# Seismic Toppling Assessment of Cylindrical Nuclear Transport Flasks

*Dave Everett, Stefan Stojko*
*Rolls-Royce*
*PO Box 2000, Derby DE21 2XG England*

*Chi-Fung Tso, Andy North*
*Ove Arup and Partner*
*13 Fitzroy Street London W1P 6BQ England*

*Dr Colin Taylor*
*Bristol University*
*Queen's Building, University walk Bristol BS8 1TR England*

## Introduction

A review of flask and spent fuel handling operations was carried out as part of a Site Safety staged improvement programme and one aspect of this review covered seismic capability. This review coincided with the introduction of a new spent fuel transport flask, known as the Used Fuel Flask (UFF). Prior to the introduction of the UFF, spent fuel was transported by the NTL3M flask. A new facility, under construction is designed to comply with modern standards with a full seismic capability to withstand a 1 in 10000 year plus 40% margins earthquake. At the existing facilities, which have a limited operational life until the new facility becomes operational, a 1 in 1000 year earthquake event was the agreed seismic withstand requirement.

Both spent fuel flasks are cylindrical and are stood vertical during fuel loading. The lid is removed and replaced with an indexing mechanism that also provides impact and shielding functions. The fuel is transported to the UFF/NTL3M in a purpose built flask called the Module Replacement Container, (MRC). The MRC, mass 17 Te, diameter 0.91m, length 3.5m, is designed for on-site use only and carries a single fuel module. The MRC is located above an empty pocket and the fuel module lowered in to the UFF/NTL3M. The location on the indexing mechanism is by gravity loaded shear connection.

The objective of the seismic assessment was to determine whether a seismic clamp was required to prevent toppling of the MRC at the facilities where the design basis was specified as a 1 in 1000 year return period seismic event. Although fitting of a seismic clamp would provide an assured engineering safeguard against toppling, there were ALARP considerations. Firstly, the use of a seismic clamp could incur risk due to operator error. Secondly, operators would be exposed to radiological exposure during the fitting and removal of the seismic clamps. Therefore if it could be demonstrated by a combination of tests and finite element analysis that the MRC was stable during the prescribed seismic event, the ALARP solution would be to operate without a seismic clamp.

## Seismic Analysis

Seismic analysis of cuboid bodies has been carried out and there are empirical and finite element solutions for the onset of rocking and toppling. However, the solutions, in general, only cover a single axis input motion. For cylindrical flasks, it was envisaged that the process to final toppling would progress from the initiation of rocking, i.e. breaking of the gravity bond, through a precession mode and then to instability. It was considered that during the rocking/rattling phase of the instability process, kinetic energy would be dissipated as a result of the minor impacts/contacts between the mating surfaces. However, if the input energy was greater than the energy losses, displacement would increase and transition in to a precession mode would occur. The precession mode dissipates less energy than in the rocking/rattling phase, since it is a rolling contact between the two mating surfaces, hence toppling would be expected to occur shortly after the precession mode was established.

A review of the available finite element codes was carried out and it was concluded that LS-DYNA, Reference 1, was the most suitable program to model the complete process. Due to the complexity of the analytical solution, it was also recognised that validation of the model was required. Hence, a programme of shake table tests was commissioned. Since the UFF had recently completed a drop test programme, it was decided to use the 1/3-scale model of the flask in the shake table tests. This model was refurbished and 1/3-scale representations of the MRC, indexing mechanism and shear connection were manufactured.

## Shaker Table Testing

The seismic tests were carried out on the 15 tonne, six axis earthquake simulator (shaking table) at BEELAB, Bristol University. Support frames were bolted to the table either side of the UFF and MRC models as shown in Figure 1. Displacement transducers mounted between the support frames and the flask allowed the motions of the flask relative to the table to be measured. Accelerometers were used to monitor the table, MRC and UFF motions in the three axes. Video records were made of all tests.

