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THE USE OF IMPACT ANALYSIS IN LICENSING AN INDUSTRIAL CONTAINER FOR TRANSPORTING NEW FUEL

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ABSTRACT

The Finite Element Method (FEM) is a powerful tool for the simulation of mechanical and thermal behaviour of structures. In recent years, the explicit FEM has increasingly been used in the development of transport packages and as part of approval applications to demonstrate the performance of packages.

Testing and analysis are the two methods specified in the IAEA Regulations for the Safe Transport of Radioactive Material for demonstrating the structural and thermal performance of a transport package against the requirements of the Transport Regulations. The roles of testing and analysis, and the relative prominence of the two, may vary between Competent Authorities in different countries. This can range from analysis being regarded as the primary mode of demonstration with testing as confirmatory, to testing being the primary mode of demonstration supplemented by analysis.

This paper describes the use of the non-linear finite element code LS-DYNA in the licensing of a new container for the transport of new nuclear fuel. The package was classified as an Industrial Package (Fissile) in accordance with the IAEA Regulations, and hence it was necessary, among other things, to demonstrate that criticality criteria were satisfied under postulated impact conditions. Physical drop tests were carried out and the results are compared with LS-DYNA computer calculations using the same finite element (FE) models developed to support the design of the new container. The analyses and tests clearly demonstrate the novel use of polyurethane foam as the container main energy absorber.

The FE predictions are compared for accelerations, bolt loadings and global deformations of the container. In general good correlation was obtained between predictions and tests and the differences, which did occur, particularly for accelerations, are discussed and reconciled. The paper concludes that explicit analysis codes are now so reliable for container impact calculations that minimal test work should be pursued basically for key confirmatory impact scenarios.

INTRODUCTION

Testing and analysis are the two main methods of demonstrating the structural and thermal performance of a transport package in satisfying the requirements of the IAEA Transport Regulations for the Transport of Radioactive Materials, **[1].** The role of testing and analysis, and the relative prominence of the two, may vary between Competent Authorities in different countries. This can range from, at one end of the spectrum, analysis as the primary mode of demonstration with testing as confirmatory, to the other end of the spectrum, testing as the primary mode of demonstration supplemented by analysis.

This paper describes the analysis and tests carried out to support the licensing of a container for the transport of new fuel in the UK. The package was classified as an Industrial Package (Fissile) in accordance with the IAEA Regulations. Hence it was necessary to demonstrate that IAEA regulations were satisfied under postulated impact conditions, i.e. the 9m drop test, 1.2m normal operational drop and the 1m punch test. The design of the package was influenced by impact analysis simulation and a comprehensive upfront analysis programme was also undertaken to consider a range of impact orientations to identify the limiting orientations for drop testing. The impact analysis simulation was performed with the explicit non-linear finite element code LS-DYNA, **[2]**.

Physical full-scale drop testing of a selection of the most onerous orientations was undertaken and the results are compared with LS-DYNA computer simulations using the same FE models developed to support the design of the new package. The drop test programme consisted of a normal operational drop from 1.2m, accident drops from 10.7m and 1m punch tests only. Three of the large drops from 10.7m and one drop on to the punch was modelled in the validation analysis.

DESCRIPTION OF NMTSP

The New Module Transport and Storage Package (NMTSP) is a double skinned stainless steel container with a mineral fibre blanket under the outer skin and a impact absorbing polyurethane foam intermediate layer between the mineral fibre and the inner skin. The container is fabricated from a thin outer skin over the main body and lid, and thicker plates at the ends. All external skins are of stainless steel sheet or plate. The inner skin, which provides the cavity for the payload, is a thicker stainless steel plate with thicker ends. There are also 6 off box section hoops, again fabricated from Stainless Steel, equally spaced out along the length of the NMTSP, which are formed to encircle the inner cavity. These hoops provide structural integrity to the box shape and local hard spots for stacking and for securing to a vehicle. They also provide attachment surfaces for the outer skin.

The lid is secured using 36-off captive recessed socket head cap screws. These screws clamp the flange faces of the lid and body together against a double O Ring seal, as shown in Figure 1. This seal is to provide a gas-tight environment within the NMTSP such that a positive pressure can be maintained within the container during storage to minimise the potential for atmospheric or dirt contamination of the payload.

Bolting flanges are recessed within the container, requiring the bolts to be accessed down tubes, following removal of the water-shedding plastic caps. A spring cap feature beneath the bolt heads will lift each bolt out of engagement with the flange threads, as it is unscrewed.

FINITE ELEMENT MODELLING OF NMTSP

The FE model developed to support the design of the NMTSP was used for the assessment of the drop tests. The key structural components were identified for each attitude and then an appropriate mesh designed. Optimal element sizes were determined by comparing the crushing and buckling behaviour of FE models for representative sections of the package with closed form solutions. The mesh of the skins was refined in the regions where large deformations would occur and the bolt tubes were refined for buckling. A full 3D model of the package was developed because the internal furniture and payload were not symmetrical about the longitudinal and lateral axes. There was also a clear advantage of using a full model for impacts on an edge. The FE mesh of the NMTSP is shown in Figure 2. The model contains around 300,000 elements, the outer skins and a majority of the thin plate material were modelled with shells and the foam, rubber, bolts and bolt flanges were modelled with solid elements. The payload was also represented by solid elements.

The Competent Authority recognised that LS-DYNA had been extensively used in the automotive and nuclear industries for impact problems involving the buckling and crushing of metals. These applications were validated as part of Rolls-Royce Quality Assurance procedures.

The NMTSP lid bolts were modelled as solid elements and tied-into the base flange by equivalencing the mesh and contact surfaces defined between the bolt and the lid flange. Bolt pre-load was applied using thermally induced strains across the central shank, hence the local behaviour of the bolted flanges was accurately represented.

The following modelling assumptions were applied:

(1) A thick mineral fibre fire blanket is placed between the foam blocks and the outer skins, predominantly to protect the foam against fire and heat damage during fabrication welding and accidental fire. The blanket, which is very soft and offers no structural protection. For the purposes of modelling, the cavities around the foam have been modelled as empty spaces, i.e. the presence of these blankets has been ignored.

(2) The welds in the body of the package are modelled as a continuous mesh. The plug welds joining the box sections to the outer skins have not been modelled. Modelling the fillet weld constraints changes the mode of deformation of the box sections in which more energy is absorbed.

IMPACT ANALYSIS METHODOLOGY AND SENSITIVITY STUDIES

In the traditional approach the critical attitudes for drop testing are selected on the basis of experience, reasoned argument supported by some FE analysis. Subsequently only a limited number of attitudes would be assessed. In this project a detailed FE model was used and a very wide range of attitudes were assessed. The selection of the drop test attitudes were based on the following assessment criteria:

(1) Greatest knock back of a long face, i.e. knock back is the amount of deformation that the container undergoes in an impact.

(2) Deceleration of the package and payload.

(3) Bolt failure/Lid retention, it is essential that the payload be retained within the package when subjected to the drop tests. Since this was a new design a key design target of no bolt failures was set.
(4) Deformation of the internal furniture. Internal to the package the payload is secured by internal furniture, damage to this furniture may influence the loads in to the payload.
(5) Gross bending of the package.
(6) Greatest access to the payload due to a punch drop.

