Dynamic Explicit SPH Simulation and Material Characterization of Road Tankers using LS-DYNA

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Abstract

Crossland Tankers is a significant manufacturer of bulk-load road tankers from Northern Ireland. Thirty thousand litres of liquid are carried over long distances and varying road conditions. The effect of sloshing within the tank can significantly impact the driveability and lifespan of the tanker. As part of this project with Crossland Tankers, we will develop a model using LS-DYNA to investigate the applications as part of the design process.

Multiphysics simulations are now more emphasised than physical tests due to environmental, financial, and time requirements in the competitive manufacturing industry. Thus, developing models to predict and analyse the system's behaviour accurately is imperative.

Fluid simulations are typical when studying baffle design but only consider the dynamics within the tank. This project aims to create a general-purpose model of a road tanker that captures road, tyre and suspension dynamics and the effect on the chassis. With this model, different driving conditions can be applied, and the effects on various components can be studied.

This paper describes the process of using OASYS PRIMER as a preprocessor for DYNA to build a Fluid-Structure Interaction (FSI) model with Smooth Particle Hydrodynamics (SPH) used to model the fluid and Explicit Dynamic FE techniques to model the chassis. The model will simulate a tanker undergoing emergency braking and other worst-case scenarios to identify areas that experience high fatigue levels due to liquid sloshing. The model was attempted to be validated using road testing carried out on a tanker using acceleration and strain data by Resonate Testing Ltd.

Crossland uses 304 stainless steel sheet metal in the construction of their tank, and high cycle fatigue and tensile testing were carried out to produce load curves to characterise the material using *MAT_123 (MODIFIED_PIECEWISE_LINEAR_PLASTICITY).

In this paper, we describe (i) The process of creating a Multiphysics simulation of a road tanker. (ii) The process of material characterisation for S304 steel. (iii) The testing was undertaken on a road tanker to validate the model.

1 Introduction

Crossland Tankers began in 1988 as a tanker repairs and servicing company but soon began manufacturing their tankers for the UK road industry. Specialising in bulk liquid tankers, Crossland works with customers from concept to completion to build a tank to the customers' requirements.

Bulk liquid transportation is a significant portion of the UK supply chain, with approximately 300 terminals for importing, exporting and distribution. These tankers can travel hundreds of miles in a day and are subject to forces that can seriously affect the lifespan and driveability of the vehicle, mainly road vibrations and sloshing forces induced by the liquid.

With the road network of the UK being of such varying quality, Tankers across Ireland are subject to worse road conditions than those in Great Britain. A milk collection tank, for example, will drive between farms on rural country roads at various fill levels, and the poor road conditions can take years off a tanker's lifespan.

Fluid Sloshing is the oscillatory motion of liquid inside a partially filled container due to external disturbances. In a road tanker, this can lead to safety concerns. Rapid braking or cornering can induce severe sloshing and destabilise a tanker by shifting the centre of gravity, increasing the risk of rollover.

For Crossland, a better understanding of the sloshing forces means they can make informed design choices and suggestions for improving the driveability and lifespan of the tanker. Designing a lightweight tanker allows for a greater payload, so the model will also be used to identify areas where weight reduction can be made without affecting the integrity of the tanker. This is an obvious selling point where lightweight products mean more carrying capacity.

In today's manufacturing industry, there is a shift away from physical prototyping to more emphasis being placed on Multiphysics simulations spurred on by advancements in computational capabilities and

developments in simulation software. As these methods become more accurate and reliable, their presence in the design process will only become more prevalent as virtual testing on numerous design iterations can be done at a fraction of the cost. Model validation must be undertaken to ensure model accuracy through collecting real-world test data.
Currently, Crossland has no method of verifying design changes and has experienced the removal of parts for weight saving, resulting in premature chassis failure. By creating a "worst case scenario" load case of the tanker undergoing an emergency braking manoeuvre, it is hoped that a better understanding of the key areas of weakness in the tank and the effect of new design iterations will be gained.

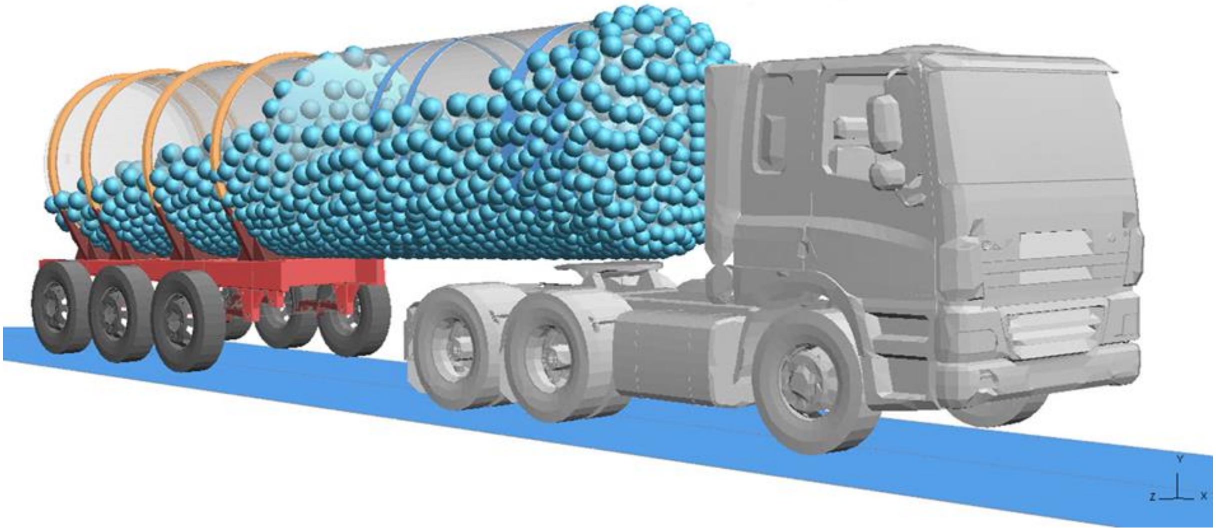


Fig.1: Multiphysics Tanker Model

This project aims to create a general-purpose Multiphysics model of a road tanker sown in Figure 1, so different areas of simulation and analysis must be combined to achieve this. The key areas include:

- SPH modelling of the fluid in the tank.
- FSI between the SPH and the FEA chassis.
- Suspension and road dynamics.

