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The Application of Fluid Structure Interaction Techniques within Finite Element Analyses of Water-Filled Transport Flasks

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1 INTRODUCTION

Historically, Finite Element (FE) analyses of water-filled transport flasks and their payloads have been carried out assuming a dry environment, mainly due to a lack of robust Fluid Structure Interaction (FSI) modelling techniques. Also it has been accepted within the RAM transport industry that the presence of water would improve the impact withstand capability of dropped payloads within containers.

In recent years the FE community has seen significant progress and improvement in FSI techniques. These methods have been utilised to investigate the effects of a wet environment on payload behaviour for the regulatory drop test within a recent transport licence renewal application.

Fluid flow and pressure vary significantly during a wet impact and the effects on the contents become complex when water is incorporated into the flask analyses. Modelling a fluid environment within the entire flask is considered impractical; hence a good understanding of the FSI techniques and assumptions regarding fluid boundaries is required in order to create a representative FSI model. Therefore, a Verification and Validation (V&V) exercise was undertaken to underpin the FSI techniques eventually utilised.

A number of problems of varying complexity have been identified to test the FSI capabilities of the explicit code LS-DYNA, which is used in the extant dry container impact analyses. RADIOSS explicit code has been used for comparison, to provide further confidence in LS-DYNA predictions.

Various methods of modelling fluid are tested, and the relative advantages and limitations of each method and FSI coupling approaches are discussed.

Results from the V&V problems examined provided sufficient confidence that FSI effects within containers can be accurately modelled.

2 ANALYSIS CODE SELECTION

The general-purpose hydrocodes, such as LS-DYNA, concern themselves with the response of solid and fluid materials under highly dynamic conditions, eg, detonation, impact and shockwave propagation. Hydrocodes numerically solve the more fundamental time-dependant equations of continuum mechanics, thereby fulfilling requirements for which neither traditional computational fluid mechanics (CFD) nor computational solid dynamics (CSM) codes are fully suitable. Hydrocodes are therefore defined as simulation tools for multi-material, compressible, transient continuum (ie, fluid and/or solid) mechanics. Hydrocodes, such as LS-DYNA, also include the capability to model structural elements, which is crucial to FSI.

LS-DYNA is used for the extant dry container analyses, with the structural side of the code being underpinned by numerous years of evolving analyses and an extensive V&V programme undertaken at Rolls-Royce. LS-DYNA's capability to delete elements based on a number of criteria, ie maximum plastic strain, maximum principal stress etc, and then re-couple the fluid boundary to the exposed surface is fundamental to its use for the application considered here. Were an initial failure to occur then the subsequent damage needs to be quantified. Thus LS-DYNA is the primary FE code used for FSI analyses.

An additional code was employed as a verification tool to provide additional confidence in the FSI analyses results provided by LS-DYNA. A review of various codes was undertaken with requirements such as fluid and FSI capability, structural capability, independence from LS-DYNA, and product support all being considered. Modelling of material failure was a fundamental requirement of the structural capability of the verification code.

This review culminated in the explicit code RADIOSS being chosen as the most suitable verification code for this project, and it was used throughout the V&V exercise and for supporting the LS-DYNA container analysis.

3 FLUID MODELLING TECHNIQUES - Overview

LS-DYNA can utilise a number of techniques for fluid modelling, namely Lagrangian, Eulerian, Arbitrary Lagrangian Eulerian (ALE) and Smooth Particle Hydrodynamics (SPH). Other Methods, ie Element-Free Galerkin (EFG), have not been considered here as they are still under development.

LAGRANGIAN – *LS-DYNA and RADIOSS*

The computational mesh of a Lagrangian FE model remains fixed on the material. Material distortions correspond to Lagrangian mesh distortions, but excessive deformation can lead to reductions in timestep and/or the breakdown in problem advancement. Mesh rezoning can be used to extend the application of Lagrangian codes to large distortion problems, but this introduces complexities and corresponding solution inaccuracies. Also the calculation is no longer strictly Lagrangian if the mesh is rezoned. The general limitation of most Lagrangian hydrocodes to relatively low-distortion computations restricts their applicability to local and global shock/structure interaction analyses.

