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HEALTH & SAFETY LABORATORY

Technical Assessment of Petroleum Road Fuel Tankers
Work Package 1 - Full scale testing and associated modelling
MODELLING TO PROVIDE LOAD CASE DATA FOR ROLLOVER – APPROACH AND INITIAL DEVELOPMENT
ES/14/39/05rev05

Report Approved for Issue By:	**Nigel Corlett, BEng(Hons), MSc, PhD, ACSM**
Date of Issue:	**26 November 2014**
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HSL Project Number:	**PE05832**

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Disclaimer
Certain aspects of this report, and any results and conclusions set out within it, may be disputed by the tank manufacturer.

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EXECUTIVE SUMMARY

Background

Following examination, certain petroleum road fuel tankers have been found to not be fully compliant with the provisions of Chapter 6.8 of the European Agreement on the Carriage of Dangerous Goods by Road (ADR). Amongst other things, these tankers are seen to exhibit extensive lack-of-fusion defects in the circumferential weld seams which, based on a leak-before-break assessment[1], could rupture under rollover and ADR load conditions.

The Department for Transport (DfT) commissioned research consisting of three work packages (WPs):

- WP1 – Full scale testing and associated modelling; Health and Safety Laboratory (HSL).
- WP2 – Detailed Fracture and Fatigue Engineering Critical Assessment (ECA); TWI Ltd.
- WP3 – Accident data and regulatory implications, and production of an overall summary report of the research; TRL Ltd.

HSL has taken forward the tasks set out in WP1 to:

1. Develop an independent non-proprietary structural hydrodynamic model of GRW tankers, validate this model against the results of tanker tests, and report modelling findings.
2. Design, construct and commission a test rig for tests of tankers, including selecting and procuring suitable instrumentation for data gathering.
3. Undertake tests on tankers, including preparing the tankers, assessing the tanker test method and results, and reporting the findings.
4. Determine suitability of tankers for large scale tests and acquire tankers, as appropriate, in accordance with project objectives as specified by DfT.
5. Capture collision and/or deformation data from relevant impacts, for example by laser scanning, to corroborate the modelling and tanker tests, and reconcile any inconsistencies.
6. Engage in peer review activities on the overall DfT research programme.

This report describes the work undertaken to create the first iteration of the model used in task 1. Refinement of this model, validation against experimental data from HSL topple tests and application of the model under other similar conditions is described in HSL report ES/14/39/06.

Objectives

The work described in this report contributes towards the overall objective for task 1, namely:

- Create and validate a structural hydrodynamic model of GRW tankers under rollover conditions.

The specific objective of the work being:

- Create an original representative tanker rollover model which includes impact with the ground, realistic fluid motion and rotational velocity, refining an existing HSL structural model of a partial tanker to represent a full GRW tanker so that transverse loading can be modelled.

[1] *'Short-term Fitness for Service Assessment of [non-compliant] Road Tankers, TWI (Draft) Report 23437/1/13, September 2013 and 'Project 23437 Contract Amendment: Additional FEA for assessment of [non-compliant] road tankers, TWI (Draft) Report 23437/2/13, October 2013.*

Main Findings

A suitable finite element model for GRW tanker rollover based on HSL's topple test has been created. This model will be refined and validated against experimental data from HSL's topple tests of GRW tankers.

The Euler/Lagrange fluid structure interaction approach was chosen for the analysis of the tanker topple event. This approach allows the detailed geometry of the tanker to be represented using shell elements and the liquid in the tanker to be modelled.

The empty space in the tanker's compartments was modelled as a void, as opposed to assuming air or air/fuel vapour, as this approach is much more efficient in terms of solution time. It also prevents the build-up of pressures in the compartment due to the reduction in volume caused by crushing, as in reality this build-up would be prevented by the pressure relief valves.

As this model does not consider the detailed behaviour of the welds at the extrusion bands, a mesh size of between 10 mm and 20 mm was found to be appropriate for the sections of the tanker subject to the largest deformations, and very little difference in deflection values was observed with further refinement. However, when data from this model is compared to test data the mesh size will be reviewed.

GRW tankers J3190 and J2580 used different extrusion designs in the construction of the bands which join the sections of the tanker together. So, geometries for both designs were created for the model of the extrusion band. These tankers also included fillet welds in different positions on the joint between the extrusion band and the shell plate. Geometries for the extrusion band with and without fillet welds were created for use where appropriate.

The adoption of the techniques of mass scaling (adding mass to some small elements to increase the solution speed) and Euler subcycling (solving the fluid regions of the model less frequently than the solid parts) were found to offer large benefits in terms of solution times without significantly affecting the results obtained.

Varying the bulk modulus (the compressibility of the fluid) had an insignificant effect on the deflection of the tanker, even for large changes in modulus. Fluid density (with associated change in volume to keep the mass constant) has a larger effect. An equivalent mass of petrol resulted in a larger deflection than water.

1 INTRODUCTION

This work has been conducted as part of the Department for Transport's (DfT) technical assessment of petroleum road fuel tankers.

Following examination, certain petroleum road fuel tankers have been found to not be fully compliant with the provisions of Chapter 6.8 of the European Agreement on the Carriage of Dangerous Goods by Road (ADR). Amongst other things, these tankers are seen to exhibit extensive lack-of-fusion defects in the circumferential weld seams which, based on a leak-before-break assessment[2], could rupture under rollover and ADR load conditions.

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Previous assessments of fuel tanker integrity during a rollover event have simply applied internal pressures to a structural finite element model. The pressures used for these analyses were based on work undertaken on behalf of the Health and Safety Executive by Frazer Nash in 1996 [1]. This work used finite element modelling to assess the pressures developed in the fluid due to impact with a flat surface, but the assessment did not consider stresses in the structure itself.

The main aim of this work package is to develop a new finite element model to predict the behaviour of a tanker in a roll over event more accurately; in particular, modelling the action of the fluid more closely, and taking into account the structural impact. The model will be validated by performing full scale tests on a tanker filled with water. Once validated, the model can then be used to assess a variety of different loading cases, the first of which would be for a similar impact but using fuel instead of water.

This report presents the general approach that will be used for the modelling. HSL report ES/14/39/06 will describe the model in more detail, present the predictions and results from the model, and compare these with the measurements from the experimental tests. This report is part of a package describing HSL's work on WP1 up to 29 August 2014. The reports in this package are given in Table 1.

Table 1 List of HSL reports in this report package for Work Package 1

ES/14/39/00	Technical Assessment of Petroleum Road Fuel Tankers; Work Package 1 - Full scale testing and associated modelling; Overall Summary
ES/14/39/07	Technical Assessment of Petroleum Road Fuel Tankers; Work Package 1 - Full scale testing and associated modelling; Assessment and Supply of Tankers
ES/14/39/04	Technical Assessment of Petroleum Road Fuel Tankers; Work Package 1 - Full scale testing and associated modelling; Tanker Topple Test Methods and Results
ES/14/39/05	Technical Assessment of Petroleum Road Fuel Tankers; Work Package 1 - Full scale testing and associated modelling; Modelling to Provide Load Case Data for Rollover – Approach and Initial Development **THIS REPORT**
ES/14/39/06	Technical Assessment of Petroleum Road Fuel Tankers; Work Package 1 - Full scale testing and associated modelling; Modelling to Provide Load Case Data for Rollover - Validation and Application

2 FLUID STRUCTURE INTERACTION USING EULERIAN/LAGRANGE APPROACH

For a fuel tanker with a full load, the majority of the mass consists of the fuel load (approximately 30 tonnes of fuel and 5 tonnes for the tanker body). Therefore, an appropriate representation of the fuel is necessary to accurately model the event. The approach adopted for modelling the interaction of the fluid with the tanker shell was a fully coupled Euler/Lagrange model, using Ansys and Autodyn v15. The main features of the approach will be described in this section, followed by a brief discussion of some of the alternatives.

2.1 EXPLICIT SOLVER

The impact of the tanker with the ground is a highly dynamic event, with an impact velocity of approximately 4 m/s, and is likely to result in large deformations and high levels of strain. In terms of dynamic analysis, this is relatively slow (compared to ballistic events, for example) but it is still fast enough to be suitable for an explicit analysis. The duration of the main impact which causes the majority of the deformation and stress in the tanker was approximately 100 ms.