## Scaling Issues

As the MRC/UFF arrangement represented a 1/3-scale scale model, the input motion was scaled accordingly. The rocking motion of a rigid block may be modelled as an inverted pendulum. The equation of motion for this, assuming no damping and free vibration is:

$$\ddot{\theta} + \frac{g}{L}\sin\theta = 0 \qquad (1)$$

where $\theta$ is the angle of tilt of the block, g is the acceleration of gravity and L is the characteristic length of the block.

For small $\theta$, when $\sin\theta \approx \theta$, this equation may be written as:

$$\ddot{\theta} + \frac{g}{L}\theta = 0 \qquad (2)$$

from which the effective linear natural frequency is:

$$\omega = \sqrt{\frac{g}{L}} \qquad \text{rads/sec} \qquad (3)$$

Thus the natural frequency is only dependent on the characteristic length of the block. The required time scale factor may be determined by taking the ratio of the prototype to model natural frequencies as follows:

$$\frac{\omega_P}{\omega_M} = \sqrt{\frac{L_M}{L_P}} = \sqrt{\frac{1}{3}} \quad \text{or} \quad \frac{T_M}{T_P} = \sqrt{\frac{1}{3}} \qquad (4)$$

Thus, the duration of the earthquake must be 0.577 that of the prototype. As gravity is the same in both the prototype and model cases, then so must be all the accelerations.

## Seismic Test Requirements

The test programme was aimed at determining whether the 1/3-scale MRC and UFF flasks will topple during a seismic event. The test programme started with exploratory tests of the MRC. Sine dwell tests with input frequencies of 15 Hz, 12 Hz, 9.4 Hz, 5.2 Hz and 1 Hz were performed with gradually increasing amplitudes until the MRC toppled.

A set of thirteen tri-axial tests was performed on the MRC using time histories generated to match frequency scaled UK hard site spectra. The amplitude of the tests was increased until the MRC toppled. These tests were repeated with the MRC placed centrally on the UFF, and in an extreme position.

## Finite Element Model Development and Stability Analysis

The objective of the finite element analysis process was to generate validated stability assessment models such that the methodology could be extended to full-scale arrangements for both the UFF and NTL3M. Finite element model development and validation was carried out by generating 1/3-scale representations of the MRC and UFF flasks. Eight tests from the shake table testing programme were modelled using the explicit finite element code LS-DYNA, and results correlated with test results.

## Modelling Methodology

The finite element model for the MRC centrally located on the UFF is shown in Figure 2. Contact conditions between the MRC and its support are crucial in determining the seismic behaviour of the MRC.

There are two alternatives to modelling the components and the contacts:

- modelling the components as rigid, relying completely on contact surfaces to take into account the contact conditions, or
- modelling the components as deformable, relying on the solid elements in the components to take care of deflection at the contacts and energy absorption at contact.

To benefit from the latter, a fine mesh at the contacting points is required, demanding a small analysis timestep. Considering the timescale of the events, this option is computationally prohibitive. The

MRC and shake table were therefore modelled solely with solid rigid elements and the UFF with both solid and shell rigid elements.

In this study, the contact surfaces were modelled with surface-to-surface contact elements which allow separation and closure of the relevant surfaces. The behaviour of the contact surface depends upon its specified coefficient of friction, damping and contact stiffness. A discussion of the latter two parameters is detailed below:

- Contact damping generally accounts for the effect of the coefficient of restitution (i.e. energy losses) and any material damping which would not have been taken into account in the analyses, as all elements were modelled as rigid bodies.

- Contact stiffness allows a certain amount of deformation between the surfaces. If two infinitely rigid bodies collide, the resulting force would be infinitely large occurring over an infinitesimal time. Thus, the stiffness of the contact allows deformation that would occur between two non-rigid bodies.

