8. Results comparison

8.1 Introduction

Contained in this chapter are the summarised results of the various outputs encountered during the course of this investigation. They were compared to each other to ascertain their accuracy and shortcomings. The output sources compared are those of the experimental data, the finite element simulation and the results of the composed MATLAB code. The sequence of comparison is as follows:

- The experimental data was captured from the scale model as outlined in section 6. Preliminary comparisons were drawn between these results and the MATLAB code.
- When the range of experiments was completed, a finite element model of the experiments already completed was generated. A simulation of the experiments was executed and the results were compared to the data captured during the experiment itself (refer: section 7.).
- Once the quality of the FEM had been confirmed by accurate comparison to the experimental data, the assumption was made that further exploration of the MATLAB code could be done by means of comparison with the FEM simulated output. This was a sound assumption given the good correlation that was achieved (refer: section 7.1).
- A further investigation was conducted involving the inertial effects of the system on the deceleration levels and the performance of the deceleration systems. The inertia of the system was varied by means of adjusting the density of the strip material in the FEM, and simulating the same full scale scenario.

By making use of this technique, the restrictions encountered with the physical scale model testing were avoided, yet the reliability of the MATLAB code could still be comprehensively evaluated. Further, an understanding of the inertial effects was obtained and quantified.

8.1.1 Experimental data compared to Finite Element Analysis output

The physical component measured in the experimental data capturing process was acceleration (refer: section 6.). The output of the FEM for the simulations was the velocity of the strip and impacting mass. For this investigation to have a common ground on which to compare the systems, the velocity output from the FEM was differentiated to obtain an acceleration profile. Once the acceleration profile was determined, a comparison could be drawn based upon the same reference plane. One experiment from each group was selected for FEM simulation, which was compared to the recorded data (refer: Figure 60). The MATLAB program output was included in the velocity and deceleration comparisons for preliminary evaluation.

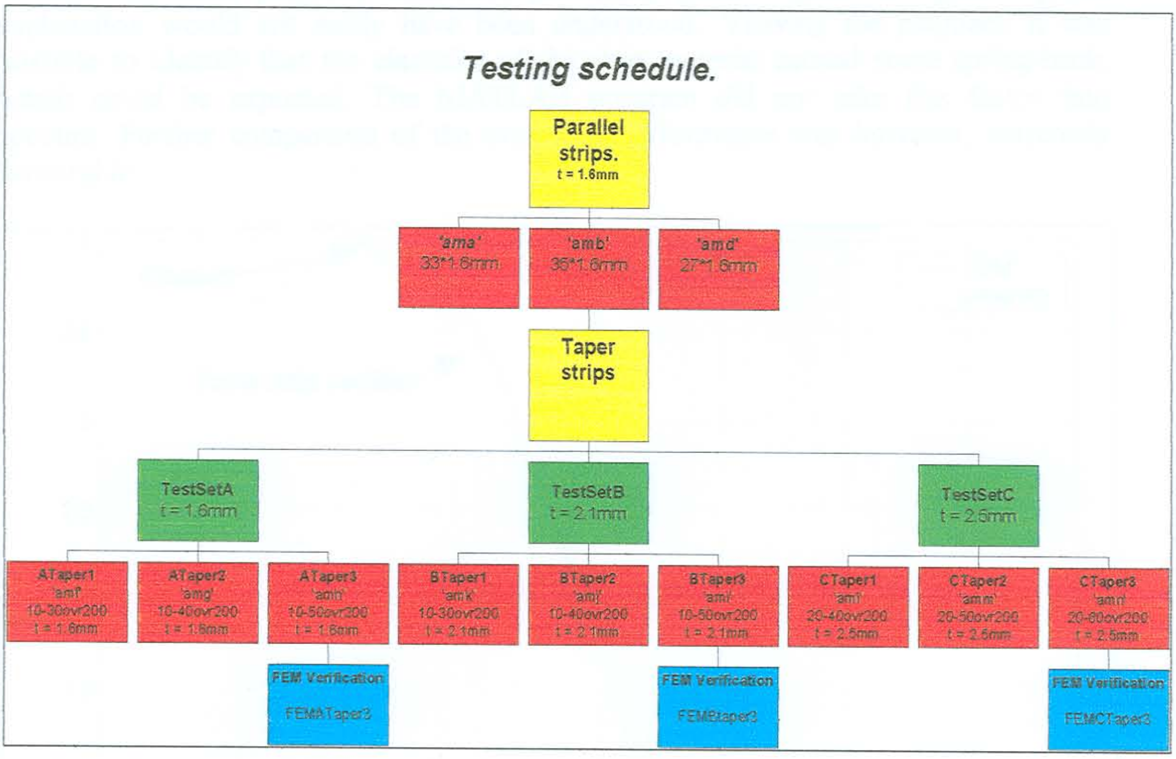

Figure 60 Finite element analysis verification schedule.

8.1.1.1 First comparison set

The schedule seen in Figure 60 shows which of the experiments had been chosen for simulation. Since the output of the FEM was velocity, the velocity output could be directly compared to the velocity output of the MATLAB program (refer: Figure 61). The FEM data was unfiltered. Referring to Figure 61, the FEM velocity profile only started at the indicated contact point. The FEM simulation was initiated at the contact, with the mass having an initial velocity equal to that of the experimental mass, which had been dropped from the predetermined distance before making contact with the deceleration systems. The FEM simulation also indicated the mass overshooting zero velocity, implying that the retarded mass moved backwards after it came to rest. Without the visual playback mentioned previously (refer: Figure 56-Figure 59), the explanation would not easily have been understood. Viewing the playback it was possible to identify that the elasticity of the strip material caused some spring-back, which could be expected. The MATLAB program did not take this factor into account. Further comparison of the predicted performance was however, extremely favourable.

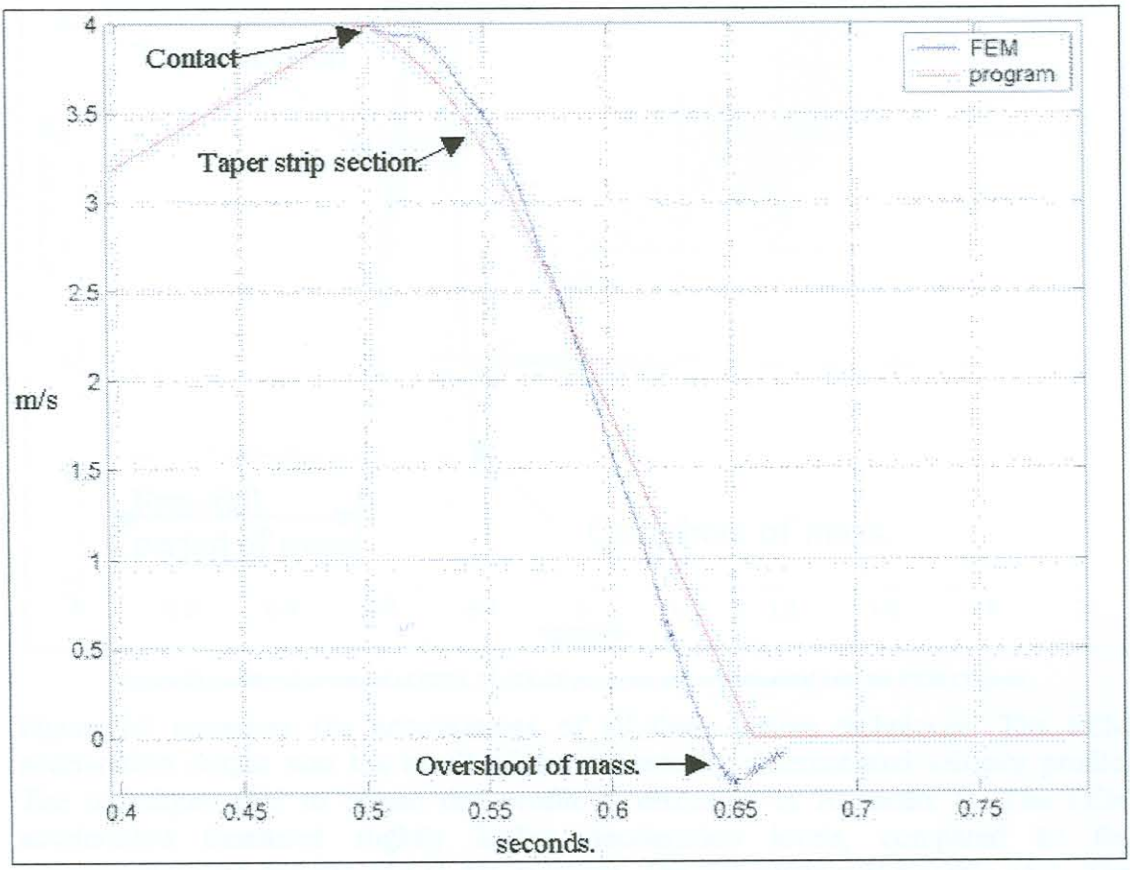

Figure 61 Velocity output of FEM and MATLAB program for FEMATaper3.

Once the velocity data of the FEM had been filtered and processed to yield an acceleration curve, it was compared to the data measured experimentally as well as the prediction from the MATLAB program (refer: Figure 62). The processing procedure performed on the data to obtain the acceleration plot is outlined in Appendix B.