Explicit solvers are particularly suited to dynamic events and are the main type of solver used for crashworthiness modelling. The more common implicit finite element solution techniques can be used for transient loading but can have problems converging to stable solutions, especially for highly nonlinear problems.

The explicit dynamic solver uses a central difference time integration scheme. After the forces have been computed, the nodal accelerations are derived by equating the acceleration to force divided by mass. The velocity at time n+1/2 (half a timestep later) is then found from the calculated accelerations. Finally, the displacement for the next timestep (n+1) is calculated by integrating the velocities over the timestep. This method can be much quicker than the implicit method as no iteration is needed during the time integration; however, small timesteps are normally needed resulting in a large number of solutions being needed for even short events.

To ensure stability and accuracy of the solution, the size of the timestep is limited by the Courant-Friedricks-Lewy (CFL) condition. This condition sets a limit to the timestep such that it prevents a stress wave travelling across an element in a single timestep. The timestep is therefore dependent on the smallest element dimension and the speed of sound in the material attributed to the element (which is dependent on the material stiffness and density). Mesh quality is therefore important in explicit analyses as a single small element could control the timestep and solution time, although this can be avoided to some extent by using mass scaling, as discussed in Section 3.3.

2.2 LAGRANGE MESH

The Lagrange meshing approach is the standard approach used for meshing solid objects in finite element analyses. In this method, the volume of the solid is divided into discrete elements, with each element given a proportion of the mass of the component. The mass associated with each element remains with the element at all times, and the element deforms according to the strains on that element of material. When strains are very high, the elements can get highly distorted leading to convergence problems.

2.3 EULER MESH

With an Euler mesh, the mesh stays fixed in space and the material flows through the mesh. Each element has a single value for density, velocity and pressure so the amount of fine detail that can be represented using an Euler mesh is limited. It is therefore less suited to modelling solids with fine geometric detail. However, as the mesh does not distort with the material, the Euler approach is well suited to situations where high deformations are expected, such as metal forming or fluid applications.

2.4 COUPLING

In a Fluid-structure interaction (FSI) model, the Euler and Lagrange domains need to interact with each other. This is achieved by defining coupling surfaces. A coupling surface acts as a boundary to the Euler domain, restricting the flow of the Euler material. The pressures in the Euler domain acting on the coupling surface are applied to the Lagrange elements associated with the coupling surface. The position of the coupling surface is updated as the Lagrange elements deform.

As the Euler elements have a single value for their properties, it is not possible to determine where in any Euler cell the material is located. Therefore, if shell elements are used as a coupling surface, an artificial thickness must be applied to avoid a cell being split; in this case it would not be possible to determine which side of the coupling surface the fluid lay. Therefore, an artificial thickness needs to be applied to ensure that at all times at least one full cell is completely covered by the coupling surface. The artificial thickness does not affect the stiffness of the elements, or the contact of the elements with other structural elements.

When the fluid is all on one side of the shell coupling surface, as in the case with the main tanker shell, the artificial coupling surface thickness can be applied to the outside of the tanker. In this case, the thickness has no effect on the solution. However, if an internal bulkhead was to be defined as a coupling surface, the artificial thickness would result in a loss of some fluid. In the model of the tanker, the bulkheads were not defined as coupling surfaces to avoid loss of fluid as the pressures exerted on each side of the coupling surface would be practically the same. Any model containing an empty compartment would be modelled with the bulkheads dividing the empty and full compartments defined as coupling surfaces, with the artificial thickness positioned so that it covered elements in the empty compartment.

2.5 ALTERNATIVES - SMOOTH PARTICLE HYDRODYNAMICS

Sometimes referred to as a meshless method, Smooth Particle Hydrodynamics (SPH) uses smooth particles to represent the fluid domain. The particles are packed into the desired volume and given appropriate material properties for the fluid to be modelled.

For SPH, coupling surfaces are not required, as the particles interact with the structure using the standard contact algorithm used in the model ('gap' or 'trajectory'), although in the code used, 'trajectory' contact cannot be used with parallel processing.

Both Euler and SPH methods have been shown to be suitable methods for modelling liquid sloshing in tanks. The choice of which method to use was largely based on the practicalities of using the techniques in the software used by HSL.

A major consideration in the decision was the fact that, in the current release of the software used by HSL, 'trajectory' contact cannot be used with SPH when using parallel solvers. Therefore, using SPH would require 'gap' contact to be used; otherwise the problem would have to be solved using a single processor. The 'gap' contact algorithm is not as efficient as the trajectory contact algorithm, and requires an initial small gap between contacting components which makes setting up the geometry more difficult. Test runs revealed that an SPH model initially ran more quickly, as SPH is generally quicker to solve, but once the initial gap had closed and the gap contact algorithm was in use, the solution times were slower.

2.6 ALTERNATIVES – LAGRANGE REPRESENTATION OF FLUID

It is possible to model liquids using Lagrange elements. The main problem with this approach is that as the liquid would have a very low stiffness, large deformations would be likely to develop, thus distorting the mesh.

3 DETAILS OF MODELLING APPROACH

A number of options are available for the modelling of tankers using the Euler/Lagrange interaction method. Some options are discussed in this chapter. Where test cases have been analysed, this has been performed on a simple model of a single compartment (the rearmost compartment) in order to assess a number of different variables as quickly as possible. The results have been expressed in terms of deflection of the rear of the tanker as this simple result gives a good indication of the overall deformation caused by the impact.

3.1 ULLAGE: VOID OR AIR

In reality, the unfilled volume (known as ullage) of each compartment would be filled with a mixture of air and fuel vapour. In the finite element model, the free space could be modelled either as a gas or as a void. If modelled as a void, the cells not filled with liquid are simply left empty. This would also apply to empty cells on the outside of the compartment so there would be no pressure difference due to the lack of air.

The air/vapour in the compartment would be likely to have two effects on the behaviour of the fluid:

1. It would provide some resistance to the movement of the liquid

2. It would pressurise in the event of a reduction of volume of the compartment

The resistance to movement of the liquid would be likely to be minimal, so it would not be worth the additional resources to model the air/vapour to capture this effect. The pressurisation of the compartment would depend on the reduction in volume, but would be limited to the pressure at which the pressure relief valve was set, which would be likely to be in the order of 1 bar. As no method of pressure relief or limiting pressure is incorporated in the model, it may be more accurate to model the ullage as a void. This approach would also be quicker to set up and much quicker to solve.

3.2 WEAK COUPLING

When running a fluid structure interaction model using Euler for the fluid domain, it is possible to record the pressures in the fluid in a form that enables them to be applied to a structural-only model. This method is called weak coupling, as the coupling acts only in the direction from fluid to structure; any changes in the structural response would not be transferred back to the Euler domain.

As it is often the Euler domain that requires the majority of the computational effort, replacing the Euler domain with recorded pressures could be an effective way of reducing solution times. It would be possible to perform a run using an Euler approach to obtain the pressure files, and then a series of structural-only models, perhaps with varying mesh size. One would have to be confident that any changes to the model would not have a significant effect on the pressures.

There are two main drawbacks in terms of solution times for this method. Firstly, saving the pressure files slows down the solution of the Euler model. The degree to which the solution is slowed is related to the frequency of recording of the pressure files. Recording the pressures less frequently would reduce the solution times, but may affect the accuracy of the subsequent models.

The second drawback for solution times is the fact that, at present, parallel processing is not available in The software used by HSL for structural models when using weak coupling inputs. While a structural only model, using the weak coupling inputs, running on a single processor could be quicker than a model with the Euler domain running on multiple processors, using Euler subcycling would remove this advantage. Euler subcycling is discussed in Section 3.4.

3.3 MASS SCALING

As the timestep used in solution of explicit models is based on the time taken for a stress wave to travel across the smallest element, overall solution times can be highly dependent on the quality of the mesh. A single poorly formed, or small element could significantly reduce the timestep and therefore increase the solution time. To overcome this issue, it is possible to artificially increase the density of problematic elements, which reduces the speed of sound in those elements, thus allowing larger timesteps and faster solutions.

