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A STUDY ON THE PERFORMANCE OF HYBRID GUARD FENCES SUBJECTED TO VEHICLE COLLISION

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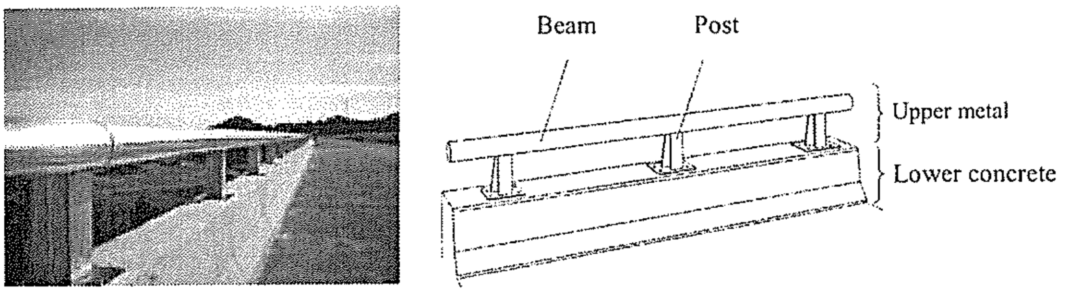
Abstract

Traditionally, road guard fences were made of single materials such as timber, metal, and concrete. In order to combine the merits of diverse materials, hybrid guard fences have been developed in recent years by constructing metal rails longitudinally on the concrete guard fence bases. Moreover, on-site full-scale tests were also conducted to examine what happens to the hybrid guard fences when vehicles collide with them. However, little research has been carried out to study the performance of such guard fences under collisions of vehicles through numerical simulations by using computers. The purpose of the research presented in this paper is to model the collision process by developing finite element method (FEM) models of both heavy trucks and metal-concrete hybrid guard fences. Comparing the results generated from computer simulations and on-site experiments demonstrates that the developed models can be applied to simulate the performance of vehicles and guard fences when collisions happen. The developed simulation method can further provide the data to design new guard fences and analyze existing ones.

Keywords: hybrid guard fence, vehicle collision, computer simulations, modeling

1. Introduction

Safety guard fences are normally required on roads where trucks are permitted to travel at a high speed, and the traditional types of road guard fences are made of single materials such as timber, steel, aluminum, and concrete. With the improvement of road network and vehicle capacities, both function and safety of conventional guard fences are challenged by increased allowable vehicle weights and speeds. It is well known that a metal guard fence is able to absorb a large portion of the kinetic of a colliding vehicle by its out-of-plane displacement [1]. It is however inappropriate to build metal guard fences at curved or urban viaducts where a dropping vehicle involved in an accident at a bridge may cause further serious traffic accident. Moreover, the metal guard fences are expensive and require frequent maintenance. The concrete guard fence is considered as a rigid type of guard fence and can prevent vehicles from derailing from the road [2]. The kinetic energy of a moving vehicle transfers a little to the concrete guard fence and much to the internal energy of the vehicle in case of a vehicle colliding with a concrete guard fence. So the vehicle driver and passengers may be fatally injured. Under such circumstances, hybrid guard fences have been developed worldwide in recent years to combine the merits of diverse materials by constructing metal rails longitudinally on the concrete guard fence base. On-site full-scale tests were also conducted to investigate the collision performance of hybrid guard fences subject to collisions of heavy trucks [3]. Figure 1 shows a real metal-concrete hybrid guard fence and a sketch drawing. The upper metal may be made of aluminum alloy or steel, which can be rigid or deflective according to the types of upper metal especially that used for the posts. The rigid base is made of reinforced concrete.



(a) A real hybrid guard fence (b) Sketch of a hybrid guard fence

Fig. 1. Aluminum Alloy-concrete Guard Fence

Given the recent development of faster computers and more accurate software, the use of computer modeling to simulate the vehicle versus roadside hardware has become the subject of much research into steel guard fences [4], aluminum highway guard fences [5], and concrete guard fences [1]. However, few studies have been published to investigate the computer simulations of hybrid guard fences [6]. The purpose of the research presented in this paper is to study the computer modeling of aluminum alloy-concrete guard fences collided by heavy trucks. Finite element method (FEM) models are developed for both vehicles and fences with a consideration of the nonlinear performances of materials. LS-DYNA, a nonlinear and large deformation FEM analysis, has been used to simulate the collision progress [7].

2. Full-scale Crash Test of Aluminum Alloy-concrete Guard Fence

To better understand the strength and deformation characteristics of hybrid guard fences, the Public Works Research Institute (PWRI) chose aluminum alloy-concrete guard fences for full-scale testing in 2003 [6]. Figure 2 describes the collision transience and longitudinal features of the tested hybrid guard fence. The length of the reinforced concrete base is 32 m. The total length of the upper metal rail (beam) is 30 m with 15 equivalent-length spans. All posts are numbered from P1 to P16 from the vehicle approach side. The crash point is between P7 and P8 and at 950 mm from P8. The height of the concrete base is 600 mm and the height of the upper metal from the top of the concrete base to the center of the round aluminum alloy rail is 500 mm.