The drop attitudes chosen are shown in Figure 3. A drop height of 10.2m was used for large drops since this represented a combined normal operational drop plus an accident drop. In total sixteen initial impact assessments were undertaken which considered all the different orientations, drops on to a punch and also combined drops which assessed accident drops followed by a punch drop. Slapdown analysis from the full accident drop height was also considered. From the above assessments, the most onerous cases were considered for further review as sensitivity cases which examined the extremes of foam properties, bolt preload, flange clearances and temperature effects on material properties. These sensitivity cases demonstrated that there were no cliff-edge effects and that the design was not overly sensitive to extremes of the operating parameters.

DROP TESTING AND VALIDATION

The drop testing was out sourced to a dedicated test house. A comprehensive test programme was undertaken, however only the large drop cases are presented in this paper. The drop height, mass and attitude for all tests were used as input conditions to the validation analyses. The lifting frame and the chainset are attached to the falling package and as such their mass was included in the model mass of the package. This has the affect of smearing the added mass over the entire package and is valid since it is less than 3% of the total package mass. The analyses went to extreme lengths to simulate the exact impact angles (about two axes) and foam properties were adjusted to match the drop test temperature.

The drop height was factored up from 10.2m to 10.7m to account for the target package and payload masses. Three containers were tested and the following impact orientations have been used for validation of the LS-DYNA FE analysis models:

(1) 10.7 m flat end-on impact on to one end of the package, as this case had the potential to maximise the damage to the internal furniture.
(2) 10.7 m flat drop on to the side of the package, since this has the potential to maximise the deceleration of the payload and also provides the largest permanent set to the lid bolts adjacent to the impact face. A punch impact from 1.05m, close to the side C of G was also undertaken. This punch test has the potential for maximum penetration in to cavity of the package.
(3) 10.7 m slapdown on to the lid short edge. The initial impact was on one lid short edge of the package such that the slapdown would occur at the opposite end. This attitude has the potential to maximise the bending applied to the NMTSP and payload, and will also incur a large knock-back to one end of the lid which in-turn provides a severe challenge to deformation of the lid bolts.

The slapdown orientation was derived using a simplified model of the NMTSP. A comprehensive study was carried out with this simplified model to confirm that an initial impact orientation of 30^o would result in the maximum normal force being generated at the second impact (slapdown) to maximise bending of the package.

The containers were instrumented with accelerometers at specified locations that corresponded to monitoring positions on the FE model. Accelerometers were installed at internal locations in the package and also along the length of the payload. All drop tests were recorded on high-speed video. Examination of the high-speed video showed that the orientations at the point of impact were not perfectly normal to the target. The actual orientations were all within a few degrees of that intended. The FE analysis models were adjusted to replicate the drop test orientations as closely as possible.

COMPARISON OF TEST WITH FE PREDICTION

A large volume of data was generated during testing hence only a summary of the comparisons between test and analysis is presented in this paper.

1. Knock-back

A comparison of predicted knock-back from the analysis with that from the tests is shown in Table 1 below:

Table 1 –Impact Knock-back Results

Impact Orientation	Position	Direction	Maximum/Average	Drop 2 Test Results Knock-back (mm)	FE LS_DYNA Results Knock-back (mm)
End-on	Trunnions (Impact End)	Longitudinal	Maximum	79	96
	End Plate (Impact End)	Longitudinal	Maximum	48	57
	End Plate (Impact End)	Longitudinal	Average	28	42
	Base short edge (Impact End)	Longitudinal	Average	37	40
Side	At raised side profile	Horizontal	Maximum	18	12
Slapdown onto Lid	Lid Short Edge (Slapdown end)	Vertical	Maximum	93	87
	Lid Short Edge (Slapdown end)	Vertical	Average	49	47
Punch Side C of G	At Punch	Horizontal	Maximum	87	90

In general there is good agreement between analysis and test, the maximum knock-backs measured were well within the acceptable limits. Figure 5 illustrates the deformation of the end-on impact for the test and from the FE analysis. Figure 6 shows the deformed shape for the side impact case and Figure 7 presents the deformed geometry for the slapdown impact case. Figure 8 presents the deformed shape of the package following a 1.05m Punch drop on to the side centre of gravity position. The predicted deformed shapes agree well with the test results for all of these impact drop attitudes.

2. Accelerations

For comparison of accelerations, data from the analysis was extracted from parts defined local to the accelerometer positions. A standard C180 filter was chosen to determine the underlying trace and remove the high frequency content of the signal. The same filter was applied to the measured and FE results to be consistent. In general good agreement was obtained for the majority of accelerometers. Any differences that occurred were accounted for in terms of features or behaviour that was deliberately omitted from the FE model in order to provide a conservative assessment. Figure 9 shows the results for the End-on impact for the accelerometers mounted on the payload, and Figure 10 shows the results for the accelerometers mounted on the package. The solid curves starting near time zero are from the filtered FE validation analysis, and the dashed curves to the right of the figures are the filtered measured accelerometer traces. All the traces showed good agreement for impact durations and increase in slope of the acceleration.

Figure 11 illustrates the typical response of the accelerometers mounted on the payload for the side impact, and Figure 12 shows the acceleration response of the payload for the slapdown on to the lid case, again good agreement was achieved.

3. Bolt Assessments

The bolt representation in the FE model was based on the results of tests on a representative bolt. Bolt tensile testing was carried-out on a representative batch of bolts at two different strain rates. The results of the testing confirmed that the bolts satisfy the specification and that the bolt material was relativity strain rate insensitive. A sub-model was created to replicate the pull tests and this model used the same bolt representation as used in the NMTSP model. This sub-model showed that the FE model representing the on-set of failure of the bolt in the NMTSP model is very conservative when compared with real failure data.

For all drop attitudes the FE model predicted that no bolts failed and there was adequate reserve bolt capacity. The side impact was most onerous for the bolts and the testing demonstrated eight bolts would bend. The validation analysis confirmed that the same eight bolts underwent some plastic deformation, as illustrated in Figure 13. Also, both testing and analysis showed that the lid was retained for all the impact orientations considered. The retention of the lid was a key requirement to be demonstrated for all drops as part of the licensing of the NMTSP.

4. Internal Furniture Damage

For the end-on impact the internal furniture endures considerable damage. The combined deformation of the furniture agreed to within 5% of the analysis prediction.

5. Gross bending of the Package

For the case of a slapdown of the lid short edge an inspection of the internals with the lid removed revealed that the base flange underwent permanent deformation with a resultant convex curvature when upright. Figure 14 shows the test deformed base flange compared with a long straight edge and illustrates the curvature due to bending. The FE analysis model indicated plastic strains in the base flange and a convex permanent bend in the base flange showing good agreement with test. The extent of bend in the package was however negligible to be of any concern.

6. Greatest access to the Payload due to Punch Impacts

The punch test on to the Side C of G has the potential for maximum penetration into the cavity of the package. The maximum knock-back of the package outer skin measured at the impact location with the punch was within 3% of that predicted by analysis. Inspection of the inner cavity of the package showed no signs of penetration indicating that the deformation was taken up by bending of the external side skins and crushing of the foam. This punch drop only caused local surface damage with little or no global deformation. The package was shown to be acceptable since there was no penetration in to the inner cavity.

