Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 13 (14): 2767-2773, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.2767.2773

Analysis on the Crash between Height Limit Protection Frame with Shocks and Superelevation Vehicles

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Abstract: The collision between the height limit protection frame with rubber shocks and superelevation vehicles has been simulated analyzed based on ANSYS/LS-DYNA. It has been found that, with the set of the rubber shocks, plastic strain energy of the protection frame has been decreased for 15.6%, plastic strain of vehicles decreased obviously. The Plastic Strain Energy without shocks is 31.8 times as long as the plastic strain energy with shocks. Shocks can provide good protection and buffer effect for Protection frame and vehicles, the research can provide basis for the design of efficient and energy-absorbing protection frame, also can provide improvement of related specification.

Key words: Height limit protection frame, rubber shocks, ANSYS/LS-DYNA, inelastic collision

INTRODUCTION

Height-limiting protection frame is used to protect Railway Bridge to avoid collision of Railway Bridge caused by vehicles under the bridge, which may affect the normal railway transportation. With the rapid development of railway construction in our country, in order to ensure the safety of railway operation, a series of protective measures need to be carried out, especially the railway with lower vehicle driving, the railway bridge must be protected to ensure the normal operation of the railway transportation (Decree of the state council of China, 2004) (The People's Republic of China, 2005). As is shown in 'Railway transportation safety regulations' (China, 2005), the railway with bridge and culvert under it, need to set high limit marks and limit protection according to the relevant state standards. However, there is little research on collision mechanism (such as size of the collision, energy absorption mechanism of energy absorption device and so on) of vehicle and bridge anti-collision facilities, principles for the protective frame design and protection effect evaluation are lacking (Chung *et al*., 2004; Sharma *et al*., 2008) and the application is greatly limited in practical engineering.

Height limit protection frames in use are largely rigid structure, which are welded by section steels or steel tubes. When it crashes with vehicles, it will be impacted by the collision, under the impact of dynamic loads, the protective frame will be damaged, the impact load will be transmitted to pillar and foundation, which will finally lead to a overall overturning of the high limit protection or cause secondary damage. So, it is necessary to find out a new efficient and cost effective energy absorption device, in order to lessen the impact damage to a minimum level (Song *et al*., 2007).

In this study, rubber shocks are equipped in the height limit protection frames; collision process is analyzed based on ANSYS/LS-DYNA. The results of dynamic response and energy conversion are obtained and also it will provide reference to the improvement of the engineering design and related specification of the height limit protection frames (Schenker *et al*., 2005; Zhang *et al*., 2003).

FINITE ELEMENT MODELING

Assumed condition: (1) Bottom of the height limit protection frame is fixity. Soil-structure interaction is ignored, (2) Impact angle of vehicles and frames is 9 and (3) In order to prevent the appearance of the displacement in vertical direction, the displacement degrees of freedom of Z direction is restrained.

Material model: Definition of material model plays a very important role in numerical simulation. It affects the accuracy and reliability of numerical simulation directly, So, it is important to get the accurate material data. LS-DYNA provides more than 40 material models. In this study, Plastic Kinematic material model is used in protection and ultra-high vehicles, Mooney-Rivlin material model is used in rubber shocks.

Protective frame and model of the vehicle: Under rapid loading conditions, yield strength limit of any metal

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materials will be improved. The yield of hysteresis is called Material strain rate effect. In this study, collision between protective frames and vehicles is a transient process of loading. Based on considerations of material strain rate effect, the plastic material Plastic Kinematic related to strain rate model is selected. Material model parameters: material density $\rho = 7.8\times10^3$ kg m^{-3}, elasticity modulus $E = 2.1\times10^{11}$N m^{-2}, tangent modulus $E_{tan} = 7.63\times10^{-8}$ N m^{-2}, initial yield stress $\sigma_0 = 3.1\times10^8$ N m^{-2}, Poisson's ratio $\mu = 0.27$. Cowper-Symonds is used to describe the strain rate, yield stress should be expressed by parameters related to the strain rate. As is shown in Eq. 1:

$$\sigma_Y = \left[1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right]\left(\sigma_0+\beta E_P \varepsilon_P^{eff}\right) \tag{1}$$

