Development, Analyses and Validation of Finite Element Model of FSC 2005 – 14591

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ABSTRACT

Between 1986 and 2011, WAK GmbH packaged wastes from the experimental reactors at Karlsruhe Research Centre into about 3000 Konrad-type IV type of steel containers for on-site storage, pending transfer to permanent disposal at Konrad. In order to demonstrate the impact performance of these package, WAK GmbH has carried out three drops tests of a current prototype container FSC 2005, developed a finite element model of the prototype package and validated it against the drop tests, prior to using the validated model to demonstrate the performance of the older packages. This paper presents the modelling of the test specimen including the approach and decisions involved in the design of the model, the analysis of the model in the drop test scenarios, the behaviour of package in one of the drop test scenarios, and comparison of the analyses against the drop tests to demonstrate the reliability of the model.

INTRODUCTION

Between 1986 and 2011, WAK GmbH packaged wastes from the experimental nuclear reactors at Karlsruhe Research Centre into about four thousand Konrad-type IV steel containers for on-site storage, pending transfer to a permanent disposal facility at Konrad.

Although the packages are consistent with Konrad’s waste acceptance criteria, none of them has so far been licensed for disposal in Konrad since the waste acceptance criteria was not defined until 2007.

The German waste acceptance criteria allows licensing of packages like these type-IV containers retrospectively if performance can be demonstrated by prototype testing and quality assurance by modern standards in the manufacturing of these containers can be provided.

WAK GmbH has agreed with the responsible authority - Federal Office for Radiation Protection (BfS) with their consultant the Federal Institute for Materials Research and Testing (BAM) - to qualify the old packages retrospectively, with the following steps:

1. Establishing a new quality assurance program by modern standards for new containers.
2. Carrying out prototype drop tests to study the performance of the container.
3. Developing a finite element (FE) model of the prototype drop test specimen and validating it against the drop tests.
4. Demonstrating the performance of the older packages using the results of the prototype drop test by reasoned argument and by FE analyses based on the validated FE model but modified to represent the old packages.

In response to Step 2, WAK GmbH has carried out three drop tests of a FSC2005 package - one of the Konrad-type IV type of steel containers - at BAM in 2012.

In response to Step 3, WAK GmbH has commissioned Arup to develop a FE model of the FSC2005 test package and to carry out FE analyses of the test package in the drop tests in order to validate the FE model.

DROP TESTS

In 2012, three drop tests were carried out at BAM of a prototype FSC2005 container with simulated waste content. The content of the drop test box consisted of 14 drums, each consisting of layers of lead blocks encapsulated in sand as shown in Figure 1. The drums were arranged in two layers in the box and were encapsulated in concrete.

Figure 1: Content of a typical drum during loading showing the lead blocks encapsulated in sand, and loading arrangement of drums inside the container.

Three drop tests were carried out

1. A flat base down drop from a drop height of 0.8m
2. A slap down drop from a drop height of 0.8m with the base twistlock fittings at the short edge contacting the target first and with the base at an initial angle of 10° to the target
3. Centre of gravity over the edge of two twistlock fittings at a long edge, drop from 0.8m

The impact orientations are shown below:

Figure 2: Impact orientations for drop tests.

MODELLING – OVERVIEW

The FE model consists of 1.2 million elements which consisted of a combination of thin shell, solid and beam elements. An overview of the model is shown in Figure 3. Contact surfaces were defined to model interaction between components and CONSTRAINT_LAGRANGE_IN_SOLIDS was used to model the interaction between the drum content and concrete on the one hand and container and drums on the other. Additional refinement was defined at strain gauge locations to match the size of the strain gauges. The target was modelled explicitly. The analysis code was LS-Dyna.

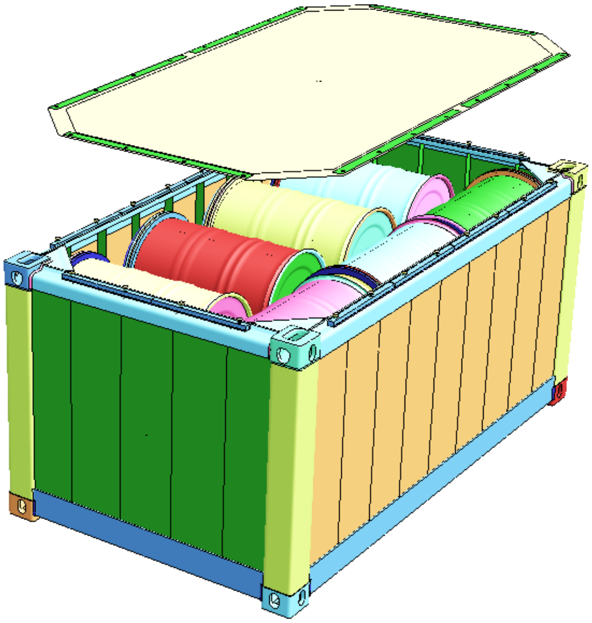


Figure 3: Overview of the FE model of the FSC2005 package (concrete blanked from view).

MODELLING PHILOSOPHY

The model was designed with the following principles:

- The model has been designed taking into account the capabilities and limitations of the FE code.
- The mesh is more refined in areas where the quantity to be calculated is undergoing steeper change.
- The mesh has been designed taking into account computing resources – larger the number of elements, longer the analysis; smaller the elements, smaller the time step, and hence a longer run time.
- Element quality in terms of aspect ratio, warpage and internal angle has been taken into account when designing the mesh.
- Identical mesh have been used for all the lid bolts and the area surrounding the lid bolts so that the same accuracy can be attributed to the results for all bolts.
- Identical mesh has been used for similar components that undergo similar deformations.
- Since the analyses need to be compared with test results, the details of the model, the initial conditions and boundary conditions applied to be model need to be like-for-like with the drop tests.

MODELLING OF THE FSC2005

The FSC2005 is a “welded fabrication” made up of predominantly flat plate components, shaped plate components and the twistlock fittings, connected together by welds.