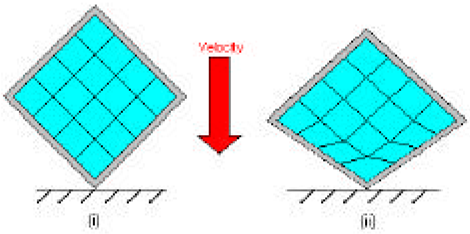


Figure 1 – Lagrangian fluid mesh inside box impacting a rigid wall. (i) Prior to impact (ii) During impact

Considering Figure 1, showing the impact of a fluid-filled box, it is apparent that as the fluid compresses the fluid mesh becomes highly deformed, this leads to a significant reduction in timestep and eventually results in premature termination of the analysis.

EULERIAN – *LS-DYNA only*

The Eulerian method advances solutions in time on a mesh fixed in space instead of a mesh fixed on the material. Using this approach, the Eulerian method avoids the Lagrangian problem of mesh distortion. Correspondingly, and unlike Lagrangian simulations, timesteps can remain essentially constant. The difference between Eulerian CFD codes and Eulerian hydrocodes is primarily the inclusion in the latter, of material strength (flow of solids) and multi-material capability. Furthermore, Eulerian hydrocodes are strictly transient dynamic solvers; they are not designed to solve steady-state fluid flow problems.

The usual sequence of logic within the Eulerian method, unlike traditional CFD codes, consists of a Lagrangian computation at every timestep, followed by a re-map (advection) phase which restores the slightly distorted mesh to its original state.

Due to the Eulerian method allowing the material to flow through the mesh, there maybe a requirement for a refined mesh to attain a similar accuracy compared to Lagrangian. Additionally, extended element areas also need to be defined in the space where the material may subsequently flow (void elements). Hence using this method requires prior planning with a reasonable understanding of where the fluid might flow, and it can potentially lead to very large models. Additionally, the treatment of moving boundaries and interfaces (coupling) can prove difficult with Eulerian elements.

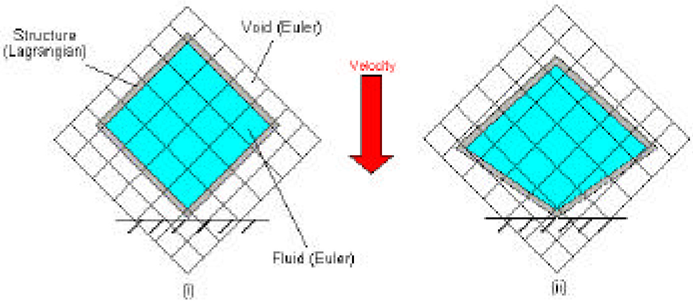


Figure 2 – Eulerian fluid mesh inside box impacting a rigid wall. (i) Prior to impact (ii) During impact.

Figure 2 (i) shows the additional void elements surrounding the fluid material allowing it to flow as the box deforms. The mesh remains fixed in space and hence neither the timestep nor the analysis stability is reduced due to elements becoming skewed or highly deformed, see Figure 2 (ii).

ARBITRARY LAGRANGIAN EULERIAN (ALE) - *LS-DYNA and RADIOSS*

Arbitrary Lagrangian Eulerian (ALE) hydrocodes share aspects of both Lagrangian and Eulerian methods. The Lagrangian motion is computed every timestep, followed by a re-map phase in which the spatial mesh is either not rezoned (Lagrangian), rezoned to it's original shape (Eulerian) or rezoned to some more 'advantageous' shape (between Lagrangian and Eulerian). In this way the spatial description of the mesh is neither restricted to following the material motion nor remaining fixed in space.

ALE rezoning can also have limitations where, for certain problems, it cannot cope with severe rapid deformations, unlike the Eulerian method. It does have some advantages over the Eulerian method however, in that it utilises a Lagrangian mesh, meaning the meshing is quicker to set up. Also ALE elements can either be integral with the Lagrangian structure, or use traditional contact methods, hence stability at moving boundaries and interfaces is more robust than with the Eulerian FSI approach.

