Comparing Predicted and Measured Accelerations from a Simple Drop Test Experiment

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1 Abstract

The objective of this paper is to present the results from a series of simple drop test experiments compared with the equivalent Finite Element Analysis (FEA) models. There are several methods of obtaining acceleration-time histories in LS-DYNA. The experiments looked to demonstrate the validity of utilising predicted acceleration-time histories through a selection of methods including nodal output, Newton’s second law (F=ma) and by calculating the accelerations from kinematic equations. The purpose was to understand how comparable the predicted and measured accelerations are.

2 Introduction

Measured accelerations are used in drop testing and crashworthiness to validate FEA models. It is common practice to utilise accelerations for limits in design calculations. Accelerations of objects are often recorded with accelerometers, but often little is understood about the associated signal processing to determine the accuracy of the data. This work compared the use of accelerations predicted from nodal output to measured accelerations recorded from an attached accelerometer. It also looked to use the derived accelerations from Newton’s second law to compare the accelerations. Finally the acceleration of the impactor could be determined from kinematic equations knowing the initial drop height and the final deformation experienced by the pipe samples.

In order to provide a simple test, a small section of standard stainless steel 304 pipe was located on a stationary plate, fitted with a load cell, and a steel cylindrical impactor (OD=150mm, L=1000mm) weighing 140kg was raised to achieve a drop height of 3.88m above the 100mm long sample. An accelerometer was attached to the top of the impactor to produce acceleration-time history data. Two different sizes of pipe were selected; 2"Schedule 10 and 2½"Schedule 5. The tests were reproduced using LS-DYNA R7.1.2 **[1]** FEA software to extract acceleration-time histories from four nodal outputs, and reaction forces in order to compare these with the results from the physical tests.

3 Experimental and FEA Set-Up

The physical drop tests were performed on a test rig by an external test facility. The pipe samples were selected from standard 2"Sch10 pipe and 2½"Sch5 pipe. The ends of the pipes were machined to be perpendicular to the side of the pipe in a lathe prior to testing. The acceleration of the impactor was measured using a piezoelectric accelerometer attached to the upper free surface that was mounted off-centre to accommodate the hoist attachment. The resulting forces on the pipe sample were measured using a 650kN piezoelectric load cell positioned under a steel plate. The samples were sat on this plate to prevent any inadvertent damage to the load cell during the impact.

In the FEA model an initial velocity representing the equivalent drop height was applied to the impactor. The acceleration-time histories from four nodes around one element face in a similar location to the physical accelerometer were recorded using **`*DATABASE_HISTORY_NODE`** and the output was defined using **`*DATABASE_NODOUT`**. A rigid wall was defined under the stationary pipe samples using the keyword **`*RIGIDWALL_GEOMETRIC_FLAT_ID`**, and the data output using **`*DATABASE_RWFORC`**.

A sufficient sampling rate had to be chosen to avoid clipping or aliasing the data, which was based upon the minimum time-step of the model. To ensure accuracy when comparing the physical results and the FEA results, both had to be filtered consistently.

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4 Comparison between FEA and physical tests

In order to validate the accelerations predicted using FEA, several variables were compared between the physical results and the FEA models. These included measured results such as deformation, acceleration-time histories, and also derived results such as the acceleration calculated from a=F/m and from equating kinematic equations. Several pipes were crushed at the test facility and compared, with all 2"Sch10 pipes producing repeatable results and all except one of the 2½"Sch5 pipes collapsing in a repeatable manner. For the comparisons within this paper the 2"Sch10 pipes were compared to Test 15 (T15), and the 2½"Sch5 compared to Test 21 (T21). Test 21 was the only pipe which collapsed with two symmetric concertina folds so gave the closest agreement with the FEA model.

