Numerical Models of the Behaviour of Frangible Steel Guard Rail Posts Under Colliding Vehicles

Tristan Bridge
School of Civil and Resource Engineering, University of Western Australia
Arcady Dyskin
School of Civil and Resource Engineering, University of Western Australia
Adam Lim
Main Roads Western Australia (MRWA)

Abstract

Steel guard rails are used along motorways to protect errant motorists from leaving the road in areas of increased danger. However the terminating ends of the rail can create a significant hazard to motorists who lose control of their vehicles, and impact the rail in a direction parallel to its length. To address this danger, the posts which support the rail in the end terminals are designed to safely break away upon impact. Main Roads W.A (MRWA) currently use frangible wooden posts in the end terminal of a common guard rail system - the West Australian Modified Eccentric Loader Terminal (WAMELT). Due to a number of issues associated with the use of timber, including those of supply and maintenance, a study to find a suitable replacement composed of steel was undertaken. Three years ago a previous CEED student Peter Kapitola, began investigation into this problem and developed a design for a potential steel post replacement. The next step was to test the post under impact using finite element analysis. The aim of this project is to investigate the performance of the proposed post design under impact scenarios which simulating physical crash testing. Findings from resultant analysis will help MRWA to develop guidelines for the final post design. Two programs are being used to simulate the post behaviour, SAP2000 and LS-Dyna. Multiple tests have been run involving differing impact velocities, masses and geometries. All tests thus far show the post design proposed by Kapitola performs in a satisfactory manner.

1. Introduction

The unprotected ends of guard rails can pose a serous danger to errant vehicles which collide with the rail in a parallel direction. In such collisions, the rail has been known to act as spear, penetrating through the engine bay and into the interior of the vehicle, in a manner that is extremely hazardous to occupants. As the government body charged with ensuring safety for all road users, Main Roads W.A. are particularly concerned with this potential hazard.

Figure 1 (Left) Guardrail impact resulting in spearing through vehicle

Figure 2 (Right) WAMELT end terminal

Frangible wooden posts are used in the terminals of many guard rails, including the non-proprietary system used commonly in Western Australia known as the WAMELT. These posts are designed to have a much lower stiffness than the standard posts which support the rail in areas where errant vehicles are redirected back onto the road. The idea is for a colliding vehicle to break easily through the frangible post and push safely through the rail thus avoiding high deceleration forces being imparted on the occupants.

The latest report issued by MRWA on the current state of the WAMELT and the need for improvement was made by Woon et al (2003). The report identified the numerous drawbacks associated with the use of timber posts. These included;
- maintenance issues (the need for continuous repair and periodic checking)
- supply issues (difficulty in obtaining quantities required)
- susceptibility to external factors (eg: fire, rotting and insects)
- difficulty in guaranteeing homogeneity of specimens (which commonly exhibit splits and knots)

In response to these factors the report stated that "a future programme of testing or research to develop a modified steel post that will provide a similar stiffness to the timber posts is considered worthwhile."

The research began with a previous CEED student, Kapitola "Kapitola (2005)", comparing the breaking strength of wooden and steel posts. Having developed a suitable steel replacement, the next step in the process was to test the new design using finite element software. The aim of this project is to carry out that analysis, replicating Kapitola's results while also simulating the physical crash test which will eventually be needed to show compliance with Australian standards. Australian standards stipulate that terminals of this type must pass crash testing involving impacts from 800kg and 2000kg vehicles, travelling at 100km/h and on a 20° angle to the road direction.

2. Background

The aim of Kapitola's project was to develop a replacement breakaway post using a standard structural member by comparing the strength characteristics of wooden posts with various steel post designs. He achieved this by impacting a number of posts with a 1.5 tonne pendulum impactor at the Centre for Advanced Structural Engineering at Sydney University. Kapitola's criteria for a successful steel post design were to show that it had a similar breaking force to that of the wooden post, and that it exhibited a clean breakaway mechanism upon impact. After testing a number of posts he designed and had fabricated, his results favoured a 125x125x4 square hollow section weakened by the removal of some material situated approximately 100mm above ground level, as shown in Figure 3.