This approach can be very effective if a small number of elements are significantly smaller than the majority of elements. When using the mass scaling approach, limits are set for both the maximum factor that can be applied to an individual element mass, and to the total increase in mass for a part. The default settings in the software used by HSL are for an element factor of 100 (i.e. increasing the mass 100-fold) and the maximum increase in a part mass of 5%. The applied mass scaling can be viewed, as shown in Figure 1. Here, the elements not coloured blue have had additional mass applied to them to prevent these small elements overly constricting the timestep. In this example, the mass scaling resulted in a timestep three times larger, reducing the solution time by over 60%.

The effect of using mass scaling on solution times and displacement results are shown in Figure 2 and Figure 3 respectively.

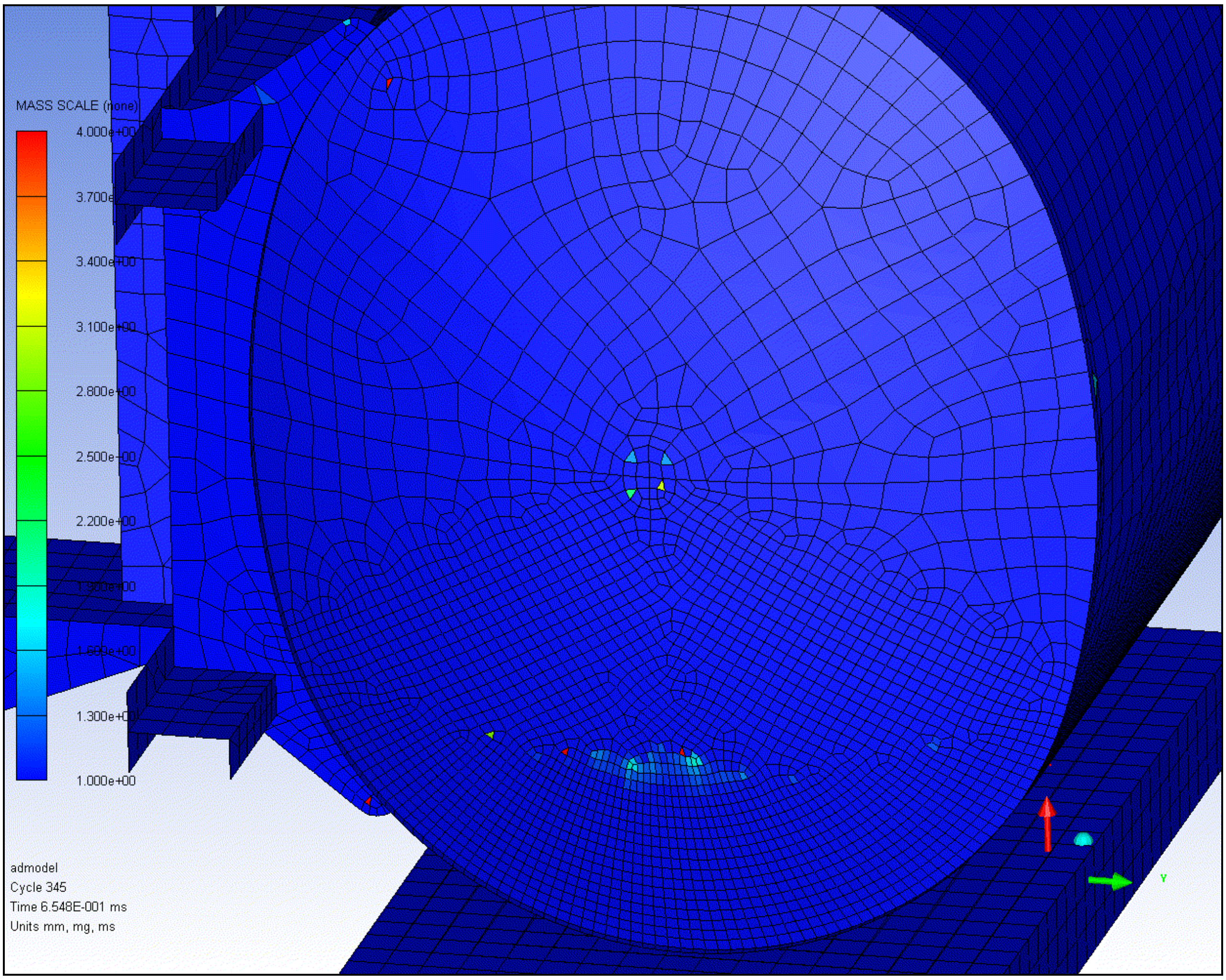


Figure 1 Mass scaling on a typical mesh

3.4 EULER SUBCYCLING

The materials modelled in the Euler domain are often fluids with much lower sound speeds than the solid materials modelled using the Lagrange mesh. Also, the cell size can be larger and more uniform than for the detailed Lagrange solid mesh. Therefore, the minimum timestep for the Euler domain is often much larger than for the Lagrange domain. As the Euler domain is frequently the most computationally expensive, unnecessarily small timesteps in the Euler domain can impose a heavy penalty on solution times.

The software used by HSL allows Euler subcycling, which effectively allows the Euler domain and Lagrange domains to use different timesteps. The Euler equations are just solved once for several Lagrange steps, with the number of Lagrange steps between Euler solutions being determined by the difference in required timesteps. The pressures exerted on the coupling surfaces by the fluid in the Euler domain remain constant between Euler solutions.

Figure 2 shows deflection/time plots for model run with and without mass scaling and Euler subcycling.

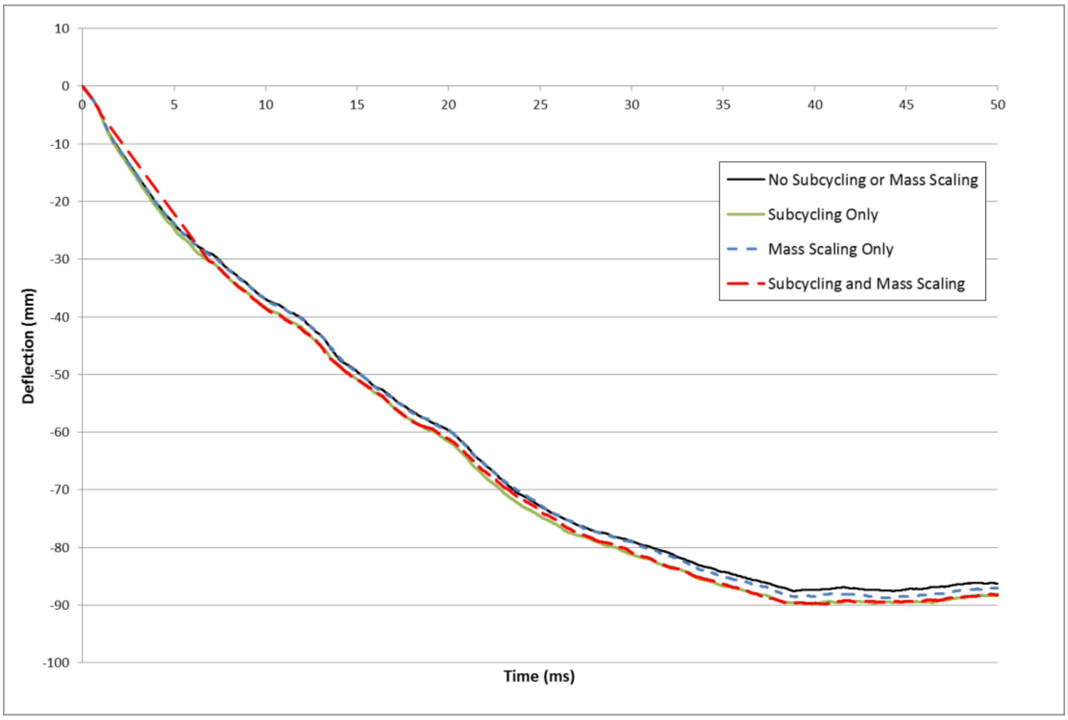


Figure 2 Effect of subcycling and mass scaling on deflections
(ignore red line for first 7 milliseconds – data lost due to restart of solution)

Figure 3 shows the effect of mass scaling and subcycling on the maximum deflection of the rear of the tanker. The speed of the solution for the different approaches, in terms of minutes of solution time per millisecond of event time modelled, is also shown.