4.1 Deformation

It was expected that the pipes would collapse by progressive buckling in one of the two primary collapse modes; either in a symmetric concertina mode or in a non-symmetric mode often referred to as a diamond mode whereby the collapsed shape is polygonal in plan view. The conditions under which each type of collapse occurs under axial loading have been the subject of extensive experimental research, and it has been found that the collapse mode depends primarily on the ratio of mean radius (R) and mean wall thickness (H). Other studies have also looked at the effect of the initial axial length (L) and how this could influence the collapse mode of the pipes **[2].** Various theoretical methods predict that thicker tubes with R/H <40-45 deform symmetrically while thinner tubes with larger R/H values tend to buckle in non-symmetric modes. This is not a defined rule, and some tubes may switch during loading thus producing a mixed mode of collapse **[3].** The 2"Sch10 pipes had R=57.53, H=2.77 giving R/H=20.8. The 2½"Sch5 pipes had R=70.89, H=2.11 giving R/H=33.6. This showed the anticipated mode of collapse for both pipes was axisymmetric.

Although not the most important factor of this study, the final deformation of each pipe sample was compared to gauge whether the FEA model had been accurately set up in order to represent the physical drop tests.

Fig. 1 shows the final deformation of the 2"Sch10 pipe for both FEA and physical tests. All physical tests were repeatable, with the final shape for all 2"Sch10 pipes almost identical, with all experiencing a symmetric collapse mode. As shown below the final deformed shape is similar between FEA and Test 15. The final length of the deformed specimens was within 7mm (10%) of each other (62.7mm FEA and 69.7mm Test). The stroke efficiency was therefore 37.3% FEA and 30.3% Test, a 7% difference in efficiencies predicted. This is good agreement. (For note the largest sample measured 72mm in final length, 14.8% different from the FEA prediction.)

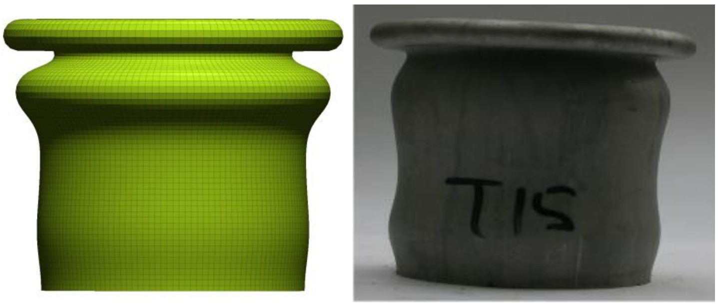

Fig. 1: Final deformation of 2"Sch10 pipes in FEA (Left) and from Test 15 (Right)

Fig. 2 shows the final deformation of the 2½"Sch5 pipes for FEA and the typical collapse from the physical tests. The 2½"Sch5 pipes all deformed in a similar manner, but were not completely identical; all exhibited the diamond mode of collapse to various degrees. Test 21 was the only pipe which collapsed with two symmetric concertina folds. This was the closest representation of the 2½"Sch5 tests, as none of the FEA models replicated the triangular deformation. Although the model did not reproduce the deformation in the tests, the final length of the deformed specimens was within 9mm (14%) of each other (52.3mm FEA and 60.6mm Test). The stroke efficiency was 47.7% FEA and 39.7% Test, a difference of 8%. This is also good agreement. (For note the largest sample measured

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was T21, all pipes that collapsed in a diamond mode their final lengths were varied between 8% and 12% of the FEA model).

From this it is fair to conclude that although the FEA models did not always accurately predict the final deformed shapes, they did accurately predict the stroke efficiency of the pipes.

Fig. 2: Final deformation of 2½"Sch5 pipes in FEA (Left), typical deformation (Mid) and from Test 21 (Right)

4.2 Acceleration-Time Histories

4.2.1 Accelerometer data

An accelerometer attached to the top of the impactor recorded the accelerations during the physical tests. These were filtered before the data was analysed. The filter characteristics used by the test facility were unknown, other than the cut off frequency applied was 4.7 kHz. Each of the resulting FEA signals written out using keyword **`*DATABASE_HISTORY_NODE`** went through a process of filtering in HyperMath **[4]** in order to produce comparable signals to those obtained by test. This process also helped to ensure the filter stability.