SUMMARY AND CONCLUSIONS

The following conclusions may be deduced from the comparison of NMTSP drop test results and validation impact analyses carried out using LS-DYNA explicit FE code:

- The test and analysis of the NMTSP has shown that FE impact analysis is sufficiently reliable to be used as evidence for demonstrating to Competent Authorities that the package is capable of meeting the specified impact criteria.
- All drop attitudes shown in Figure 3 were analysed using LS-DYNA and the NMTSP was shown to meet all the IAEA requirements.
- The time and costs to carry out these analyses are far less than that of physical drop tests. Furthermore, once the model is built the costs and time for analysing additional impact attitudes, drop heights and design modifications are reduced.
- The good agreement of the full-scale test results with analysis further adds to the validation evidence of the FE analysis method employed in LS-DYNA.

Finally, Rolls-Royce have been involved in the design, manufacture and operation of many nuclear flasks and packages over the past 40 years. Through the extensive design, FE analysis and in-house testing expertise, Rolls-Royce have been able to produce a novel design for the NMTSP which used novel materials, such as polyurethane foam as an energy absorber, and rubber pads to protect the payload. Full scale drop testing and FE analysis have demonstrated that the package is capable of satisfying all its required design criteria.

The challenging design, manufacture and test programme was successfully undertaken and delivered to the customer on time and within costs.

ACKNOWLEDGEMENTS

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2. LS-DYNA, Version 970, Livermore Software Technology Corporation.