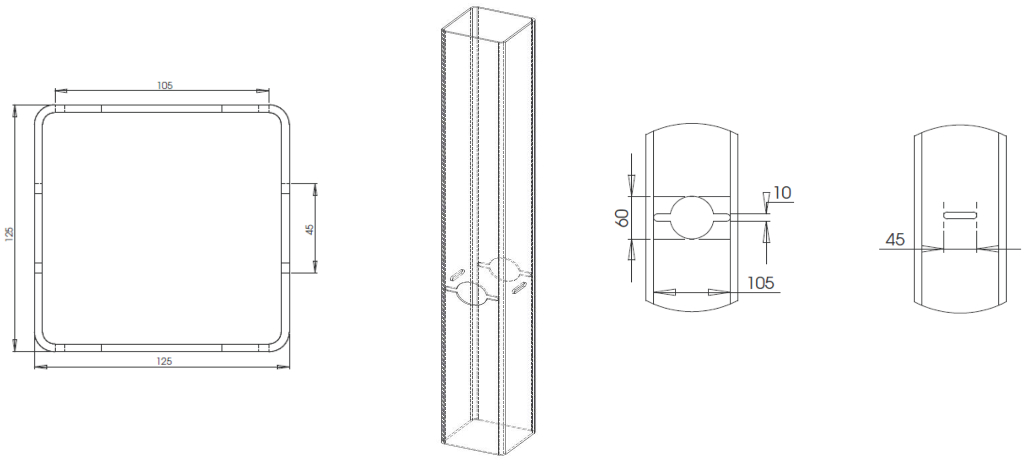

Figure 3 Kapitola's proposed design (PK1.3) 125 x 125 x 4 square hollow section with weakened section

2.1 Analysis of Kapitola's Results

Kapitola used accelerometers attached to the pendulum to record the acceleration-time history of the pendulum/post impact. Using this, the force required to break the post was derived. However anomalies in the accelerometer data cast doubt over the accuracy of the resulting force magnitudes. Kapitola later discovered that the tangential accelerometer had been calibrated as the radial should have been, and vice versa. However he was still able to extract useful comparative results from the accelerometer data, and show that his favoured design (PK1.3) had a breaking force very similar to that of the wooden posts. PK1.3 also demonstrated a clean breaking mechanism, and hence was his recommendation upon which future investigation should be based.

2.2 Other Related Research

In the past decade, with the increase in technology and computing power, finite element simulations have become a popular method of studying vehicle and road-side hardware impact behaviour. There are many publications on such topics, with research showing simulations are able to reflect crash test results very accurately "Plaxico et al (1998)". The high cost of carrying out such crash tests has meant prior simulation of any new design is a necessity to reduce the likelihood of costly test failures.

Plaxico et al used LS-Dyna to investigate the effects of soil strength and post composition on guardrail post response under impact. This paper used a model vehicle to collide with the post and compared results to experimental pendulum test data. "A comparison of these results along with the comparison of acceleration histories supports the conclusion that the finite element model of the post is realistic and can be used with confidence in an extensive model of a guardrail terminal system", as seen in Figure 4. Another notable feature of this paper was the decision to use non-linear springs to model the soil behaviour. Although an entire soil continuum could be modelled using discrete elements, the results show the much simpler method of using non-linear springs can also be used to accurately simulate soil response.

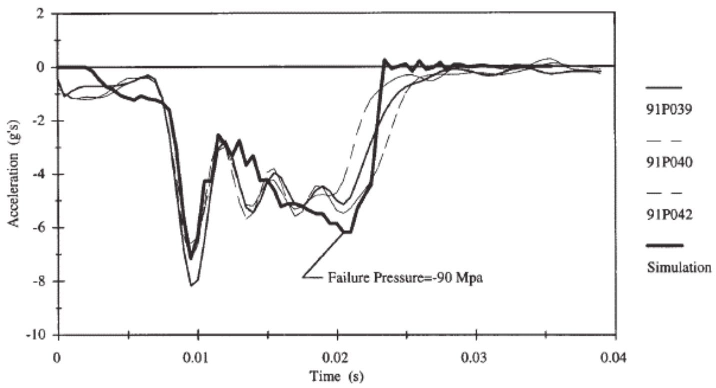

Figure 4 Comparison of pendulum tests and corrensponding finite element simulation acceleratoin time history from "Finite-Element Modeling of Guardrail Timber Posts and the Post-Soil Interaction"

An earlier study "Ray et al (1997)" by two of the same authors as the above paper, investigated vehicle impacts on a guard rail terminal very similar to the WAMELT. Using LS-Dyna, and recorded images from a physical crash test, they were able to reconstruct the prior test very accurately, as seen in Figure 5.