As the data generated from FEA contained many more data points than provided through the experiments, the signal was first passed through a preconditioning second order forward-backward Butterworth filter, with a cut off frequency of 10 kHz. The data was then down-sampled from 6 MHz to 1 MHz, and filtered again at 4.7 kHz. To guarantee the signal from the physical experiments had been filtered consistently, the signal was passed through the same 4.7 kHz Butterworth filter as the FEA acceleration-time history.

Fig. 3 shows the filtered FEA results and the results from Test 15. The signals have both been cropped to include the rigid body pulse (9ms). One of the noticeable differences between the curves is the effect that damping has on the signal; the FEA model did not include damping.

Originally, the magnitude of the first acceleration peak was compared between test and FEA. This was because the oscillations produced by the undamped FEA model are not attenuated as they are in reality. In shock analysis it is common to assume that the first peak occurs so rapidly that damping has a very small affect. Even when both signals have been filtered with the same Butterworth filter, the initial peak for FEA measures 265g whilst the initial peak from Test 15 is 370g, a difference of 28%.

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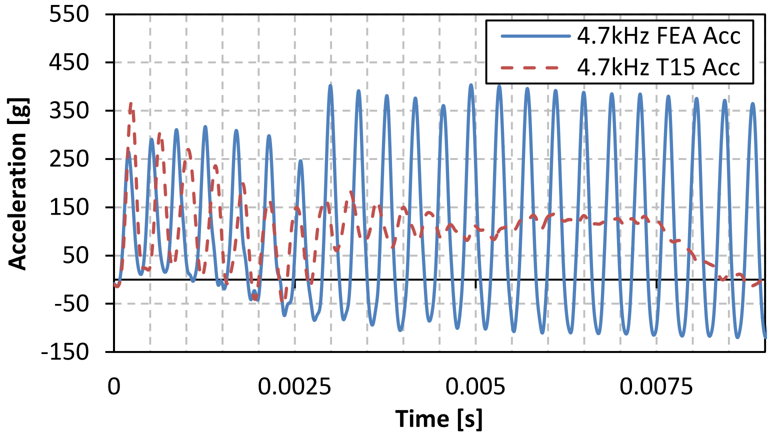

Fig. 3: Filtered acceleration-time histories from2"Sch10 FEA (blue solid) and T15 (red dashed)

Fig. 4 shows just the filtered FEA and Test 21, cropped to only include the rigid body pulse (14ms). As with the 2"Sch10 pipes the magnitude of the initial acceleration peak is under-predicted in FEA, but the time the maxima's and minima's occur match closely with the test signals illustrating the frequencies and phase are matched. When compared to the FEA signal, the initial peak magnitude predicted in the 2½"Sch5 samples differed by 4.5% (FEA peak 349.1g, Test 365.4g).

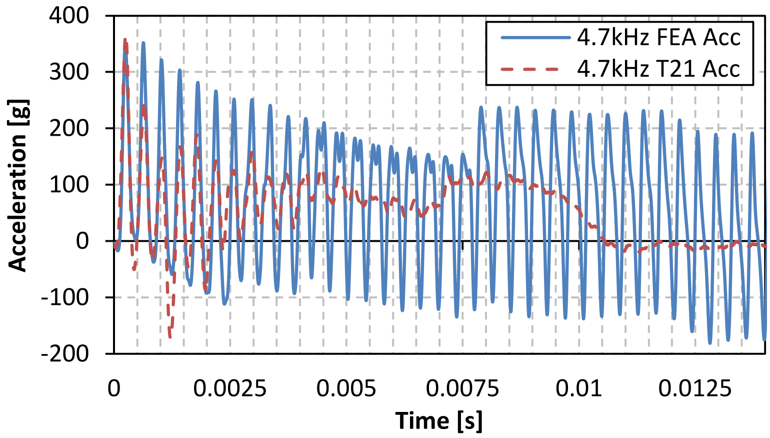

Fig. 4: Filtered acceleration-time histories from 2½"Sch5 FEA (blue solid) and T21 (red dashed)

