Numerical Simulations of the Performance of Steel Guardrails under Vehicle Impact

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Abstract: Road side barriers are constructed to protect passengers and contain vehicles when a vehicle crashes on a barrier. In general, full-scale crash testing needs be carried out if a geometrically and structurally equivalent barrier has not previously been proven to meet the requirements of containing the vehicle and dissipating sufficient impact energy for passenger protection. As a full-scale crash testing is very expensive, the number of data that can be measured in a test is usually limited, and it may not always be possible to obtain good quality measurements in such a test, a reliable and efficient numerical simulation of a crash testing is therefore very useful. This paper presents finite element simulations of a 3-rail steel road traffic barrier under vehicle impact. The performance levels defined in Australian Standards AS5100 Clause 10.5 for these barriers are checked. The numerical simulations show that the barrier is able to meet low performance levels. However, the maximum deceleration is higher than the acceptable limit for passenger protection. If present, a kerb launches the vehicles into the barrier, allowing for the possibility of overriding the barrier under certain circumstances, but it redirects the vehicle and reduces the incident angle, which reduces impact force on the barrier. Further investigation on all common kerb profiles on roads should be carried out, as only one kerb profile is investigated in this study.

Keywords: vehicle impact; steel barrier; kerb; performance level; vehicle containment; passenger protection

1. Introduction

The performance of the roadside barrier under vehicle impact assists in minimising the occurrence and/or severity of injury to the vehicle passengers and other motorists. Guardrails such as the two-rail steel barrier and the three-rail steel barrier are a critical road safety feature and are commonly used in Western Australia. As the new standard (AS5100 2004)^[1] gives different low and regular performance levels for guardrails, and sets out the new criteria for design and performance of guardrail barriers, it is imperative to check if these existing steel barriers meet the performance requirement. AS5100 defines and specifies that: 1) low performance levels are for the effective containment of light vehicles with low traffic volumes; and 2) regular performance levels are for the effective containment of cars, heavy utilities and light to medium mass trucks on freeways, highways and main roads. Table 1 describes the low and regular performance levels. Several other performance levels are defined in AS5100. However, only the regular and low performance levels are tested in this study.

Table 1 Required Performance Level

Level	Vehicles	Design speed (km/h)	Impact angle (degree)
Low	0.8t small car	70	20
	2.0t utility	70	25
Regular	0.8t small car	100	20
	2.0t utility	100	25
	8.0t truck	80	15

Usually vehicle impact tests are conducted to verify the performance of guardrails. However, it is not economically

feasible to perform full-scale field-testing on a wide range of parameters. Moreover, such crash tests, despite their considerable costs, furnish relatively little information. Numerical simulation utilising non-linear finite element analysis is thus rapidly becoming an effective tool in the design and evaluation of these systems^[2]. A computer simulation also supplies far more information than impact tests^[3]. Early development of finite element analysis of roadside safety occurred in the 1960s at Cornell Aeronautical Laboratories with the creation of the simulation model of automobile collisions for the New York Department of Public Works. Since that time, a series of projects has been carried out to develop the special purpose finite element codes to analyze traffic barriers^[4,5,6]. Unfortunately, none of these codes gained the confidence of analysts due to a variety of problems including coding errors, poor analytical formulations and restrictive assumptions. In 1991, The US Federal Highway Administration (FHWA) sponsored three projects for developing improved capabilities for analytical simulations of roadside hardware collisions^[7]. The outcome of these projects was that the general-purpose non-linear finite element program DYNA3D and LS-DYNA3D became the new standard for simulating these collisions. Reliable numerical methods are now available for roadside hardware design and for further improving roadside safety^[2,8-13].

The first attempt that successfully used LS-DYNA for roadside hardware research was the model of a 1991 GM Saturn^[9]. The model was used to simulate a frontal impact with a slip-base luminaries support, a rigid wall, and a U-post sign support, demonstrating the feasibility of using the non-linear finite element analysis. Another simple model of an 820 kg small passenger vehicle for FHWA was developed for frontal impacts with guardrails terminals and redirection collisions with guardrails and bridge railings^[10]. Some recent vehicle models developed include a 1994 Chevrolet C-2500 truck^[12] and a small 0.8t passenger car, a 2.0t utility and an 8.0t truck^[14]. In this study, the small car model and the utility model from the US National Crash Analysis Center (NCAC) finite element archive^[15] and the improved truck model in [14] are used to analyze the vehicle crash into the three-rail steel barrier. The effect of a kerb, which sometimes exists between the traffic lane and the barrier, is included in the analysis. The performance levels of the steel barrier are evaluated. Computer code LS-DYNA is used in all the simulations.

2. Vehicle model

The 0.8t small car and the 2.0t utility (Chevrolet C2500) model available in the NCAC finite element archive are used, after intensive modification, in this study to simulate vehicle-barrier impact. However the 8.0t truck model in the NCAC archive is not used because it results in the simulation not converging. Instead, the 8.0t truck model developed in [14] is used. Figure 1 shows the vehicle models.

Fig. 1 Three vehicle models used in this study

In this paper, owing to page limitation, only the 2.0t utility and 8.0t truck model are discussed since the 0.8t car imposes a less severe test on the barrier performance. The 2.0t utility model was based on a Chevrolet C2500 Pickup. It has 10500 elements, weights 1.86t, is 5.4m long, 1.98m wide and 1.83m high. The truck model was based on FORD LA9000. It has 13500 elements, weights 7.75t. More detail information on the model can be found in [14,15].

