of minimum and maximum principal stresses. The corresponding behaviour in the reinforcement bars is shown by means of axial forces in Figure 5.

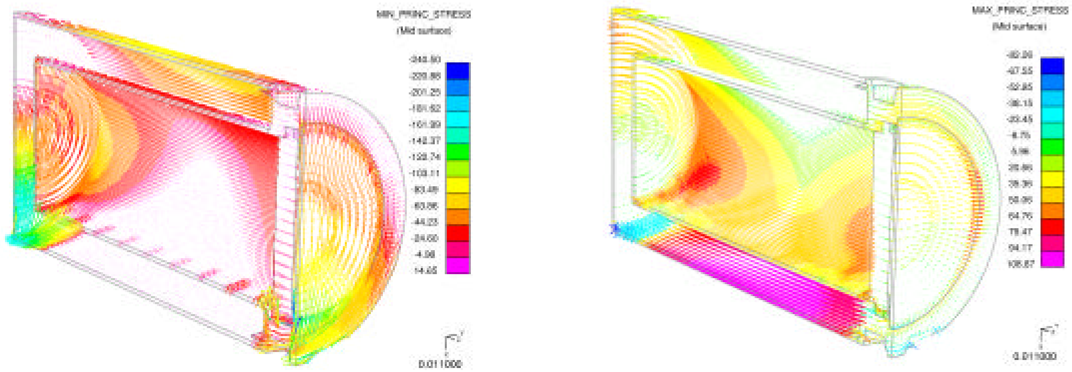

Figure 4, Side drop – Minimum and maximum principal stresses in the containment structure

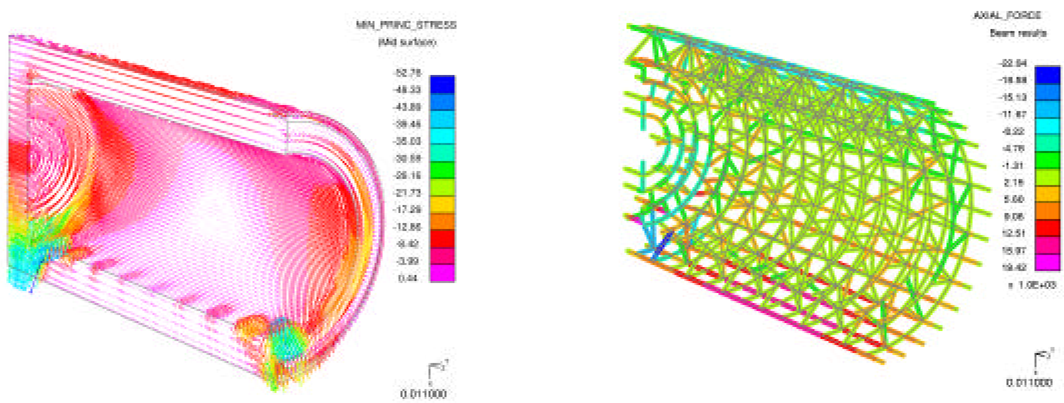

Figure 5, Side drop – Minimum principal stresses in the concrete and axial forces in the reinforcements

9M SIDE DROP - ANALYSIS/TEST COMPARISON

Acceleration and strains were measured at 5 locations on the scale model cask during the side drop. Acceleration-time histories and strain time histories at these locations were compared with those from test, see Table 1. Comparison has been found very reasonable although the peak accelerations from the analysis are consistently higher than those from test by about 20%, with event time-scale consistently shorter, indicating that the impact limiters in the analyses were stiffer than those in the test. And consistent with this, strains from the analysis were also higher than those from the test by a similar extent.

	Measuring point	Analysis Max. Value	Test Max. Value
Acceleration	B5	170 g	150 g
	B5’	200 g	150 g
	B5”	200 g	190 g
	B4’	190 g	170 g
	B4”	190 g	170 g
Strain	D5a	0.5 E-03	0.45 E-03
	D6a	0.4 E-03	0.3 E-03
	D11a	0.25 E-03	0.25 E-03

Table 1, Comparison of calculated and measured acceleration and strains

Impact limiter's steel claddings were not modelled. This on its own, should result in an impact limiter that is less stiff than the one in the test, hence lower acceleration. However, the wood properties used in the analysis came from specimens with a steel casing, which may have compensated for the absence of steel cladding in the model - although the extent of this effect is not certain from existing tests.