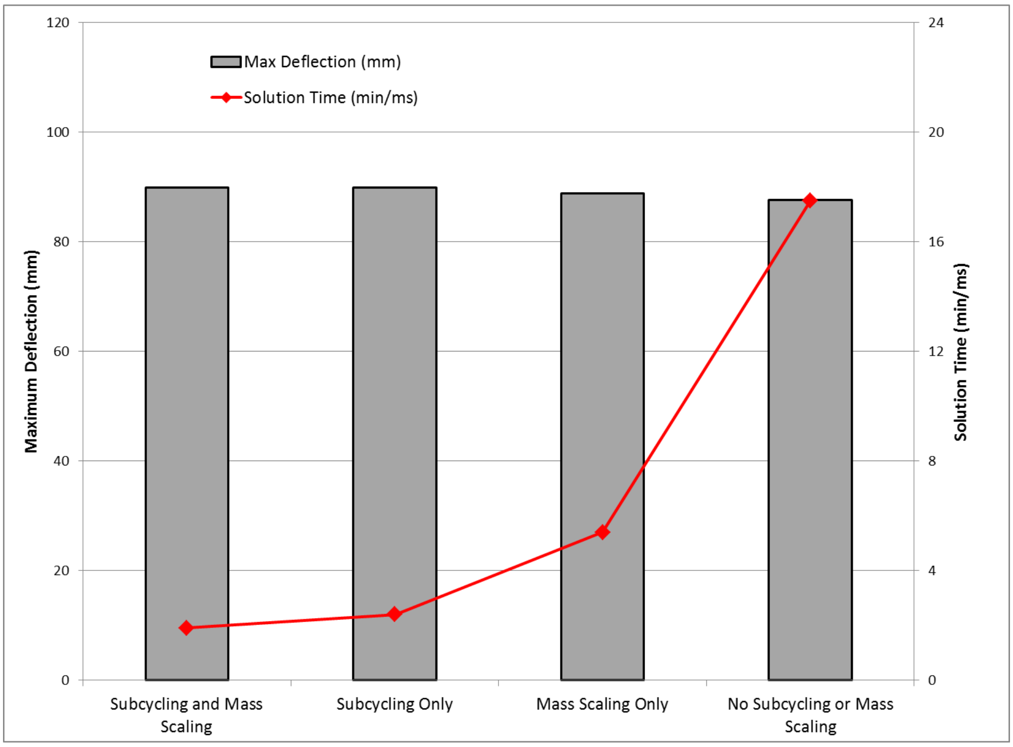


Figure 3 Effect of mass scaling and subcycling on maximum deflection and solution time

As illustrated in Figure 3, using a combination of Euler subcycling and mass scaling can have a significant effect on solution time without significantly affecting results. In this example, a nine-fold increase in the solution speed is obtained with a difference in results of less than 3%. As HSL will produce complex models which may take days to run, modelling productivity increases significantly if faster solution speeds can be used without significantly compromising model outputs.

3.5 MESH SENSITIVITY

For any finite element analysis, the results obtained are sensitive to the mesh, both in terms of the quality and the size of the mesh. Unfortunately, the computer resources required to solve a model are also highly sensitive to the mesh size. For an explicit analysis, halving the average size of the elements would result in a four-fold increase in the number of elements for shell structures (eight-fold for solids), and a halving of the timestep. Therefore, obtaining the correct balance between accuracy and solution times is important.

The increase in the total number of elements can be limited by using local mesh refinement, i.e. using a fine mesh in areas where large stress gradients occur. The timestep reduction would still occur, but this can be mitigated to some extent by using mass scaling. However, mass scaling is most effective when a small number of unusually small elements dictate the timestep; in the case of an area being meshed more finely with uniformly small elements, the mass being added to the area may be significant and therefore mass scaling may not be appropriate.

Convergence studies can be performed to assess the relationship between element size and results. A model comprising of a single compartment was meshed using elements ranging in size from 40 mm to 5 mm with all other variables kept constant, as shown in Figure 4. The results for deflection over time are shown in Figure 5. As can be seen, the difference between the 40 mm and 20 mm mesh results is significant, but subsequent refinement of the mesh did not result in a significant difference in the predicted deflection.