where, σ_0 is initial yield stress, ϵ is strain rate, C P is Strain rate parameters for Cowper Symonds, in this study they can be defined as 40 sec^{-1} and 5, ϵ^p_{eff} is effective Plastic Strain, E_p is plastic hardening modulus, which is defined as:

$$E_p = E_{tan}\ E/E\text{-}E_{tan}$$

Material of rubber shocks: The elasticity of rubber is different from general material; it is generally recognized as isotropic incompressible hyper elastic body. In this study, Mooney-Rivlin, an incompressible rubber model, is selected as material of rubber shocks, its physical properties is mainly expressed through the strain energy function. The constitutive relations of strain energy function of Mooney-Rivlin can be widely used in finite element analysis of elastomeric nonlinear.

The strain energy function W of rubber material is the function of fundamental invariant I_1, I_2, I_3, which is deformation tenser of Cauchy-Green. As is shown in Eq. 2:

$$W = W\ (I_1, I_2, I_3) \tag{2}$$

$$\left.\begin{aligned} I_1 &= \lambda_1^2+\lambda_2^2+\lambda_3^2 \\ I_2 &= \lambda_1^2\lambda_2^2+\lambda_1^2\lambda_3^2+\lambda_2^2\lambda_3^2 \\ I_3 &= \lambda_1^2\lambda_2^2\lambda_3^2 \end{aligned}\right\} \tag{3}$$

where, λ_1, λ_2, λ_3 are tree Eigen value of deformation tenser from Cauchy-Green. By using the assumption that the material is incompressible and no deformation state is isotropic, which means $I_3 = 1$, Rivlin deduced the money-S Rivlin model that is widely used in rubber materials:

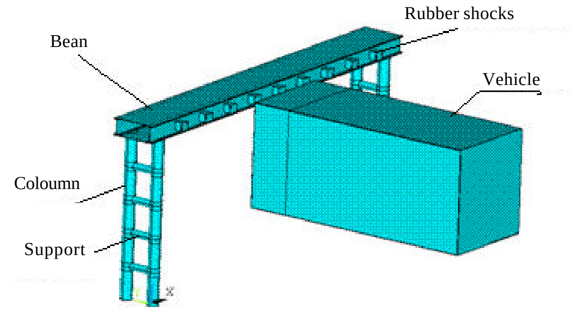

Fig. 1: Whole model

$$W' = C_{10}\ (I_1\text{-}3)+C_{01}\ (I_2\text{-}3) \tag{4}$$

where, C_{10}/C_{11} is material constant.

In this study, material model parameters of Mooney-Rivlin, $C_{10} = 5.5\times10^5$, $C_{10} = 2.9\times10^5$, Poisson's ratio $\rho = 1180$ kg m^{-3}, Poisson's ratio $\mu = 0.4995$.

Finite element model: In the model, the protective frame is composed of beams and columns, beams is welded by two H-section steels I_{40a} and two coverplates up and under it, whose thick is 6mm.the columns are 4m height, sectional dimension is $\phi300\times20$ mm; length of support between columns is 0.5m, when its sectional dimension is $\phi180\times10$ mm; rubber shock can be regarded as a mass whose size is 200×200×200 mm; size of the cabin refer to size of China's road transport container, whose size is 6.0×2.5×2.5 m, thickness of plate is 10mm. Whole model is shown in Fig. 1.

In this study, Scanning method is used to mesh the model. In the progress of messing, Grid should be messed more accurate, considering stress of the collision area is larger. Grid size of Protective beams, rubber shocks and front of the vehicles is 60 mm, while otherwise is 80 mm.

NUMERICAL ANALYSIS

In this study, the weight of the cabin is 6t and its speed is 10 m sec^{-1}. Dynamic response of the model with and without buffer device has been researched.

Displacement, speed and acceleration of representative nodes have been analyzed. The representative nodes of different areas is shown in Fig. 2. The representative nodes are listed as follows, representative nodes of Beam collision zone 24755 (without butter device)/25728 (with butter device), representative nodes of Beam and column node area 24884/2455, representative nodes of support area 39579/1183, representative nodes of Column bottom area 41757/784.