Using standard statistical data from the various acceleration curves, the root mean square (RMS) for the data was found. The RMS is often taken as a measure of the energy content within a signal, albeit for longer duration random vibrations. The acceleration-time histories were adjusted to include only the dominant accelerations before they dropped to oscillate about 0g. For the 2"Sch10 pipes this was taken as 11ms, and for the 2 ½"Sch5 pipes taken as 14ms.

When comparing the RMS of the above accelerometer-time histories there was a much larger percentage difference due to the excess noise still contained within the signals (58% in 2"Sch10 samples and 60% in the 2½"Sch5).

In order to compare the rigid body acceleration of the impactor for FEA and test, these accelerations need to be passed through a second low-pass Butterworth filter at 1 kHz to remove the elastic effects. Fig. 5 and Fig. 6 compare the acceleration-time histories for the rigid body accelerations of the 2"Sch10 and 2½"Sch5 pipes respectively.

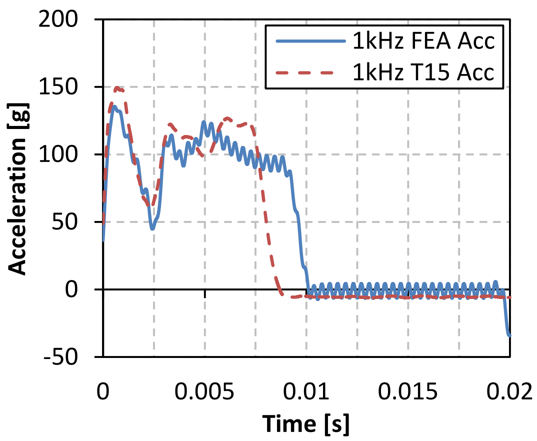

Fig. 5: Rigid body acceleration-time history for 2"Sch10 models

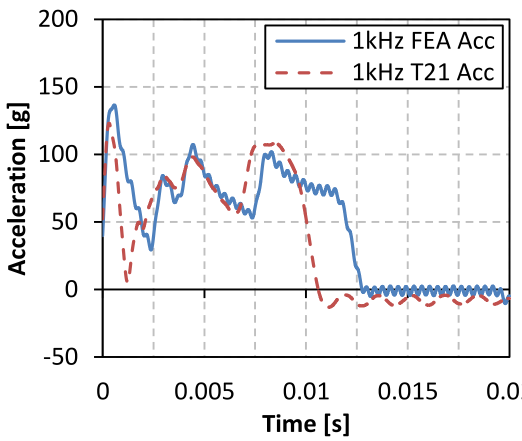

Fig. 6: Rigid body acceleration-time history for 2½"Sch5 models

The curves follow a similar profile, but with the measured filtered acceleration returning to 0g quicker than the FEA filtered acceleration. The FEA signals still contain some higher frequency content as indicated by the oscillatory nature of the curves. This is associated with the second-order filter applied to the data and the poor roll off rate which in turn means there is a large transition band. The initial peaks of the rigid body acceleration are within 10% of each other, making this a good indication of the consistency of the filters applied to the accelerations. Here, the RMS of the curves was calculated and found a maximum difference of 6% proving the remaining energy contained in the signals was very similar.

4.2.2 Newton's second law F=ma

The rigid wall that the pipe samples were positioned on in the FEA models was able to record the reaction force-time history throughout the impact using the keyword **`*DATABASE_RWFORC`**. The measured force-time histories were detected by the load cell and compared to the force-time history produced in FEA. Each of the force-time histories could be associated with the deformation of the pipe; each major maxima-minimum (taking the general profile of the curve) associated with the formation of a fold. All force-time histories returned to 0N as the impactor rebounded from the pipe sample causing the pipe to lift from the rigid wall/ load cell.