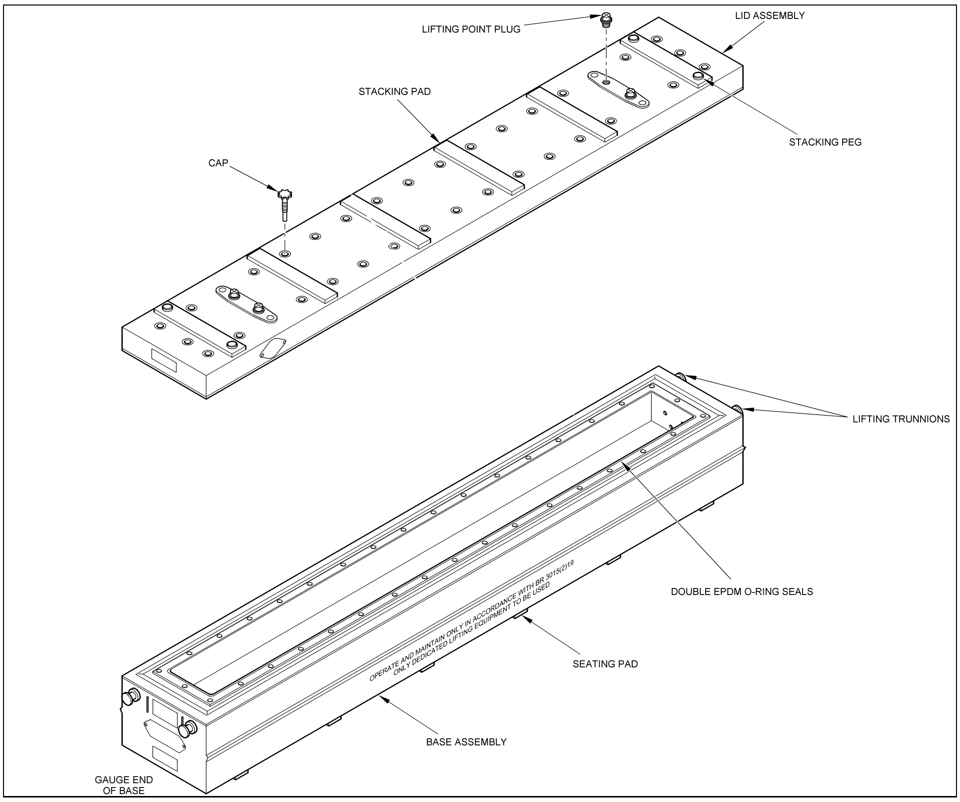


Figure 1 New Module Transport and Storage Package

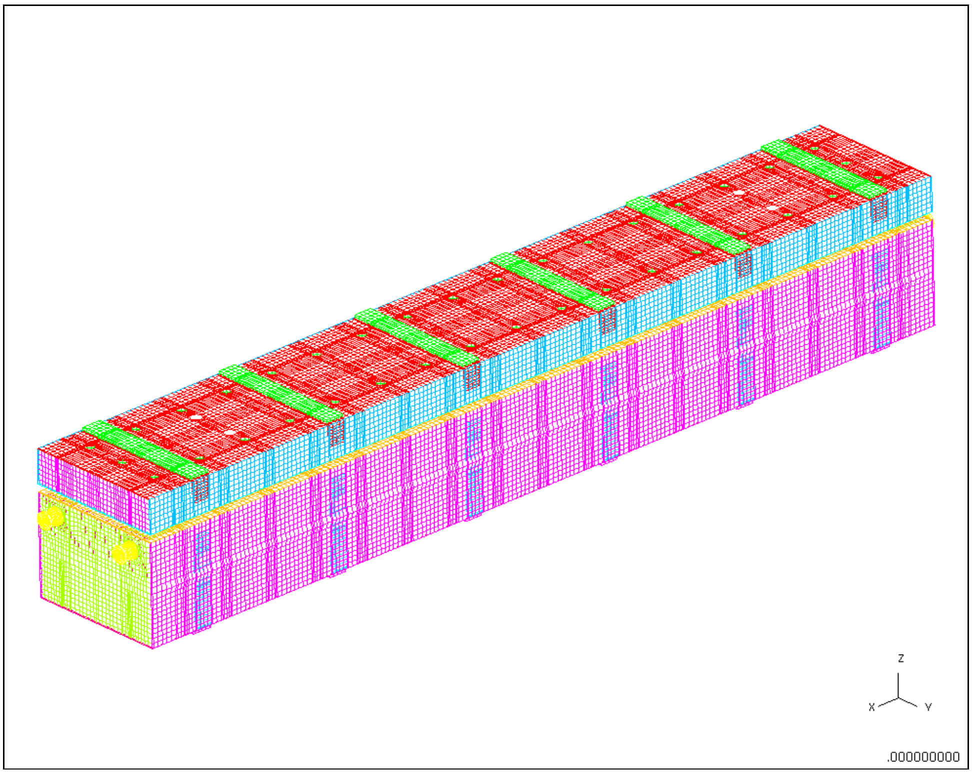
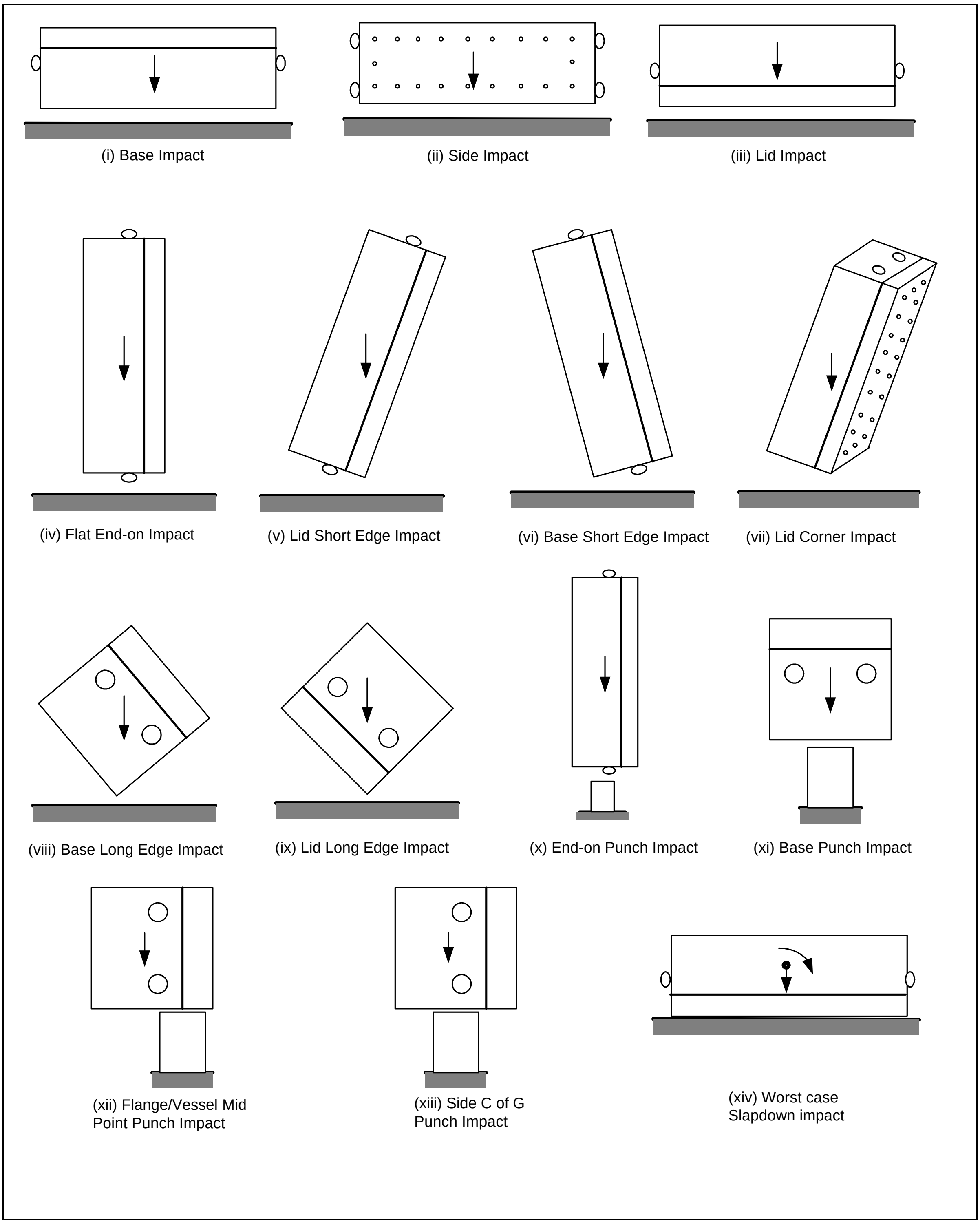


Figure 2 – FE Model of the NMTSP



(i) Base Impact

(ii) Side Impact

(iii) Lid Impact

(iv) Flat End-on Impact

(v) Lid Short Edge Impact

(vi) Base Short Edge Impact