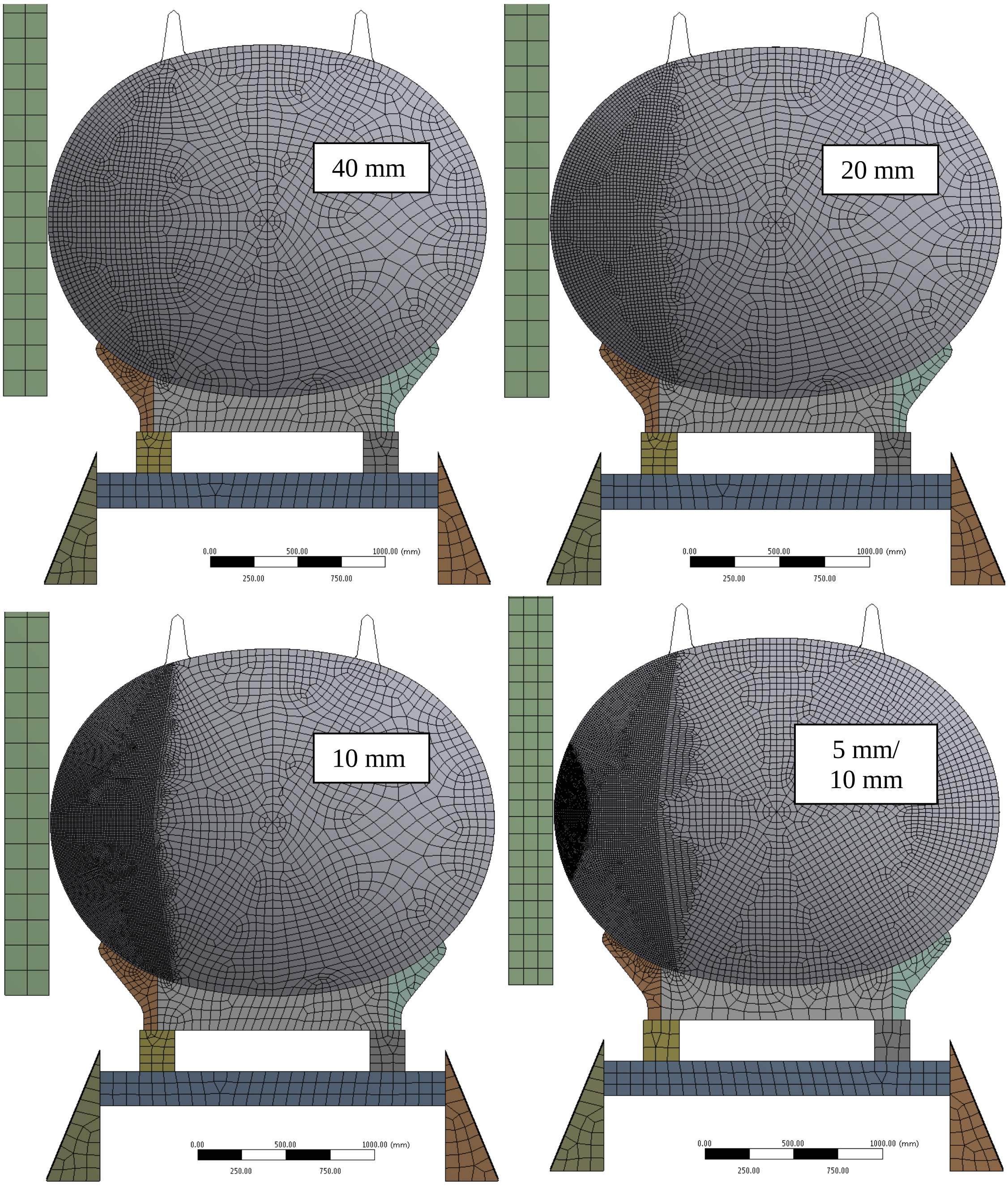


Figure 4 Meshes used for the mesh convergence study

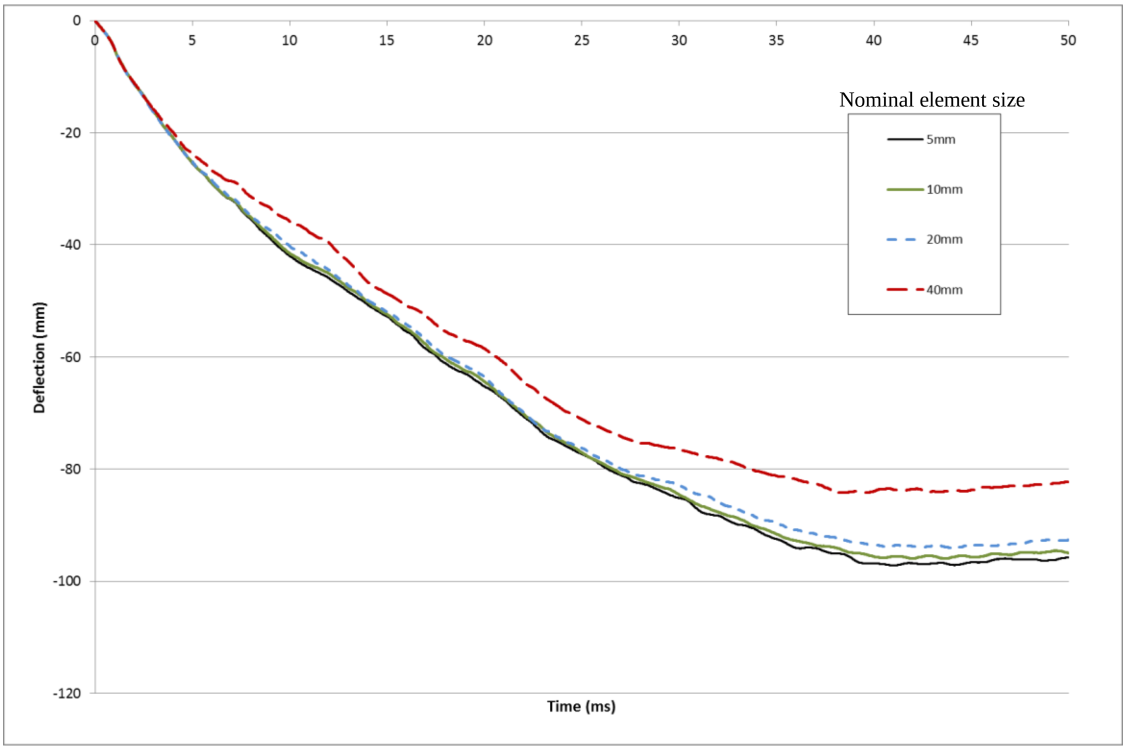


Figure 5 Effect of mesh size on deflection

Table shows the effect of mesh size on the predicted displacement, and also the time required to complete the computation for every millisecond of the impact simulation. The difference is the % increase between the result and the result from the row directly above.

For example, for element size 20, the difference = 100 x (94.0 – 84.2)/84.2 = 11.6%. So the deflection for element size 20 is 11.6% greater than the displacement for element size 40.

Table 2 Effect of mesh size on displacement results and solution times

Element Size	*No of elements*	*Max Deflection (mm)*	*Difference*	*Solution Time (minutes/millisecond)*
40	9457	84.2		1.6
20	25862	94.0	11.6%	2.4
10	98483	96.0	2.1%	8.1
5	168245	97.0	1.3%	43.0

4 GEOMETRY

4.1 SHELLS/SOLIDS

As mentioned earlier, the timestep used for explicit solutions is based on the length of time it would take for a stress wave to travel through the shortest element dimension. Therefore, if solid elements were used to model thin shells, the minimum dimension would be equal to the thickness of the material at the very least. Ideally, more than one element would be used through the thickness, resulting in even smaller element dimensions. Also, to avoid large aspect ratios the number of solid elements would be much higher. This would result in a prohibitively slow running model.

All of the tanker and the supports, suspension, wheels, fifth wheel and the steel landing pad were modelled using shell elements. The only solid elements used were for the concrete pad. The majority of the shell elements were 4-noded quadrilateral elements, with the remainder being 3-noded triangular shell elements.

4.2 TANKER GEOMETRY

The tanker geometry was based on drawing 085-45-500-04 supplied from GRW and measurements taken of the physical tanker. The drawings had the main dimensions of the shells and the front support structures, but not of the other components such as the rear supports or pipework. More detail about the exact geometry used in the model can be found in the validation report (ES/14/39/06).

4.3 MODELLING BANDS/EQUIVALENT STIFFNESS

While shell elements are ideal for modelling plane shell sections, such as the majority of the tanker shell, the extruded bands are thicker and do not have a constant profile. Modelling these sections with solid elements would present the problems discussed above as, even though the number of elements would be lower, the small solid elements would still dictate the timestep.

Therefore, the bands were modelled using shell elements, and given a thickness to best approximate the stiffness of the bands. To achieve this, the sections were drawn in the geometry creation software of the finite element code and the second moments of area were calculated by the software. This was done for the different extrusion designs used for GRW tankers J3190 and J2580, and for each design for areas with and without the internal fillet weld. These are shown in Figure 6 and Figure 7. Shell thicknesses were then chosen to give the same second moment of area (I) about the X-X axis; these are listed in Table 3. Matching the second moment of area about this axis was chosen as this is the most likely bending direction for the extrusions during the impact.