The acceleration of the impactor can also be calculated using Newton's second law of motion (F=ma), thus it was anticipated that the reaction forces from both the load cell and FEA rigid wall could be used to work back to the acceleration by dividing the force-time histories by the mass of the impactor.

Fig. 7 shows the measured acceleration (blue) and the derived acceleration from the force divided by the impactor mass (red dashed) for Test 15 from the 2"Sch10 pipes. The local agreement between the two curves is poor due to the large oscillations from the accelerometer; however, inspection suggests a moving average of the accelerometer signal would be close to the a=F/m signal. It also suggests an oscillation frequency of about 2500 Hz (6 peaks in 2ms). The initial peak magnitude for the derived acceleration is largely under-predicted and does not provide a true representation of the initial acceleration of the impactor.

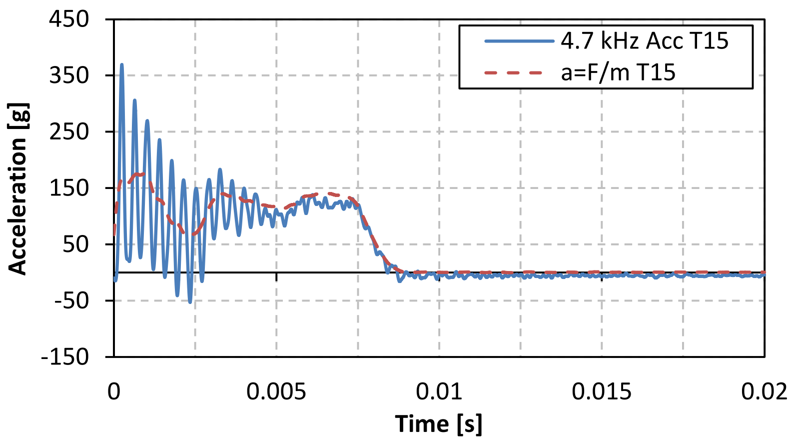

Fig. 7: A comparison of accelerations for the 2"Sch10 pipes taken from the accelerometer (blue solid) and derived from the load cell a=F/m (red dashed)

The measured and predicted accelerations when filtered still included the elastic response of the impactor. Subsequently the derived accelerations from Newton's second law are also elastic responses, possibly of the test rig and the pipe as shown in Fig. 8. Here both FEA and Test 15 accelerations have been derived through a=F/m and filtered at 15 kHz. As before with the accelerations, in order to compare the rigid body acceleration of the impactor for FEA and test, these derived accelerations need to be passed through a second low-pass filter at 1 kHz to remove the elastic oscillations. The results of this are shown below in Fig. 9, where a lot of the oscillations in the signal have been smoothed from the low-pass filter.

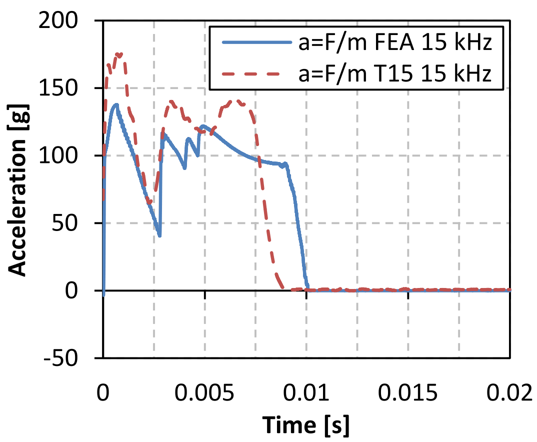

Fig. 8: Elastic derived acceleration-time histories from a=F/m filtered at 15 kHz