(vii) Lid Corner Impact

(viii) Base Long Edge Impact

(ix) Lid Long Edge Impact

(x) End-on Punch Impact

(xi) Base Punch Impact

(xii) Flange/Vessel Mid Point Punch Impact

(xiii) Side C of G Punch Impact

(xiv) Worst case Slapdown impact

Figure 3 Drop Attitudes

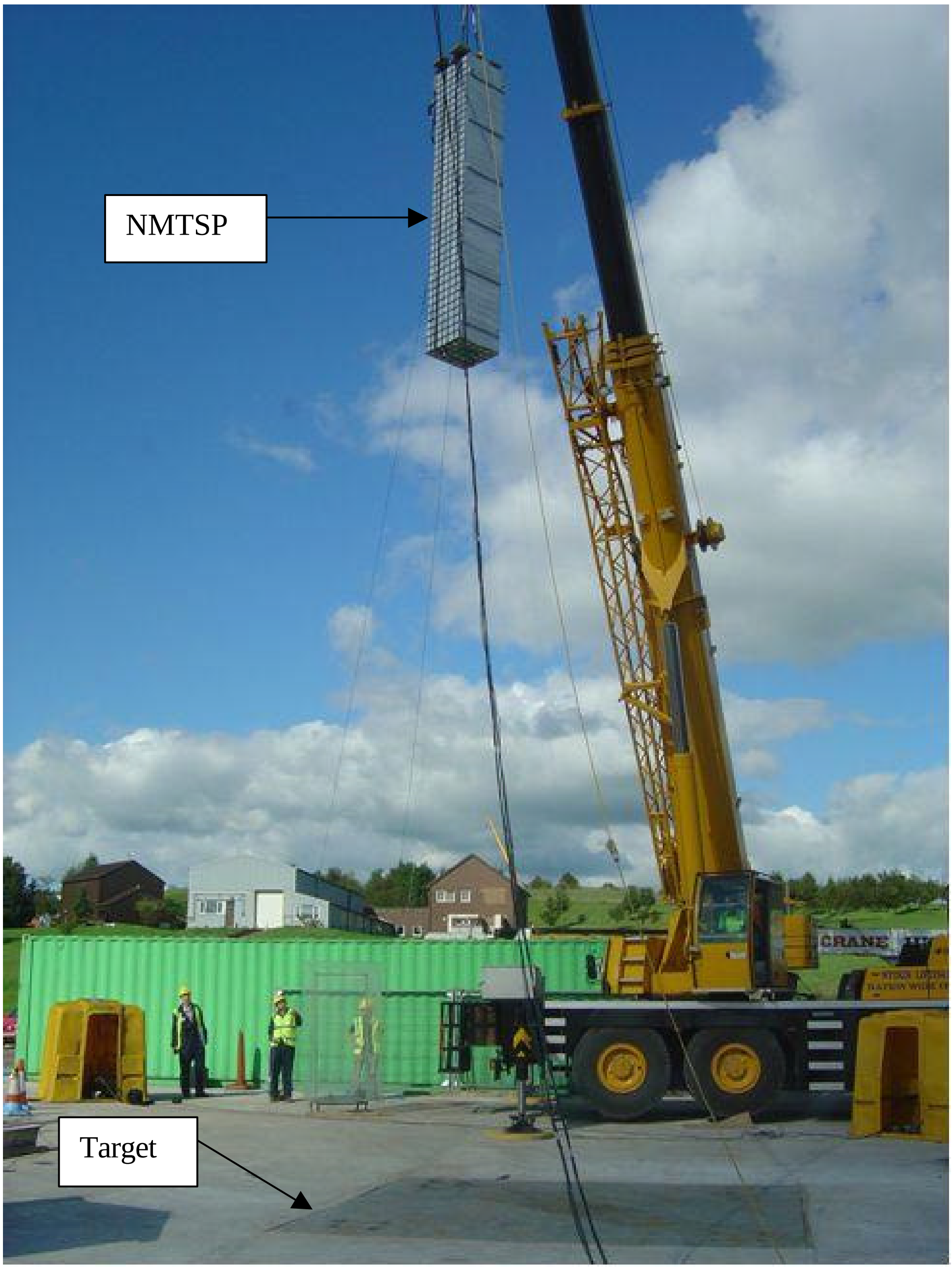
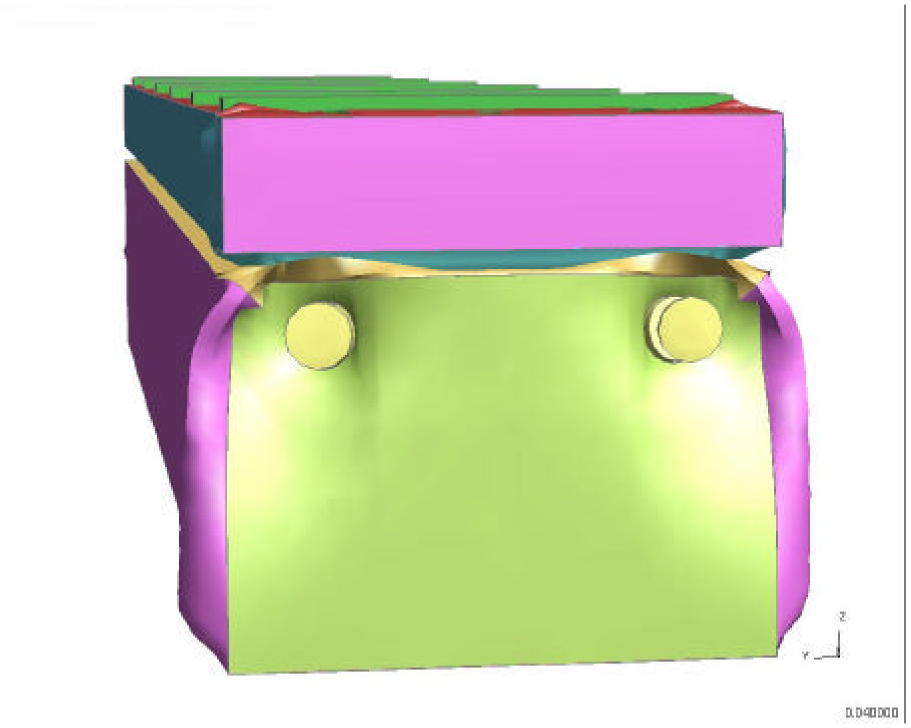