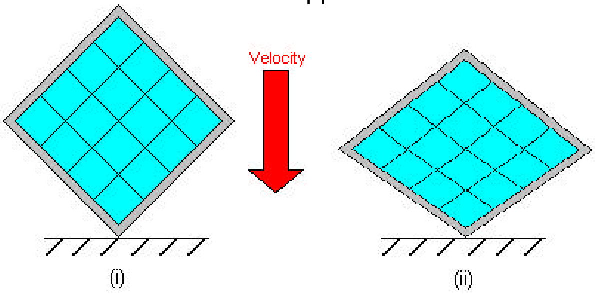


Figure 3 – ALE fluid mesh inside box impacting a rigid wall. (i) Prior to impact (ii) During impact.

Comparing Figure 3, the ALE fluid-filled box, with Figures 1 and 2, it can be seen that the mesh has been rezoned uniformly within the box structure.

SMOOTH PARTICLE HYDRODYNAMICS (SPH) - *LS-DYNA and RADIOSS*

Smooth Particle Hydrodynamics (SPH) is a Lagrangian method having the potential to be both efficient and accurate at modelling material deformation, as well as being flexible in terms of inclusion of specific material models. In addition, SPH is a meshless or gridless method, such that it does not suffer from the normal problems of severe mesh distortions in large deformation problems. Although the Eulerian method also does not suffer from grid tangling, it has some limitations in terms of modelling interfaces, and can be computationally expensive.

The grid-based methods, such as Lagrangian and Eulerian, assume a connectivity between nodes to construct spatial derivatives. SPH uses a smoothing (kernel) approximation, which is based on randomly-distributed interpolation points, with no assumption about which points are neighbours, to calculate spatial derivatives.

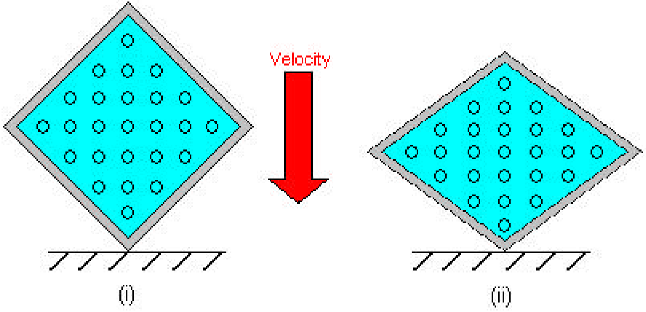


Figure 4 – SPH fluid mesh inside box impacting a rigid wall. (i) Prior to impact (ii) During impact.

SPH particles are not simply mass points that interact, but interpolation points from which values of functions, and their derivatives, can be estimated at discrete points in the continuum. In SPH, the discrete points at which all quantities are evaluated are placed at the centre of the SPH particles.

Figure 4 shows that in this case the particles would take on a uniform distribution. A random distribution of particles, ie for an asymmetric model, can lead to a reduction in accuracy.

4 FLUID – STRUCTURE COUPLING TECHNIQUES

Lagrangian - Lagrangian

There are numerous suitable contact types available, the most frequently used types are nodes to surface and surface to surface, these allow contact and separation with sliding and friction or they can be tied.

Eulerian – Lagrangian

In LS-DYNA there are two methods implemented to couple Eulerian domains and Lagrangian structural elements. They are:

1 - Constraint-based, where either acceleration or velocity and acceleration are coupled in the normal direction only.

2 - Penalty-based, which tracks the relative displacement between fluid and structure. Three types are available,
    i) normal direction, compression and tension,
    ii) normal direction, compression only,
    iii) all directions.

ALE – Lagrangian

Quite often, the ALE and Lagrangian meshes will be integral, although specific coupling interfaces can be defined.

SPH – Lagrangian

Since SPH is essentially Lagrangian in nature, *Lagrangian – Lagrangian* techniques are used between the SPH particles and the Lagrangian structure.