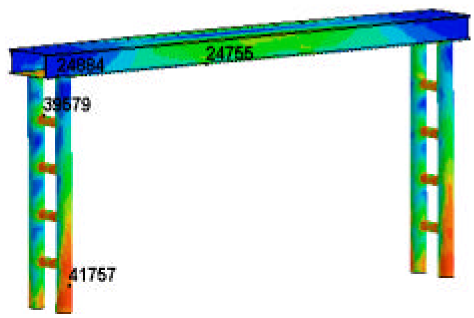

Fig. 2: Nodes location

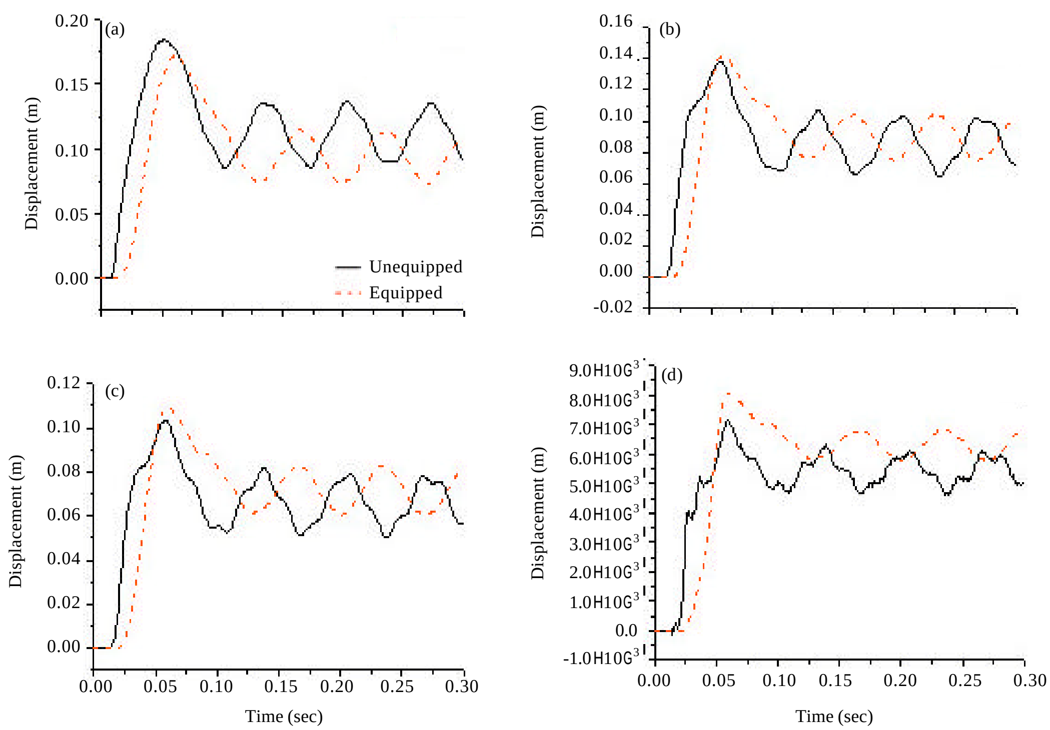

Fig. 3(a-d): Compare of nodes' displacement from different time, (a) Nodes 24755/25728, (b) Nodes 24884/2455, (c) Nodes 9579/1183 and (d) Nodes 41757/784

Dynamic response: (1) The displacement response. The compare of displacement in Y direction from different time of representative nodes has been shown in Fig. 3. As is shown in Fig. 3, after the buffer device equipped, peak displacement of representative nodes area (representative node 24755) has been decreased but the peak displacements of the nodes from the collision area to column bottom area have been increased but they are very close compared with the result from the model without device equipped. This is because when the frame is impacted from Y direction, collision area of beam is the first to contact the vehicle, without the buffer device equipped, local deformation of the beams is larger and it absorbed more energy. But under the condition that the buffer device equipped, due to its effect of absorbing energy, the peak displacements of the nodes from the collision area are decreased.