Figure 4 – General view of Package prior to an End-on Drop

(a) Actual Drop Test



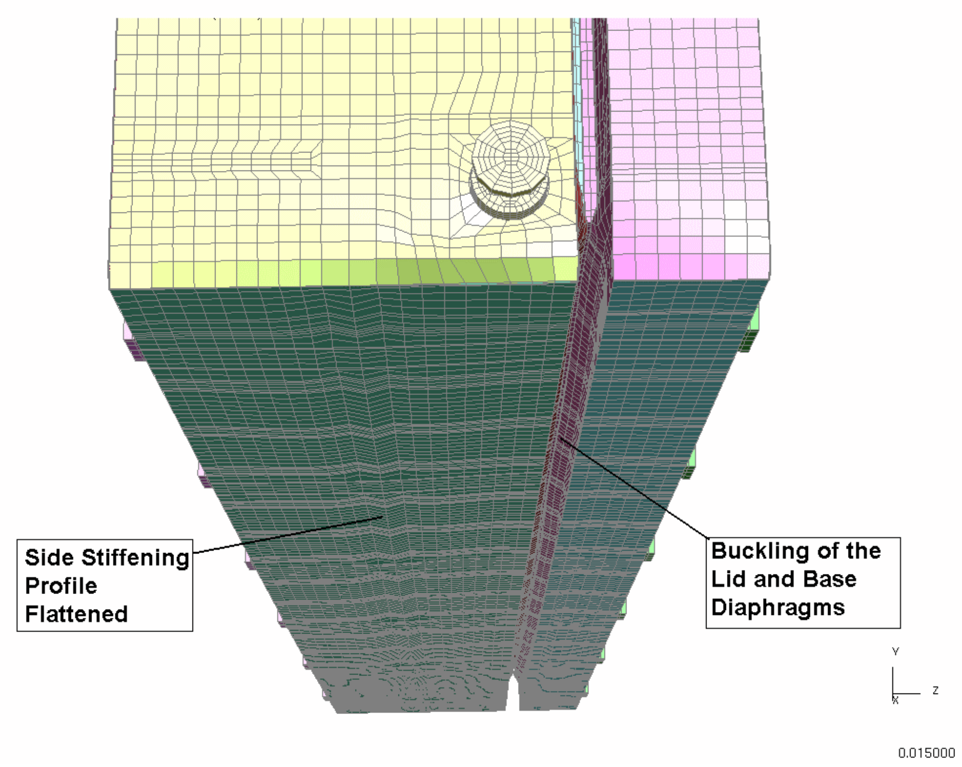
(b) Finite Element Model

Figure 5 – Impact Damage of Specimen 1 following End-on Drop

Side Stiffening Profile Flattened

Buckling of the Lid and Base Diaphragms

(a) Actual Drop Test

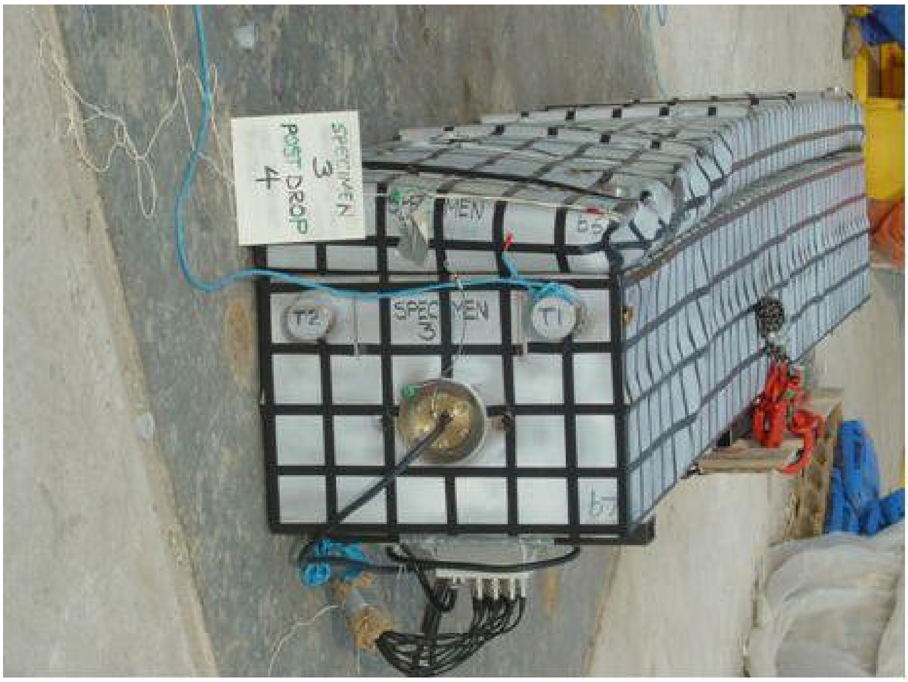


Side Stiffening Profile Flattened

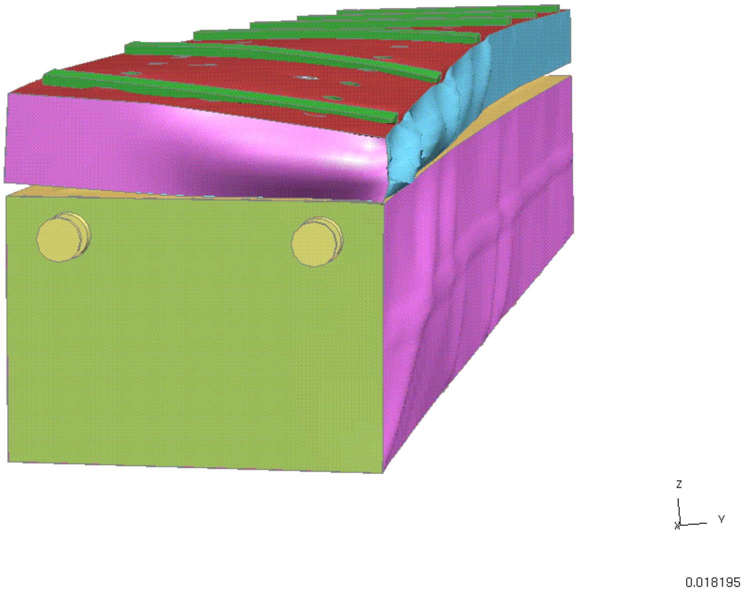
Buckling of the Lid and Base Diaphragms

(b) Finite Element Model

Figure 6 – Impact Damage of Specimen 2 following Flat Side Drop

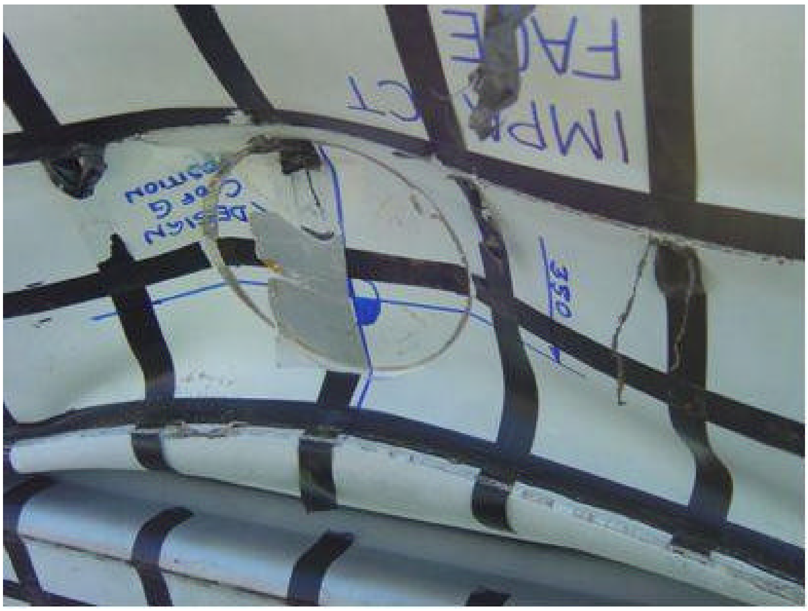


(a) Actual Drop Test

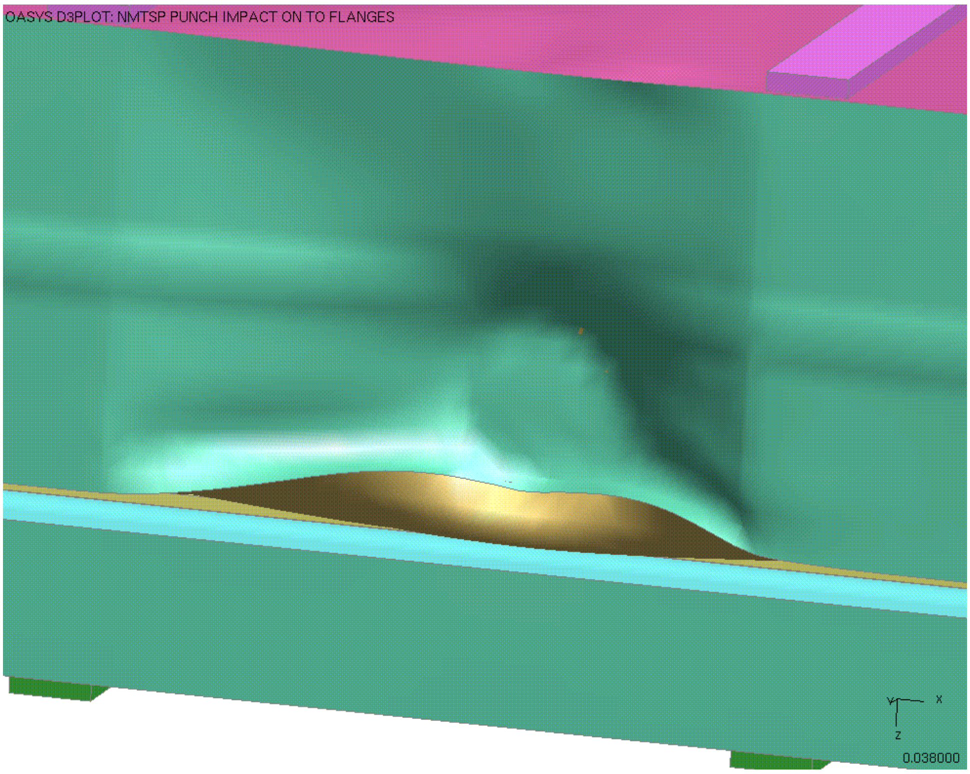


(b) Finite Element Model (Perspective Switched on)

Figure 7 – Impact Damage of Specimen 3 following Slapdown on to Lid



(a) Actual Drop Test



(b) Finite Element Model

Figure 8 - Impact Damage of Specimen 2 following a 1.05 m Side C of G Drop on to a Punch