3. Guardrail Model

Figure 2 shows the drawing of a three-rail barrier and the kerb modelled in this study. The finite element model of the barrier is shown in Figure 3. The rails are modelled with the Belytschko-Lin-Tsay shell model. The posts are modelled with the Eight-node solid hexahedron elements. The posts are fixed at the base. The kerb is modelled as a rigid block. Although

the use of a nonlinear spring to simulate the connection between the rail and posts is the more accurate way to simulate the actual behaviour of the physical system, Atahan and Cansiz^[16], through their work with W-Beam guardrails, observed in crash tests that none of the W-Beam to post attachments were separated, thus utilisation of non-failing rigid links was judged to be reasonable approximation in representing the connection between W-Beams and offset blocks. In this study, to simply the problem, the barrier and post are also rigidly connected to each other by merging the common nodes. The isotropic plasticity model available in LS-DYNA is used for the rail and post. It has a density of 7830 kg/m³, shear modulus 75GPa, Young's modulus 200GPa, Bulk modulus 17500GPa, and yield stress 350 MPa.

Figure 2 Three-rail steel barrier and accompany kerb

Figure 3 Finite element model, a) three-rail steel barrier, b) post-rail joint

4. Convergence Test

Because the guardrail along a road can be considered as infinitely long, it is neither possible nor necessary to include the entire guardrail in the finite model. Therefore a convergence test is carried out to determine the number of spans that need be included in the model to derive accept results. This is carried out by starting with one span (2 posts) in the model subjected to a rigid block impact, then two additional spans (4 posts), one on each side of the center span under impact, and two more spans, etc. In each test, two more spans are added on the previous model. This process continues until the response of the center span under impact loads converges. Finite element mesh size also significantly affects the numerical results. Another convergence test is carried out to determine the finite element mesh size. Both convergence tests are carried out by using a 1t rigid cube of dimension 1 m to impact on the mid span and a post of the guardrail with an impact velocity of 10m/s. The convergence criterion used is 5% in both tests. Figure 4 shows the impact of the cube on the mid span of a one-span guardrail.

Typical numerical results of the mid-span displacements from the two convergence tests are also shown in the figure. From the convergence test results, the final model consists of 5 spans with 6 posts, and the finite element size used is 20 mm.

Figure 4 Converge test, a) rigid block impact on one-span guardrail; b) span convergence test; c) mesh convergence test

5. Results and Discussions

Numerical simulations are carried out to study the effect of a roadside kerb on vehicle guardrail interaction, the passenger risk, vehicle trajectory and guardrail response when the 2.0t utility model and 8.0t truck model collide to the guardrail. Figure 5 shows the snapshot of the utility collision with the guardrail at a speed of 100 km/h and an incident angle of 25°. Figure 6 shows the comparison of the vehicle damage and the actual vehicle damage in crash test conducted by the Connecticut Department of Transportation in the USA. As shown, the simulated vehicle damage resembles the crash test observation. Figure 7 shows the images of the 8.0t truck colliding into the guardrail at a speed of 80km/h and an incident angle of 15°.

Figure 5 Images of the simulated utility collision into the guardrail

No study of the effect of kerb on the vehicle–guardrail interaction can be found in the literature. The present numerical results indicate that the kerb slightly launches the vehicle in the air before colliding into the guardrail. If the guardrail is not high enough, this launching effect may result in the vehicle overrun the guardrail. On the other hand, the kerb provides a restoring force to the vehicle and subsequently redirects the vehicle, reducing the impact angle as shown in Figures 5 and 7. Because only one kerb configuration is considered in the present study, more analyses with different kerb configurations are needed to draw a more reliable conclusion of the kerb effect on vehicle-guardrail interaction.

LS-DYNA USER INPUT
STEP 100 TIME: 0.000007

Figure 6 Simulated and observed utility pickup damage after collision into the guardrail (test done by Connecticut Department of Transportation, USA)

LS-DYNA USER INPUT
STEP 1 TIME: 0.000000

LS-DYNA USER INPUT
STEP 100 TIME: 0.000007

LS-DYNA USER INPUT
STEP 200 TIME: 0.000000

LS-DYNA USER INPUT
STEP 100 TIME: 0.000007

Figure 7 8.0t truck collide into the guardrail

The numerical results indicate that the vehicles remain upright after collision. However, excessive deformation of the vehicle may directly impact on passengers. The deceleration at a node on the driver's seat is recorded in the simulation. It is found that the maximum deceleration in the 8.0t truck is about 5g, far below the acceptable deceleration limit of 15g for causing serious injury. However, the maximum deceleration in the 2.0t utility is 40g, greatly over the acceptable limit, implying the three-rail steel barrier is too stiff and it absorbs insufficient energy during collision to protect the vehicle passengers.

The guardrail successfully contains both the 2.0t utility and 8.0t truck. However, it suffers significant damage as shown in Figure 8.

Figure 8 Guardrail deformation after vehicle impact, a) 2.0t utility pick up; b) 8.0t truck

6. Conclusion

This paper conducts numerical simulations of the three-rail steel guardrail response to vehicle impact. Numerical results indicate that the guardrail successfully contains both the 2.0t utility at a speed of 100 km/h and incident angle 25°, and 8.0t truck impact at a speed of 80 km/h and incident angle 15°. The kerb lifts up the vehicle before it impacts on the guardrail, which may result in the vehicle overrunning the guardrail. However, the kerb redirects the vehicle direction and thus reduces the incident angle, therefore reducing the impact force. The maximum deceleration in the truck is 5g, which is smaller than the acceptable limit for passenger protection, but it is 40g in the utility pickup, greatly exceeding the acceptable limit for passenger protection, indicating the guardrail is too stiff to absorb sufficient impact energy during collision.

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