Speed response: The compare of speed in Y direction from different time of representative nodes has been shown in

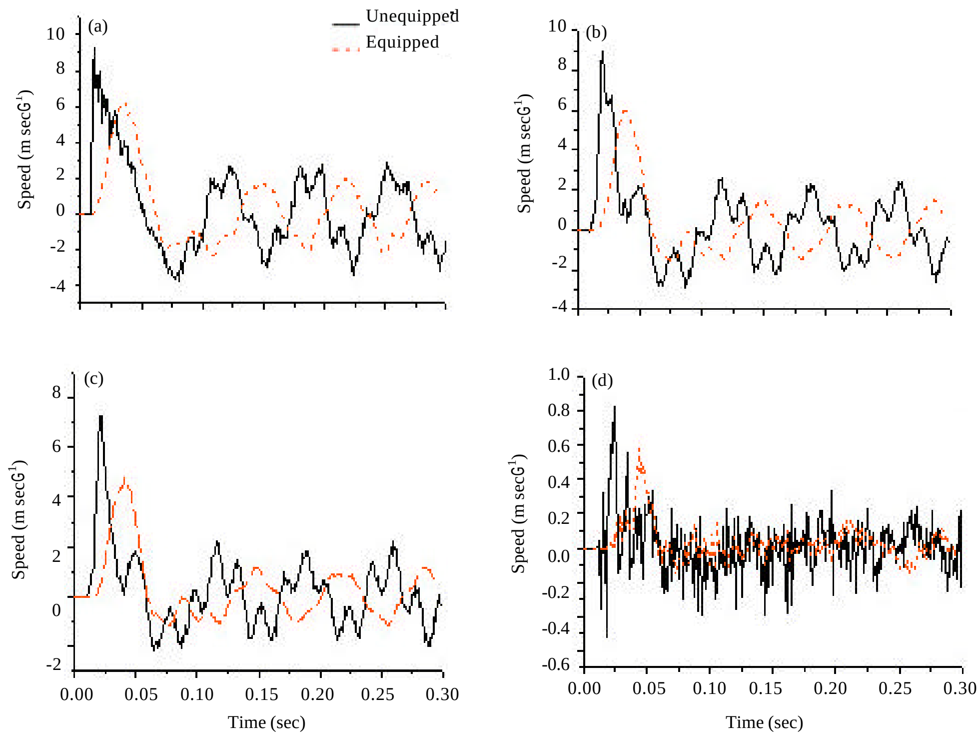

Fig. 4(a-d): Compare of nodes' speeds from different time, (a) Nodes 24755/25728, (b) Nodes 24884/2455, (c) Nodes 39579/1183 and (Nodes 41757/784)

Table 1: Peak speed

	Items	Unequipped	Equipped	Change rate (%)
Peak speed	Nodes24755/25728	9.25	6.27	-32.22
	Nodes 24884/2455	8.98	5.98	-33.41
	Nodes 39579/1183	7.27	4.75	-34.66
	Nodes 41757/784	0.82	0.58	-29.27

Table 2: Peak acceleration

	Items	Unequipped	Equipped	Change rate (%)
Peak value	Nodes 24755/25728	1.74E+04	5.05E+03	-70.98
	Nodes 24884/2455	1.64E+04	1.07E+04	-34.76
	Nodes 39579/1183	7.24E+04	5.12E+04	-29.28
	Nodes 41757/784	1.17E+04	9.61E+03	-17.86

Fig. 4, peak data and variation of the speed has been shown in table1. It can be seen from the calculated results above, under the condition of buffer device equipped and unequipped, peak speed of the nodes (representative nodes 24777-11281-42417-41757) from the collision area to column bottom area is getting smaller. When the buffer device is equipped, the peak speeds of the nodes from the representative area have 30% average decreasing amplitude compared with buffer device unequipped model. When the device is equipped maximal displacement time caused by impact will increase, which means process of speed increasing is slow.

Acceleration response: The compare of acceleration in Y direction from different time of representative nodes has been shown in Fig. 5, peak data and variation of the speed has been shown in Table 2. It can be seen from the Figures and Table above, under the condition of buffer device equipped and unequipped, change of the maximum acceleration seems to be the same. When the buffer device is equipped, the peak accelerations of the nodes from the representative area have obvious decrease amplitude compared with buffer device unequipped model. The maximum decrease amplitude reaches to 70.98% at Beam collision zone. The minimum decrease amplitude is about 17.86% at bottom of the column. It can also be conclude that under the two conditions the maximum accelerations of representative nodes from support area is also the biggest, which means in the process of the spread of stress wave, stress wave mutations here is strong.