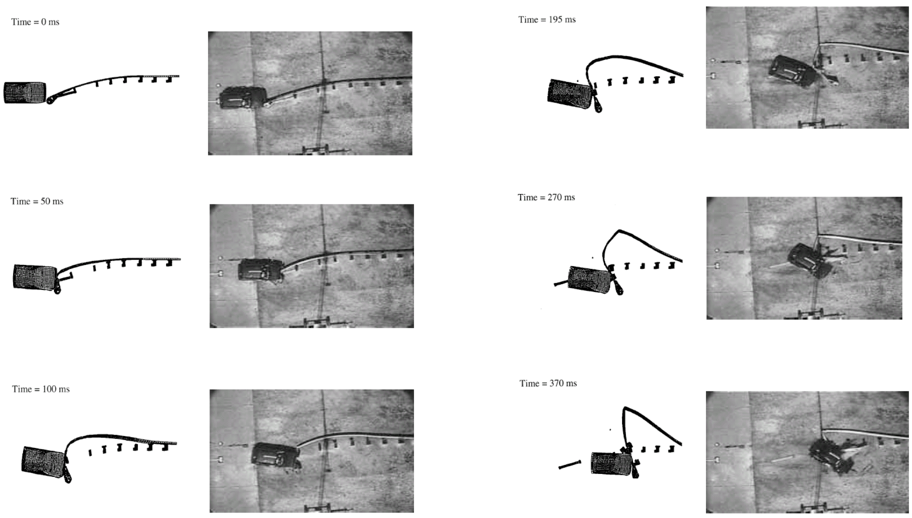

Figure 5 Comparison of physical crash testing and corresponding simulation

Other relevant studies include "Sicking et al (2000)" and "Wu & Thomson (2006). Sicking et al created a design for a steel breakaway post, using two separate sections attached though bolts and welds. Wu & Thomson analysed soil/post interaction in LS-Dyna by modelling a steel post imbedded in an entire soil continuum comprised of discrete soil elements. They used a relationship proposed by Cowper and Symonds which describes the material behaviour at different strain rates.

3. Finite Element Analysis

Two programs are being used to simulate the behaviour of the post under impact. SAP2000 has been used to create preliminary models of the post, using acceleration time histories sourced from crash test data involving similar impact parameters. LS-Dyna is a general purpose transient dynamic finite element program, and allows for a full scale reproduction of a vehicle/post impact.

3.1 SAP2000

SAP2000 was initially used to get an idea of the forces and stresses involved in a vehicle impact at 100km/h (in accordance with Australian Standards). The post model, shown in Figure 6 was given a fixed boundary at the ground level so that the stresses developed around the weakened section of the post could be analysed in isolation from the post/soil interaction.

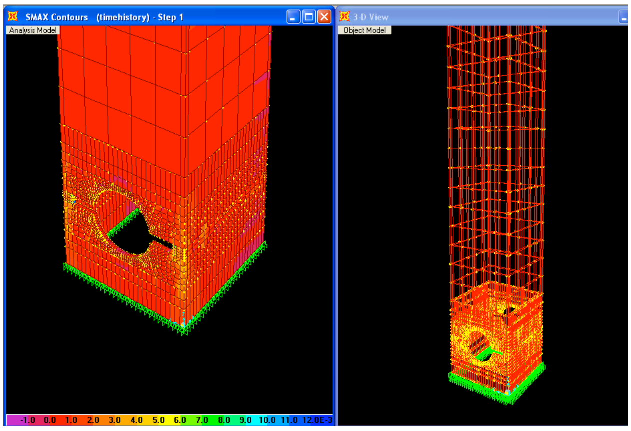

Figure 6 Steel post model using SAP 2000.

Using the United States Federal Highway Association's (FHWA) extensive database of crash test information, several data sets were chosen. Tests were selected on the basis of

- vehicle collision with steel poles or posts
- approximately 800kg vehicle mass
- approximately 100km/h impact velocity

Acceleration time history data from these tests was used to apply a dynamic force to the post, and maximum stresses were determined. Stresses at the weakened section were calculated to be in excess of 1300 MPa. With typical structural steel ultimate stresses in the vicinity of 500 MPa, it was clear an impact of this type would easily be able to break the post.

3.2 LS-Dyna

With the knowledge that Kapitola's design will fail as required in the event of an impact at 100 km/h, LS-Dyna was then used to gain an idea of the exact failure mechanism of the post.