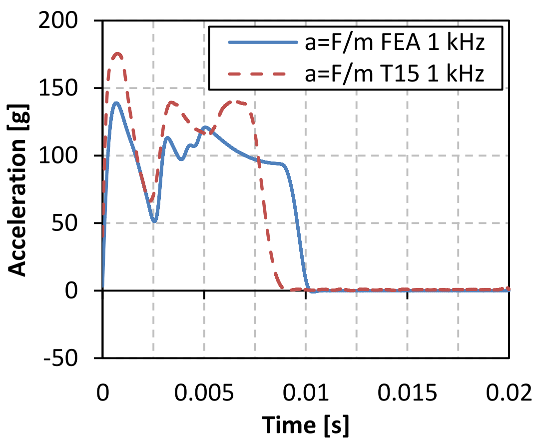

Fig. 9: Rigid body derived acceleration-time histories from a=F/m filtered at 1 kHz

The initial peak magnitude of the FEA model was under-predicted by ~20% when using the force from the rigid wall in FEA to derive the acceleration as opposed to the load cell output in the physical tests. This fits with engineering expectation because the FEA 2"Sch10 pipes crushed further than the sample used for Test 15, a more flexible structure due to materials applied, and thus the accelerations recorded took longer to return to 0g. The RMS of the rigid body accelerations reduced to a difference of 6%. Again, this showed the remaining energy within the FEA model was very similar to the physical test.

This was the same for the 2½"Sch5 pipes (not shown here), with the derived acceleration from the rigid wall in FEA under-predicted when compared to the accelerations using the load cell output.

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4.2.3 Calculated average acceleration

Finally, the average acceleration of the impactor could be calculated knowing the original drop height of the impactor, and the overall deformation of the pipes. This comes from equating the kinematic equations of accelerated motion for both the impactor and the pipe $v^2 = u^2 + 2as$.

$$v_i^2 = u_i^2 + 2a_i s_i$$

$$v_p^2 = u_p^2 + 2a_p s_p$$

Where:

v	=	Final Velocity (mm/s)	u	=	Initial Velocity (mm/s)
a	=	Acceleration (mm/s^2)	s	=	Displacement (mm)
$\_i$	=	Impactor variable	$\_p$	=	Pipe variable

If both initial velocities are zero, the equations can be rearranged in terms of *a* and equated to give:

$$v_i^2 / 2s_i = v_p^2 / 2s_p$$

Substituting in the variables:

$v_i^2 = 2gh$ $s_i = h$ (Height to base of impactor)

$v_p^2 = 2gh$ $s_p = d$ (Deformation of pipe)

Then the calculated average acceleration (units of g) of the impactor and pipe can be estimated by:

$$2gh / 2h = 2gh / 2d$$

$$g = gh / d$$

$$\bar{a} = h / d$$

This is also equivalent to equating the potential energy of the impactor before falling with the work done to deform the pipe sample:

$$mgh = Fd$$

$$mgh = mad$$

$$a = gh / d$$

$$\bar{a} = h / d$$

Measure	**2"Sch10 samples**	**2½"Sch5 samples**
Calculated average acceleration from equation above for FEA models. [g]	104	81
Calculated average acceleration from equation above for physical test models. [g]	128	89
Difference	19%	9%

Table 1: Calculated average acceleration for FEA and test models

As mentioned before, comparing only the peak values was not always accurate, and was largely affected by the filters applied to the signals. As the RMS provides an average measure (accounting for positive and negative values), the calculated average from the above equations was compared to the RMS of the curves in order to determine whether they were an applicable representation.

It is inaccurate to compare the calculated average acceleration to the RMS of the FEA acceleration-time history due to the large magnitude differences and the oscillatory nature of the undamped signal. The best comparison to make was taking the calculated average acceleration for the FEA model with the RMS of the measured tests. This is shown for clarity in Table 2 below. For the tests carried out there is a 12% difference between the 2"Sch10 pipes and 4% in the 2 ½"Sch5 pipes.