There are three key considerations in the modelling of the structure:

1. Element type
2. Through-thickness refinement if modelled by solid elements
3. Modelling of welds

A typical detail is that shown in Figure 4, at the lid body interface at the top of the box. If it is a relatively straightforward decision to model the 3mm thick plates as thin shell, how about the 7mm plates and 10mm plates ? Should they be modelled with thin shell elements, solid elements or even thick shell elements ?

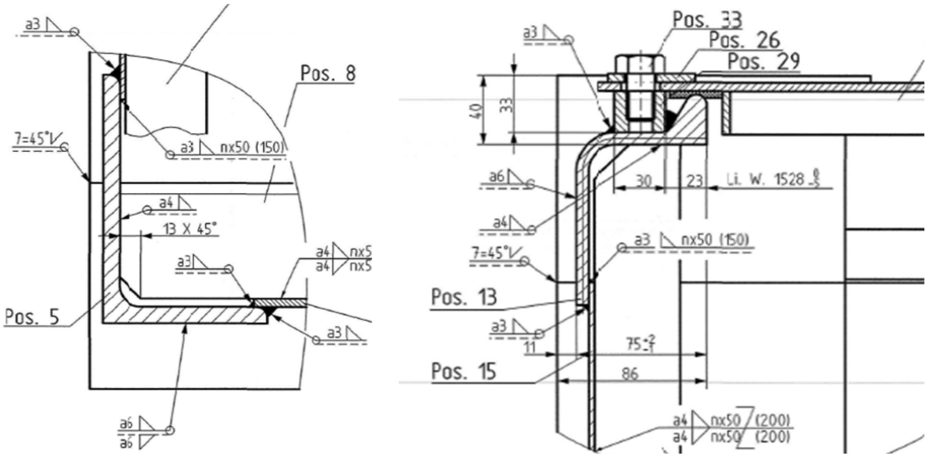


Figure 4: Section details of steel plated sections of FSC 2005 container.

(1) Choice of element type

The element type options in LS-Dyna are as follows:

- Thick shells elements
- Solid elements
- Thin shell elements

In LS-Dyna, thick shell elements are difficult to use and the results may not be robust. So the choice is between solid elements and thin shell elements. The advantages and disadvantages of these two types of elements are as follows:

Solid elements:
- Advantage:
  - Interaction between components can be visualised easily.
  - Connection between components can be modelled as they are with actual dimensions.
- Disadvantage
  - There is a limit as to how many solid elements can be used through the thickness of the plate components.
  - Associated knock-on effect on element aspect ratio.

Thin shells:
- Advantage:
  - No problem with choice of through-thickness integration points
- Disadvantage:
  - Need to stretch adjacent components to the shells, i.e. geometry of adjacent

  components will be wrong; (or move component, but location will be wrong!).
- Complicates the modelling of the interaction between the plates
- Complicates the modelling of welded connections

The choice between solid and thin shell in this situation is not straight-forward. There is no perfect solution.

(2) Through thickness refinement if solids are used

It is well known that the prediction of bending behaviour improves with the number of elements through the thickness. However, more elements through the thickness results in a smaller element size, smaller timestep and a larger number of elements through the thickness and in other directions in order to maintain a small enough aspect ratio.

In general, each plate component should be considered on a case by case basis - the behaviour of each plate component in the impacts, the importance of the specific plate component and the accuracy required must all be considered. For example, if the behaviour of the plate is irrelevant and its response does not affect the response of the structures adjacent to it, then a coarser representation is adequate. And if the plate only deflects elastically, then fewer elements will suffice than if the plate were to undergo large plastic deformations. In the case of the angle plates, out of plane bending is not significant compare with lengthwise bending and few elements through the thickness is therefore justified.

(3) Modelling of welds

There are a large number of welds in the box (as shown as example, in Figure 4 and Figure 5), the majority of which are fillet welds with a throat thickness of 3mm, 4mm and 6mm.

At present, no “simplified” model in LS-Dyna is available that can robustly model the behaviour of fillet welds, and the best way to model them is explicitly using solid elements. The problem, however, is how many elements can realistically be used in the cross section. For example: modelling 3mm fillet welds with three elements in the cross section will result in elements with a side that is as small as 1mm. This has an adverse effect on both the model’s timestep and the number of elements in the lengthwise direction, taking into account aspect ratio limits. In addition, the difficulty with modelling welds, is that no matter how they are modelled, there is the uncertainty with the actual stress strain properties of the weld itself and in the heat affected zone adjacent to it. As with the modelling and decision of mesh refinement for plate components, the behaviour of the weld, the importance of the weld, and the accuracy required, must also be taken into account in the decision on how they should be modelled.

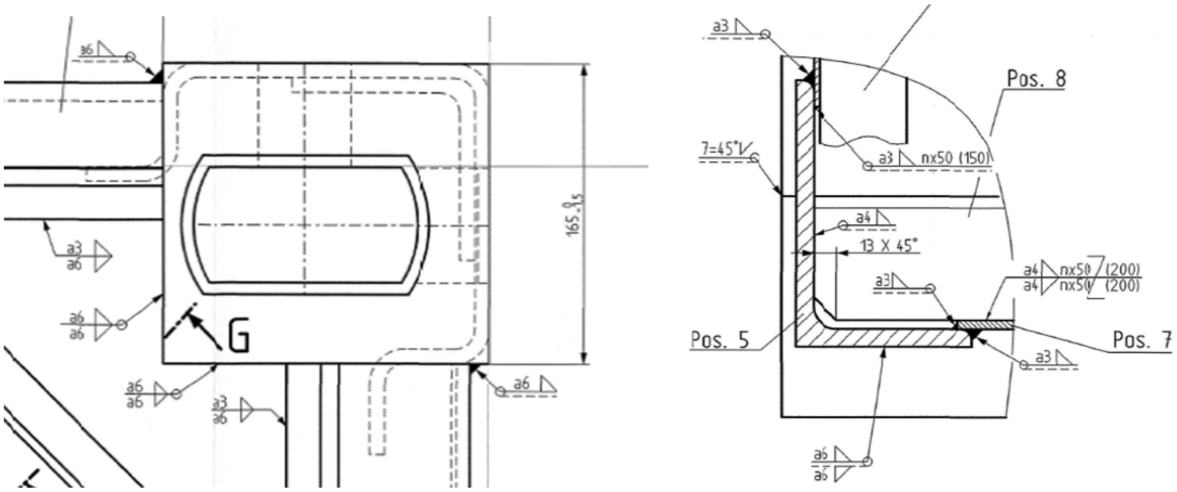


Figure 5: Welded connections around (a) twistlock fittings and (b) side and base stiffeners.