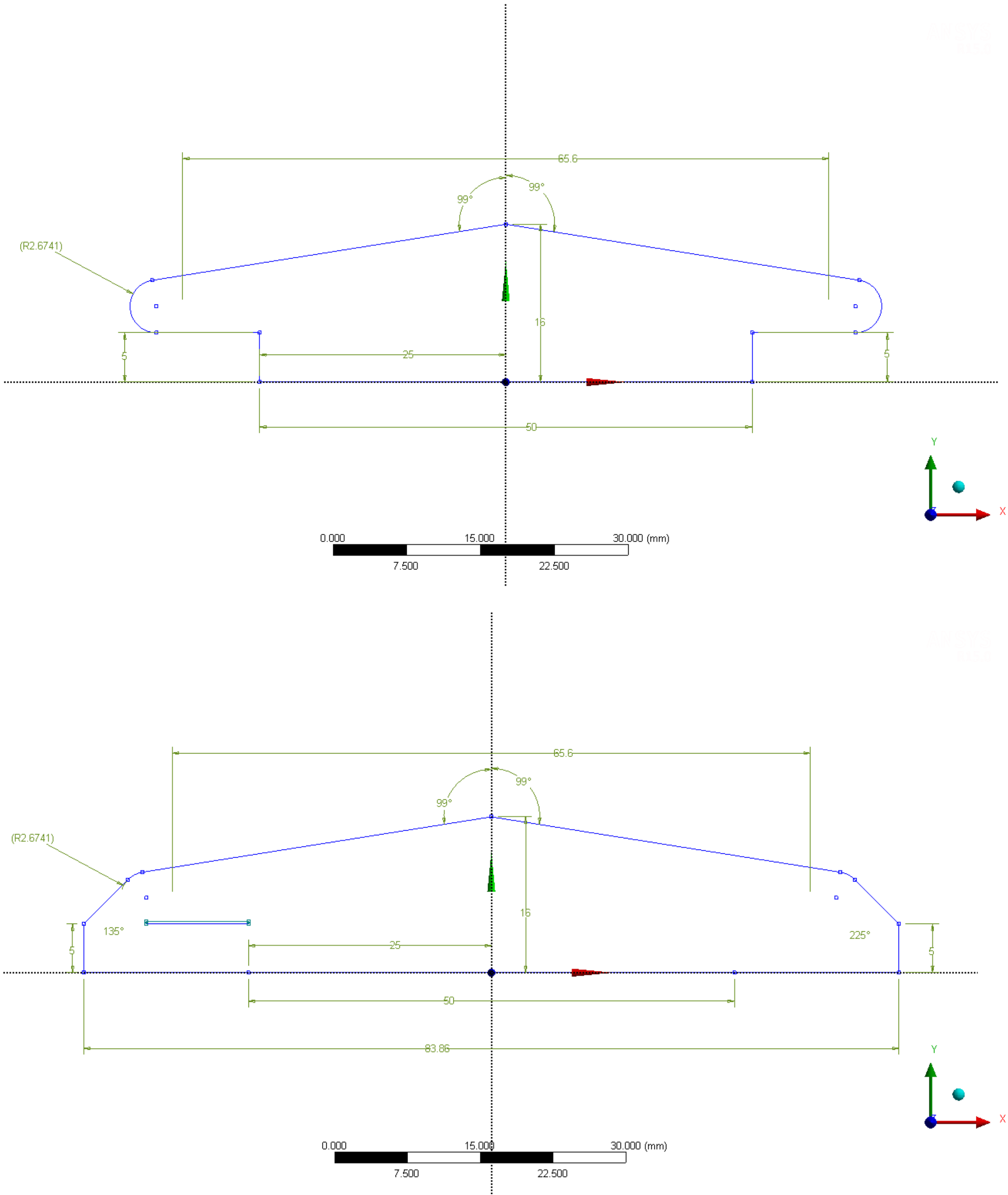
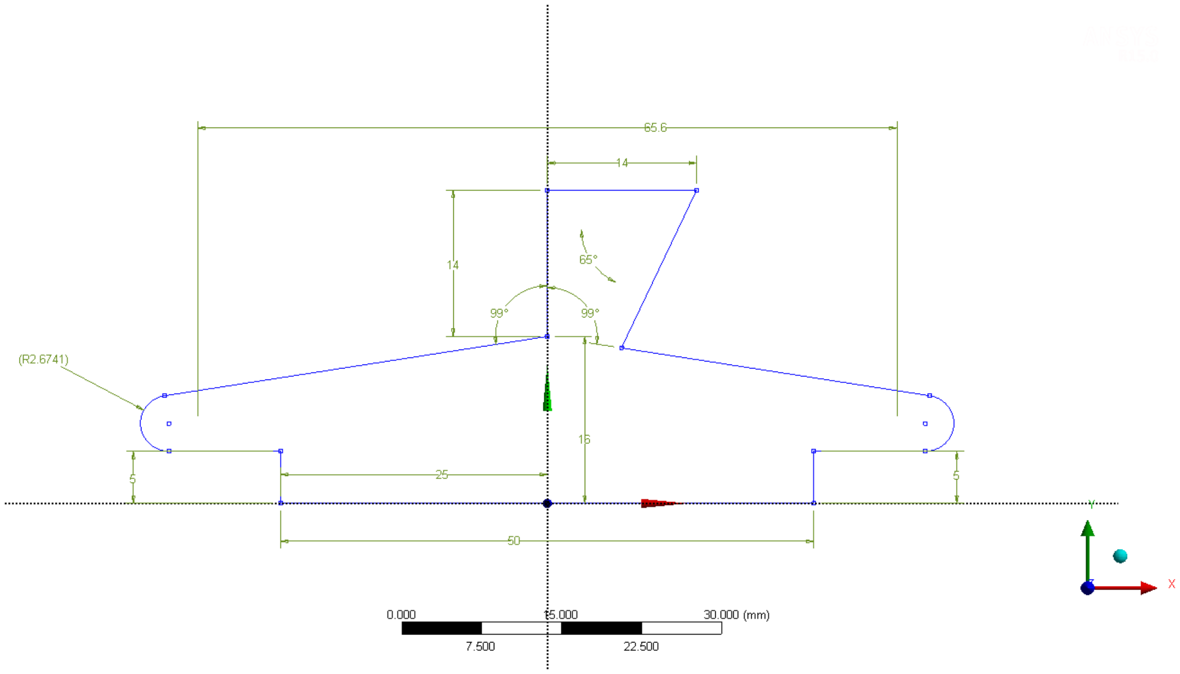


Figure 6 Band extrusion profiles for GRW tanker J3190 without and with fillet weld
without fillet weld - top; with fillet weld - bottom



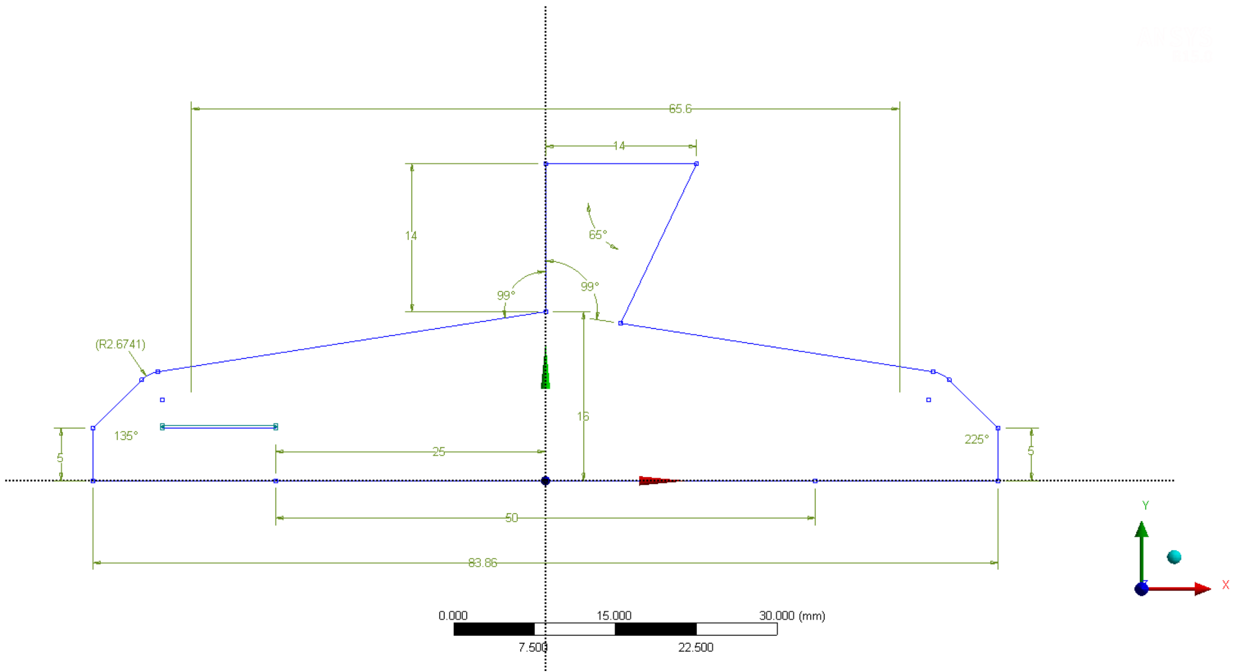


Figure 7 Band extrusion profiles for GRW tanker J2580 without and with fillet weld
without fillet weld - top; with fillet weld - bottom

Table 3 Properties of extruded bands with equivalent properties for shells

		J2580		*J3190*	
		Without fillet	***With fillet***	***Without fillet***	***With fillet***
Extrusion properties	I_x (mm^4)	49739	57762	12538	16076
	I_y (mm^4)	288140	507700	282000	504000
Shell properties	Thickness (mm)	22.7	21.0	14.3	13.7
	I_x (mm^4)	49739	57762	12538	16076
	I_y (mm^4)	250968	737751	158537	481678

5 MATERIAL PROPERTIES

5.1 TANKER ALUMINIUM

In an email communication with The Welding Institute (TWI), a series of test results on plate and weld metal from GRW tanker J3025 were supplied. As the vast majority of the tanker consists of parent plate material and the welds are not explicitly represented in the model, only the parent metal test results were considered.

The software used by HSL has a multi-linear isotropic hardening model to represent the behaviour of the aluminium beyond the yield point. The inputs for this model are true stress[3] and true plastic strain. Therefore, the test data was first converted from engineering stress and strain to true stress and strain using the following two equations:

$$\sigma_T = \sigma_{eng}(1 + \varepsilon_{eng})$$

$$\varepsilon_T = ln(1 + \varepsilon_{eng})$$

Where σ_T and σ_{eng} are the true and engineering stresses respectively, and ε_T and ε_{eng} are the true and engineering strains respectively.