5 VERIFICATION AND VALIDATION PROBLEMS

A number of problems have been analysed in a comprehensive V&V exercise to provide confidence in FSI modelling techniques. Two of these are presented here, which test some of the key features of the methods that are relevant to FSI container analyses.

5.1 The Response of Two Coupled Plates to an Incident Pressure

This problem considers two flat plates coupled by an acoustic fluid. The fluid is essentially irrotational, inviscid with a speed of sound independent of pressure. This is essentially a 1D problem.

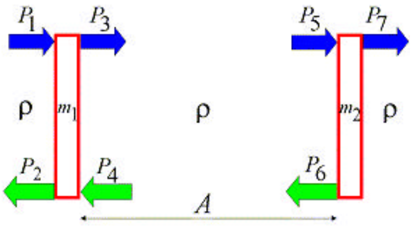


Figure 5 – Schematic of two plates

As shown in Figure 5, the plates are separated by a distance 'A' with mass per unit area m_1 and m_2 and fluid within the three regions. P_1 is the initial incident shockwave, which for this case is an exponentially decaying pressure wave.

The equations describing the motion of the two plates have been established for the following three cases:

(1) $m_1 = m_2 = m$ (2) $m_1 \neq m_2$ both with ρ the same in all regions, ie water
(3) $m_1 \neq m_2$ with ρ behind the second plate representing air

ALE Results

Figure 6 shows the LS-DYNA and RADIOSS comparison of pressures (P1+P2 and P5+P6) with the exact solution for $m_1 = m_2$. The exact solution has been shifted in time to account for the time the pressure wave takes to travel 2A in the analysis, before arriving at Plate 1. It is apparent that these analyses capture the transmitted and reflected waves correctly. It is noted that a more accurate solution can be achieved by refining the mesh. For this 1D problem the ALE and Lagrangian solutions are essentially the same.

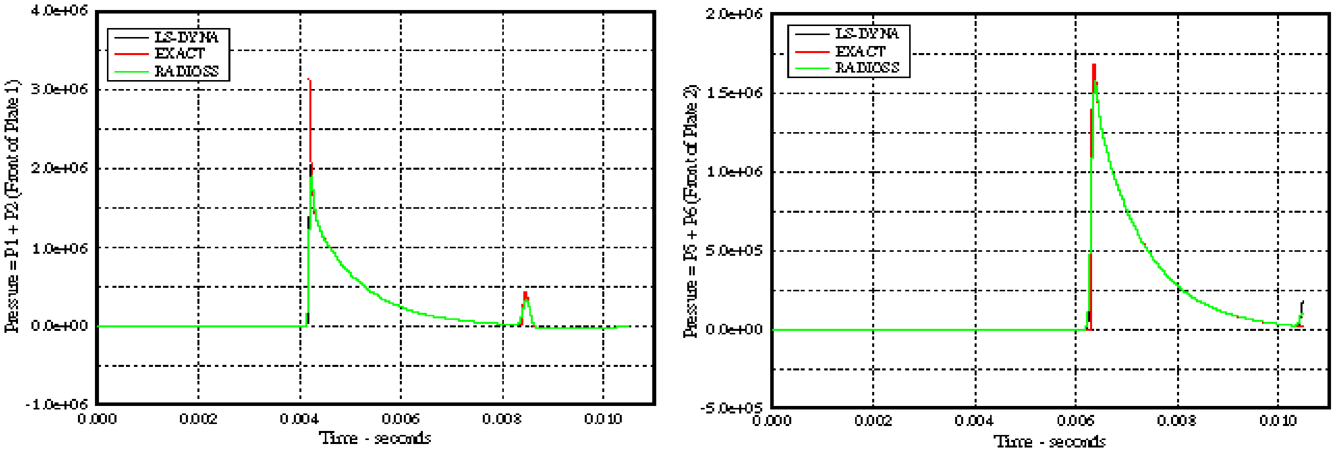


Figure 6 – ALE $m_1 = m_2$ water backed. Pressure on front of plates.