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Measure	2"Sch10 samples	2½"Sch5 samples
RMS of 4.7kHz acceleration-time history from Test. [g]	118	84
Calculated average acceleration from equation above for FEA models. [g]	104	81
Difference	12%	4%

Table 2: Comparison of accelerations using RMS for Test and equation for FEA

4.3 Frequency Analysis

The frequency spectrum of the acceleration-time histories was calculated to compare:

1) The frequency content between test results and FEA results and,
2) The predicted signal frequencies with the eigenvalue analysis.

This operation was performed using HyperMath to convert the time domain data to the frequency domain data using a Fast Fourier Transform (FFT) of the filtered acceleration-time histories. In this case because the FEA signals were undamped it is unrealistic to compare magnitudes; the purpose of this comparison was to match the frequency content, not the magnitude of the peaks.

Comparing only the frequency content for the 2"Sch10 pipes, there appears to be an approximate match between the first four spikes. Table 3 shows the dominant frequencies for both FEA and Test 15 in Hz. These predictions compare favourably to the associated natural frequencies, also shown below. As anticipated, the eigenvalue predictions are very similar to the frequency of the FEA acceleration-time history and the difference is due to the interaction with the pipe under impact. In both cases, the 1st peak is equivalent to the duration of the shock pulse.

	1st Peak	2nd Peak	3rd Peak	4th Peak
FEA	67 Hz	2577 Hz	5154 Hz	7663 Hz
2"Sch10 Test 15	67 Hz	3120 Hz	5018 Hz	6646 Hz
Eigenvalue	N/A	2521 Hz	5021 Hz	7477 Hz

Table 3: Comparison of dominant frequencies contained in acceleration-time history for 2"Sch10 pipe samples

Table 4 below shows the dominant frequencies for the 2½"Sch5 pipes in FEA and T21. Again the frequency content is similar between the test facility results and the FEA results.

	1st Peak	2nd Peak	3rd Peak	4th Peak
FEA	67 Hz	2577 Hz	5154 Hz	7663 Hz
2½" Sch5 Test 21	67 Hz	2848 Hz	4815 Hz	6758 Hz
Eigenvalue	N/A	2521 Hz	5021 Hz	7477 Hz

Table 4: Comparison of dominant frequencies contained in acceleration-time history for 2½"Sch5 pipe samples

5 Discussion

This study was to validate accelerations predicted using Finite Element Analysis with acceleration measurements from an impact drop experiment. Variables such as the deformed shape of the pipes after impact, the acceleration-time histories, the derived accelerations from force-time histories and also the frequency content of the signals were all compared for the 2"Sch10 and 2½"Sch5 pipes.

Before any analysis of the data could be carried out, the raw measured and FEA data had to be checked to ensure the numerical signals were not aliased or clipped. This study highlighted the importance of selecting a sampling rate to record data small enough to reflect the smallest time step (or highest eigenvalue) within the model, and having an equivalent sampling rate and filter frequency in the data acquisition equipment used in the physical tests.

It can often require a large amount of effort and iterative stages to determine whether a selected sampling rate has been sufficient, and then to filter the resultant signal to manipulate and compare against test data.

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5.1 Deformation

Section 4.1 showed that the final deformation of the pipes was over-predicted in the FEA models. This was likely to be due to the material properties applied and the omission of any strain rate effects. In all cases, the model allowed for the elastic recovery of the pipe sample once the impactor rebounded. The 2"Sch10 pipe models were representative of the deformed pipe samples, both in final shape and final length. There was a maximum difference of 9.3mm in the recorded final lengths for the 2"Sch10 pipes, but down to 7mm for Test 15 compared in this report. The stroke efficiency was calculated for both FEA and test samples and resulted in a difference that varied as much as 10%.