Collision force analysis: Figure 6 is System crash force time history curve. It can be seen from Fig. 6, collision process of vehicle and protection frame is nonlinear, Time history curve shows the characteristics of the nonlinear

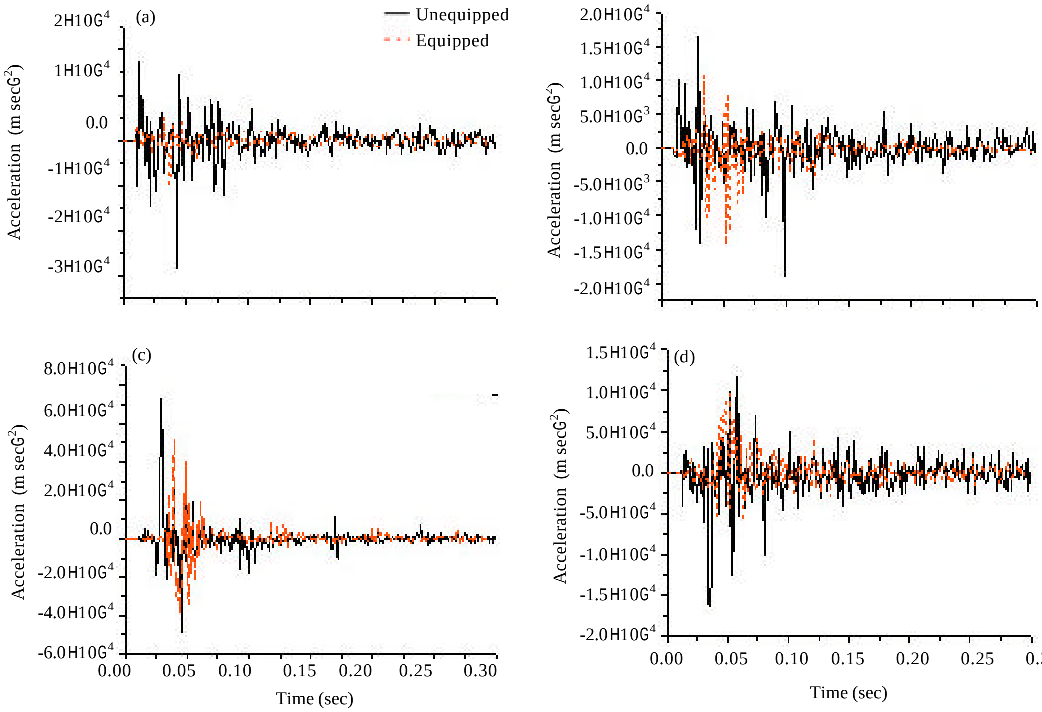

Fig. 5(a-d): Compare of representative nodes' acceleration from different time, (a) Nodes 24755/25728, (b) Nodes 24884/2455, (c) Nodes 39579/1183 and (d) Nodes 41757/784

wave. Under the two conditions of collision, force reaches maximum at the instant of the crash, after that, along with the process of the collision, component unit from collision zone of protective frame and support area quite out of working, collision force decreases sharply, as parts of frame enter into plastic state, much energy turns into the plastic deformation energy, which makes collision force fluctuates up and down on a small scale and tend to be stable. collision force decreases along with the separation of the two, finally the collision force reduces to zero when completely separate. Under the condition of buffer device unequipped, maximum impact force appears at 0.01 sec and its value is 4.49×10^6N. Under the condition of buffer device equipped, maximum impact force appears at 0.03 sec and its value is $1.89H10^6$N. So, after buffer device equipped, appearance of the impact force will be delayed and the decrease amplitude is 57.9%.