It is not sufficient to rely on correlation with one or two tests. To obtain a robust validation, it is required to correlate with a series of tests over a range of test conditions. In this work, these parameters were chosen iteratively such that a good test/analysis correlation was obtained throughout all eight analyses carried out. It was assumed that the coefficient of friction and the damping for each surface contact within each analysis would be the same. It was found that a friction coefficient of 0.2 and contact damping of 20% of critical gave the best correlation to the tests and these values were used in all the analyses. Additional sensitivity studies were carried out such as initial positioning of the MRC within the locating spigot. This particular aspect could not be easily covered in the test.

Shake table motions were defined in the tests by base acceleration motion. However, accelerations cannot be applied directly to rigid bodies in LS-DYNA. Acceleration time histories were integrated to velocity time histories before they were applied to the finite element model.

## Comparison of Analysis Results with Test Results

The analyses were compared to the shake table test in two ways:

(1) Comparison of overall response behaviour - especially the timing between the rattling, rocking and precessing phases of the response.

(2) Comparison of acceleration time histories.

A typical comparison of LS-DYNA and test acceleration time histories for sine dwell at 1 Hz is shown in Figure 3. In the shake table test, the MRC begins to rock at 3.0 to 3.2 seconds after which the MRC eventually topples between 3.9 and 4.2 seconds. The same time for rocking and toppling were observed in the analysis.

## Summary

The following conclusions can be drawn from the LS-DYNA and 1/3-scale test comparisons:

- There is in general good correlation between analysis and test, across all the different set-ups and input, in terms of overall behaviour and acceleration-time histories.
- Differences between test and analysis, in overall motion and acceleration, has been associated with on-set of precession. This is expected for such a highly non-linear instability problem.
- It was found from sensitivity studies that a friction coefficient of 0.2 and contact damping of 20% gave the best correlation to the tests.
- Contact stiffness is the key factor that governs contact stability. To predict accurate responses for different model arrangements, i.e. MRC only or MRC on UFF, a process of iteration for contact stiffness must be used to find the optimum balance between contact stability and minimal contact penetration.
- The response of the MRC is shown to be sensitive to a number of input parameters, namely friction coefficient, contact damping/stiffness and initial position of the MRC in its seating. None of these parameters were measured in the tests. However, the consistent test/analysis correlations across the whole suite of tests analyses give confidence that the values used were robust.
- The work
    - has demonstrated the capability of LS-DYNA in simulating this class of problems.
    - has validated the methodology for these analyses.
    - has successfully developed and validated LS-DYNA models for use in predicting seismic stability of the MRC.

## Application to Full-Scale Arrangement

The full-scale model discussed here is for the NTL3M flask. Based on the methodology developed above, a non-linear seismic assessment of the MRC on the NTL3M Flask whilst located in the fuel transit area was carried out. The full-scale LS-DYNA finite element model is shown in Figure 4. The model consists of the MRC, indexing mechanism, NTL3M flask and supporting floor. The seismic motion is applied at the floor level. The case selected demonstrates precession of the MRC followed by toppling. Figure 5 shows the X-Y displacement plots for the MRC centre of gravity and the top of the flask clearly showing the precession motion of the MRC in this plane. This is for a seismic input, which is greater than a 1 in 10000 year earthquake. The precession of the MRC increases as the low frequency acceleration occurs which ‘locks in’ to the vertical Z relative displacement (uplift), also shown in Figure 5. After 10 seconds, the vertical uplift peaks at 90 mm which then results in the MRC eventually toppling off the platform.

For a 1 in 1000 year earthquake, the analysis demonstrated that the MRC and NTL3M flask combination was stable with very adequate margins. As a result of this assessment programme, it was concluded that seismic clamps were not required at the existing facilities.

## Conclusion

Comparison of the test and analytical results in terms of acceleration, onset of precession and final instability showed good agreement. Test videos and analysis animation comparisons clearly show good agreement for global response of the arrangement up to the onset of precession and eventual instability. It was concluded that the analytical method developed to predict the onset of precession and eventual instability of cylindrical flasks could be used with reasonable confidence for this type of rigid body analysis and hence for full-scale flask predictions.