Sloshing models have been used extensively in baffle optimisation to reduce sloshing force with multiple methods of modelling the fluid existing across various software.
Most early attempts use a numerical approach of deriving the equations of motion and simplifying the fluid load as a swinging pendulum. Simplified Multibody Sloshing models from Otremba et al. [1] are an excellent place to start when understanding the dynamics and various forces in a road tanker system. The numerical methods provide a computationally cheap way to analyse the system's response to specified inputs such as road vibrations and braking-in-a-turn (BIT) manoeuvres. A pendulum-based model can predict, with some accuracy, the roll angle and forces induced by sloshing but fails to capture any real-time position or shape of the free surface.
Zheng et al. [2] describe a simplified model only considering that the tank and internal baffles determine the sloshing force on the rigid structure. Fluent finite volume methods are used to model the fluid in the tank, and a constant acceleration field is applied to mimic an emergency braking scenario of [-3.5 m/s^2].
Another common approach is the use of Arbitrary Lagrangian Eulerian (ALE). The ALE approach has been an industry standard for years but requires tedious adaptive meshing techniques for a case like ours.
This is where Smooth Particle Hydrodynamics (SPH) can simulate the fluid. SPH is a meshless, Lagrangian method where the fluid is described as a discrete number of particles whose interaction mimics the fluid's viscosity.
SPH was selected for a few reasons:

- Because it is a meshless method suited for problems with large boundary deformation and free surface flows. The lack of mesh also simplifies the implementation and parallelisation compared to ALE methods.
- The fluid properties are easy to define, and Ls-Dyna has excellent functionality to generate SPH particles for various fill levels and densities.

- Contact and interactions are more accessible to define within Ls-Dyna than in other meshed methods.
- Boundary conditions such as inlets and outlets are difficult with SPH but are not necessary as the fluid exists within the sealed environment of the tank.

Xu et al. [3] compare ALE to the SPH method. They conclude that the most significant advantage of SPH is that it avoids the heavy task of meshing and re-meshing. The price to be paid for modelling efficiency is that the SPH method may need finer resolution to achieve accuracy comparable with the mesh based. However, the ability to parallelise SPH using MPP in Ls-Dyna can offset this.
The application of SPH to sloshing problems has been carried out by Delorme et al. [4], Landrini et al. [5], and Chen et al. [6] to validate impact pressures based on SPH with forced roll motion in two dimensions. However, SPH still comes with a degree of trial and error to tune results from Jonsson et. Al. [7] investigated the impact of parameters such as EOS, artificial viscosity constants, dynamic vs. static smoothing length and SPH resolution. When measuring the shape and position of the free surface waves, the error for all cases is within 5% of each other. It shows roughly a 15-20% discrepancy between experimental and numerical results. What is most evident is that SHP resolution and artificial viscosity coefficients have the most significant impact. Setting the artificial viscosity constants q1 and q2 to 1 for high-resolution cases produces the best results. However, this choice results in a highly viscous and unphysical solution for the lower resolution cases, so values of 0.1 and 0 are more applicable for the artificial viscosity coefficients.
As concluded in their paper, only the SPH resolution and choice of artificial viscosity constants significantly impacted the results. Increasing resolution increases the number of flow features resolved, and a highly viscous fluid can be obtained if the artificial viscosity constants q1 and q2 are set to 1.

2 Methodology

2.1 Use of Smooth Particle Hydrodynamics (SPH) for fluid modelling

A few different software was used in the creation of the model. Firstly, Crossland tankers use Creo Parametric to create their tankers' CAD models. This program has specific functions for designing parts from sheet metal, allowing the user to fold and unfold parts to check manufacturability.
As any FEA engineer knows, meshing is often the most critical stage. As the tank and chassis being studied are constructed from folded sheet metal, the problem is best tackled by meshing the structure as shells. ANSA from BETA CAE is an excellent preprocessor used to meshing the parts. Its batch processing and mid-surface extraction tools proved critical to the efficiency and quality of the meshing stage.
Once the parts had been meshed, OASYS PRIMER created the Ls-Dyna model. The Oasys suite offers excellent pre-, post and job submission tools that I found helpful in interpreting and presenting results.
A simplified model of a rigid tank filled with water was created, as shown in Figure 2:

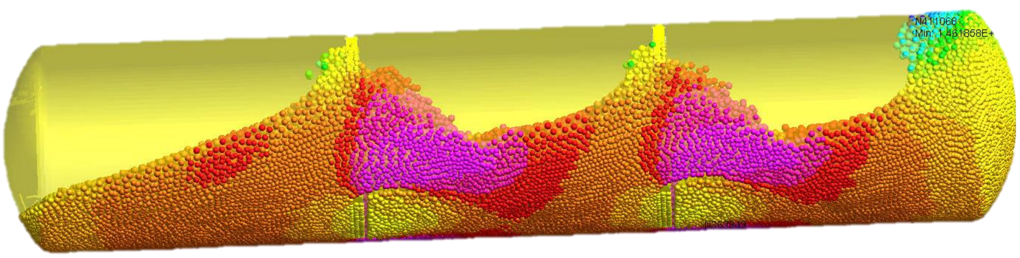


Fig.2: SPH Tank model

The tank was treated as a constrained rigid structure, and a constant acceleration field of 3.5m/s^2 was applied to the fluid. The SPH was generated in LS-Dyna to a 60% fill level. As the literature review describes, a high enough resolution is needed to render the flow features. So, a similar parametric study was done to investigate the impact of different resolutions and Artificial viscosity constants [7]. Figure 3 shows the comparison between the different artificial viscosity parameters.