SPH and Eulerian Results

The LS-DYNA SPH model revealed anomalous results and is therefore not presented. From the RADIOSS SPH analyses it was observed that the pressure and velocity results were similar to the ALE predictions presented above. A degree of mesh ringing was seen due to the reduced SPH viscosity used; applying the default viscosity removed the ringing but this substantially reduced and broadened the peaks. The ringing increased for an analysis where the viscosity value was reduced to zero, but not such that it invalidated the solution.

The results observed from the Eulerian analysis were again similar to the ALE results, it was noted however that a degree of fluid oscillation similar (but reduced) to that seen in the SPH analysis was apparent.

5.2 Impact of Box Container with Baffles Filled with Water

Figure 7 illustrates this problem, which demonstrates FSI in two dimensions for a square box container with baffles, filled with water, and dropped corner first onto a rigid wall. LS-DYNA SPH was not used in this problem, as an earlier problem had identified an issue with increasing energies in this method.

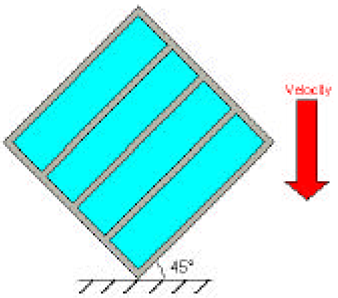


Figure 7 – Schematic of square box container with baffles, filled with water

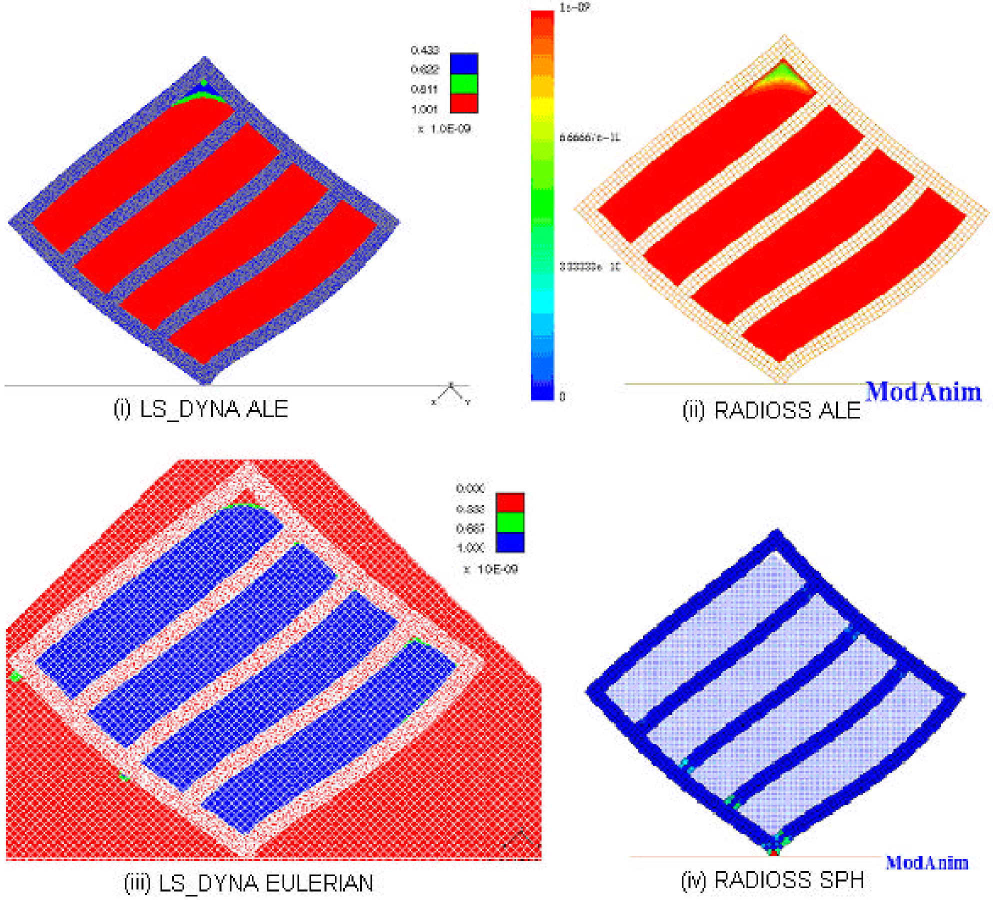
Comparison of Results - Deformation

As the box deforms, the internal volume changes and a void appears between the fluid and the structure; Figures 8(i) and (ii) show good agreement between LS-DYNA ALE and RADIOSS ALE in this regard. The asymmetry in deformation introduced by the incorporation of the baffles is also apparent.