Two or three test runs were performed per experiment for the sake of repeatability, which is the reason for more than one data plot in Figure 62. The initial negative 0.8Gs section in Figure 62 indicates free fall of the mass, bearing in mind that, for this experiment, the model cage dropped a certain distance before making contact with the deceleration systems installed in the shaft (refer: Figure 30, Figure 31). The MATLAB program takes this into account. In this section the effect of the friction in the rails of the conveyance can be seen. The conveyance only reached 0.8Gs when freefalling, indicating resistance. This was also accommodated for in the MATLAB program. The user describing the situation can make the choice of height above the arrestors.

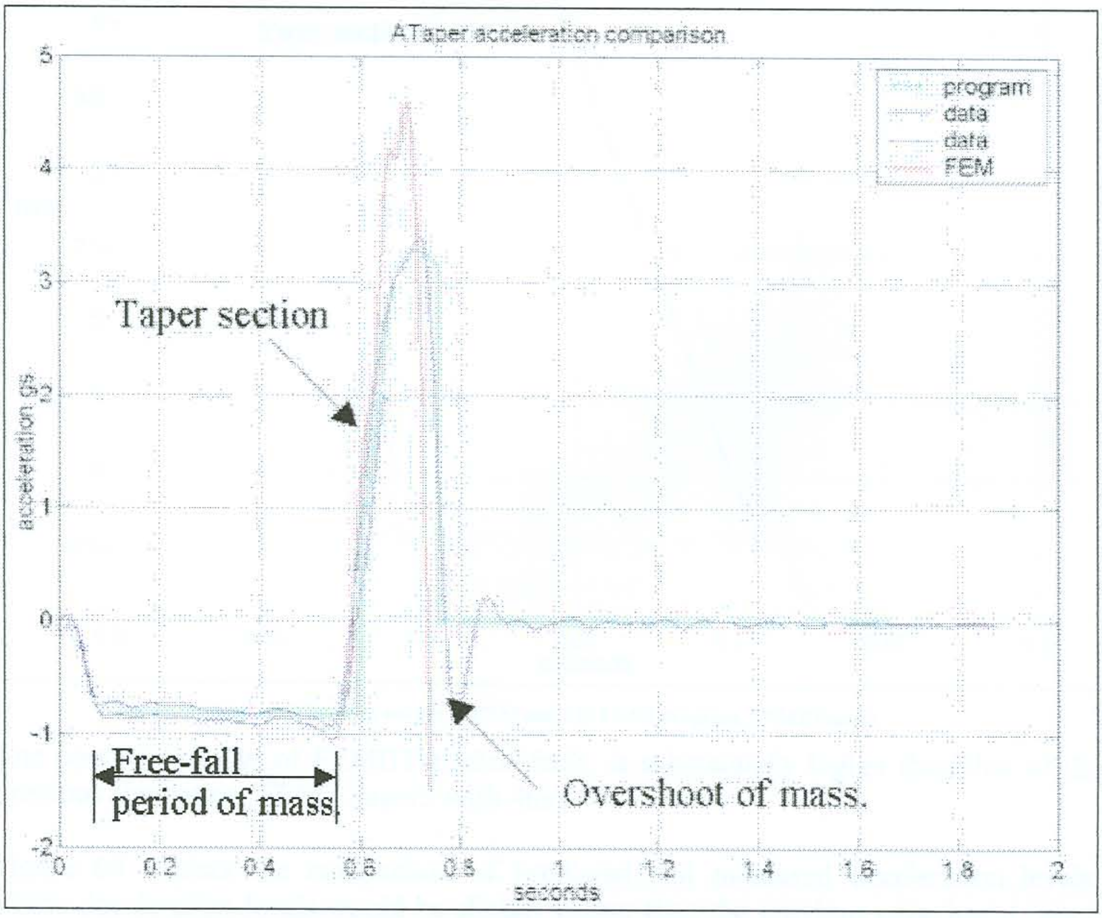

Figure 62 Acceleration output of FEM, MATLAB program and experimental data for FEMATaper3.

Figure 62 compares the accelerations of all three testing techniques. The FEM acceleration output was the result of the numerically differentiated velocity profile. The technique used to obtain this profile is discussed in Appendix B. The FEM acceleration measured slightly higher deceleration levels, compared to the experimental data and the MATLAB program. The difference was roughly 25%. The prediction of the MATLAB program, in this case was totally accurate, compared to the measured data.

The gradient of the initial deceleration showed the effect of the taper section of the strip gradually increasing the applied deceleration force (refer: Figure 62). The overshoot of the mass is clear from the experimental data recorded in Figure 62, as well as the FEM results. This similarity also confirmed the accuracy of the FEM simulation.

8.1.1.2 Second comparison set

The second comparison set, FEMBTaper3 also compared favourably, confirming the accuracy of the simulations already seen. The FEM simulation was interrupted at the final stages of the procedure thus not showing the mass coming to a halt, but the comparison proved to be of great accuracy (refer: Figure 63)

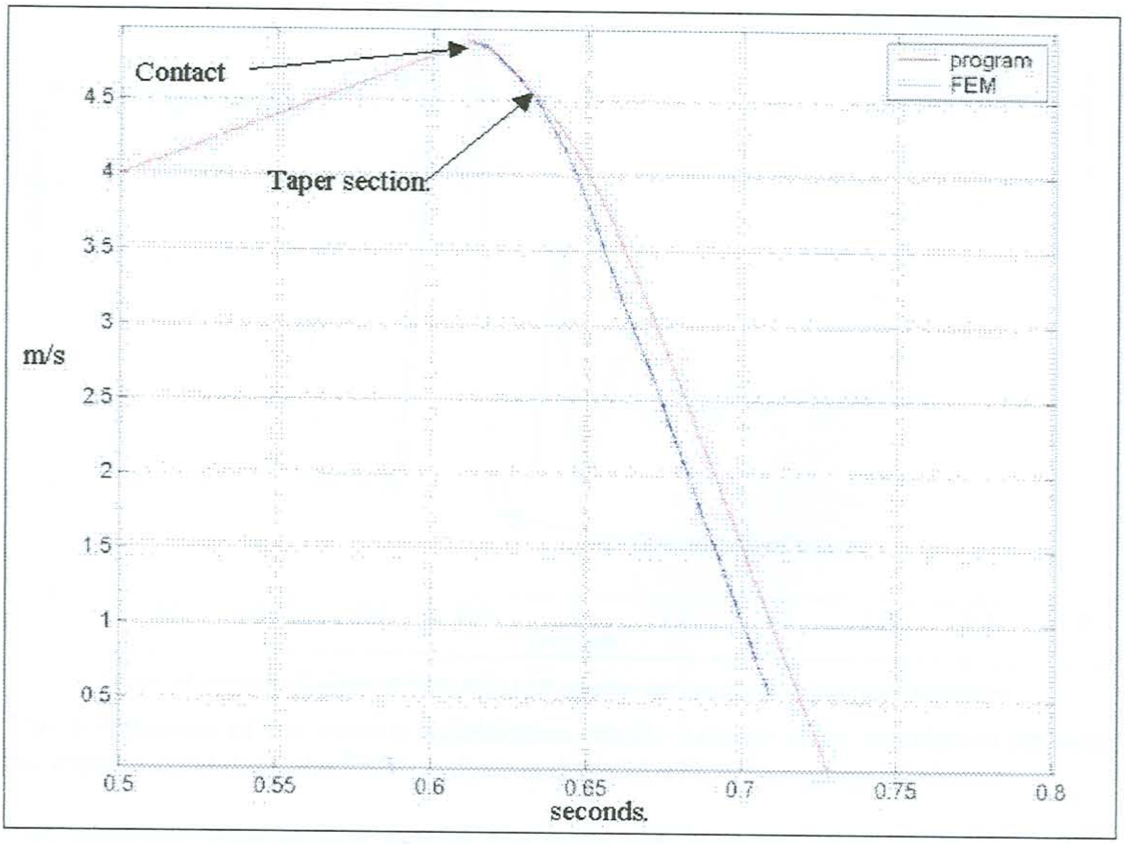

Figure 63 Velocity output of FEM and MATLAB program, FEMBTaper3.

The contact velocity of FEMBTaper3of 5m/s, is substantially higher than that of the previous simulation, FEMATaper3 with 4m/s.

Figure 64 depicts the comparison of predicted and measured deceleration levels. These deceleration levels would be slightly higher than the previous experiment, since with the scale experimental model at the University Pretoria, the space available to decelerate the mass at the bottom of the shaft was limited. Thus with the higher impact velocity required for the experiment, the deceleration rate of the mass had to be higher to allow for retardation within the distance available.