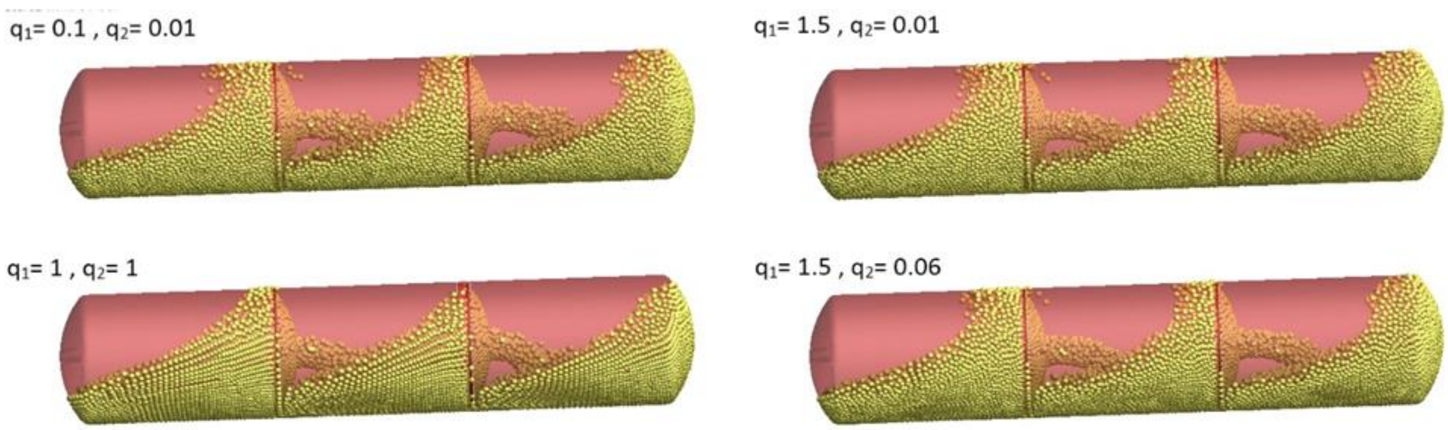


Fig.3: Artificial Vsicosity Comparisson

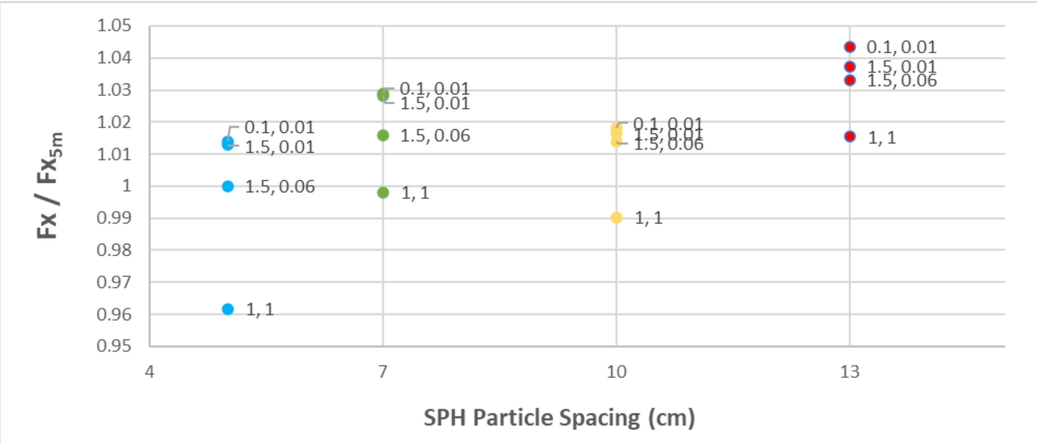


Fig.4: SPH Parametric Study

The maximum horizontal sloshing force is normalised around the default artificial viscosity values for the highest resolution case and plotted in Figure 4. Since the highest resolution case should give the most accurate rendering of the free surface features, the results are normalised so we can compare.
We can see that a value of q1=1 and q2=1 results in a significantly lower force and a less viscous fluid for each particle resolution. What is also clear is that the value of q2 significantly impacts viscosity more than q1.
If the assumption that the default values q1=1.5 and q2=0.06 for the highest resolution are the most accurate to real life, then to achieve similar results at the other resolutions, values of q1=1 and q2=1 should be used.