Details of the mesh as discussed above are shown in the figures below:

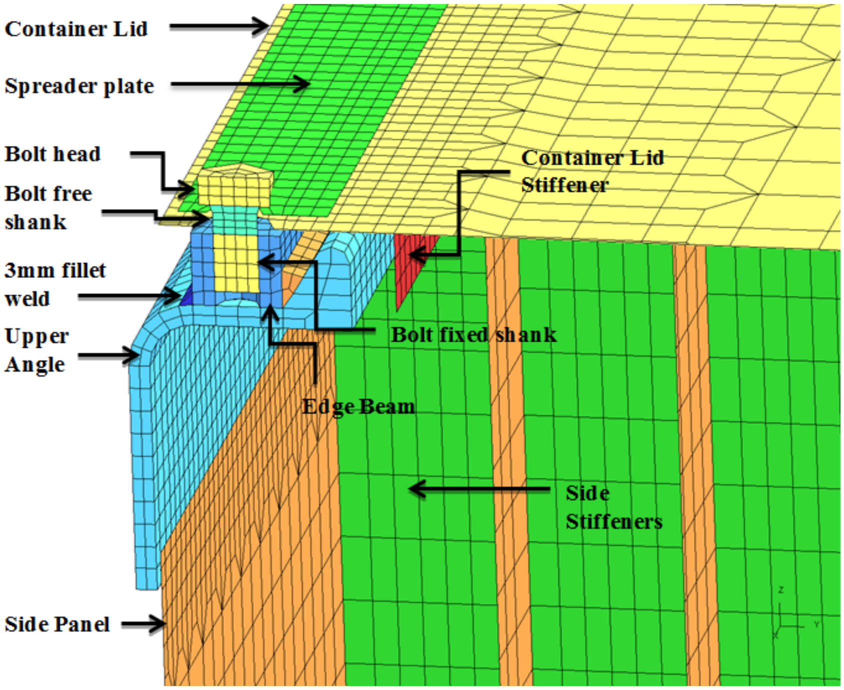


Figure 6: Section through container lid edge.

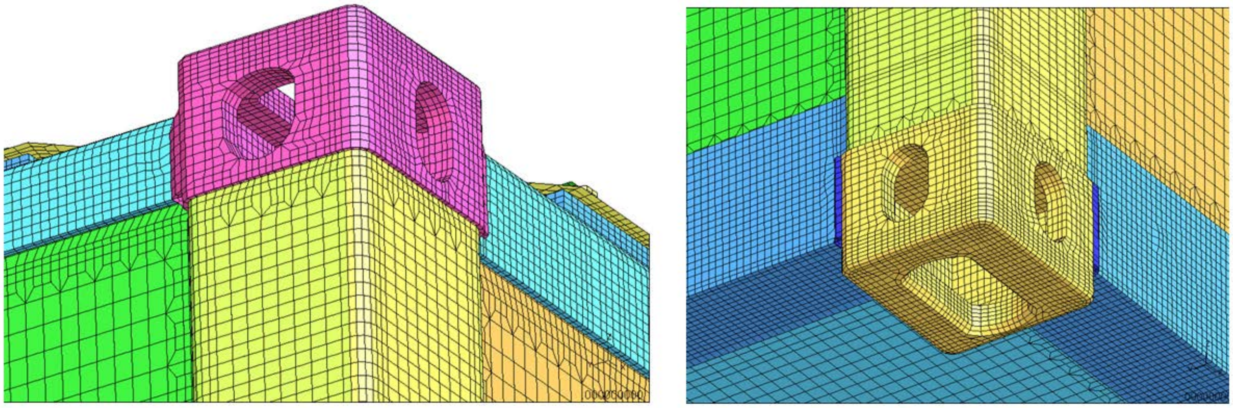


Figure 7: Mesh details around the twistlock fittings.

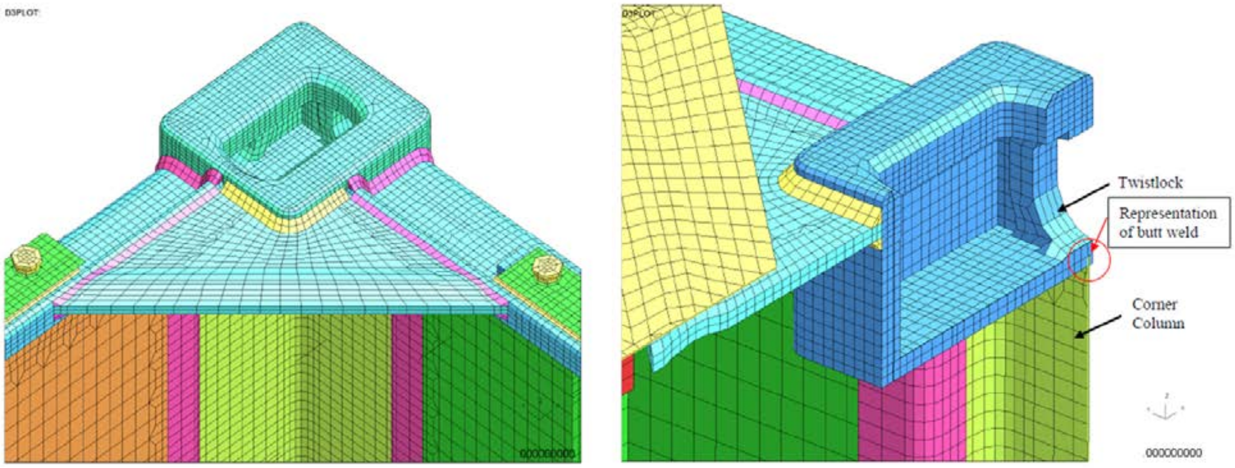


Figure 8: Modelling of welds around the twistlock fittings.