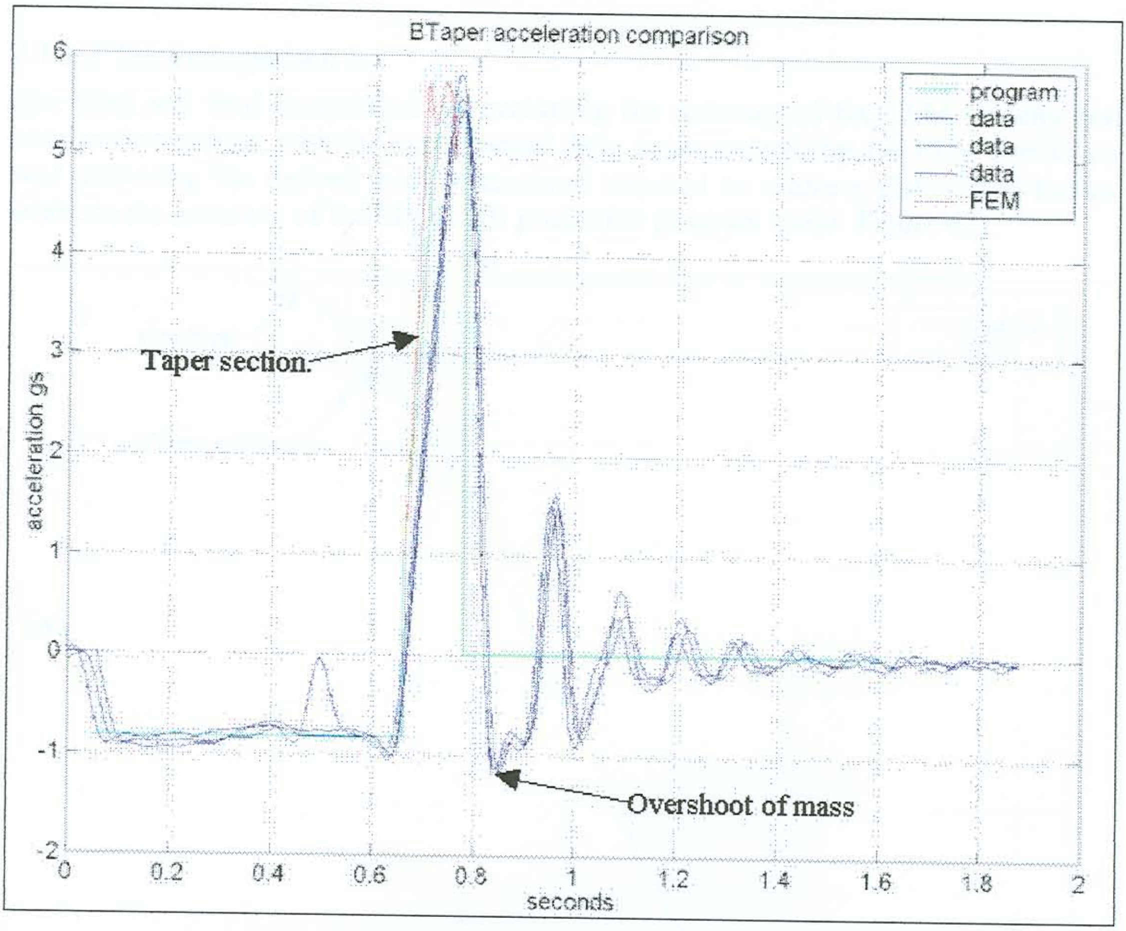

Figure 64 Acceleration output of FEM, MATLAB program and experimental data for FEMBTaper3.

This comparison of the various acceleration results indicate close correlation between the experimental data, the FEM analysis and the MATLAB program prediction.

This particular experimental section had three runs with the scale model to capture data. Figure 64 shows that the repeatability of the deceleration profile was close to perfect. The superimposed FEM acceleration profile corresponded closely to the data profile, including the maximum deceleration level expected, of approximately 5.8 Gs. Due to the interruption of the FEM calculation, the overshoot of the mass cannot be seen. The MATLAB program prediction again was extremely accurate, following the first two outputs of the experimental data and the FEM closely.

8.1.1.3 Third comparison set

The third and final comparison set evaluating the accuracy of the FEM velocity and acceleration output, with the experimental data, again proved that the FEM simulation was delivering the desired level of accuracy required to create a platform to further evaluate the accuracy of the MATLAB prediction program (refer: Figure 65).

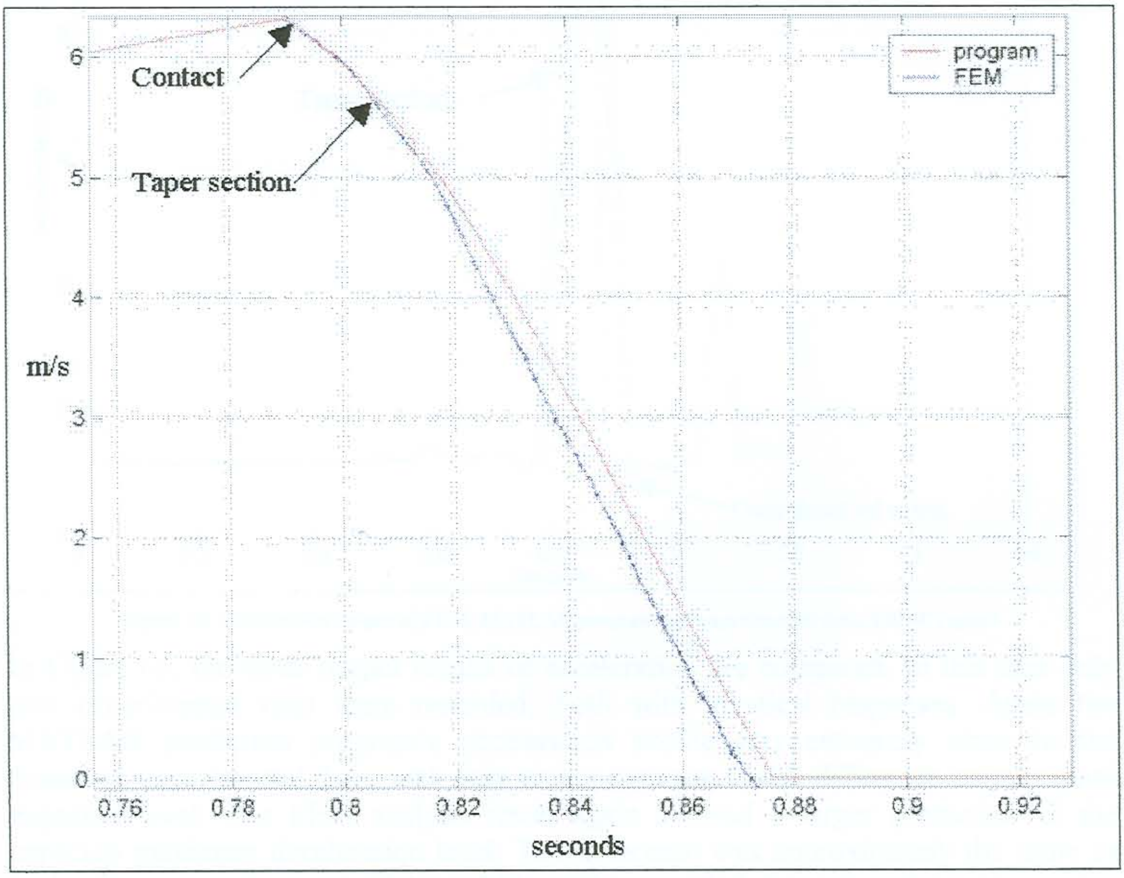

Figure 65 Velocity output of FEM and MATLAB program, FEMCTaper3.

The preliminary velocity plot shown in Figure 65 shows the close resemblance between the FEM velocity output and the MATLAB program velocity prediction.

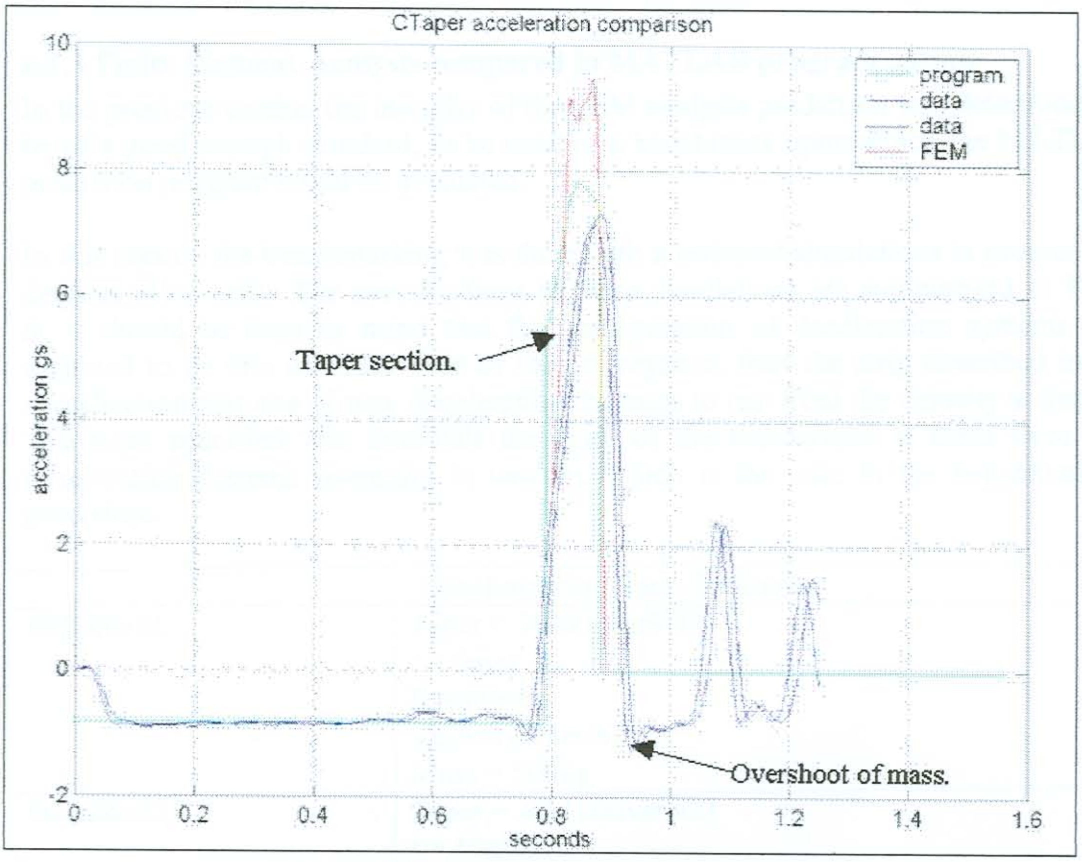

Figure 66 Acceleration output of FEM, MATLAB program and experimental data, FEMCTaper3

In Figure 66, the three output results of acceleration are compared. In this case only two experimental runs were recorded, both with identical responses. Again the MATLAB prediction program's acceleration profile was extremely close to the measured experimental data, with only an approximate 0.4Gs difference on maximum expected level. The FEM analysis result again showed a larger prediction of the expected maximum deceleration level. The difference was approximately the same as in the first comparison set of about 25% to the recorded data, as explained in section 8.1.1.1. The significance of this difference will be discussed at the end of this chapter (refer: section 8.1.2 and section 8.1.5).