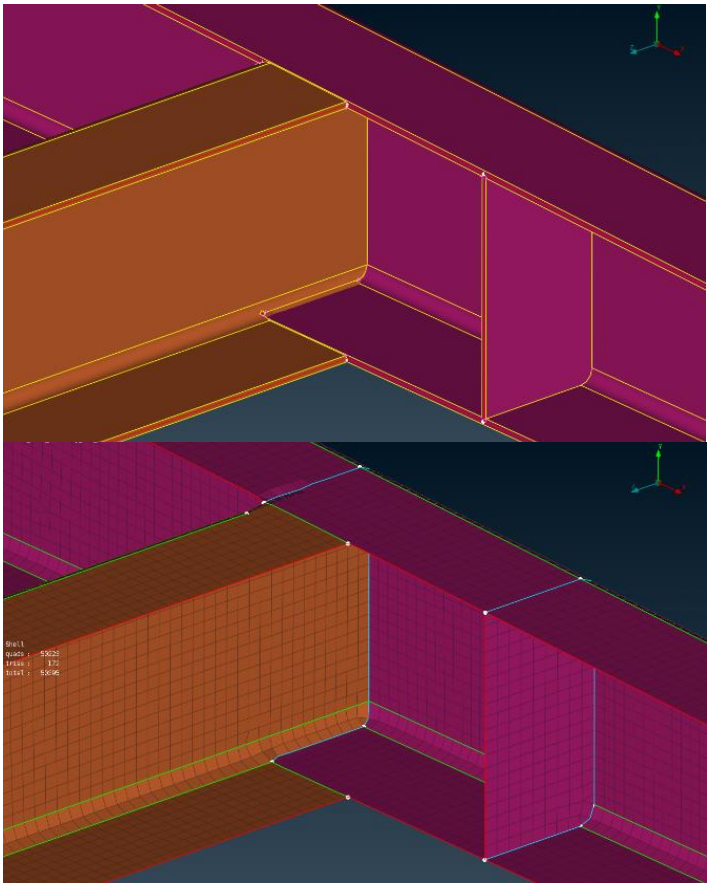
2.2 Fluid-Structure Contact Algorithm

Within Ls-Dyna, a penalty-based contact algorithm is used to model the interaction between the fluid and the inside of the tank. Contact algorithms have been studied extensively, and details can be found in Belyshko et al. [8]. This contact algorithm can be used for implicit and explicit analysis, making it suitable for our general-purpose model. In penalty-based contact algorithms, a contact force is computed proportional to the penetration depth. It is represented by linear springs between the agent nodes and the nearest master segment. The stiffness of these springs is determined by the following formulation from the Ls-Dyna manual:

2.3 Challenges and Limitations

The tank being simulated is 9m long and 2m in diameter. With such a large area, there must be a compromise between having a high enough resolution to capture the flow features and having a feasible run time.
Because we want a two-way contact algorithm where the penetration of nodes is checked each way, the total CPU time spent on SPH, and its respective contacts can be significant. From the full tanker model created, SPH and its contact can be 25-40% of total CPU time, depending on SPH resolution.
However, we are not particularly interested in capturing the free surface features with extreme resolution. We are more interested in the more significant free surface dynamics within the tank and the effects on the structure, so a balance must be found to manage these two factors.

2.4 FE Techniques for Chassis Modelling



The Full Tanker Assembly is exported from Creo as a .step file and imported to ANSA. Surface Extraction is used to batch-process the model assembly into a proper mesh. ANSA can extract the middle plane of a sheet metal part and then mesh it as shells to your specified mesh criteria. Doing this for each part would still require the parts to apply a tied connection and become tedious.

Using the Weld parts feature, this tool can be set up to batch process an entire assembly so that any parts within a certain distance tolerance can be "welded" together and defeatured of any unwanted holes or notches in the part geometry as shown in Figure 5. With around 100 parts in the assembly, this proved a fast and effective way to represent the joints without defining *TIED_NODES_TO_SURFACE contacts between each part.

Fig.5: Mid-Surface Extraction and Meshing of Components

2.5 Suspension Elements

Crossland is supplied with BPW Airlight suspension and axel systems. The axle moves on a suspension arm that pivots on a hangar mounted to the bottom of the chassis. An airbag spring and damping arm provide the suspension. The manufacturer provided the following values.
Spring stiffness, k = 150000 n/mm
Damping coefficient, c = 10000-50000 n/mm^2 compression / tension

Figure 6 shows the arrangement of the suspension and how the system was translated to FEA.

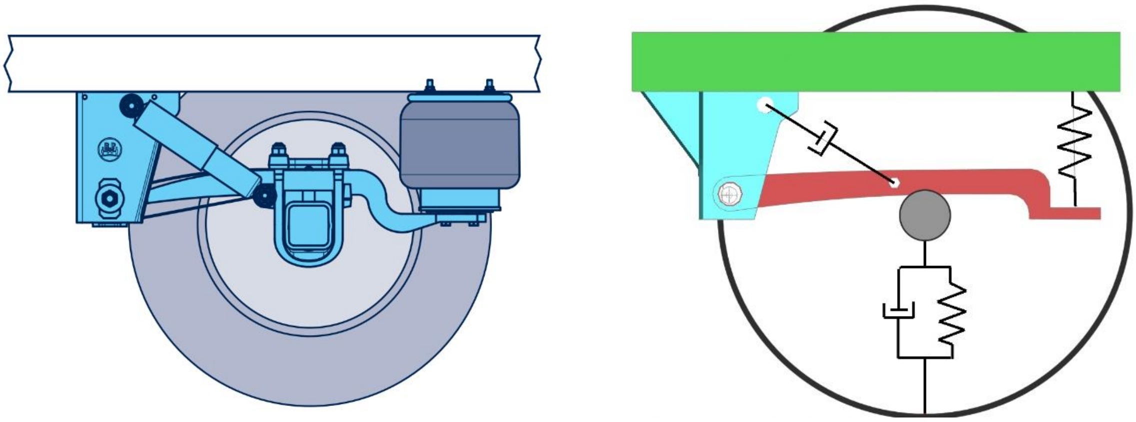


Fig.6: BPW suspension and FEA model

Figure 6 shows how the spring and damper elements are represented by beams with MAT_074 (ELASTIC_SPRING_DISCRETE_BEAM) and ELFORM = 6 (DISCRETE Beam) where the obtained values from the manufacturer can be used. This part of the model can be validated in future using accelerometer data from the axel and the chassis directly above. The tyre was also included as a linear spring damper element between the axel and the road.