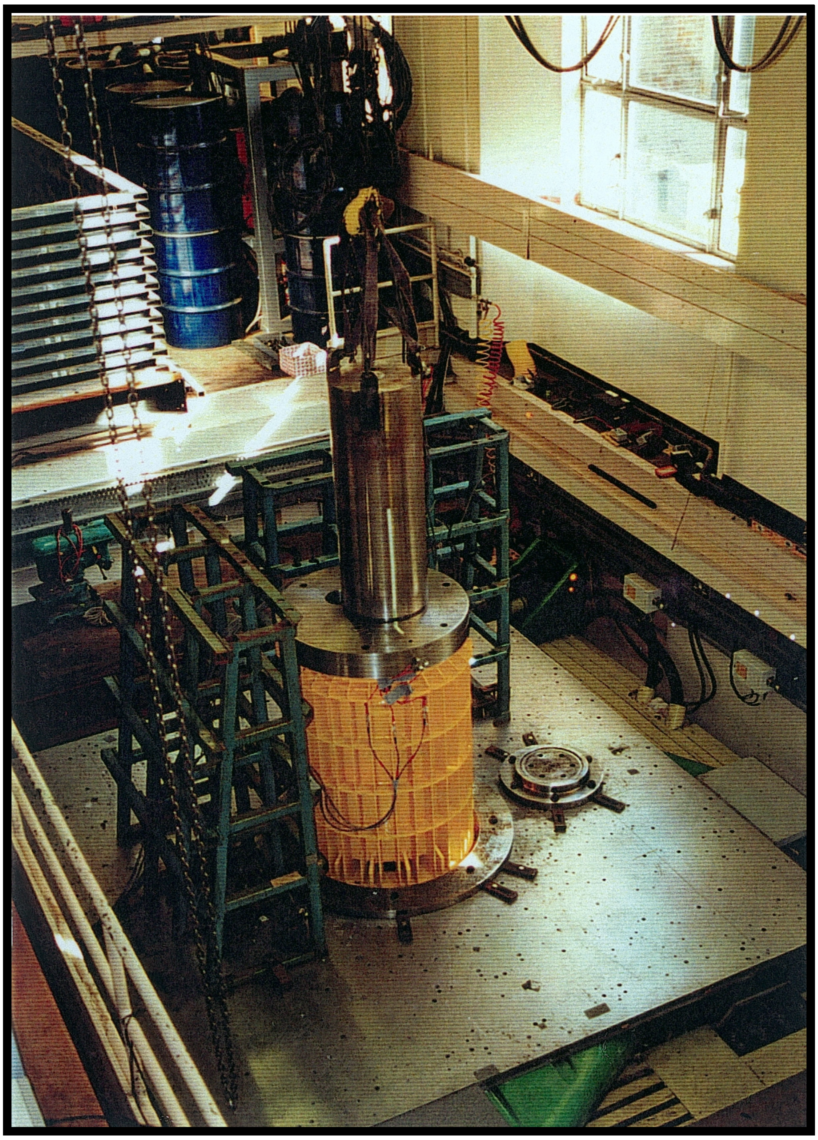

Fig. 1 1/3-Scale Test Arrangement of MRC and UFF

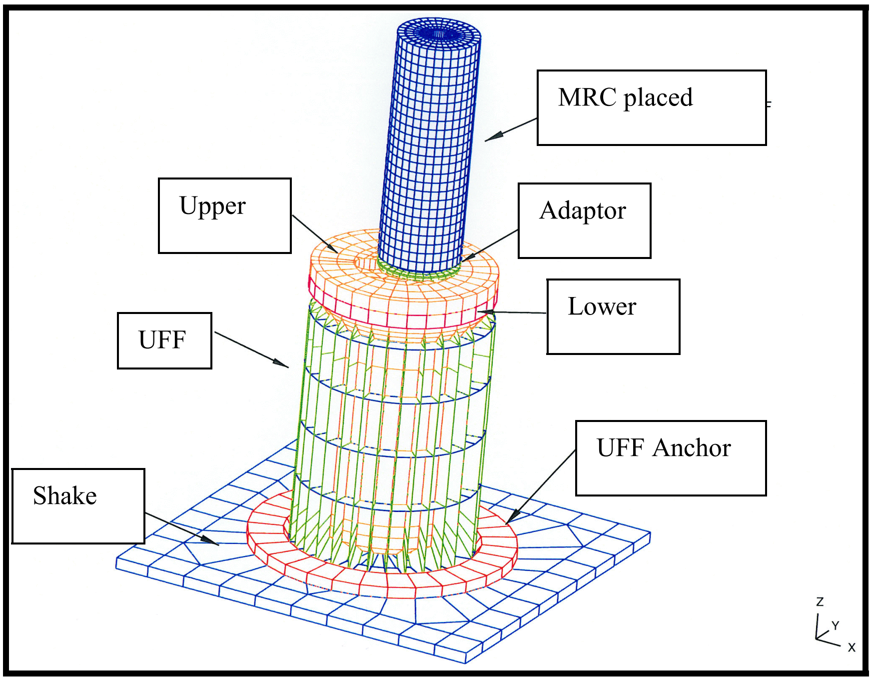

Fig. 2 LS-DYNA Finite Element Model of 1/3-Scale Test Arrangement of MRC and UFF