The plastic strains were then calculated by subtracting the elastic strains from the total strain data; these are plotted in Figure 8 with a curve fitted to the data for use in the model.

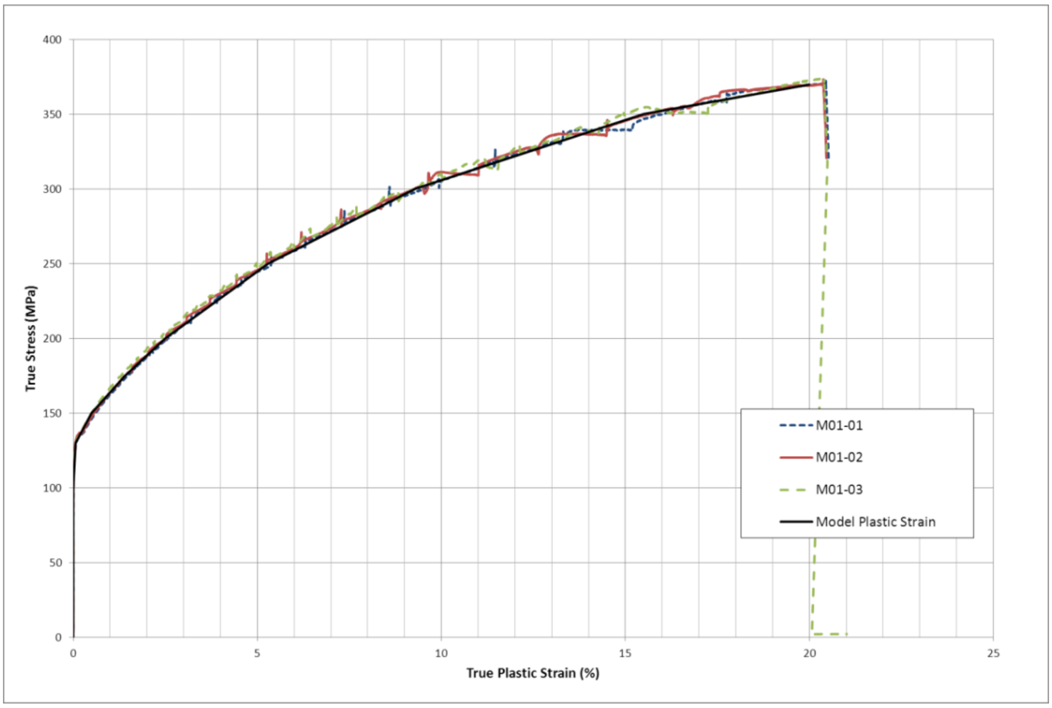


Figure 8 True stress – true plastic strain curves

[3] *Engineering stress is calculated using the original cross sectional area. However, as tension is applied, the specimen thins slightly and then necks, reducing the cross sectional area. The true stress in the material is based on this reduced area. Similarly with strain, the engineering strain is based on the initial gauge length, whereas the true strain takes into account the incremental change in length.*

Other material properties set for the tanker material were a density of 2770 kg/m^3, a Young's modulus of 71 GPa and Poisson's ratio of 0.33. These were the standard values of the non-linear aluminium alloy material in the software material library.

5.2 CONCRETE

The material properties used for the concrete of the test pad were taken from the software material library for 35 MPa concrete (i.e. the specification for the concrete pad). This had a density of 2314 kg/m^3 and a shear modulus of 16.7 GPa. The model also had a polynomial equation of state and a porosity equation of state. As the concrete was solely acting as a hard surface for the impact and would be unlikely to be subject to high levels of stress, the exact material model used for the concrete is likely to be unimportant to the model of the tanker.

5.3 STEEL

As the steel components of the model (i.e. the fifth wheel, axles, suspension, steel wheels and the plate covering the concrete pad) were not expected to experience significant stresses or deformations, the standard structural steel elastic material properties were used. These were a density value of 7850 kg/m^3, a Young's modulus of 200 GPa and a Poisson's ratio of 0.3. The material was assumed to be elastic (i.e. no yield properties were necessary).

5.4 WATER

The water material properties were taken from the software material library. These were a density value of 1000 kg/m^3 and a shear modulus of zero. The library water properties also contain a shock equation of state.

A brief investigation into the effect of fluid properties was conducted to determine the effect of changes to density and bulk modulus. The single compartment 30 mm mesh model was run with three different fluid properties:

1. standard water with a bulk modulus of 2.15 GPa;

2. water with the bulk modulus reduced to 1.0 GPa; and

3. petrol, with a density of 750 kg/m^3 and bulk modulus of 1.3 GPa.

The volume of the fluid in the petrol model was increased to maintain the same mass.

The results from the three runs are shown in Figure 9. Reducing the bulk modulus was shown to have a very small effect (<1%) on the deflection of the tanker even though the value was reduced to a value lower than would be normal for any fuel carried. Modelling the fluid as petrol, with the volume increased to keep the mass the same as the water models, had a larger influence on the deflection, with the maximum deflection increasing by almost 5%.

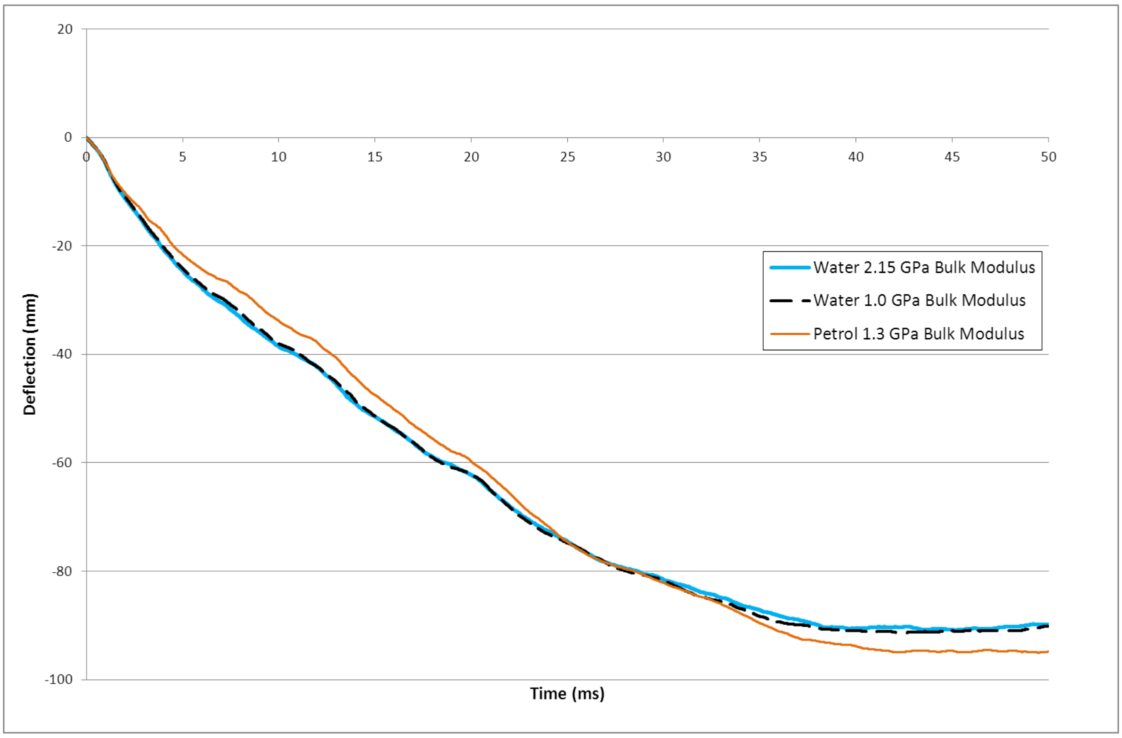


Figure 9 Effect of different fluid properties on tanker deflection

6 BOUNDARY CONDITIONS

6.1 GENERAL

The lower surface of the concrete was fixed in all directions. The steel plate was bonded to the top face of the concrete.

Contact was defined between the tanker shell, bands and baffle and the ground steel plate. No contact was defined between the supporting structure of the tanker and any of the other components.