3 Material Characterisation

3.1 304 Stainless Steel used by Crossland

Crossland uses S304 Stainless Steel for most of the chassis and structure of the tank. Therefore, it is vital to characterise this material model correctly. The parts are first laser cut from large sheets and then folded to form the part. In Crossland's experience with repairs, the failures in real life are not a direct result of the laser cutting or folding process, so it can be assumed that these processes do not add any significant weaknesses to the material. They result from high cycle fatigue in areas of high stress, specifically where the weld quality is poor.
For this reason, the material model of choice is *MAT_123, as it can incorporate S-N and stress-strain curves and specify various failure criteria.
Ls-Dyna requires true Stress-Strain curves for material characterisation. Kweon et al. [8] describes the method for calculating true stress-strain from Uniaxial Tensile load tests and how to validate using an FEA model. Following the procedure set out in BS IOS 1099, laser-cut dog bone samples were used as they are more representative of the materials used. 5 Tensile load tests were performed at Queens University Material Labs and are shown in Figure 7.

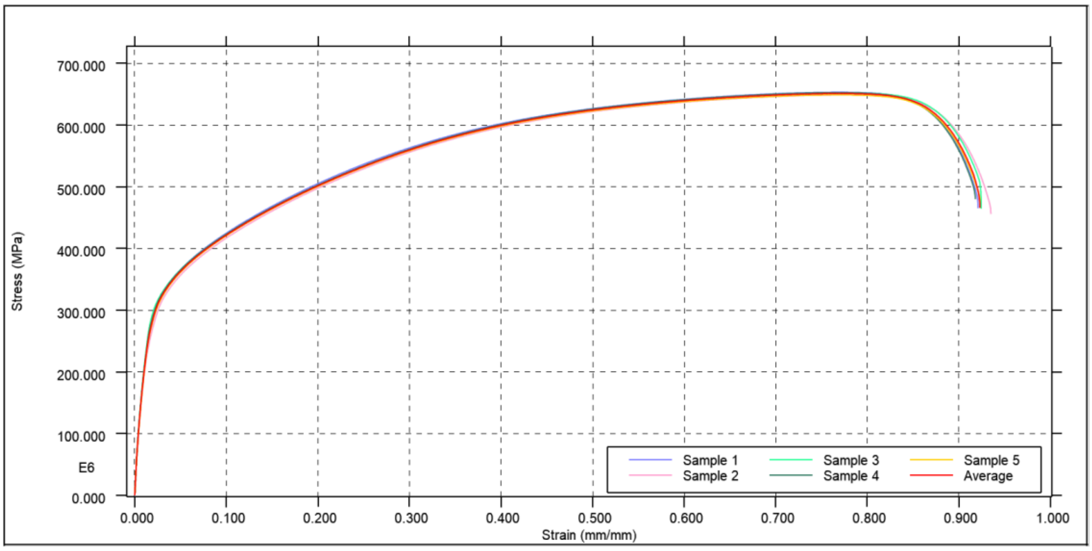


Fig.7: Engineering Stress-Strain curves of test samples and average.

The tests show excellent consistency, with only a 1.77 % standard deviation in maximum force. An average is plotted and used as the basis for the material characterisation. Following the steps by Kweon et al. [9], the true Stress-strain curve up to the necking region is obtained using their equations. The stress and strain at fracture are then calculated using Brigman's correction theory. The Hollomon-linear model is then used to extrapolate between the necking and fracture points. Figure 8 shows the Tensile test data and the calculated true stress-strain.

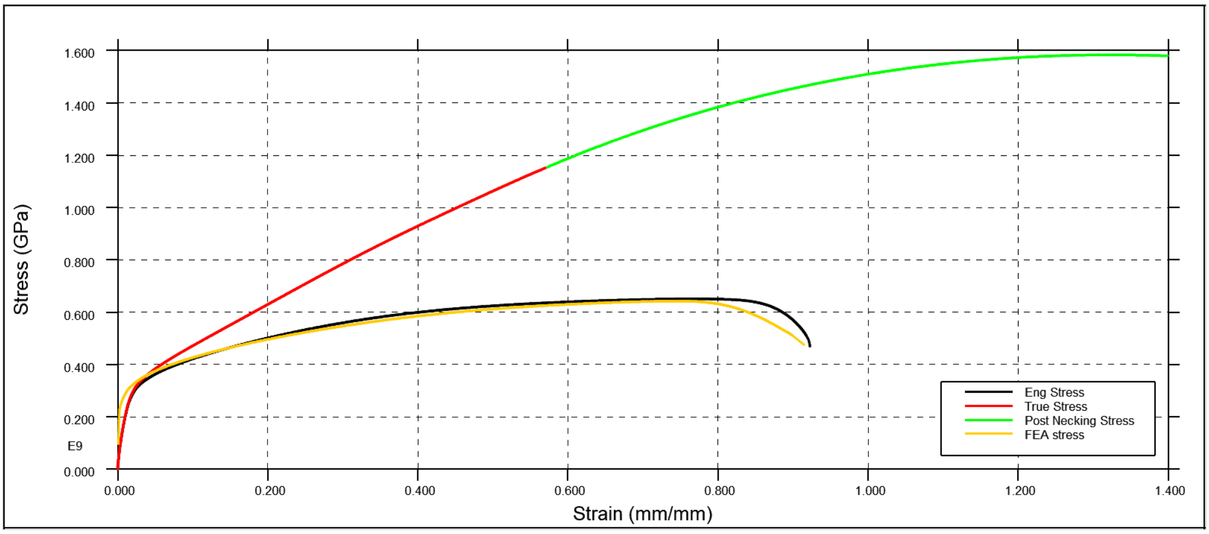


Fig.8: Corrected true Stress-Strain curves and FEA results.

A quarter model of the tensile test is then performed in Ls-Dyna shown in Figure 9, and the engineering stress-strain is obtained from the results. The FEA results are also plotted in yellow in Figure 8 and show good similarity with the test results. By changing the parameters for the post-necking region, the FEA results are iterated to match the test results better.

