Numerical Analysis of Impact Effect on Mechanical Behavior of Strong Guardrail System

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Abstract. The purpose of this study is to estimate the crashworthiness of a guardrail system, and to optimize the relative vertical distance between centroid of vehicle and mounting height of W-beam. Abaqus/Explicit 6.5 software is used to simulate the dynamic response of the post and W-beam guardrail systems under vehicular impacts. Numerical results of maximum displacement of vehicles during dynamic contact between vehicle and guardrail system with various given masses of vehicles are obtained. Energy-absorbing properties of the guardrail system are studied for different values of centroid height. Influence of frictional coefficient between ground surface and vehicles is also investigated.

1. Introduction

One of the energy absorption devices currently widely used along highways is the semi strong-post guardrail system. This system is used to contain and redirect the errant vehicle during a collision with a guardrail. A conventional guardrail system mainly consists of steel or wooden posts and a steel W-beam rail connecting posts via offset blocks. Investigation on the mechanical behaviour of the guardrail system has been a topic of various references[1][2][3] for more than a dozen years. Although full-scale crash testing has been the most prominent method in evaluating the performance of roadside safety hardware[4], the use of analytical methods is more popular in this area[2]. With the use of simulation results, researchers can assess deficiencies and make adjustments to existing roadside safety features. Simulations also allow optimization of roadside safety hardware and development of improved roadside safety structures. They have used simple models, such as springs, dash-pots, beams, and links to examine the dynamics of vehicles and the strength of barriers[5]. Ref[6]-[9] have investigated ballistic impact simulation of composite with a novel microstructure model. Only in the recent years, development of computational technology enabled a detailed simulation on the nonlinear behavior of a vehicle and guardrail system in a crash.

The purpose of this study is to verify the crashworthiness of a given design of guardrail system, and optimize the relative vertical distance between centroid of vehicle and mounting height of W-beam. Abaqus/Explicit 6.5 has been used in simulating the dynamic response behavior of the post, W-beam guardrail systems when subjected to vehicular impacts. Numerical results of maximum displacement of vehicles with various given masses have been given out. Energy absorbing properties have been

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compared for different height of centroid of vehicles. Influence of frictional coefficient between ground surface and vehicles was also investigated.

2. The model
The model of the guardrail system was designed with reference to the data provided by engineering institution [6]. The mounting height of the W-beam rail was 600 mm measured above the ground level to the center of rail, and supported on posts spaced at 4000 mm. The standard embedment depth for the posts was 950 mm. The W-beam rail elements were attached through the offset blocks to the posts. To evaluate the structural adequacy and the overall performance of posts of a guardrail system in containing and redirecting an impacting vehicle, numerical simulation were performed with different values of mechanical parameters. This include a 1,500-kg car to strike the installation at 80 km/h and 20° angle between car velocity direction and guardrail line, and a 10,000-kg truck to strike the installation at 40 km/h and 20° angle.

The assembly of the guardrail system is given in Fig 1. The length of the w-beam rail is 29 meters. Spacing between two end-posts is 2m, and that between two central-posts is 4m. There are totally 10 posts consisted in the system. In order to simplify the model with reasonable accuracy on prediction of crash response behavior of guardrail system, vehicle is modeled as an elastic block, which is also shown in Fig.1. Road surface was modeled as a rigid surface. Hard-frictional-contact was assumed between vehicle and road surface. Soft-frictional-contact was assumed between vehicle and the W-beam. Figs 2 to 4 give out the illustration of the components of the guardrail system.

Figure 1. The assembly of the guardrail system.
Figure 2. W-beam rail is a shell structure of 3 mm thickness.
Figure 3. Offset block is a 3 mm thick shell structure.
Figure 4. Post-to-rail connection model.

As shown in Fig. 4, connections between posts and offset blocks are face–to-face contact combined with bolts; and connections between guardrail and offset-blocks are “tie” connection form of Abaqus. Spring-elements together with frictional contact were used to simulate the interaction between posts and soil foundation.
Since guardrail system sustains large deformations and possible crushing, large plastic deformations are likely to occur in the W-beam and posts. To account for these, a piecewise linear plastic-hardening material definition and finite strain constitutive relationship were used to model the steel material of the guardrail systems.

3. Numerical results
The finite element model of the whole model was generated by assembling all of the individual models mentioned above. For the discretization of W-beam, 2482 nodes and 2320 four-point shell element were used; 135 nodes and 126 four-point shell elements were adopted for discretization of each post; 430 nodes and 378 four-point shell elements were adopted for discretization of each offset block. The discretization of vehicle adopted 500 nodes and 336 3-dimensional solid elements. A picture of the final model is shown in Fig. 5.

Values of material parameters such as density $\rho$, Young’s modulus $E$, Poisson ratio $\nu$, initial strength $\sigma^0$, and hardening strength limit $\sigma_s$ used in the calculation are given below for the model:

$$\rho = 7860 \text{ kg/m}^3, \quad E = 2 \times 10^{11} \text{ Pa}, \quad \nu = 0.33, \quad \sigma^0 = 528 \text{ MPa}, \quad \sigma_s = 550 \text{ MPa}$$

Frictional coefficients between vehicle and ground surface and that between vehicle and W-beam surface are set as $f_1=0.7$ and $f_2=0.2$ respectively. The value of frictional coefficients between posts and foundation was set as $f_3=1$.