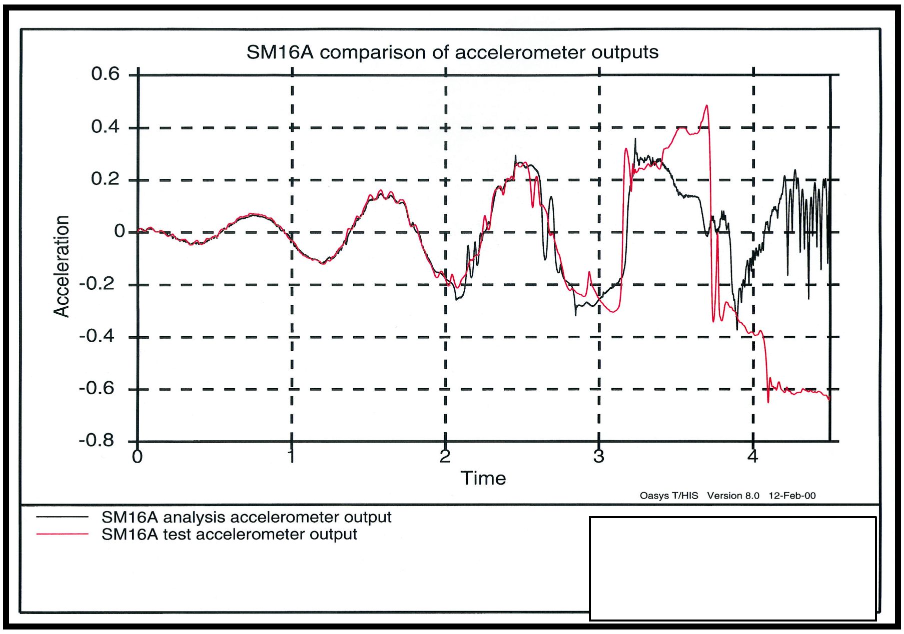

Fig. 3 Comparison of LS-DYNA and Test MRC Acceleration for Sine Dwell at 1.0 Hz

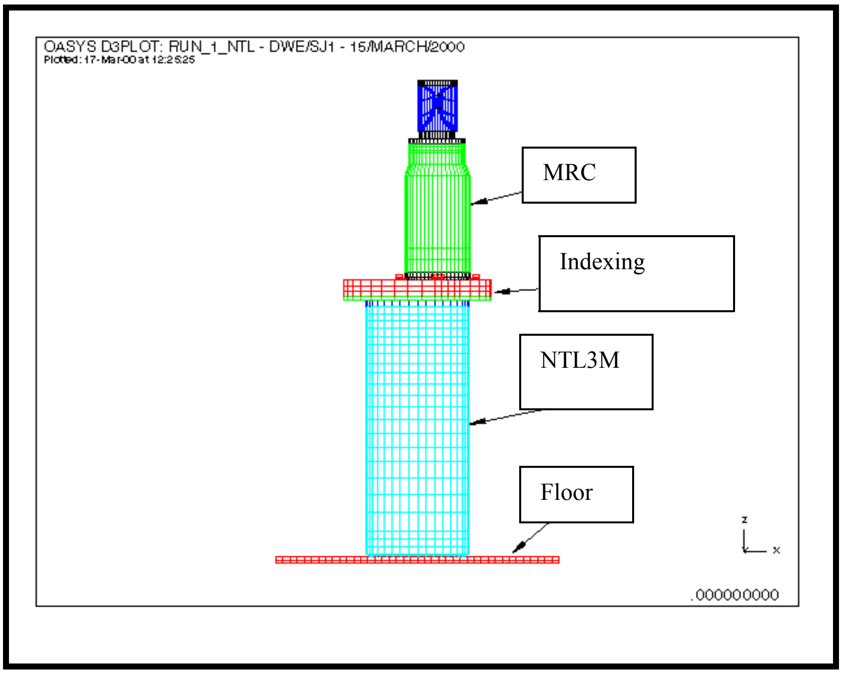

Fig 4 Finite Element Model of MRC, Indexing Mechanism, NTL3M Flask and Floor