3.2.1 Post Dimensions

As mentioned previously, the steel post is a modified 125x125x4 SHS. The current timber breakaway post is 1100mm long, and sits in a buried steel tube 1500mm long. The total length of the two elements when the wooden post sits partially inside the steel tube is approximately 2185mm. The steel post was designed to replace both elements of the current post. It extends approximately 1425mm below ground with a 600mm by 600mm soil plate welded to the front 50mm below ground level to increase soil resistance. The weakened section was modelled 100mm above ground level. An impact point 300mm above ground level was employed after a survey of common vehicle bumper bar ground clearance distances.

3.2.2 Steel Parameters

To accurately model the structural steel which composes the post, the program asked for the yield stress, failure strain, Young's modulus, Poisson's ratio and eight points of stress/strain data in the plastic region. Data for C350 grade structural steel was provided by Onesteel. It was interesting to note that although rated as 350 MPa steel, recorded yield strengths were closer to 430 MPa. The data also provided isolated tests for the corner sections of the post, which exhibited markedly different stress/strain behaviour to the face sections. The increased yield strength of the steel in the corner sections is due to the cold working that is done to those areas in the manufacturing process. To account for this, a different material profile was created and applied to the corner sections of the post.

Strain rate affects were also taken into consideration by using the relationship proposed by Cowper and Symonds. They suggested that the effects of increased strain rate on strain rate dependent materials could be accounted for by the following equation:

$$\frac{\sigma'}{\sigma} = 1 + \left(\frac{\dot{e}}{D}\right)^{\frac{1}{q}} \tag{1}$$

where σ' and σ are dynamic and quasi-static stresses respectively, $\dot{e}$ is strain rate and D and q are Cowper–Symonds coefficients. A paper presented at the Metal Bulletin International Automotive Materials Conference in 2000, reported values for the parameters D and q relating to automotive type impacts for structural steel. LS-Dyna uses those two input parameters to apply the Cowper–Symonds to a selected material. Values of $D = 424s^{-1}$ and $q = 4.73$ were used.

3.2.3 Impact Types

In order to refine the model, a simple impacting plate was initially used to simulate the collision. An extremely large density was applied to the plate so it would reflect the momentum of a vehicle impact.

Once initial problems with the technical aspects of the program were overcome, a large solid element was created to simulate Kapitola's pendulum tests. The corresponding mass and impact velocity were applied so that the breaking mechanism could be compared to Kapitola's tests, and used to validate the model.

Several models of full scale vehicles were available through a website run in conjunction with the FHWA. A model of an 808kg hatchback vehicle, shown in Figure 7, was downloaded and included in the model. At this point, different velocities and impact geometries have been applied and simulated to ensure the post behaves satisfactorily under a range of impact scenarios.

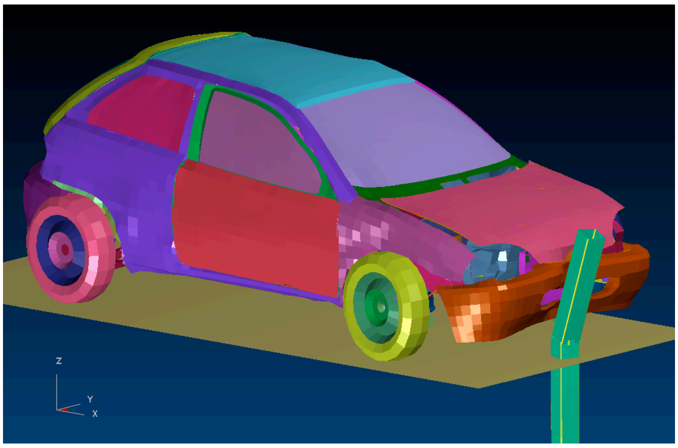

Figure 7 Model of 808 Kg vehicle impacting steel post

3.3 Post/soil interaction

The soil/post interaction is an important aspect of the impact simulation. There are two ways to simulate soil response in finite element simulations; modelling the post embedded in a continuum of solid finite elements with corresponding soil properties, or using non-linear springs attached to the post. While modelling the entire soil continuum may be a more realistic method, using non-linear springs have been previously been employed with success, and have the added advantage of significantly reducing computation time.

The non linear spring method was chosen for this project. Using a program called Oasys Alp, a profile of post deflections at ground level was composed by altering the lateral force and recording the resulting deflection. The force/deflection profile was associated to a spring which was placed at ground level on the back side of the post. Using the program, profiles for three different soil types were created, loose, medium and dense sand.