System energy: The system with and without buffer device have the same energy change process, they differ at the amount of energy conversion. Firstly, internal energy. Under the condition of buffer device equipped and unequipped, peak internal energy of system are the same but final value of the internal energy of system with buffer device equipped is lesser than that of the system unequipped, which means under the condition of buffer device equipped, there are more kinetic energy converted into the plastic strain energy compared with the system unequipped. Secondly, kinetic energy. The initial kinetic energy of the System is the kinetic energy of the vehicles, they are the same under the two conditions. Final value of the kinetic energy of system with buffer device equipped is bigger than that of the system unequipped, which means more elastic strain energy has been saved, system changed much energy into kinetic energy of vehicle and frame.

Energy of protective frame: As is shown from Fig. 9, kinetic energy of protective frame first increases then decreases, then trends to steady. Under the condition of buffer device equipped and unequipped, change of the kinetic energy seems to be the same but peak kinetic energy of frame equipped is bigger than that of the frame unequipped.

Time travel curve of internal energy of protective frame is shown in Fig. 10. Under the condition that buffer

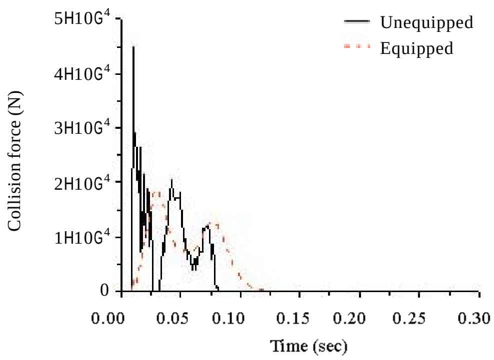

Fig. 6: System crash force time history curve Energy analysis

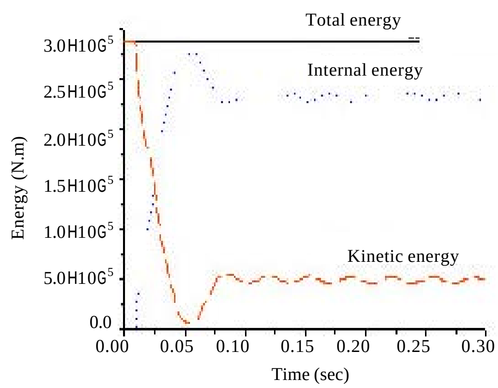

Fig. 7: Time travel curve of system energy (unequipped)

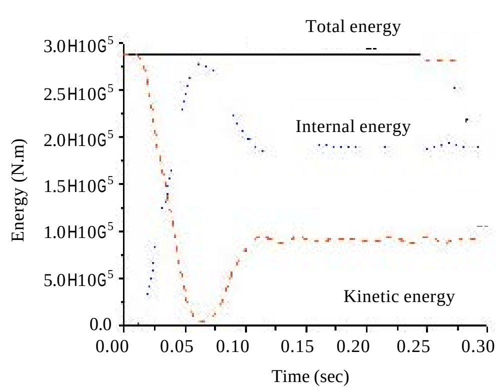

Fig. 8: Time travel curve of system energy (equipped)

device equipped, peak internal energy of protective frame is bigger but final value of the internal energy of protective frame with buffer device equipped is obviously lesser than that of the protective frame unequipped, the difference between peak value and final value has been absorbed as elastic strain energy by the protective frame. It can thus be seen, plastic strain energy of protective frame unequipped is bigger and it will be damage heavily.