MODELLING OF THE DRUMS

The body and the lid of the drums were modelled with thin shell elements with the thickness of the respective plate materials. The flange and rubber seal were modelled with solid elements and the bolts were modelled with beam elements as shown in the figure below.

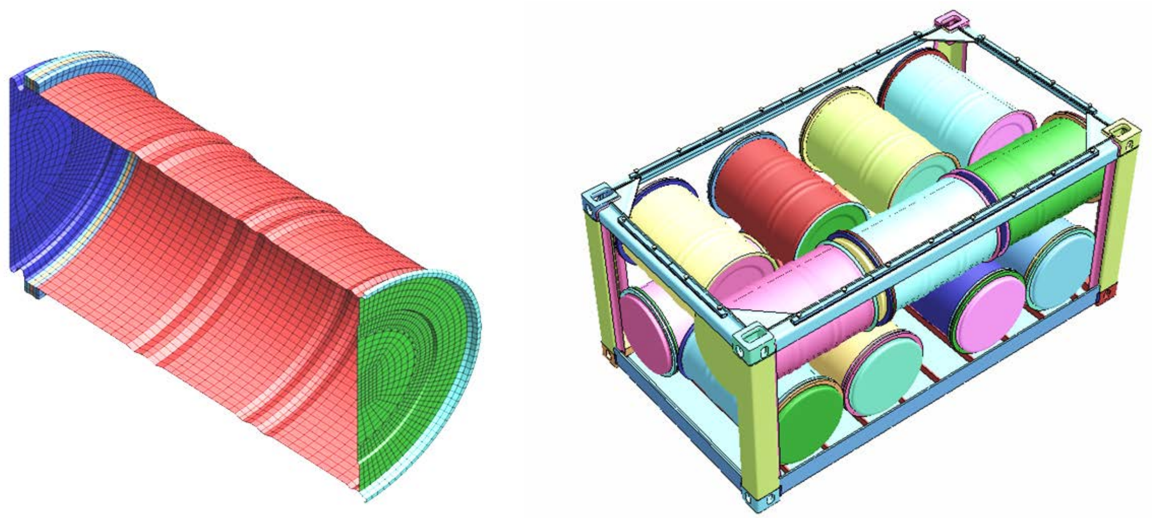


Figure 9: Cut section of drum and arrangement of the drums inside the package.

MODELLING OF THE DRUM CONTENTS

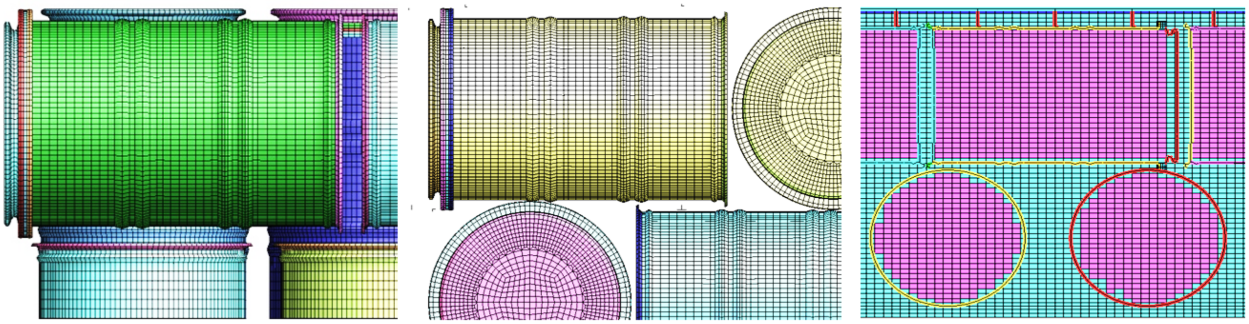
As has been noted above, the radioactive waste content in the drums is simulated in the test package by layers of lead blocks encapsulated in sand. The behaviour of this drum filling is impossible to simulate precisely as the exact location of the lead blocks within the drum is unknown.

Because of the location of these contents (inside of the drums, encapsulated inside concrete, inside the box) their effect on overall behaviour besides their mass, is likely to be secondary. Therefore the contents have been modelled as homogeneous with appropriate properties of sand but with the density scaled up to include the mass of the lead blocks.

MODELLING OF THE DRUM CONTENT, DRUM AND CONCRETE ENCAPSULANT

An ideal mesh for the drum content and the concrete encapsulant is a mesh in which the mesh of drum content matches the mesh of drum, and the mesh of each drum matches the mesh of the concrete over the curved faceted surfaces. However, considering the layout of the drums in the box - with drums axes at 90 degrees to each other and with drums bearing onto another drum but at 90 degrees, etc - this is geometrically impossible especially when only eight noded solid elements (or even six noded solid elements) are used.

The solution is shown in Figure 10. A regular rectangular continuous mesh consisting of eight noded brick elements has been used to model the entire block of concrete and drum contents. The solid elements that are located entirely within the drums, were assigned with material properties of the drum contents. The remaining elements were assigned material properties of concrete, such that the thin shell elements which were used to simulate the drums were located entirely within solid elements which were modelled with properties of concrete. Interaction between the drum and the concrete were simulated by the LS-Dyna facility *CONSTRAINT _LAGRANGE _IN_SOLIDS.