8.1.2 Summary of Experimental Data and Finite Element Analysis Comparison

The objective of this section was to determine the quality of the FEM analysis prediction. The three phases of comparison clearly indicated that the proximity of the deceleration levels were adequate to accept that the prediction of the FEM analysis could be used as a benchmark to further evaluate the quality of the MATLAB program's output. In all three cases the MATLAB program was more accurate than the FEM, and delivered a conservative prediction of the expected deceleration levels. This tendency could be expected since the dynamic impact of the collision in the FEM attributes for higher decelerations encountered with the absence of cable damping as was the case in the experimental setup. The following section discusses the results of the FEM analysis for various simulated scenarios as compared to the MATLAB program outputs. By making use of the versatile FEA program and changing the density of the strip element material, the influence of inertial effects under braking conditions was also explored.

8.1.3 Finite Element Analysis compared to MATLAB program output

In the previous section the integrity of the FEM analysis prediction was determined to be of a good enough standard, to be used as a benchmark upon which the MATLAB prediction program could be evaluated.

In this section the benchmarking was done with a series of simulations in progressing degrees of severity. The specifications of these simulations are summarised in Table 5. It should be kept in mind that the configuration of deceleration systems was assumed to be one on either side of the conveyance, thus the strip described in the specification was one of two, decelerating the mass to rest from the velocity at impact. The mass specified was thus half the mass of the conveyance if there were two deceleration systems operating in tandem, which is the case in the benchmarking procedure.

Benchmarking Specifications.	
DeltaRoll1	Taper = 30-60over300 t = 6mm R = 80mm Velocity= 8m/s Mass = 500kg
DeltaRoll2	Taper = 40-100over500 t = 10mm R = 150mm Velocity= 12.5m/s Mass = 1000kg
DeltaRoll3	Taper = 100-250over1500 t = 20mm R = 300mm Velocity= 18m/s Mass = 5000kg

Table 5 Specifications of the MATLAB program Benchmarking.

The deceleration levels for the following scenarios were kept in the region of human tolerance, which is in the order of 2.5Gs (refer: section 2.1).

8.1.3.1 First Benchmark Scenario, DeltaRoll1

The first scenario was a simulation of a minor scale incident. The summary described in Table 5 gives all the specifications of the incident. Conceptually this scenario was equivalent to a 1000kg conveyance dropping four meters, at 0.8Gs or eight tenths of the gravitational acceleration. The reduced acceleration took into account the friction in the guide rails of the cage and this was measured experimentally on the scale model and was implemented into the MATLAB program's code (refer: Figure 62).

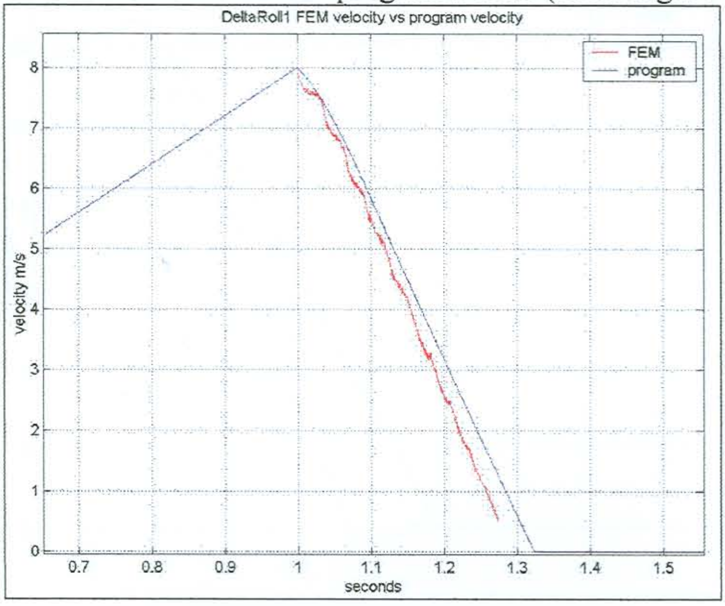

Figure 67 DeltaRoll1 velocity comparison.

In Figure 67 the velocity profiles of both predictions are compared. The velocity profile of the FEM analysis was then used to determine the acceleration performance by means of calculating the gradient of the curve. This procedure is further described in Appendix B.

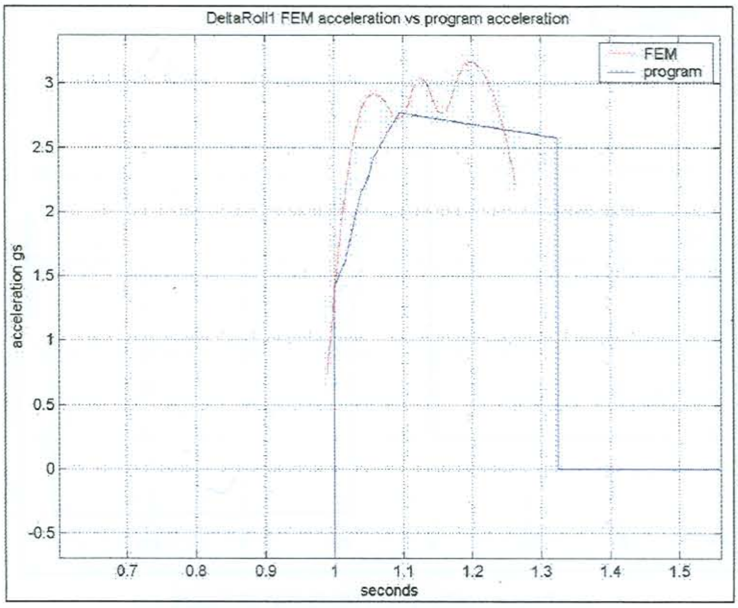

Figure 68 DeltaRoll1 acceleration comparison.

Figure 68 presents the result of the acceleration comparison. The predicted levels of deceleration were similar to the MATLAB program, once again delivering a conservative estimation as expected, based on previous performances observed.

8.1.3.2 Second Benchmark Scenario, DeltaRoll2

The conditions in the second benchmarking scenario were more severe than the first case. The equivalent situation could be described as a 2000kg conveyance, dropping ten meters at 0.8Gs or eight tenths of the gravitational acceleration, and being caught by two of the deceleration systems described in Table 5. The deceleration levels were again maintained in the region of the human tolerance limits as outlined in Table 2.

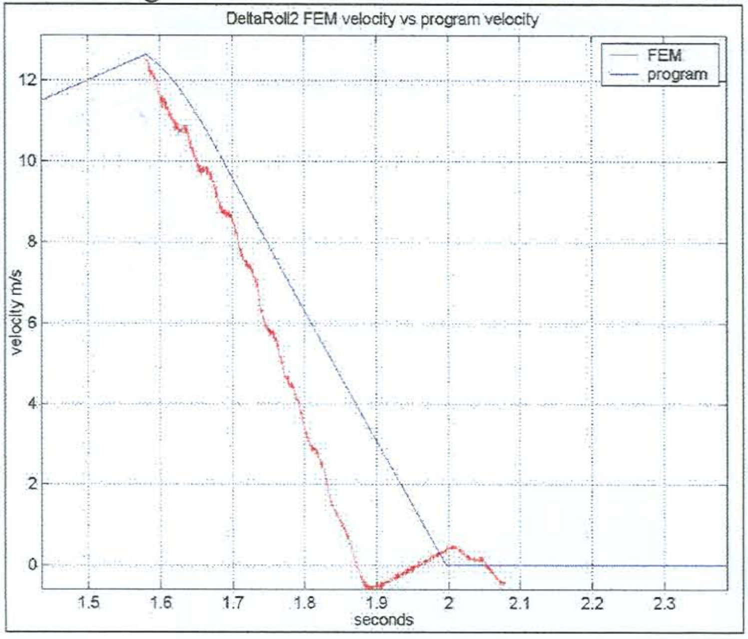

Figure 69 DeltaRoll2 velocity comparison.

The velocity comparison depicted in Figure 69 indicates a slightly sharper deceleration predicted by the FEM analysis, than the results of the MATLAB program.