4. Results/Discussion

All tests thus have shown the post failing successfully and in a relatively clean breaking mechanism. As shown in Figure 8, the post can be seen cleanly breaking at the front but creating a hinge on the back face. This behaviour is similar to some of the post failures recorded by Kapitola during his pendulum testing.

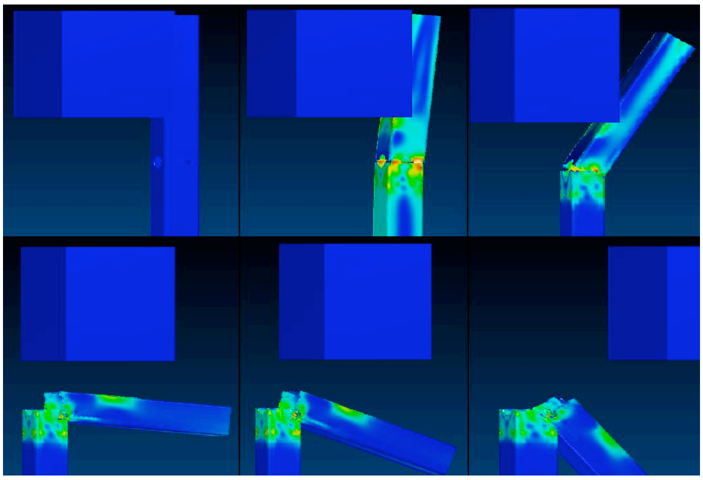

Figure 8 Frame by frame output of pendulum striking steel post - simulation of Kapitola's test

At this stage the model is still being refined. The soil effects being simulated via the non-linear spring have not yet been applied to a successful simulation. There is also a problem with the backside of the post passing through itself rather than deforming as it rotates. This is being rectified by defining a contact interface to prevent nodes in the post from penetrating through its own surface. Once the last few problems have been overcome, values for the breaking force of the post and energy dissipated during the impact will be derived from the output. Aside from those aspects, indications at this stage suggest Kapitola's design will successfully fulfil all of the required design criteria.

5. Recommended Future Study

Due to the uncertainty in the post manufacturing process and on-site assembly, varying parameters such as the distance from ground level to the weakened section, and distance from impact point to the weakened section will ensure the post performs as expected in a range of configurations. Another aspect which could be refined is the way the initial velocity is assigned to the vehicle. In this model, an initial velocity was assigned to every node on the body of the vehicle. Applying an angular velocity to wheels instead may improve the accuracy of the predicted behaviour of the vehicle after impact. The method used to simulate soil response also has its limitations. The unit weight and friction angle of the soil could be more widely varied, and parameters for clays instead of sands could be trailed. Modelling of the complete soil continuum using discrete elements would be more costly in terms of computation time, but would most likely yield more accurate results. While the current simulations involving a post/vehicle impact show the likely failure mechanism of the post in isolation, a macro model of the post attached to the rail terminal will be able to give a more accurate representation of the impact behaviour of the entire system.

6. References

Cunat, P 2000, 'Stainless Steel Properties for Structural Automotive Applications' in *Metal Bulletin International Austomovtive Materials Conference,* Euro Inox, Cologne.

Kapitola, P 2005 'Design and Pendulum Testing of a Frangible Guardrail Post for use in End Terminals', Honours Thesis Paper, University of Western Australia.

Plaxico, C, Patzner, G & Ray, M 1998 'Finite-Element Modeling of Guardrail Timber Posts and the Post-Soil Interaction', In Transportation Research Record 1647, National Research Council, Washington, D.C.

Ray, M & Patzner, G 1997 'Finite-Element Model of Modified Eccentric Loader Terminal (MELT)', In Transportation Research Record 1599, National Research Council, Washington.

Sicking, D, Rohde, J & Reid, J 2000 "Design and Development of Steel Breakaway Posts", Transportation Research Record 1720, National Research Council, Washington, D.C.

Woon, R, Karpinksi, J, Scanlon, J & Fisher, J 2003 'Review Report and Investigation into Standard Safety Barriers, Part 1: Barrier End Treatments', MRWA, Perth.

Wu, W & Thomson, R, 2006 "A study of the interaction between a guardrail post and soil during quasi-static and dynamic loading", International Journal of Impact Engineering, Gothenburg, Sweden