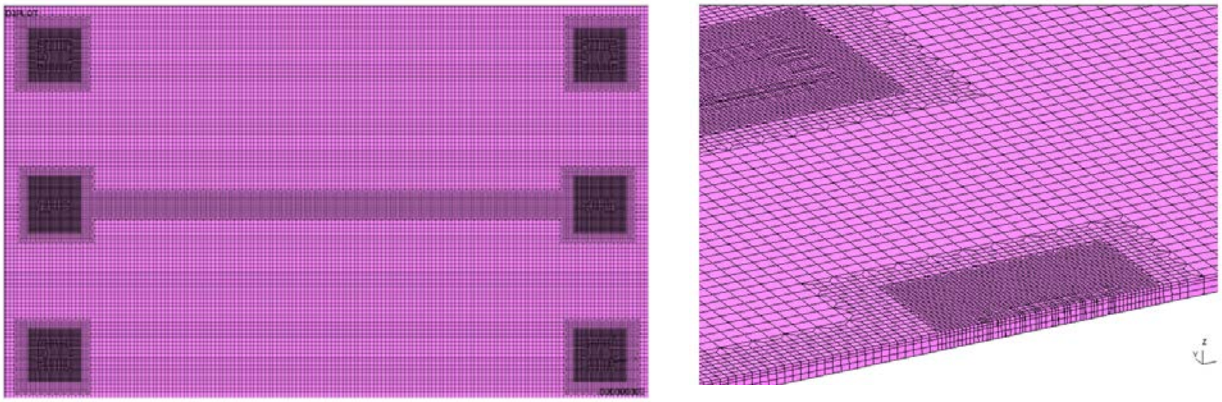
Mesh of the drums

A typical section through the model showing the mesh of the drum contents (purple), concrete (blue) and the drums

Figure 10: Mesh of the drums, drum contents and concrete

MODELLING OF THE TARGET

Only the 22mm thick cover steel plate of the target need to be modelled. The large reinforced concrete foundation was assumed undeformable, hence a fully fixed boundary condition was prescribed for the underside of the model of the steel plate. The mesh has been designed such that it is most refined at the locations where it would come into contact with the box. The central area of the mesh and a cut-section of the most refined area are shown in the figure below:



Central area of the target mesh showing the areas of refined mesh where the container makes contact with target in the three drop scenarios

Cut-section of a refined area of the target mesh

Figure 11: Close-up and cut-section of the mesh of the target steel plate

MATERIAL PROPERTIES

The box itself was modelled with bi-linear stress strain properties based on available data from material certificate of drop test box. The drums were mass produced items and material certificate was not available. Bi-linear stress strain properties based on standard material properties of the specified materials were used. The drum contents were modelled with *MAT_MOHR_COULOMB with generic sand properties.

Compressive strength samples of the concrete were cast at the same time as the concrete was cast. Compressive strength tests were carried out at specific age of the concrete and from these, a compressive strength vs age curve was obtained. Compressive strength on the day of the drop tests were obtained from the compressive strength vs age curve. The stress strain behaviour was modelled with *MAT_CONCRETE_DAMAGE_REL3. In the absence of more precise material properties (e.g pressure vs. volumetric strain characteristic; maximum principle stress for failure; initial yield, maximum and residual stress surfaces vs. pressure; damage scaling factors for compression, tension and triaxial paths; strain-rate behaviour; damage relationship), material parameters were input using the automatic method based on the compressive strength.

BEHAVIOUR OF THE BOX IN DROP TEST 1

The first drop test was a base down drop from 0.8m. The four twistlock fittings came into contact with the target first. They deformed slightly and stopped. The test package was then supported on the four twistlock fittings on the target. The inertia of the package bore onto the four twistlock fittings and this caused the package to deflect, sagging in the middle. Deflections are shown in Figure 12 with the deformation magnified by 10 and in also Figure 13 in terms of displacement contours in the vertical direction.

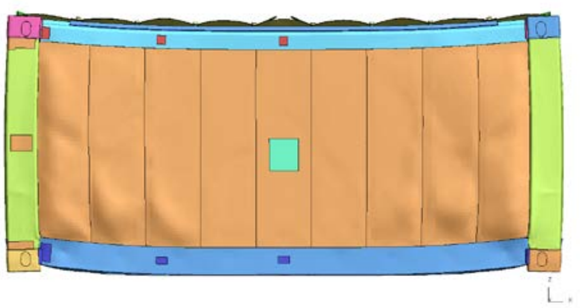


Figure 12: Deformation of the package at maximum deflection, with the deformations magnified by a factor of ten for clarity.

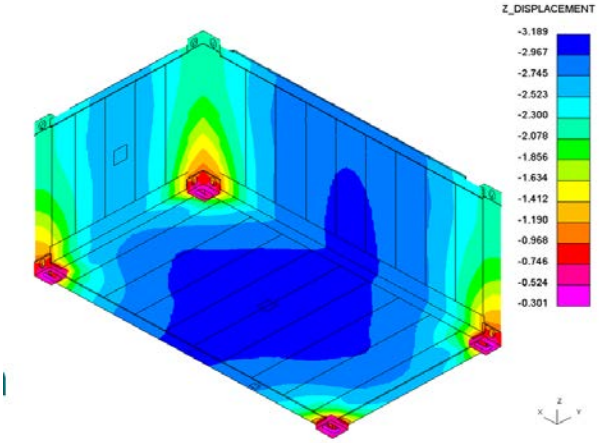


Figure 13: Vertical displacement of package at time of peak target reaction

Compressive stress load path from the target into the box and distribution of the compressive load in the box are shown in Figure 14 and Figure 15.