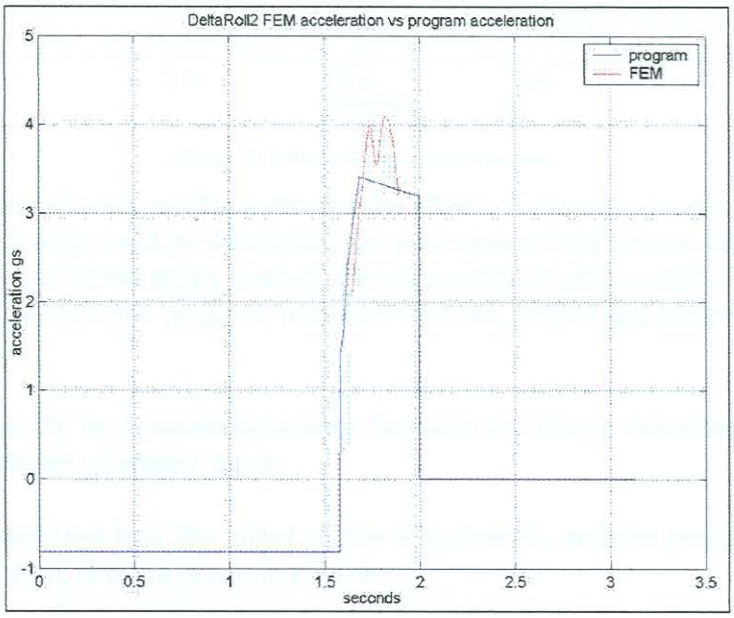

Figure 70 DeltaRoll2 acceleration comparison.

The deceleration levels shown in Figure 70, confirm the trend that the FEM analysis predicted a higher predicted level than the MATLAB program. The margin of error was in the order of 17%, which was consistent with the performance witnessed in the preceding section.

8.1.3.3 Third Benchmark Scenario, DeltaRoll3

In this scenario the situation was again more severe than previous. The equivalent description would be a 10000kg conveyance (10 Tonne), dropping twenty meters, before impacting two deceleration systems of the scale described in Table 5. This scenario is approaching the scale of real life application.

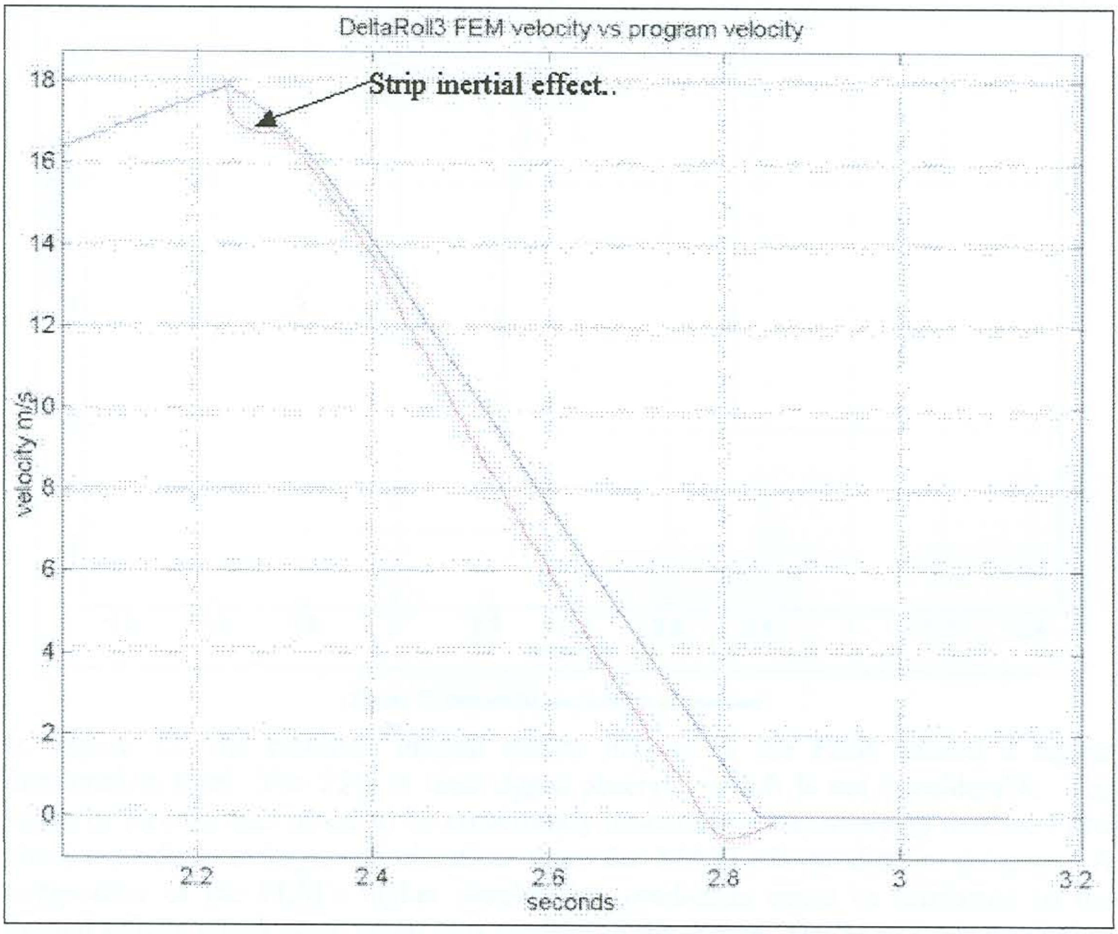

Figure 71 DeltaRoll3 velocity comparison.

In Figure 71, the velocity profile indicates the effect of the strip inertia on the system. In this case each strip used to decelerate the conveyance had a mass of approximately 273kg. With two of these strips needed, the mass ratio of strips relative to conveyance was 5.5%. The MATLAB program assumed that the strips used contributed no mass to the system.

There is a similarity in dynamic behaviour between the above described situation and two colliding masses of similar mass.

A further investigation into the effect of the strip inertia, and the performance impact made on the system, is done in section 8.1.4.

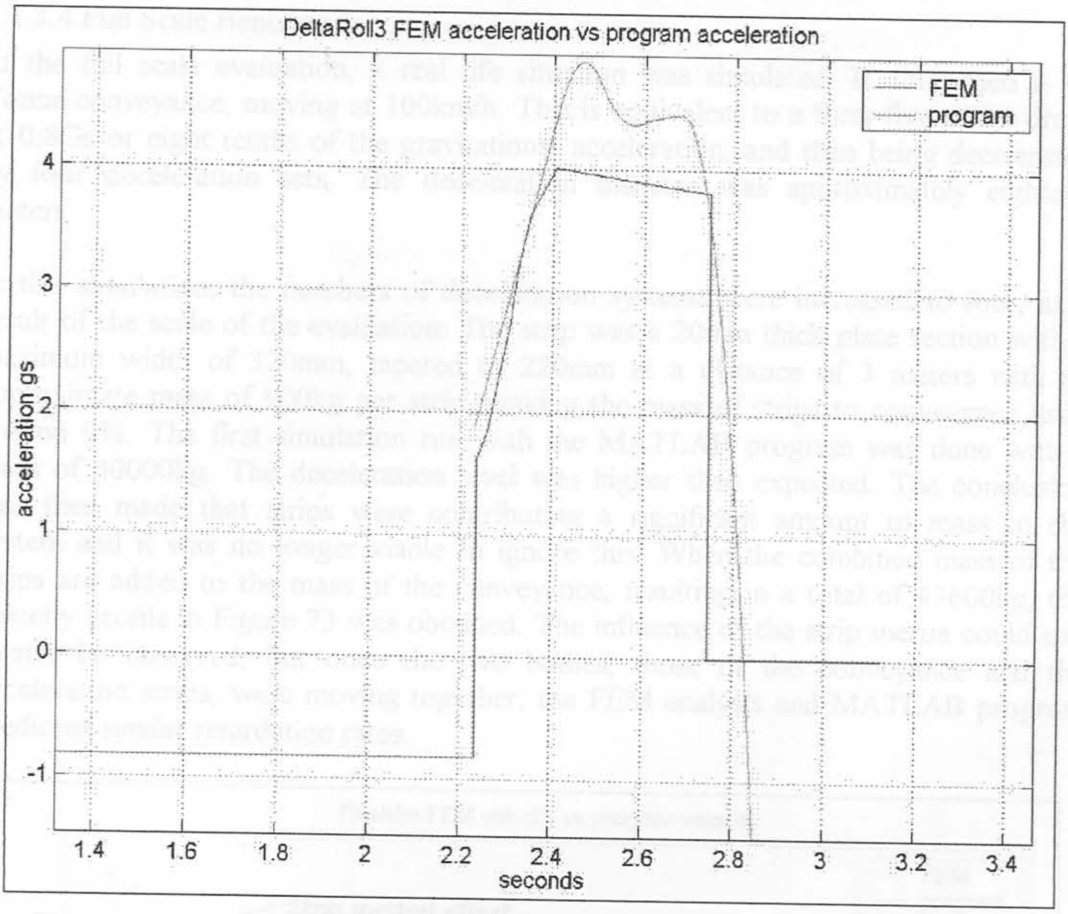

Figure 72 DeltaRoll3 acceleration comparison.

In Figure 72, the resulting inertial effects present in the FEM caused a higher deceleration level. The 25% is once again observed which is not considerable. The range of error is also noted to be consistently un-conservative, implying that the FEM always predicts a larger deceleration than the MATLAB prediction program. A component of the FEM's higher deceleration prediction could be attributed to the inertial effects which were taken into account in the model. The MATLAB prediction program ignored these effects.

A zero-density FEM was performed and compared to the MATLAB prediction program. The result of this comparison is discussed in section 8.1.4.

8.1.3.4 Full Scale Benchmark

In the full scale evaluation, a real life situation was simulated. It concerned a 40 Tonne conveyance, moving at 100km/h. This is equivalent to a forty-five meter drop, at 0.8Gs or eight tenths of the gravitational acceleration, and then being decelerated by four deceleration sets. The deceleration distance was approximately eighteen meters.