Figure 8 (iii) shows the box deformation for the Euler water representation, and the volume change is similar to that predicted for the ALE calculations. A small amount of 'leakage' is noticed in the later stages of the analysis, where the fluid material breaches the coupling boundary, although not a sufficient amount to invalidate the solution.

The RADIOSS SPH result is similar to both the ALE and Euler analyses, with the presence of voids indicated by the SPH particles, see Figure 8 (iv). It should be noted that the void appears smaller in SPH; however, this is due to the rectangles used to represent the particles in the RADIOSS post-processor.

Along with the deformations, the plastic strains within the box were observed to be in very good agreement for the different FSI techniques.



(i) LS_DYNA ALE (ii) RADIOSS ALE

(iii) LS_DYNA EULERIAN (iv) RADIOSS SPH

Figure 8 – Baffled Box Deformed Plots

<u>Comparison of Results – Energy and Wall Forces</u>

The ALE analyses, in both LS-DYNA and RADIOSS, displayed a very good agreement for both the energy balance and wall impact force.

Figure 9 shows the LS-DYNA energy comparison between ALE and Euler representations. The energies virtually overlay up to 0.8 ms and are similar for the remainder of the analysis. There is a notable loss in total energy of around 15% for the Euler calculation, this appears to be due to a reduced internal energy compared to ALE. It is considered that this loss is due to a small amount of energy being dissipated as the Eulerian material moves through the mesh; this is not being added back into the internal energy. Further work, in consultation with the code vendor, is being undertaken to further understand the energy loss. Also shown in Figure 9 are the wall impact forces which are in good agreement.

Both the energy and wall force were in good agreement for the RADIOSS SPH compared to RADIOSS/LS-DYNA ALE calculations.