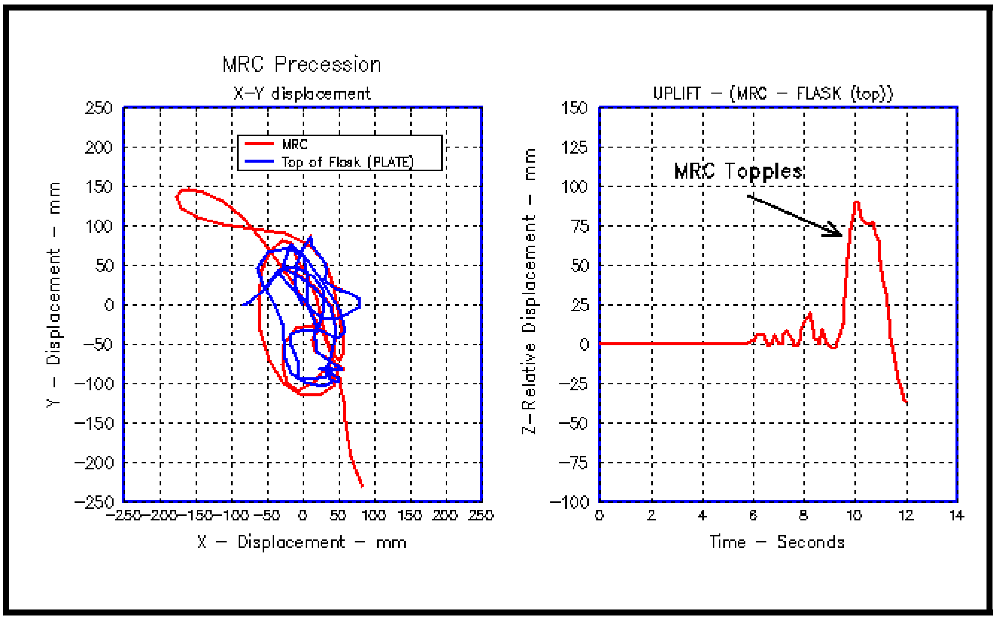

Fig 5 Motion of MRC in X-Y Plane and Vertical Uplift

## References

1 LS-DYNA Version 940_2a Software, 1999, Livermore Software Technology Corporation (LSTC), USA.