In this simulation, the numbers of deceleration systems were increased to four, as a result of the scale of the evaluation. The strip was a 20mm thick plate section with a maximum width of 320mm, tapered to 220mm at a distance of 3 meters with an approximate mass of 900kg per strip, making the mass of strips to conveyance ratio around 9%. The first simulation run with the MATLAB program was done with a mass of 40000kg. The deceleration level was higher than expected. The conclusion was then made that strips were contributing a significant amount of mass to the system and it was no longer viable to ignore this. When the combined mass of the strips are added to the mass of the conveyance, resulting in a total of 43600kg, the velocity profile in Figure 73 was obtained. The influence of the strip inertia could still clearly be observed, but once the two bodies, those of the conveyance and the deceleration strips, were moving together, the FEM analysis and MATLAB program predicted similar retardation rates.

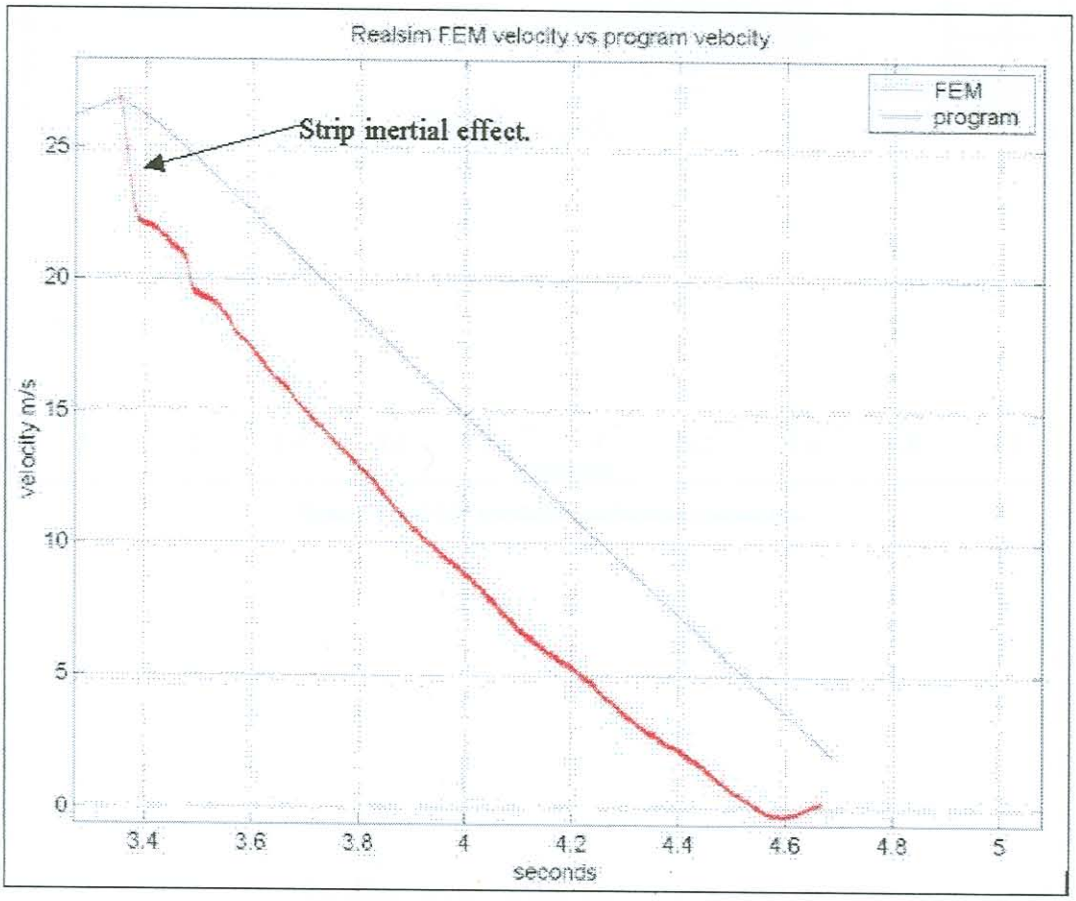

Figure 73 Real-Life simulation velocity comparison.

In section 8.1.4 a summary of the inertial effects of the strips is dealt with, and a combined graphical summary is presented to illustrate the contribution of these effects.

In Figure 74, the deceleration level predicted by the FEM analysis is in the order of 3.5Gs. This can be seen as an impulse with reference to the short length of time over which it occurs, which is approximately 0.2 seconds. With reference to section 2.1.2 dealing with the acceptable deceleration levels humans can endure, this deceleration situation would comfortably be survived by the average, fit person (refer: Table 1, Figure 8).

Apart from the initial discrepancy of the inertial effects caused by the mass inertia of the strips, the prediction of the MATLAB program was representative. Section 8.1.4 summarises the inertial effects of the strip inertia.

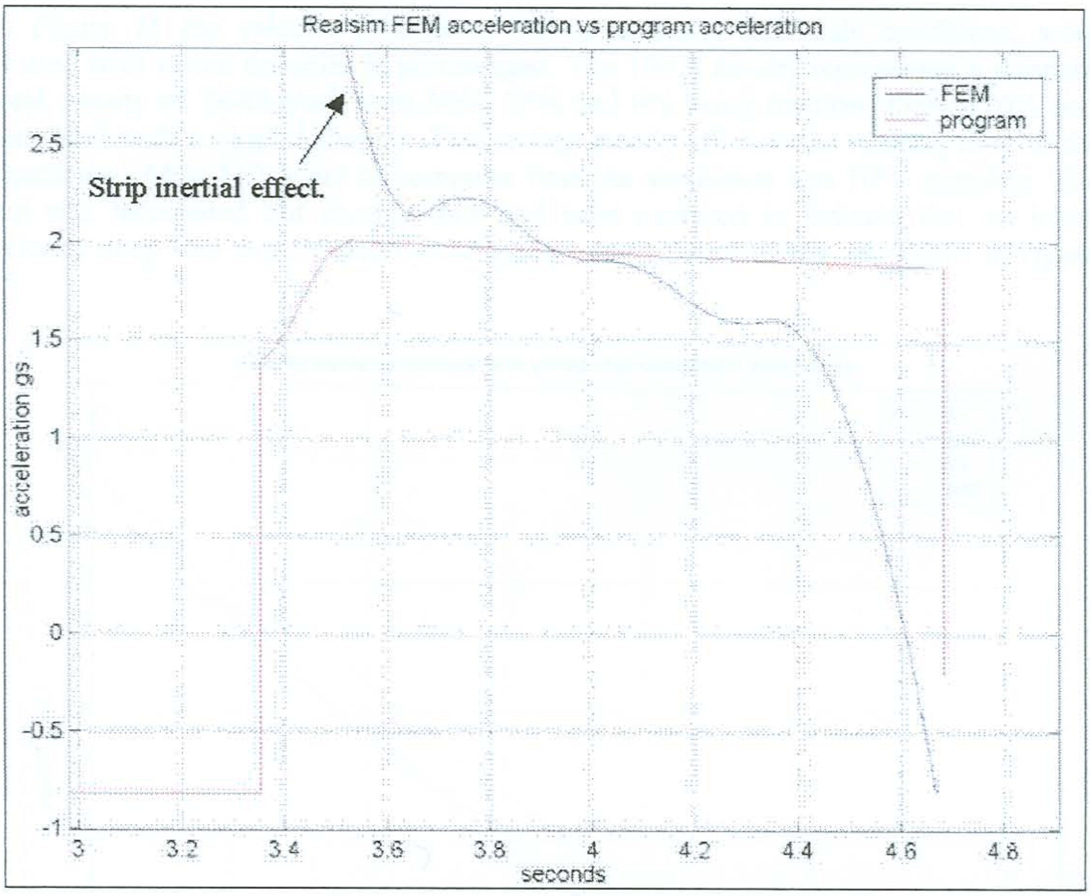

Figure 74 Real-Life simulation acceleration comparison.

8.1.4 Investigation of Strip Inertial Effect

An investigation was performed of the strip inertia effect on the performance of the cyclic bending deceleration systems. This was done by means of varying the density of the strips in the FEA package, MSC DYTRAN. The full scale scenario, as described in section 8.1.3.4, was re-simulated with the various modified strip densities and the resulting velocity and deceleration plots were compared. A comparison with the MATLAB prediction program was also drawn to clearly quantify the difference in performance of the systems relative to the strip density, which corresponded to the strip inertia.

In Figure 75 the velocity profiles of the re-simulated full scale conditions, were plotted with varied densities in percentages. The 100% density represented a standard steel density of 7800kg/m^3, with 60%, 25% and 0% being fractions thereof. 0% was simulated with a 1kg/m^3 density. This setting greatly affected the running time of the simulation. After 110 hours of computer time the simulation was 10% complete. The run was terminated but enough data had been captured to indicate that no initial velocity drop was experienced by the system due to strip inertia, as shown in Figure 75.