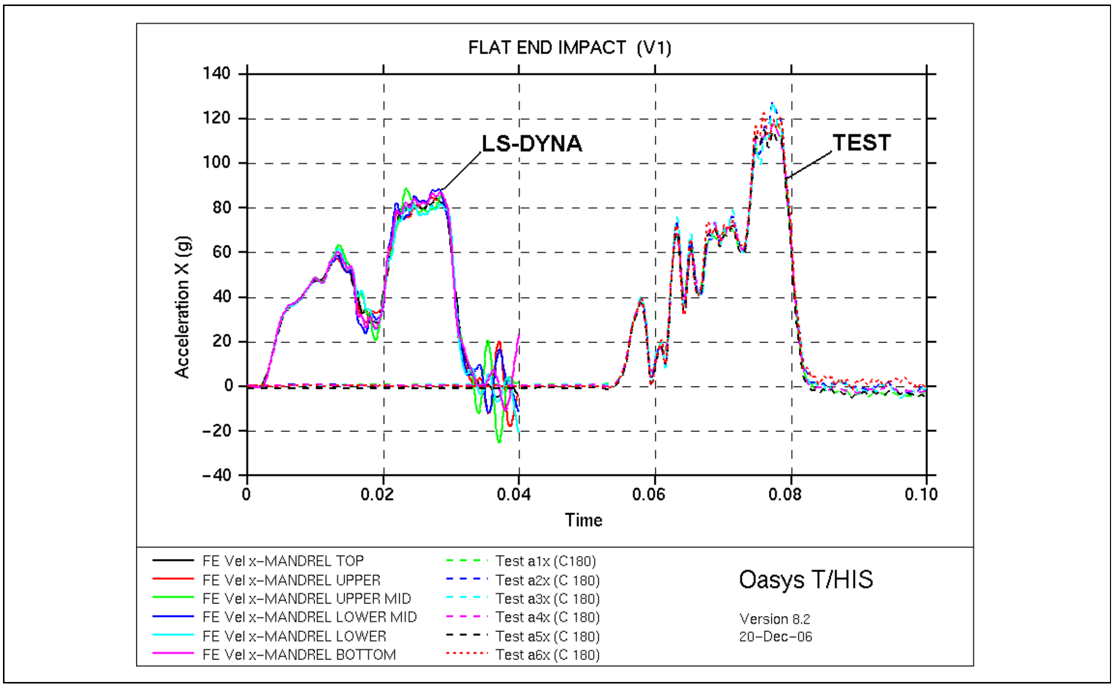


Figure 9 – End-on Drop – Filtered Payload Accelerations

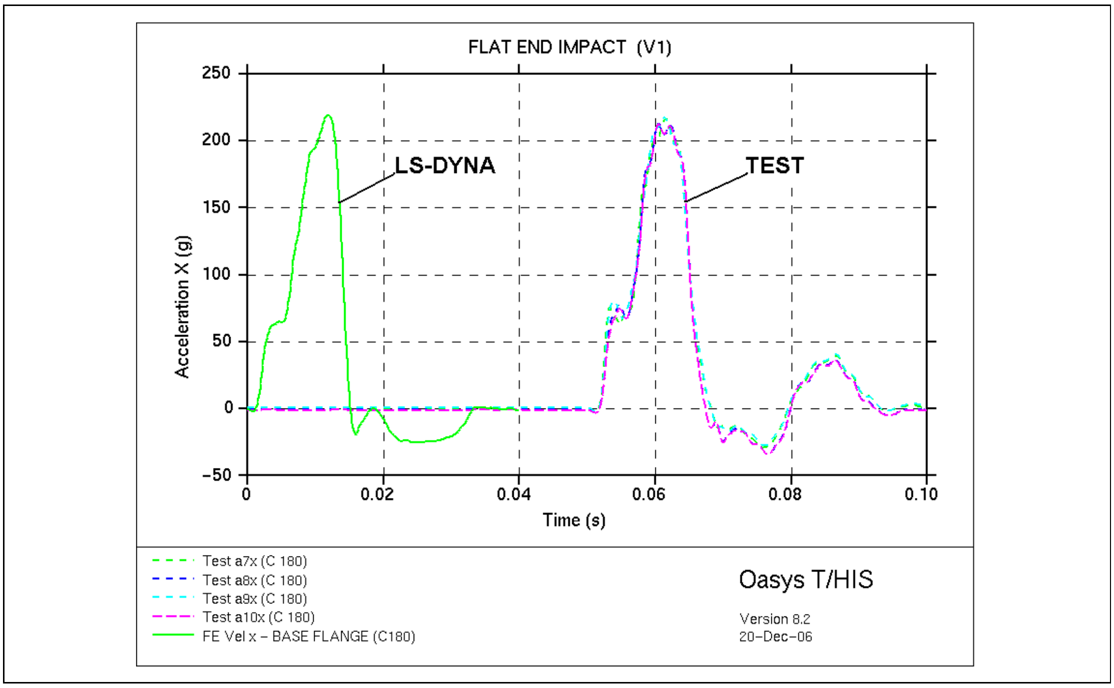


Figure 10 – End-on Drop – Filtered Package Accelerations

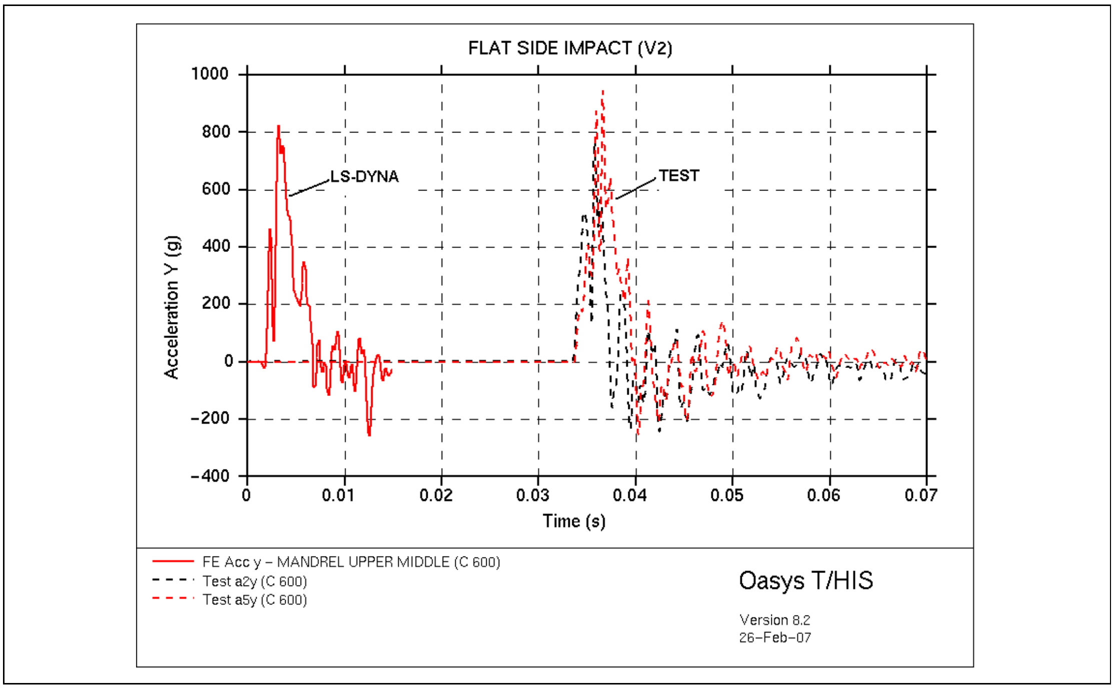


Figure 11 – Flat Side Drop - Filtered Payload Accelerations

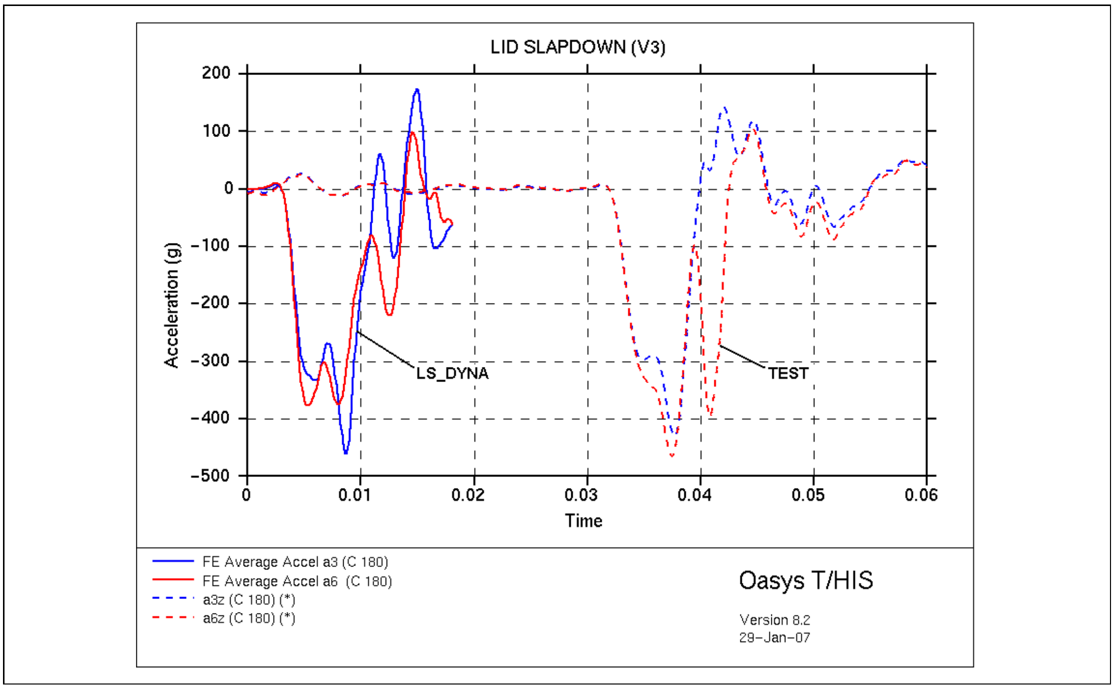
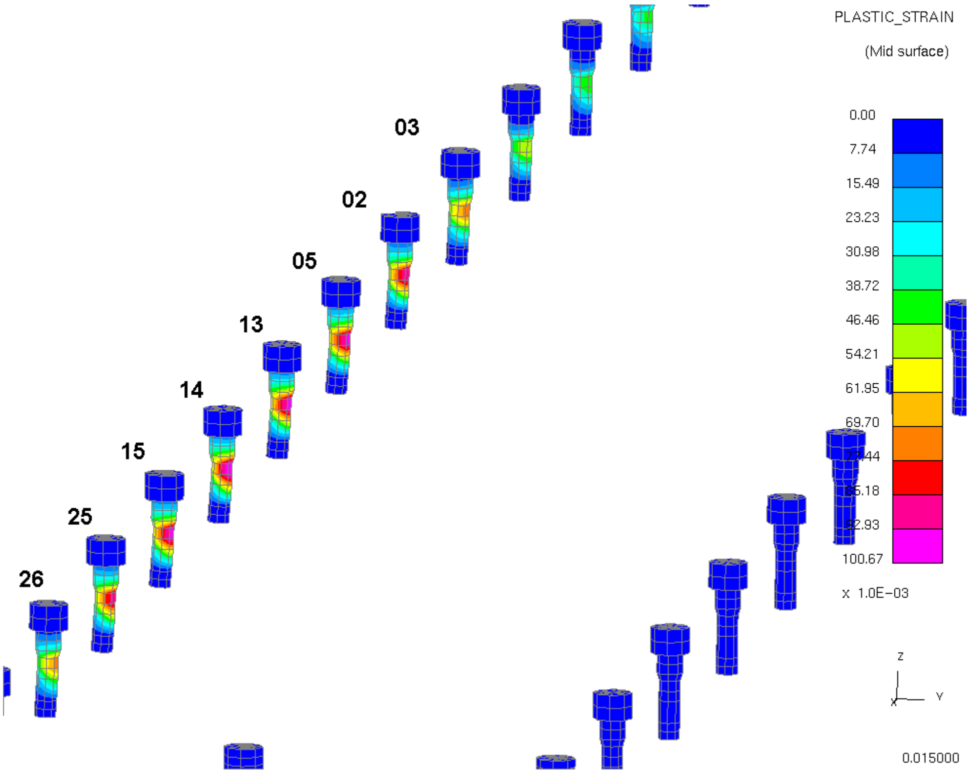