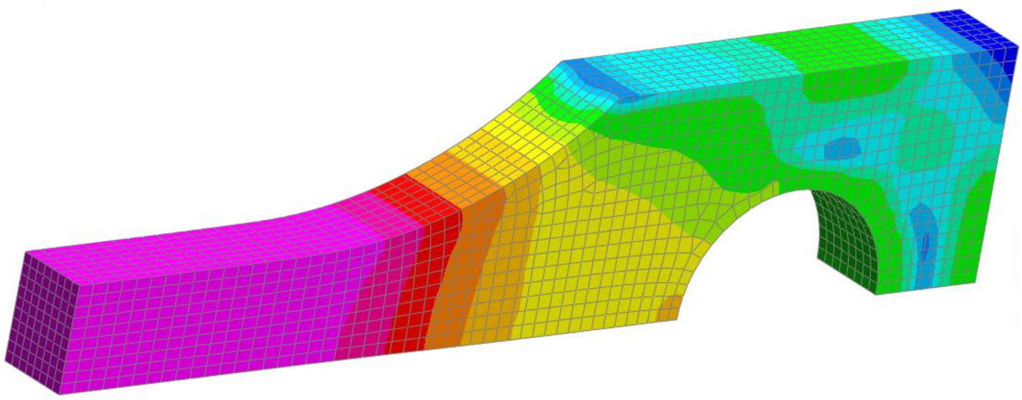


Fig.9: FEA quarter model.

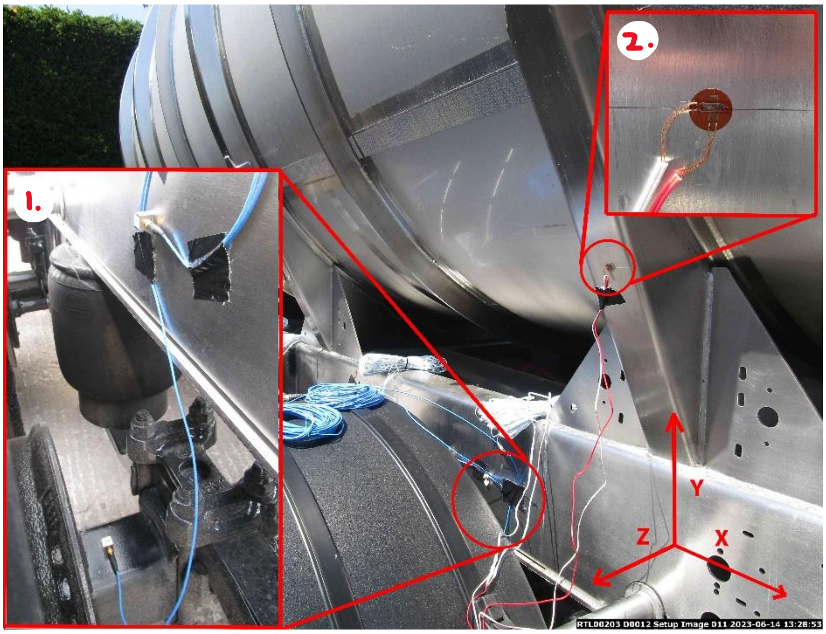
4 Model Validation

4.1 Road testing procedures by Resonate Ltd

We performed real-world testing on a tanker carrying water to validate our model. We had arranged to do the testing with Resonate Ltd, who claimed to provide the equipment and support. According to Romero et al. [10], using braking in turn (BIT) manoeuvres as the critical load case is industry standard. We performed straight-line braking to rest starting from 30, 20, and 10m/s as they were easier to do on an old airstrip to which we had access. We repeated these manoeuvres at 100%, 80% and 60% fill levels.
The setup included a portable Digital Acquisition Device (DAQ) that was wired into the power supply in the cab so the operation and recording of data could be done from the driver's cab.

We aimed to record the acceleration at the axles and the strain throughout the chassis. By applying the acceleration time data to our tanker model, we could compare the test results to the FEA results to validate the model.

4.2 Collection of acceleration and strain data



Six triaxial accelerometers in Figure 10.1 were mounted at the axle and vertically above the chassis. This arrangement allows us to validate the suspension model and gives us Acc-Time data to use as a load case for the model.
12 T-rosette strain gauges in Figure 10.2 were placed on the chassis and the bearers. The bearers are the vertical structures that connect the tank to the chassis and should show a significant response to the fluid sloshing within the tank.
As a backup, we recorded the acceleration for a few test runs using my phone taped down the truck's dashboard.

Fig.10: Sensor setup on road tanker.

4.3 Comparison of simulation results with real-world data

After the testing, we received the results and began processing to check the validity. The positive X direction is forward in the direction of travel, so a negative acceleration corresponds to braking. The acceleration data was filtered and plotted in blue. Then, integrating the acceleration data gives a Vel-Time history plotted in red, and both are shown in Figure 11. With an initial velocity of 10m/s, the velocity line should decrease from 0 to -10m/s over the braking period. As is quite evident, the velocity data does not show the decrease in speed of 10m/s as expected. The acceleration can be seen to spike initially in the positive direction and then oscillate between positive and negative. Even considering the effects of sloshing, such as the wavefront's impact, the acceleration data is features are not accurate at all. We should at least see the initial acceleration be negative.