Despite this, the generally reasonable behaviour in the whole model, and the consistent and reasonable correlation at all locations for both accelerometer and strain data are convincing evidence that the modelling methodology and the model are sufficient for modelling the present scenario.

It was not necessary to adjust the crush properties to obtain an exact match of acceleration and strain with test. Firstly because the existing correlation is sufficient - sufficiently close and conservative. Secondly because this is a robust situation - if the crush properties in the side drop is adjusted, there is no justification for using the same adjustment factor for the other drop orientations. Thirdly, there will be variation of crush properties in reality. The values from the wood tests are typical values and are as representative as those of the wood in the 1/2 scale model.

9M SIDE DROP – CASK INTEGRITY

For each component, Von-Mises stresses were scanned throughout the analysis and the maximum value of each component compared with the minimum 0.2% proof stress of the material of the full scale cask at the working temperature. Although the cask was a 1/2 scale model, scaling factor for stresses is 1, i.e. no factor need to be applied to convert stresses from the scale model cask to full scale cask. In all components, even including local stress and concentrations, the maximum Von-Mises stress is smaller than the minimum 0.2% proof stress and there is no danger that the integrity of the containment will be compromised in the event.

9M BOTTOM EDGE DROP – CASK BEHAVIOUR

Load path into the containment and the concrete are once again shown using minimum principal stresses in Figure 6. The "patchiness" at the base face of the containment is due to localised loading from the impact limiter via the bottom shock absorbers.

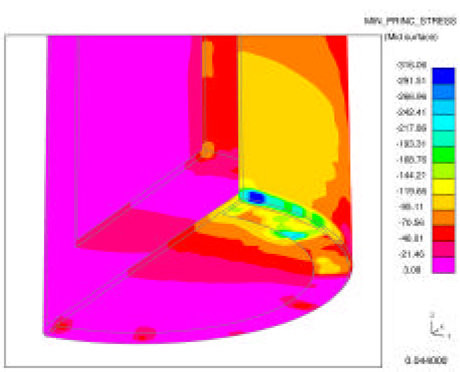

Figure 6, Bottom edge drop
Stresses in the concrete and the containments

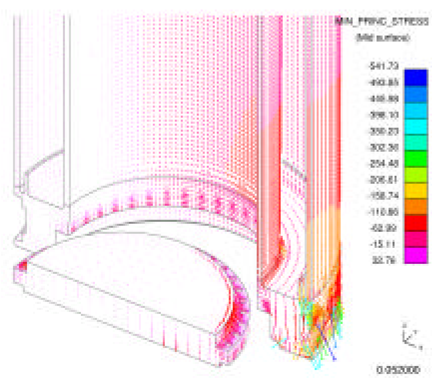

Figure 7, Lid edge drop
Compressive load path into the cask body

9M LID EDGE DROP – CASK BEHAVIOUR

Load path into the containment is shown by means of minimum principal stresses in Figure 7. The loading is predominantly in the axial direction of the cask, with only a small component in the radial direction to cause "ovaling" of the section. There are, again, localised stresses at the interface with the impact limiter. And in this drop orientation, as the impact limiter deforms, it bears onto the trunnion, which in turn causes high but localised stresses around the trunnion connection.

9M BOTTOM AND LID EDGE DROP – CASK INTEGRITY

For each component, Von-Mises stresses were scanned throughout the analysis and the maximum value of each component compared with the minimum 0.2% proof stress of the material at the working temperature. In all components, even including local stress and concentrations, the maximum Von-Mises stress is smaller than the minimum 0.2% proof stress and there is no danger that the integrity of the containment will be compromised in the event.

CONCLUSIONS

By comparing analysis with test results, the work has demonstrated the adequacy of the analysis methodology and the FE model in simulating the cask behaviour in the 9m drop scenario.

The work then demonstrated that the integrity of the cask containment is not compromised in any of the drop scenarios.

REFERENCES

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[2] Govindjee, S., Kay, G.J., and Simo, J.C., “Anisotropic Modelling and Numerical Simulation of Brittle Damage in Concrete”, International Journal for Numerical Methods in Engineering, Vol. 38, p. 3611-3633, 1995