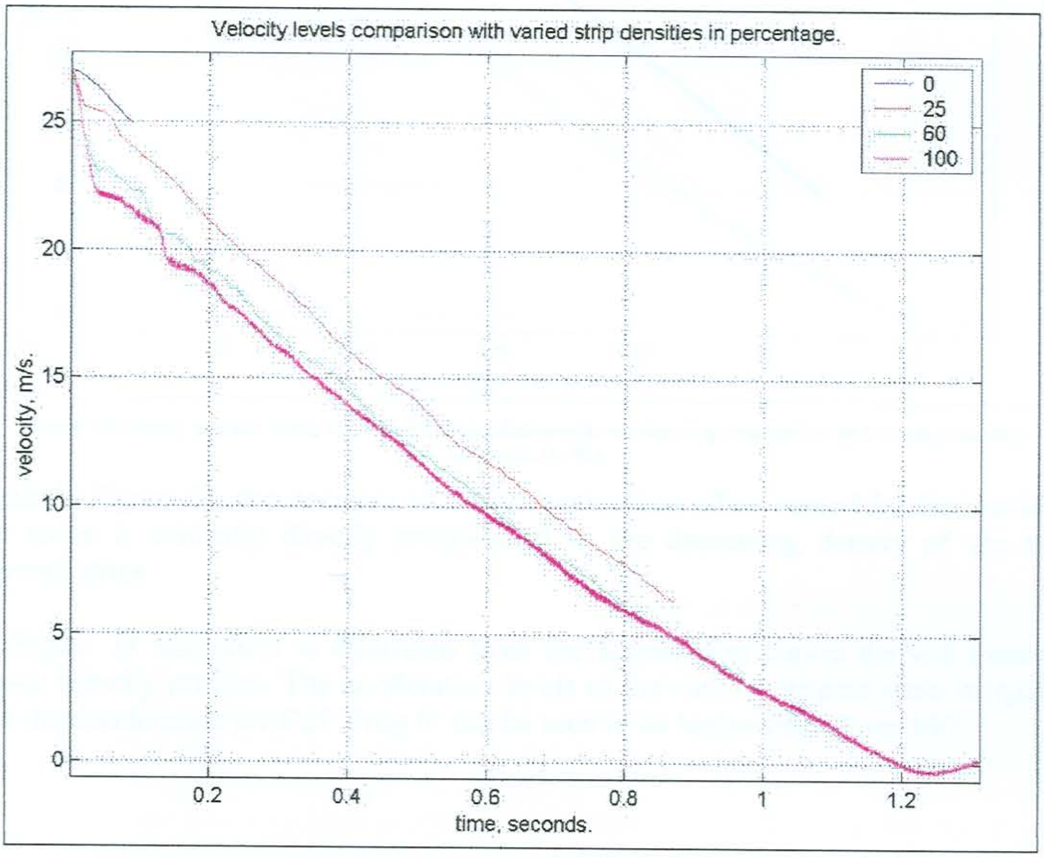

Figure 75 Velocity profiles of the full scale FEM simulation with varying strip densities. (In %)

The gradient of the velocity plots in Figure 75 are increasing (becoming steeper) as the strip density decreases. This effect can be attributed to the total mass of the system dropping, since the mass of the strips decreased. The deceleration capacity of the retardation system remained the same, and thus with less mass to accommodate, the deceleration logically became greater.

In Figure 76 the velocities were compared to the MATLAB prediction program output, with the mass of the strips included and excluded. 'Prog 0' neglected the strip mass and with the available braking force, the deceleration was greater than that experienced by the 'Prog 100' system, which included the mass of the strips. Referring to Figure 76, the gradients of 'Prog 0' and 'FEM 25' can be seen to be within the same order of magnitude, where 'Prog 100' and 'FEM 100' show their similarity in gradient.

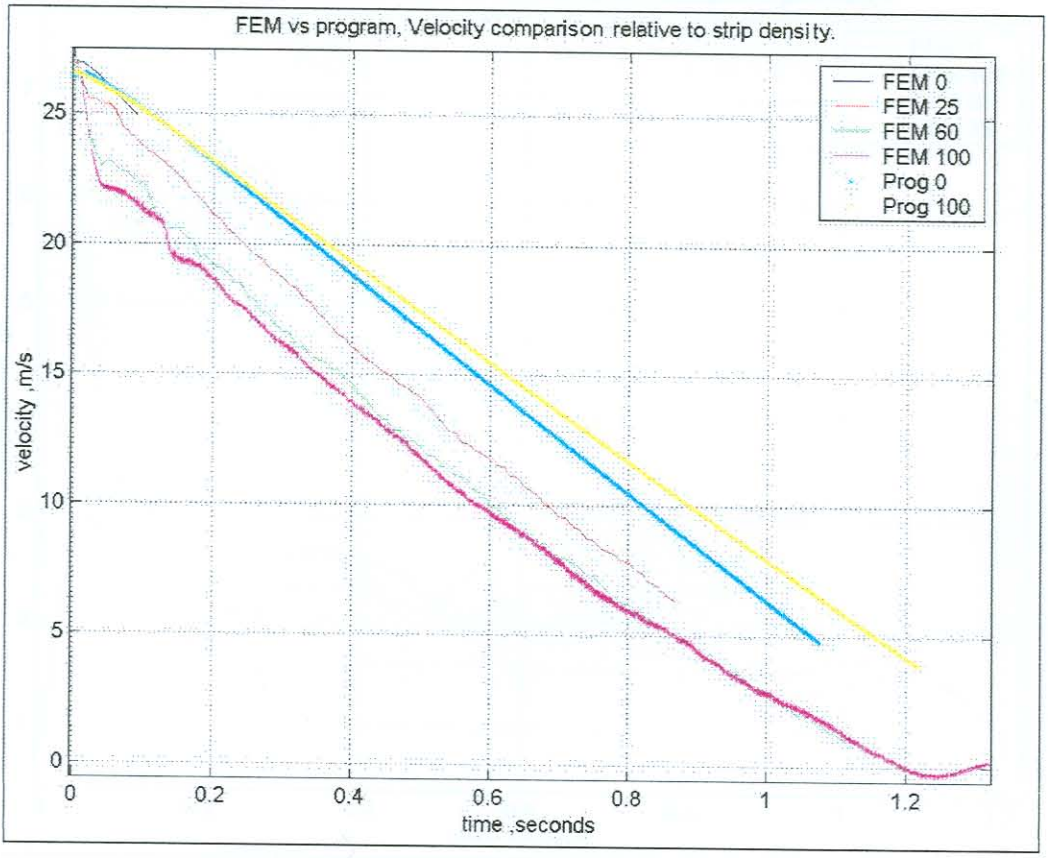

Figure 76 Velocity profiles of the full scale FEM simulation with varying strip densities vs. MATLAB prediction program. (In %)

Again in Figure 76, the decrease in initial deceleration effect caused by the inertia of the strips is evidently directly proportional to the decreasing density of the steel element strips.

In Figure 78 this effect is illustrated from the acceleration curves derived from the above velocity profiles. The acceleration levels of the various outputs were compared and the deceleration level of 'Prog 0' can be seen to be higher than 'Prog 100'.

Figure 77 is the result of differentiating the gradient of the previously plotted velocity profiles to obtain the deceleration experienced by the system. The only significant difference that can be noted in Figure 77 is the initial point of propagation. As the density of the strips decreased, so did the initial effect of the mass collision. This illustrated the crux of the investigation. 'FEM 0' shows no deceleration impulse since the mass struck a seemingly mass-less deceleration system.

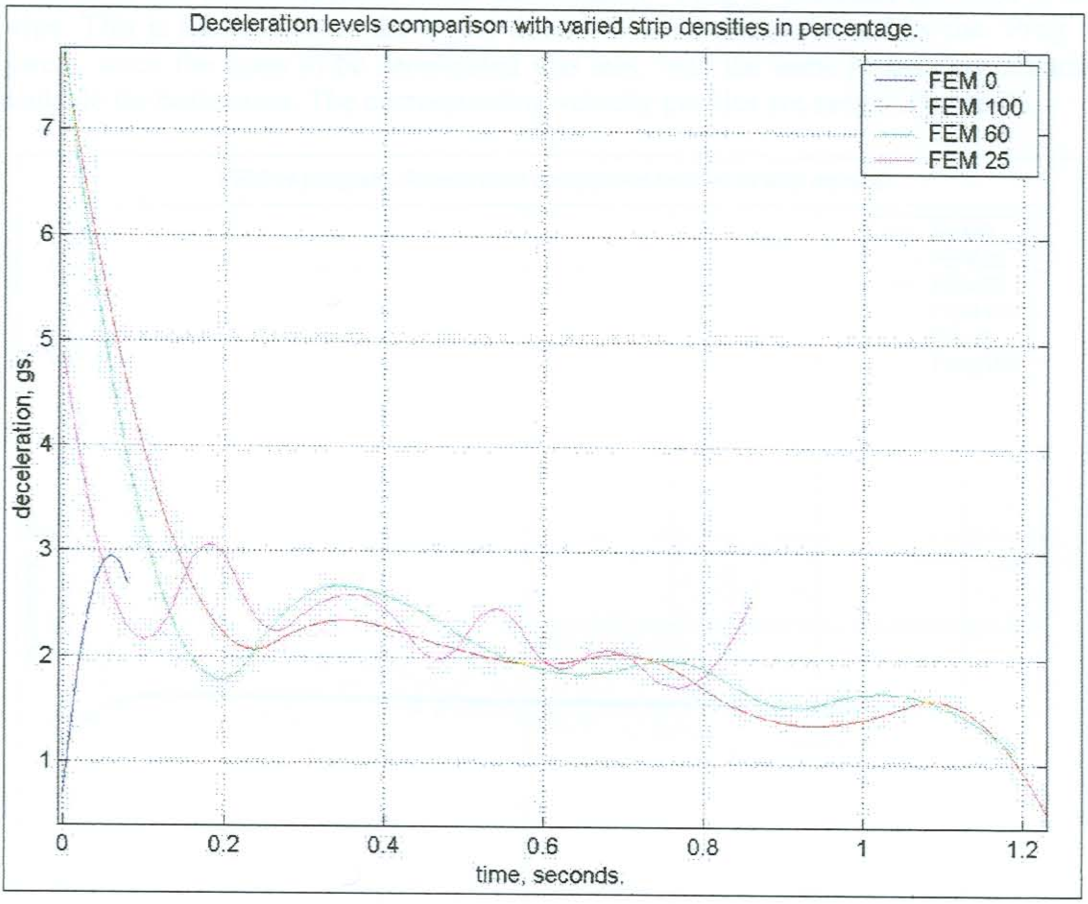

Figure 77 Acceleration profiles of the full scale FEM simulation with varying strip densities (as %).