Figure 12 – Slapdown on to Lid - Filtered Payload Accelerations

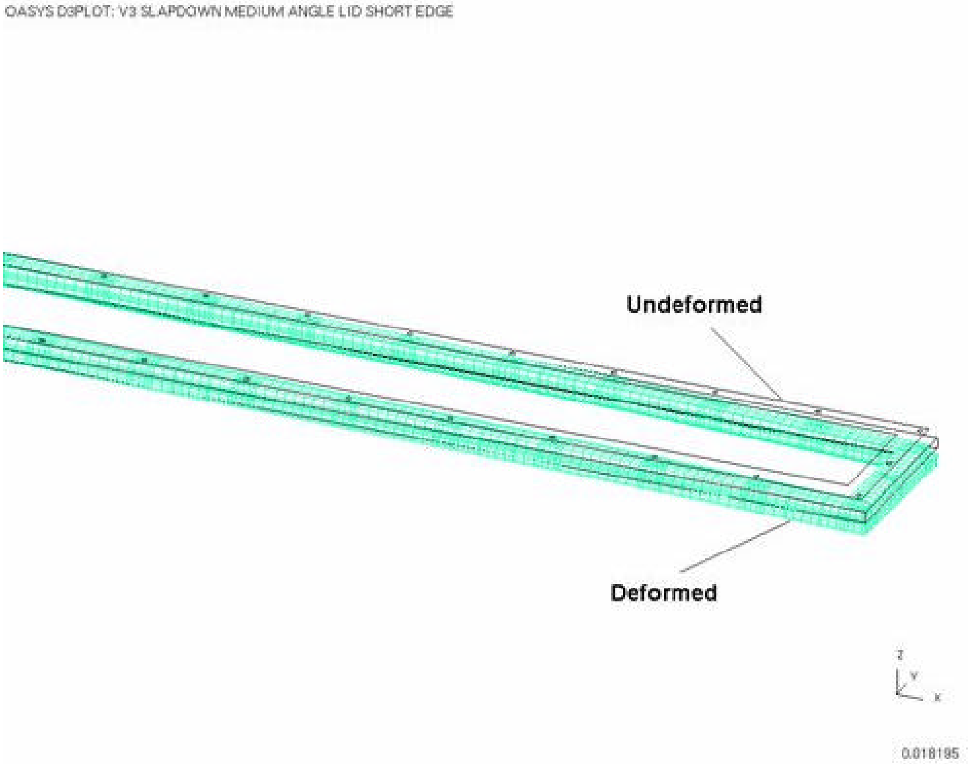
(a) Actual Drop Test



(b) Finite Element Model

Figure 13 – Flat Side Drop (Specimen 2) – Deformed Bolts

(a) Actual Drop Test (Grey strip is the straight edge)



(b) Finite Element Model

Figure 14 – Slapdown on to Lid – Base Flange Deformation