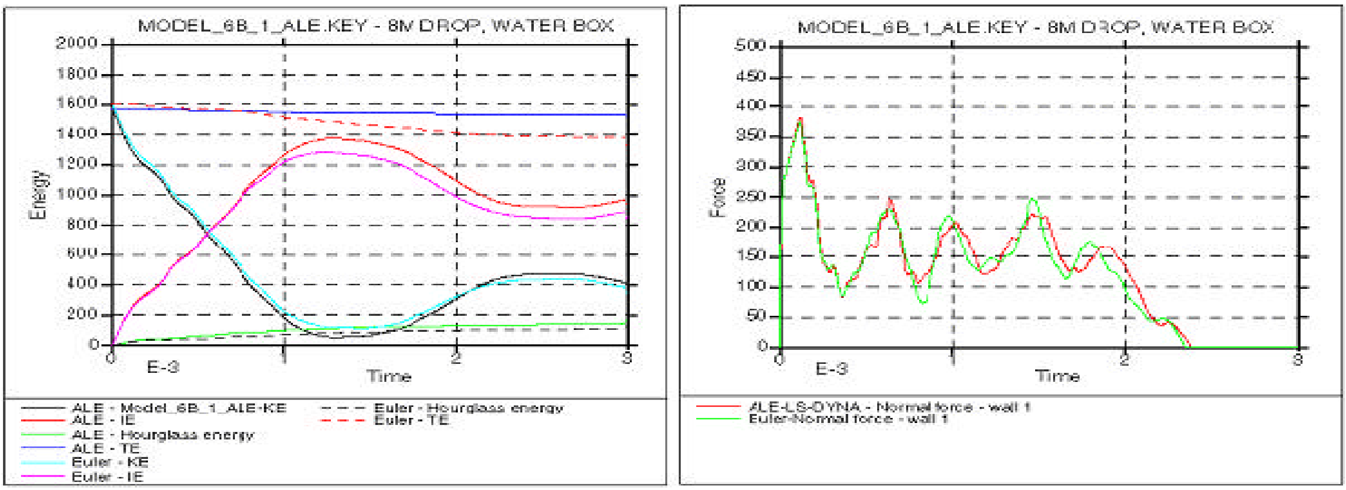


Figure 9 – ALE/Euler – Water in Box with Baffles – Energies and wall force

5.3 V&V SUMMARY

From the V&V exercise, including other relevant analyses not presented here, it was concluded that the ALE method is the most appropriate technique for modelling FSI, but has limitations due to the fluid mesh having to be integral with the structure. Both SPH and Euler are quite general representations of the fluid and do not suffer with the restriction of being integral with the structure.

For the particular application of these FSI techniques to modelling a payload surrounded by, and containing, water, it was recommended that the following methods be used.

- ALE – This method is robust, and should be an accurate representation of the FSI effects. Both LS-DYNA and RADIOSS (confirmatory) can be used.
- Confirmatory analysis can be carried out using SPH or Euler. The SPH method can only be used with confidence in RADIOSS at this stage.

6 CONTAINER ANALYSES

Modelling a fluid environment within the entire flask is considered impractical; therefore a good understanding of the FSI techniques and assumptions for fluid boundaries is required to create a representative FSI model. Boundary assumptions for the fluid and the choice of FSI representation need to be considered early on as these can affect modelling requirements.

A recent analysis providing justification for a transport flask was undertaken by applying FSI techniques to an extant dry assessment, and justified through the V&V described here. As with the structural analysis, assumptions were used to simplify the FSI finite element model. The fully laden transport flask contained a number of components held within a basket, and it was reasonable, and more practical, to demonstrate the integrity of the payload through separate analyses, ie an acceleration trace as derived from a flask drop analysis/test was applied to a separate pay-load sub model.

For both the dry and FSI analyses, the basket (made up of interlocking steel plates) was considered to ensure the payload saw the maximum deceleration, but discounted in terms of structural support, ie a moving rigid wall was used with the basket deceleration applied. Further consideration of the basket needed to be taken in the FSI analyses, again not in terms of structural support, but in defining the fluid boundaries.

The container analyses undertaken showed that the surrounding fluid had little effect on the global deformation of the structure when compared to the dry analysis. However, fluid inside the payload changed the detailed internal deformation due to the minimum volume being maintained. Additionally, it was indicated that the fluid may have a beneficial effect in preventing subsequent damage if an initial failure were to occur, further investigation is required to confirm this effect.

7 CONCLUSIONS

FSI provides a tool for better representing the dynamic behaviour of a payload within a transport container under impact. To date the majority of analyses have been undertaken assuming a dry environment, but with the ongoing development of FSI techniques, the effects of a fluid on the behaviour of the container internals can now be accurately predicted.

Incorporating a fluid into a transport container analysis is a complex process. Fluid flow and pressure can change significantly during an impact, and can be difficult to understand; hence, an extensive V&V exercise was carried out to give sufficient confidence in the FSI techniques to be used.

There are a number of FSI techniques that can be utilised, each having advantages and limitations. From the methods tested ALE is seen as the most robust technique for modelling fluid within a transport flask, but the selection of an FSI technique can be very much problem dependent.

The FSI container analyses undertaken showed behaviour that was not expected. In this case the wet and dry analyses showed little difference with the payload global deformation being similar. This may not be the case for other situations, where the different boundary conditions, geometry and material properties can all have a significant effect.

8 FUTURE APPLICATIONS

The FSI methodology is seen as an extremely useful analysis tool, and Rolls-Royce ‘Naval Marine’ considers the following to be possible future applications;

- Under water shock effects on marine structures/vessels. ie UNDEX
- Slamming – Drops onto water
- Vessel Buoyancy. Dropped load impacts onto vessels and vessel-vessel collisions.
- Shear, tearing, penetration and puncture of structural materials.