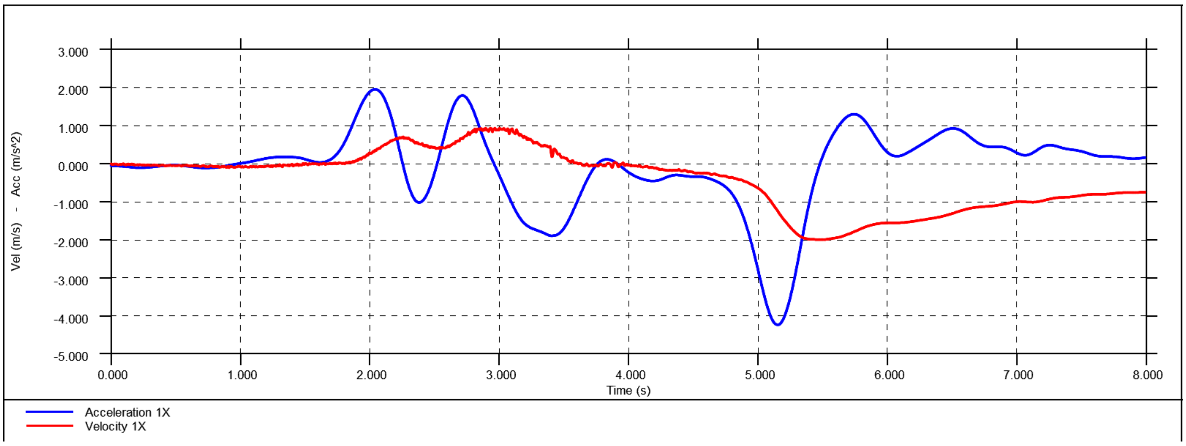


Fig.11: Acceleration and velocity data from Resonate testing.

Comparing this to the data obtained from my phone mounted in the cabin, the Figure 12 results appear more sensible. They show the apparent spike in negative acceleration at the initial braking point, followed by the wavefront impact, briefly bringing the acceleration close to zero. Looking at the integrated Velocity data in red, the decrease in speed can be seen from 10-0m/s.

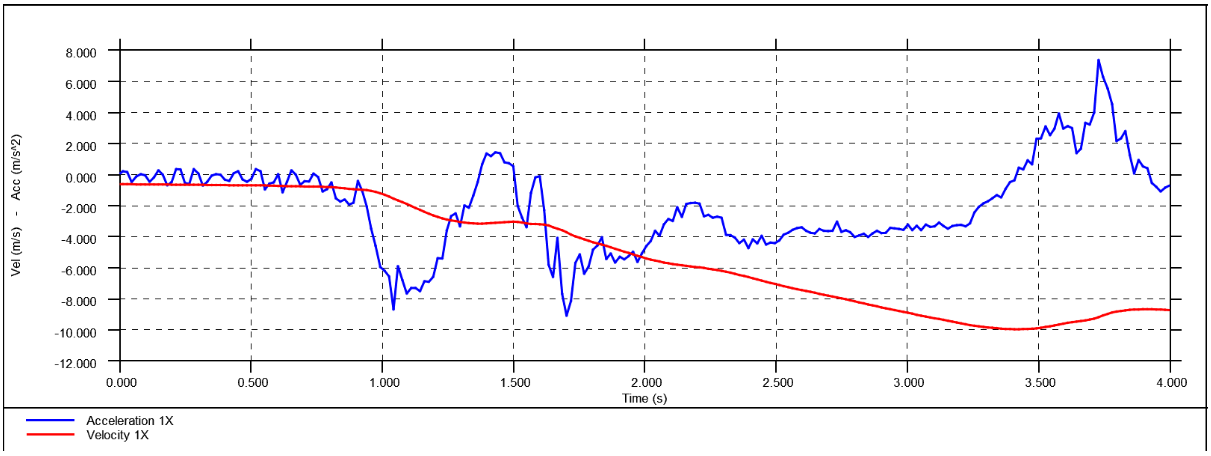


Fig.12: Real-world acceleration and velocity data from phone accelerometers.

These results were discussed with Resonate Testing Ltd. engineers. After some deliberation, they admitted there was not enough care taken on their part in the test setup. They suggested the 50g accelerometers used were the wrong type but did not clarify further. Although Resonate originally stated that their 50G accelerometers were still accurate below the 5g range, I speculate the accelerometers they used are more suited to shock and impact testing that can capture rapid and high-frequency acceleration changes rather than the smaller but sustained accelerations experienced while braking. It is hard to say, however, as we are no longer collaborating with Resonate, and they are unwilling to share their findings, so testing must be undertaken again to validate the model.

5 Multi-physics tanker model results

Although we could not gain any accurate Acceleration data to be used in the model, we opted to apply a constant braking acceleration of 3.5m/s2. This still gives us an idea of the stresses induced within the structure. As shown in figure 13, the areas of maximum stress are located around the front axle.