In Figure 77 the retardation level of all the systems, once the deceleration strips had made contact with the mass, are the same.

If in the above hypothetical situation, a cage filled with occupants were subjected to these conditions of deceleration, the time interval they would have been subjected to the impact deceleration is very short. From Figure 77 the time interval for FEM 100 is estimated to be in the order of 0.15 seconds, with a peak deceleration level of 7.5Gs. In section 2.1.2 the human deceleration limits are quantified. With reference to those models and limits discussed, the occupants of the cage subjected to the full scale condition would probably have experienced deceleration levels which they could have survived while suffering only minor injuries.

In Figure 78 a further comparison was drawn between the FEM output and the MATLAB prediction program output. The initial impact of the MATLAB program output is not present in the graph, since the impact inertia of the strips was not included in the written prediction code.

The deceleration level of 'Prog 100' simulated the performance of the combined mass of the strip and the conveyance under deceleration. 'Prog 0' excluded the mass of the strips. This is the reason for the higher deceleration level experienced by the 'Prog 0' system, since the mass to be decelerated was less, with the same retardation capacity available for both cases. The corresponding velocity profiles are seen in Figure 76.

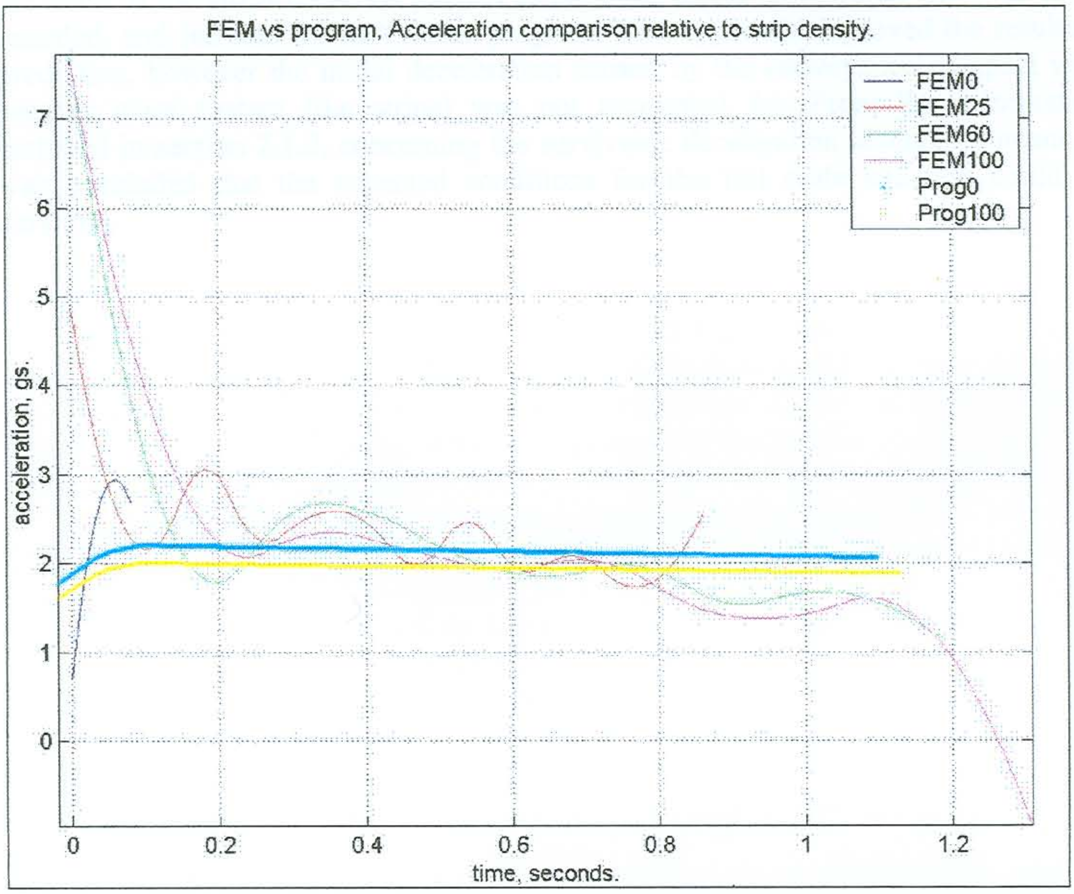

Figure 78 Acceleration profiles of the full scale FEM simulation with varying strip densities vs. MATLAB prediction program. (In %)

The constant region of deceleration, can be seen to be marginally affected by the inclusion or exclusion of the strip mass for the various simulations. The major effect of the strip mass is evident in the impact inertial effects which are directly proportional to the mass of the deceleration strips. The simulated results shown in Figure 78, bear testament to the decreasing initial impact levels for the corresponding lower strip densities.

8.2 Conclusion of Benchmarking Exercise

The comparison of outputs of the FEM analysis and the MATLAB prediction program, proved to be favourable and consistent in all cases. The prediction delivered by the MATLAB program was conservative in all cases of this investigation. The mass ratio between the combined mass of the strips and the conveyance plays a role in the accuracy of the prediction but was not crucial.

It was observed that the strip inertia contributed greatly to the high deceleration levels experienced during impact of the mass systems. When the mass ratio approached 5%, the mass of the strips could be totalled to the mass of the conveyance that was to be retarded, and fed into the MATLAB program. This approach improved the resulting prediction, however the initial deceleration caused by the conveyance's impact with another mass system (the strips) was not accounted for. From the information gathered in section 2.1.2, concerning the survivable deceleration levels of humans, it was concluded that the expected conditions for the full scale situation could be survived.

9. Conclusion and Recommendations

This investigation showed that the MATLAB prediction program promises to be a useful tool, which shows potential to be applied in various fields of industry and not only mining or conveyance applications. The MATLAB code was proved to be capable of accurately predicting the dynamic performance of the deceleration systems for a wide range of scenarios. The computational time for the MATLAB program to complete a prediction was substantially shorter than the FEM analysis. This is a great advantage. The processing time is in the order of 100 times faster and the degree of accuracy, based on the experiments conducted and the comparisons drawn, is of an acceptable standard.

As with all computer packages delivering prediction results, the user must be aware of the limitations of the program before it is applied to a problem situation.

The reason for FEM analysis consistently predicting a higher deceleration compared to the experimental data and the MATLAB program, can be a combination of the following factors:

1. The impact situation in the FEM analysis assumes that the rollers are frictionless. For this application it is a valid assumption since the contribution of friction in the rollers in the deceleration force is minimal. The MATLAB program also makes the same frictionless roller assumption.
2. Further, the FEM analysis assumed for a rigid connection between the strip and the mass. This assumption represents the worst case since the experimental set-up had a multi strand cable used for a connector (refer: Figure 4). In the FEM analysis, no energy was dissipated through the cable, where the cable did absorb impact energy in the experimental condition as well as the real-life application, and this helped alleviate some of the initial shock since the multi strand cables deliver a good amount of elasticity under load.

The finite element model and analysis was thus a more rigid system compared to the experiment set-up and would thus deliver a larger deceleration upon impact.

The MATLAB program also had no cable connection reference but it did not have an impact simulation included into the prediction. The execution of program code is such that the deceleration is applied once the mass passed the point of contact. At the point of contact the mass experienced no impact, which could influence the acceleration in terms of shock. For this reason the initial shock impulse is not seen in the graphs of the MATLAB program's predictions.

Much research would have to be done on the method and type of application of the cables proposed to be used as connectors between the deceleration systems, since their performance affects the overall effectiveness of the whole system. The ideal situation is for further work to be done on increasing the versatility of the MATLAB program code to accommodate both the inertial factors of the strips, as well as the elasticity of the cable connections.

Before this system is applied in industry, full scale tests need to be performed according to the predictions of the MATLAB program. The experimental data of these full-scale experiments then need to be closely analysed to determine the correlation between the prediction and the data captured.

The problem stated in section1.1, concerning the deceleration of a half full cage within the specified limits, can be solved practically by staggering the deceleration systems in banks of increasing deceleration capability. The idea is that when a half full cage under-winds, the first bank of deceleration systems decelerates the cage within the allowable levels of deceleration. If the conveyance is heavier or travelling faster than the deceleration capacity of the first bank of arrestors, a second bank, with larger decelerators is ready to apply a larger deceleration force. The second bank can then, for instance, be sized for a full cage under-wind, which would still be within limits of the specified human tolerance levels. A third bank could also be included with a much larger deceleration capacity, capable of accommodating a runaway cage, travelling faster than anticipated.

This third deceleration would probably be required to exceed the specified human tolerance levels, but could be used as a last line of defence, and under those conditions, injury would be better than death.

The details of such a system have to be tailor designed for each application depending on the amount of run through space at the bottom of the shaft, but the concept has potential to be investigated.