The tanker shell, bands, bulkheads, baffles, front and rear supports, ancillary items, and rear suspension and wheels were all defined as one part. These items shared topology, so the mesh was consistent and nodes were shared. Therefore, all the items were fully bonded to each other.

The fifth wheel was defined as a separate component, with bonded contact defined between the top of the fifth wheel and the bottom of the front support at the king pin location.

6.2 INITIAL VELOCITY

As the time to solve explicit models is proportional to the length of the event being modelled, it is far more efficient to model a short duration event. In order to make more efficient use of computer resources, the model of the tanker topple will begin at the moment just before impact. Therefore, the impact velocity must be an input to the model.

As the primary purpose of the model in this stage of the project is to be validated against experimental results, the impact velocity will be obtained from the high speed video of the test. The vertical velocity on impact will be translated to an angular velocity about the pivot point (the outer edge of the steel wheels).

6.3 INITIAL WATER CONDITIONS

At the point of instability, the water will have a top surface horizontal with respect to the ground. If the topple event were very slow, the water would be able to maintain the top surface horizontal to the ground until impact. This would require the water to move relative to the tanker and have a different angular velocity. However, at the other extreme, if the topple event were rapid, the water may not have time to settle but may maintain its shape relative to the tanker.

The behaviour of the water prior to impact was investigated using a much simplified model representing a small slice of the tanker. This model was initiated just after the point of instability (at approximately 35 degrees) with the surface of the water horizontal to the ground and run to the point of impact, as shown in Figure 10.

As the tanker reached the point of impact, the surface of the water was at approximately 45 degrees. Therefore, it can be inferred that the water rotated by approximately 10 degrees relative to the tanker during the topple, thus giving it a different angular velocity compared to the tanker.

In order to determine the angular velocity of the water, including finding the centre of rotation, lines were constructed perpendicular to the velocity vectors at a number of gauge points. The intersection of these lines (or the best fit approximation) was then taken to be the centre of rotation. The angular velocity was then taken to be the average of the angular velocities calculated from the linear velocities and distance from the centre of rotation. In the example shown here, the angular velocity was estimated to be 0.84 rad/s, with the centre of rotation approximately 3 m beyond the pivot point for the tanker (the edge of the steel wheels).

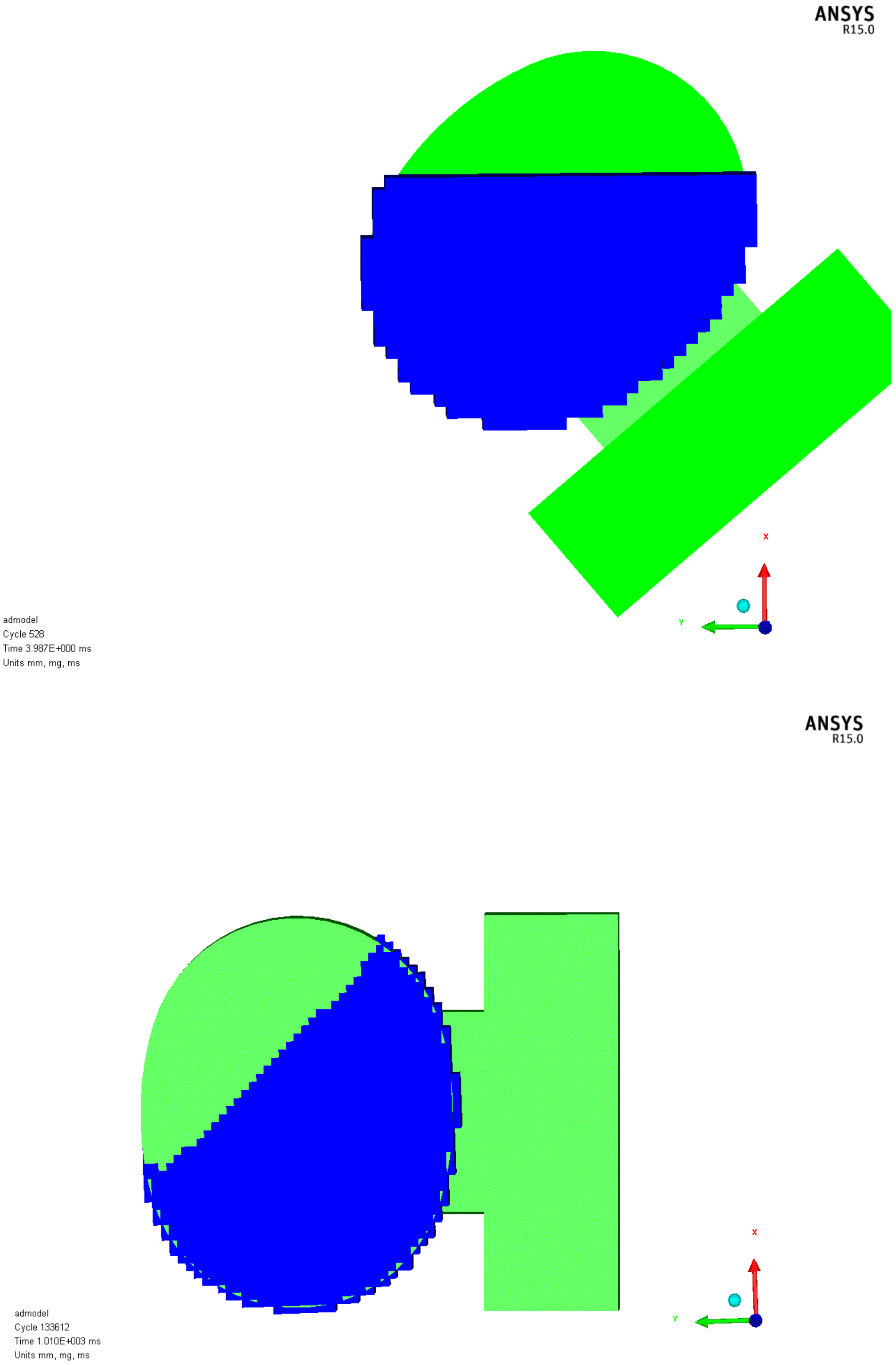


Figure 10 Starting point of topple and impact point showing change in water angle
Starting point - top image; impact point - lower image; water blue, air/vapour above water green

7 CONCLUSIONS

A suitable finite element model for GRW tanker rollover based on HSL's topple test has been created. This model will be refined and validated against experimental data from HSL's topple tests of GRW tankers.

The Euler/Lagrange fluid structure interaction approach was chosen for the analysis of the tanker topple event. This approach allows the detailed geometry of the tanker to be represented using shell elements and the liquid in the tanker to be modelled.

The empty space in the tanker's compartments was modelled as a void, as opposed to assuming air or air/fuel vapour, as this approach is much more efficient in terms of solution time. It also prevents the build-up of pressures in the compartment due to the reduction in volume caused by crushing, as in reality this build-up would be prevented by the pressure relief valves.

As this model does not consider the detailed behaviour of the welds at the extrusion bands, a mesh size of between 10 mm and 20 mm was found to be appropriate for the sections of the tanker subject to the largest deformations, and very little difference in deflection values was observed with further refinement. However, when data from this model is compared to test data the mesh size will be reviewed.

GRW tankers J3190 and J2580 used different extrusion designs in the construction of the bands which join the sections of the tanker together. So, geometries for both designs were created for the model of the extrusion band. These tankers also included fillet welds in different positions on the joint between the extrusion and the shell plate. Geometries for the extrusion band with and without fillet welds were created for use where appropriate.

The adoption of the techniques of mass scaling (adding mass to some small elements to increase the solution speed) and Euler subcycling (solving the fluid regions of the model less frequently than the solid parts) were found to offer large benefits in terms of solution times without significantly affecting the results obtained.

Varying the bulk modulus (the compressibility of the fluid) had an insignificant effect on the deflection of the tanker, even for large changes in modulus. Fluid density (with associated change in volume to keep the mass constant) has a larger effect. An equivalent mass of petrol resulted in a larger deflection than water.

8 REFERENCES

[1] I.N. Bysh and M.R. Dorn '*The generation of internal pressure in tanker rollover',* HSE Contract Research Report No 109/1996.