The 2½"Sch5 pipe models were not as representative of the deformed pipe samples; although the final lengths were within 9mm of each other giving a difference in stroke efficiency of 8%. Note the FEA did not ever reproduce the triangular deformation experienced; this could be due to any imperfections in the pipe, or potential misalignment when the impactor fell in the real tests.

5.2 Acceleration

Nodal output was recovered from four nodes and the results averaged before filtering in HyperMath. This average raw acceleration produced nearly an identical signal to that of an individual node, which was expected since the nodes chosen all came from one element. Although the results reported here are from average accelerations, the results for this work would typically be the same if only using one nodal output because the impact was essentially one dimensional.

Almost all the acceleration-time histories from the physical tests were identical for the 2"Sch10 pipes and the 2½"Sch5 pipes. This confirmed how repeatable the tests were.

The acceleration-time histories produced in FEA were deemed to be only valid for the initial impact when comparing the data. As shown in section 4.2.1, the curves contained significant high frequency content when compared to test, but once both were filtered, appeared to show a closer match for the first peak. Only the magnitude of the first acceleration peak was compared between test and FEA. This was because the oscillations produced by the undamped FEA model are not attenuated as they are in reality.

The filters applied to the FEA and measured accelerations had a varying effect on the initial peaks. As the original filter characteristics used on the physical samples were unknown, these signals had to be filtered again. In addition, the accelerometers used for the physical tests were slightly over-ranged in some tests resulting in larger measurement errors.

Instead, when comparing the RMS of the signals these appeared to show good comparisons, proving although the signals looked different, they contained similar energies.

If the force-time history is known from load cell data, using Newton's second law to derive acceleration appears to predict good rigid body acceleration when compared to the measured, filtered acceleration data. Once the filtered accelerations from FEA have been down-sampled and filtered again at 1 kHz to show only the rigid body accelerations, this proved a much closer match.

Using the "quick" calculation from the kinematic equations, this value for the calculated average acceleration predicted quite close results between the FEA models and the physical tests. Although it does not predict the peak accelerations, it provides a reduced estimate that could be used in engineering design when no acceleration data or force data is available, but the initial drop height and deformed length are known.

This calculated average acceleration for the FEA models was best compared with the RMS of the measured tests, as both provide a measure of the amount of energy contained in the signal. For the tests carried out there was a 12% difference between the 2"Sch10 pipes and 4% in the 2½"Sch5 pipes. Given the magnitudes of accelerations dealt with, this is a close approximation for the accelerations experienced by the impactor.

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6 Conclusion

Overall this study has shown that it is not difficult to generate acceleration data in FEA; the difficulty arises in the signal analysis afterwards.

The techniques used in FEA modelling to generate meaningful and comparable acceleration-time histories can be applied to represent the rigid body accelerations and frequency content of signals to validate the model against measured data. This only works if the sampling rate selected during pre-processing is sufficiently high and appropriate consistent filters are used for post-processing. Variation in the filters applied to the data was shown to have a large effect on the elastic accelerations and thus the initial peak accelerations that can be predicted in FEA.

It has also been shown that the accelerations can be calculated and verified through other means if necessary. The method for calculating the average acceleration through the known drop height and deformed length of the samples proved to be an easy and robust method for first-pass design calculations. This also compared favourably with the root mean square of the acceleration-time histories recorded from the physical drop tests. Only when more detail is required, the nodal output in FEA provides good information that compares reasonably well to the output from test.

A key point learned from this work is the importance of the data acquisition and signal processing. In order to compare data, the full characteristics must be known to allow an equivalent model to be produced. If the characteristics are not fully known, as in this case, the data has to be processed to ensure both test and FEA signals are equivalent.

7 References

[1] Livermore Software Technology Corporation (LSTC). LS-DYNA Keyword User's Manual, 2014
[2] Pled F et al, Crushing Modes of Aluminium Tubes under Axial Compression, 2014
[3] Jones N, Structural Impact, 1997.
[4] Altair Engineering Inc. Hyperworks, 2014

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