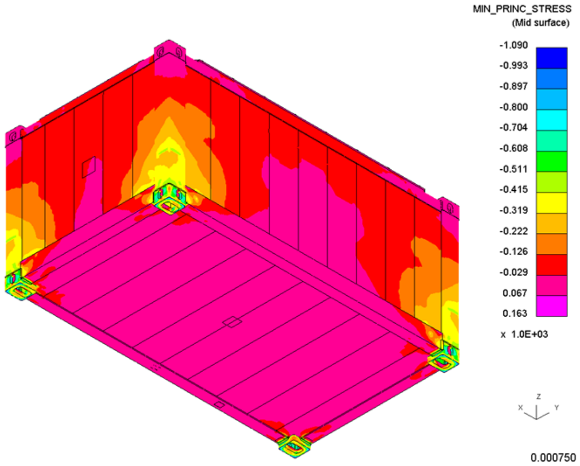


Figure 14: Compressive stresses in the box at the time of peak target reaction

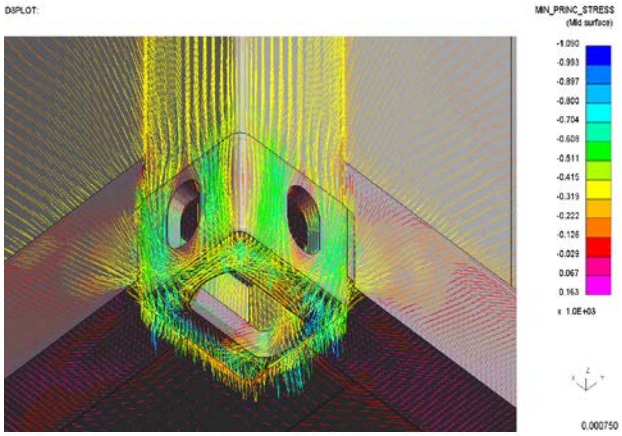


Figure 15: Load path travelling from a twistlock fitting into the rest of box at the time of peak target reaction

The compressive load path travelling from the twictlocks into the concrete at the time of peak target reaction is shown below, at a diagonal section, taken from corner to corner of the box.

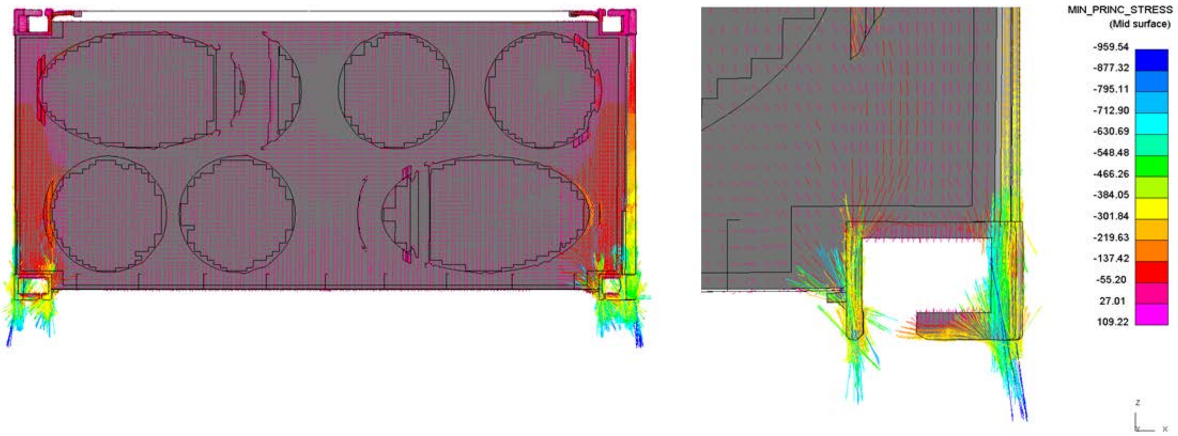


Figure 16: Load path travelling from the twistlock fittings into the concrete at time of peak target reaction, on a diagonal section of the box

Von Mises stress distribution in the box and the drums at the time of peak target reaction are shown below in Figure 17.

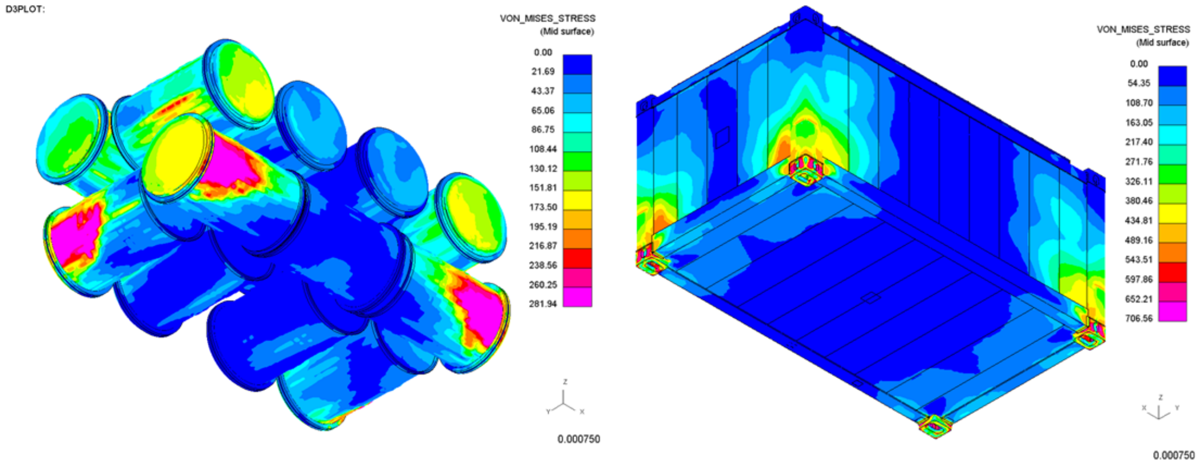


Figure 17: Von Mises stress distribution in the box and the drums at the time of peak target reaction

COMPARISON OF STRAIN TIME HISTORIES FROM THE TEST AND THE ANALYSIS OF DROP TEST 1

An extensive array of strain gauges was mounted on the test package to record its deflection behaviour in the drop tests. The location of the strain gauges is illustrated below, with each location representing two strain gauges at orthogonal directions:

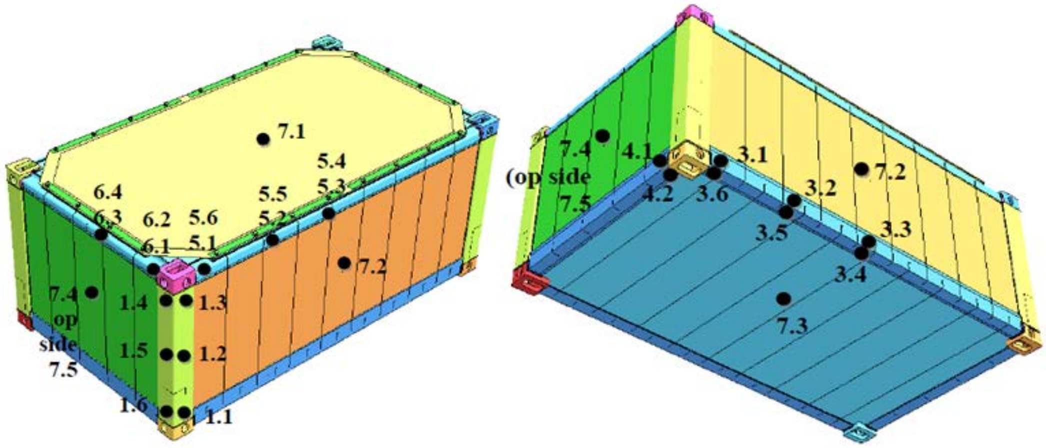
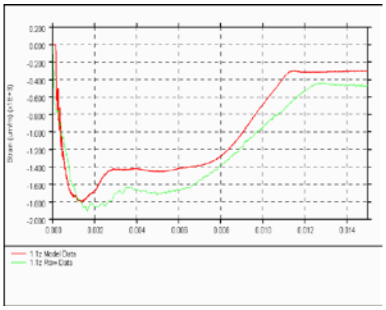
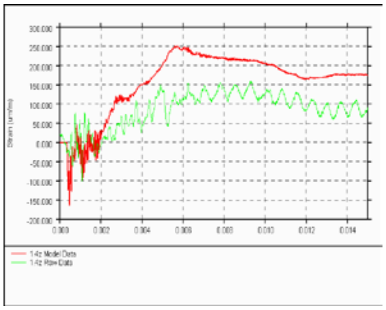


Figure 18: Strain gauge location on the test box

There are some very good correlations of strain-time history from the analysis and the test, and a selection of these is shown below:


Strain (um/m) (x1E+3)
0.200
0.000
-0.200
-0.400
-0.600
-0.800
-1.000
-1.200
-1.400
-1.600
-1.800
-2.000
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
1.1z Model Data
1.1z Raw Data


Strain (um/m)
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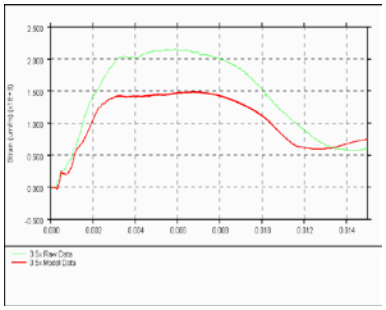
250.000
200.000
150.000
100.000
50.000
0.000
-50.000
-100.000
-150.000
-200.000
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
1.4z Model Data
1.4z Raw Data


Strain (um/m) (x1E+3)
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2.000
1.500
1.000
0.500
0.000
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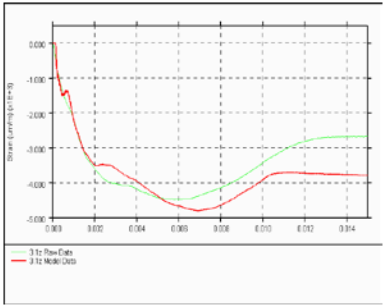
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
3.5x Raw Data
3.5x Model Data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-2.000
-3.000
-4.000
-5.000
0.000
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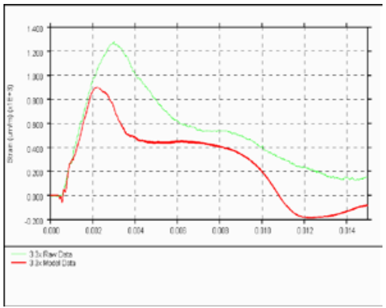
0.006
0.008
0.010
0.012
0.014
3.1z Raw Data
3.1z Model Data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0.600
0.400
0.200
0.000
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0.006
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0.010
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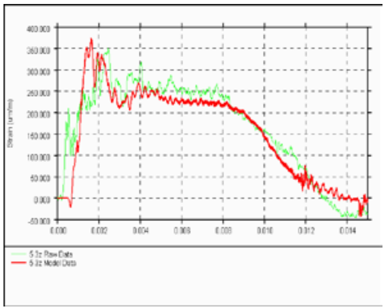
3.3x Raw Data
3.3x Model Data


Strain (um/m)
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300.000
250.000
200.000
150.000
100.000
50.000
0.000
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0.002
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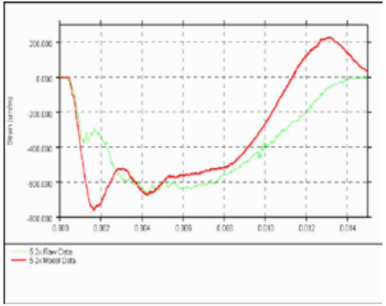
0.006
0.008
0.010
0.012
0.014
5.3z Raw Data
5.3z Model Data


Strain (um/m)
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0.000
-200.000
-400.000
-600.000
-800.000
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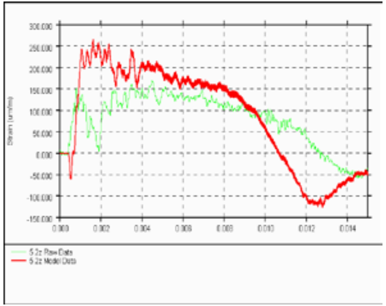
5.2x Model Data