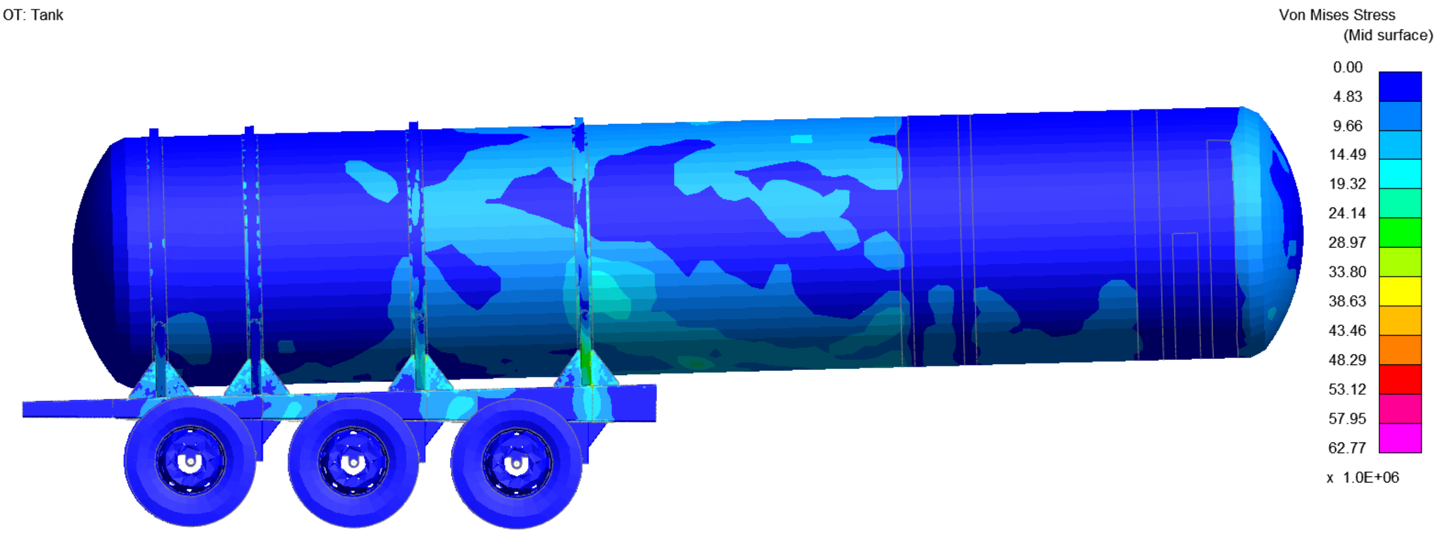


Fig.13: Von Mises stress plot for tanker under braking.

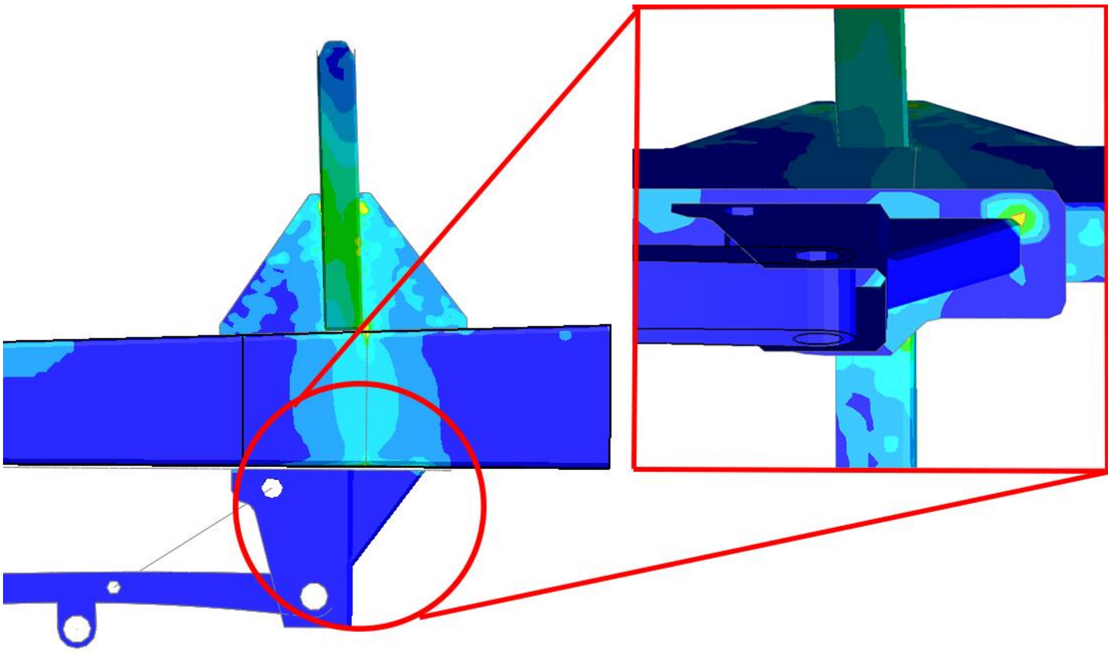


Fig.14: Closeup of chassis and hangar.

Taking stress readings at the exact locations as our experiment, we can see that as the weight of the fluid sloshes forward, the stress increases in the front bearers and decreases in the rear. This creates a stress line that comes down through the bearer and the chassis to meet the hangar. The hanger is the significant bracket connection point for the suspension arm and damper shown in Figure 14. The area where it joins the bottom of the chassis sees an exceptionally high-stress concentration in the FEA results. This can be validated anecdotally as Crossland Engineers routinely see this area fail when performing tanker repairs. If this area fails in real life sooner than the rest of the tank, it must be the area of highest stress in some instances.
This area is also highly subject to road conditions, which are not considered in this model as we have no acceleration data from the axles. With future work, this data can be integrated to account for road vibrations and may show further stress concentrations at the point where the chassis and hangar meet.
We can also see that large areas of the chassis rails experience very little stress. This could be a key area for weight reduction in future.

6 Conclusion

6.1 Summary of key findings

From our Multiphysics Road Tanker model, we can clearly see the stress concentrating around the chassis' front as the liquid sloshes forward under braking. In particular, we can see that the connection point between the hangers and the chassis is a crucial area for improvement.
Although the Road tanker model is yet to be validated, anecdotal evidence from Crossland would suggest that this area sees exceptionally high stress as it often fails under high cycle fatigue.
It can also be seen that large areas of the chassis provide little structural benefit, and investigations into weight reduction can begin in these areas.

6.2 Implications for the design and manufacturing of road tankers

The use of a Multiphysics model, as described in this paper, should be integrated into the design process at Crossland. Digital prototyping has numerous benefits, and far more adventurous designs can be pursued without the financial burden of physical prototyping. Individual parts can be iterated and updated on the road tanker to evaluate their effectiveness during the worst-case scenario. Now that the process of creating this road tanker model is known and effective automation techniques are set up, a model can be created relatively quickly for different tanker variants.
Our Material model of S304 has been validated using tensile load tests and will allow us to perform FEA compliance tests for components, such as crash bars, instead of costly physical tests.

6.3 Recommendations for future research and development

The first step in future work will be to conduct road testing on a tanker to validate the whole model without Resonate Ltd. This will give us more confidence in the design choices that result from any FEA prototyping that happens in future.
Fatigue Testing will also be conducted and integrated into the S304 material model. This again increases the options for types of analysis on the tank and new components.

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