The overall deflected rail shapes and the position of car, which is of mass 1.5 ton and initial velocity 80km/h, at the different time points are given in Fig.6 along with comparison of deformation situations of the numerical results and the experimental phenomena reported in Ref[4]. The comparison shows effectiveness of the numerical simulation. The errant car has been effectively contained and re-directed by the designed guardrail system.

A numerical simulation of car impact on guardrail system was then carried out with a truck of 10 ton mass and initial velocity 40 km/h at 20 degree angle to guardrail system. In Fig.7 it is seen that plastic joint was formed at the point of post where close to ground surface due to the bending moment caused by car impact on W-beam. The result shown in Fig.7 was obtained at time $t=0.6$S with initial contact point between car and W-beam at post-position. At the position of crash contact point, the W-beam was expanded completed.
Figure 6. Numerical results of deformation in U2 direction which is vertical to W-beam (truck mass is 10 ton, initial velocity is 40 km/h and initial angle is 20 degree) at time t=0.6 second.

A illustration of variation of displacement component U2 for points of W-beam which is vertical to W-beam length and is in the horizontal plane was shown in Fig.8. It is seen that the scope of deformed W-beam section at time t=0.4 is much larger than that at time t=0.09S. But the difference between the scope of deformed W-beam section at time t=0.4S and that t=0.6S is small. Those end-posts were actually relatively undisturbed in the crash process. The value of maximum displacement of W-beam doesn’t increase after t=0.4S. This indicates that the impact process reached its peak at t=0.4S.

Figure 8. Numerical results of deformation situation of W-beam in U2 direction at various time points during vehicle impact to guardrail system.

Figure 7. Comparison of internal energy absorbed by guardrail system with different values of centroid height of vehicle.

Figure 8. Comparison of frictional energy dissipated during the crash process with different values of frictional coefficient.

Figure 9. Kinetic energy variation of the whole system.
In order to optimize the design of the guardrail system in terms of vertical distance from vehicle centroid to the mounting height of W-beam, different values of the height of vehicle centroid have been adopted in a set of numerical simulations of the crash process. Comparison of energy absorbed by guardrail system with different values of centroid height of vehicle is shown in Fig.9. The mounting height of W-beam is a constant 600mm, and the values of vehicle centroid were set as H=1.5m, 1.2m and 1.0 m respectively. It is seen in Fig.9 that quantity of energy absorbed by guardrail system reaches its maximum as H=1.2m. In this case, the guardrail system can act most effectively as an energy absorption device.

Influence of frictional coefficient between ground surface and vehicle was estimated by performing numerical simulation with different values of frictional coefficient. Comparison of frictional energy dissipated during the crash process with different values of frictional coefficient f between vehicle and road surface is given in Fig.10. It is seen the value of frictional energy dissipation for f=0.7 is approximately twice the amount of that for f=0.2. This indirectly implicates that the frictional energy dissipation between vehicle and W-beam and that between posts and foundation are also important dissipative mechanisms.

On the basis of above analysis, numerical simulation was performed for the case in which H=1.2, f1=0.7, vehicle mass is 10 ton, and the other parameters keep unchanged. The calculation was performed for a 0.6S time period. Numerical results were given below. Fig.11 shows the kinetic energy variation of the whole model. Fig. 12 shows the variation of energy absorbed by guardrail system with time t, Fig.13 shows the variation of frictional energy dissipation. Fig.14 shows energy dissipated by plastic deformation, which is also a part of internal energy. Fig.15 shows viscous energy dissipation.

![Guardrail system internal energy absorption](image)

**Figure 10.** Energy absorbed by the guardrail system

![Frictional energy](image)

**Figure 11.** Frictional dissipation energy.

![Plastic dissipation energy](image)

**Figure 12.** Plastic dissipation energy.

![Viscous dissipation energy](image)

**Figure 13.** Viscous dissipation energy.
From the results shown in Figs. 11 to 15, it is found that frictional energy dissipation is the most important energy dissipation mechanism which takes about 65.7% kinetic energy loss of the whole model. The guardrail system can absorb 30.8% kinetic energy loss through deformation. The left 3.5% energy was the viscous energy dissipation.

4. Conclusion
The impact performance and the crashworthiness of a guardrail system were evaluated through performing numerical simulation study. Post plastic-joints occurred at ground level where bending moments reached a maximum value. Numerical results show that the given guardrail system can effectively contain and redirect an errant car which has 1.5 ton mass and 80km/h velocity. The given system can also contain the errant vehicle which has 10 ton mass and 40km/h velocity, but can not effectively redirect the errant vehicle.

Numerical results obtained with various heights of centroid of vehicle shows that the value of relative vertical distance between centroid of vehicle and mounting height of W-beam is 600mm at which the guardrail can absorb energy most effectively during crash process for the given system.

Numerical results of energy distribution among various energy dissipation mechanisms show that the designed guardrail system can absorb 30.8% kinetic energy loss through deformation.

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