Strain (um/m)
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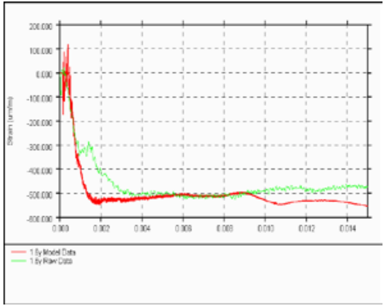
5.2z Raw Data
5.2z Model Data


Strain (um/m)
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100.000
0.000
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-400.000
-500.000
-600.000
0.000
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0.004
0.006
0.008
0.010
0.012
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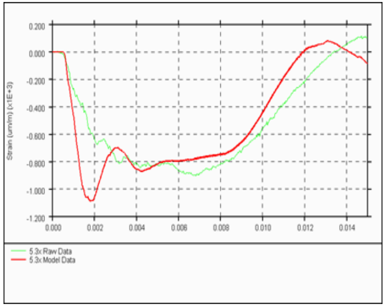
1.5y Model Data
1.5y Raw Data


Strain (um/m) (x1E+3)
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0.000
-0.200
-0.400
-0.600
-0.800
-1.000
-1.200
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0.006
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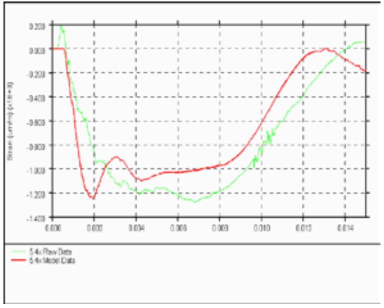
0.010
0.012
0.014
5.3x Raw Data
5.3x Model Data


Strain (um/m) (x1E+3)
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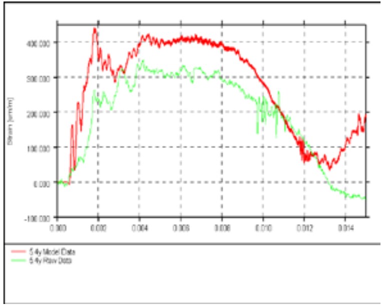
0.000
-0.200
-0.400
-0.600
-0.800
-1.000
-1.200
-1.400
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
5.4x Raw Data
5.4x Model Data


Strain (um/m)
400.000
300.000
200.000
100.000
0.000
-100.000
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
5.4y Model Data
5.4y Raw Data

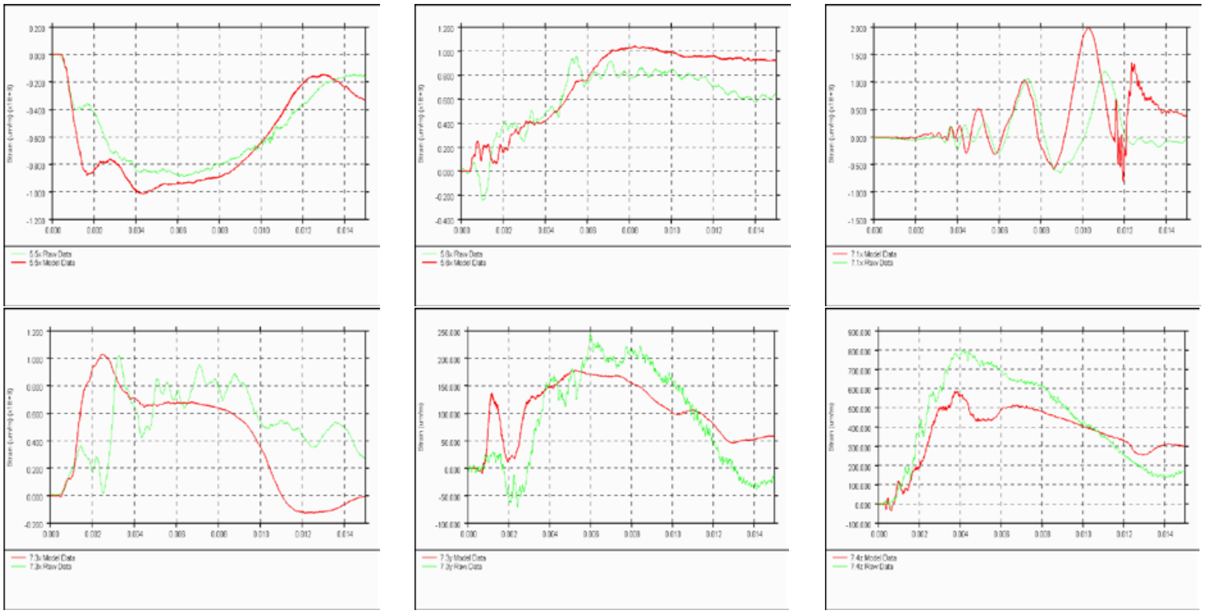


Figure 19: A selection of correlations of strain time history from test and analysis

CONCLUSIONS

Good correlation has been obtained over a large number of strain gauges between the analysis and the drop test, and in all three drop tests. There are some poor correlations in a number of strain gauges towards the lower half of the box in drop test 3. The likely cause of this was a combination of de-bonding of the concrete from the steel box structure and cracking of the concrete (which could not be modelled with any certainty) due to the impacts in drop tests 1 and 2. Sensitivity study with bounding assumptions was carried out and showed that this is the case.

Considering

- the complexity of the structure of the container
- the complexity of the make-up of the test package
- the number of uncertainties of the details of the test package (e.g. precise stress strain behaviour of the concrete and the sand, precise piecewise linear stress strain curves for steel)

the high degree of correlation at so many strain gauge positions in all three drop tests gives a very high degree of confidence in the adequacy of the model, the modelling methodology and the assumptions employed in the modelling.