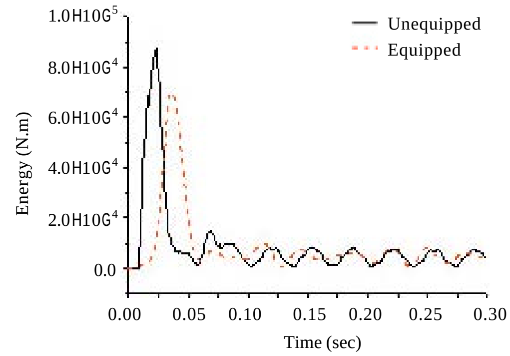

Fig. 9: Time travel curve of kinetic energy of frame

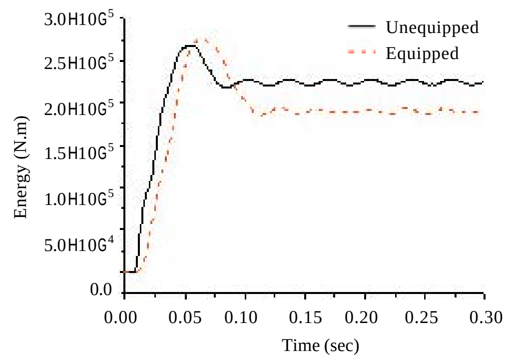

Fig. 10: Time travel curve of internal energy of frame

Vehicle energy: Time travel curve of internal energy of protective frame is shown in Fig. 11. Under the conditions that buffer device equipped and unequipped, change of the kinetic energy seems to be the same. At the beginning of the collision, vehicle crashes frame with total kinetic energy $E_k = 2.868\times10^5$J, after that, energy transformation happens in system, kinetic energy of vehicles turn into internal energy of system, kinetic energy of vehicle decrease, when forward velocity of protection frame and the vehicle is zero, The kinetic energy of the system completely converted to internal energy.

Final kinetic energy of equipped vehicle is 8.653×10^3J, which is bigger that of the unequipped vehicle whose value is 4.5×10^3J. This is because, under the equipped condition, System has more elastic strain energy saved and more kinetic energy has been transformed in the progress of rebound.

Time travel curve of internal energy of vehicle is shown in Fig. 12. As is shown in Fig. 12, under the conditions that buffer device unequipped, internal energy of vehicles can quickly achieve maximum value at the instant of the collision and then decreased and finally stay at the value of 7.0×10^3J. When the device is

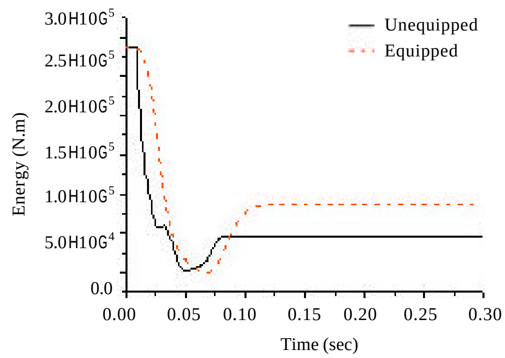

Fig. 11: Time travel curve of kinetic energy of vehicle

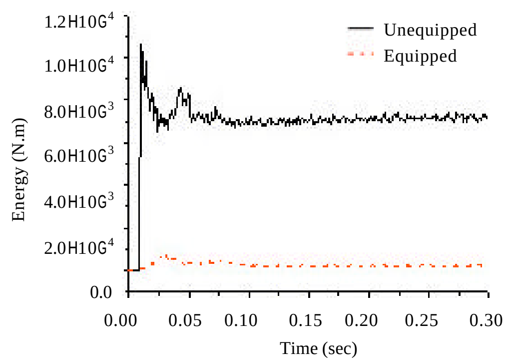

Fig. 12: Time travel curve of internal energy of vehicle

equipped, change of internal energy of vehicle is very small, the stable value is 2.2×10^2J. Under the two conditions, the stable internal energy all comes from plastic strain energy. The plastic strain energy without shocks is 31.8 times as long as the plastic strain energy with shocks, so vehicles will be seriously damaged if rubber shocks are not equipped.

CONCLUSION

- When rubber shocks are equipped, indexes of displacement and velocity response for protective frame have not changed obviously but indexes foracceleration and crash force have obvious deduction, appearance of the peak value for all entire dynamic response indexes have been putted off, which will make help to prevent the protective frame from destruction:
- When rubber shocks are equipped, plastic strain energy of protective frame has a decrease of 15.6%, the plastic strain energy without shocks is 31.8 times as long as the plastic strain energy with shocks, which means the equipped rubber shocks have a good buffering for protective frame and vehicle
- When rubber shocks are equipped, peak value of stress wave and transferring frequency have decreased obviously, which will make a very good protection effect for the bridge upside.

ACKNOWLEDGEMENTS

This study is supported by National Natural Science Fund (10872178) and Graduate Innovative Education Founds of Shandong Province (Grant No. SDYY11194).

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