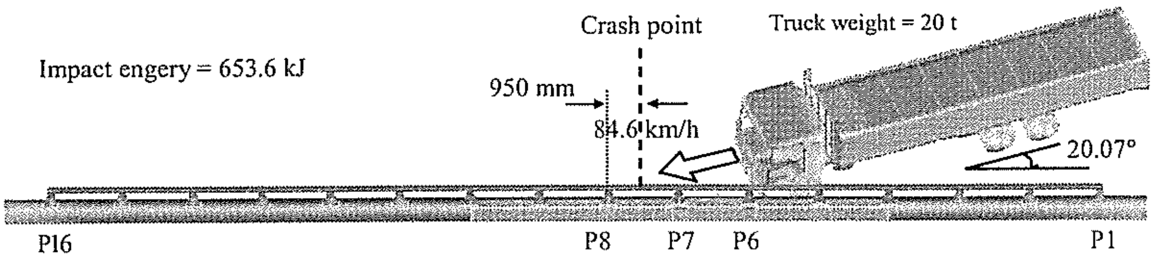


Fig. 2. Full-scale Crash Tests of Aluminum Alloy-concrete Guard Fences

The speed of the crash truck is 84.6 km/h. Due to the constraint of the pulling facility's power, a 20 tf truck was used for collision tests instead of the maximum design truck weight of 25 tf. According to the design specifications [8], the impact energy of a crash truck is determined by its crash speed and angle, and weight. The maximum design impact energy is 650 kJ while the crash truck speed and angle, and its weight are 100 km/h, 15^0, and 25 tf. The impact angle of crash trucks was increased to 20.07^0, and the actual impact energy was 653.6 kJ. As the actual impact energy is slightly bigger than the maximum design impact energy, this on-site test is considered to meet the requirements in design specifications for guard fences.

The materials of metal rail and posts are aluminum alloys A6061S-T6 and AC4CH-T6, respectively. The characters, especially the dynamic features, of these two types of aluminum alloys have not been published. In this research, dynamic material tests are conducted to obtain the stress-strain relationships as shown in Figure 3 and other basic parameters indicated in Table 1. These test results are applied in the numerical studies in the research presented in this paper.

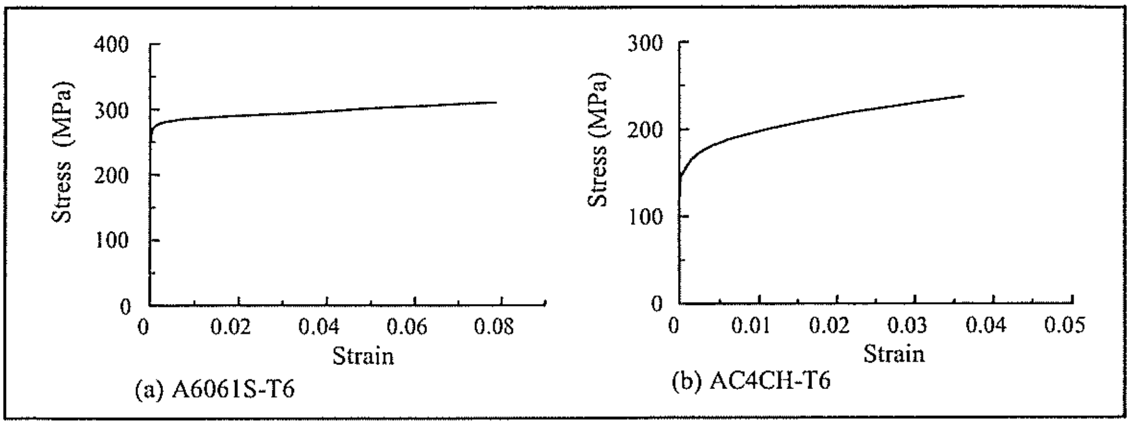


Fig. 3. Stress-strain Relationships of Aluminum Alloys

Table 1. Typical physical and mechanical properties of aluminum alloys

	Tensile strength (MPa)	Modulus of elasticity (GPa)	Yield strength at 0.2% offset (MPa)	Poisson's ratio	Elongation at break (%)
A6061S-T6	299	68.2	277	0.30	11.8
AC4CH-T6	252	72.4	174	0.33	4.50

3. Modeling Collision of Heavy Truck with Metal-concrete Hybrid Guard Fence
3.1 Models of the Heavy Truck
FEM model of the 20 tf truck used in the on-site crash tests are developed from early FEM models of a 25 tf truck [5]. The structure of the 20 tf truck is similar to the 25 tf truck apart from the strengthened frame and the loading capacity of the vehicles' vertical axles. The modeling is targeted to the truck frame, engine and transmission, driving cabin, cargo, and tiers. Their weights are 2.47, 1.6, 0.64, 1.67, and 2.57 tf, respectively. The total weight of the modeled truck structure is 8.95 tf and the remaining 11.05 tf is from the loaded freight. The size of the truck is shown in Figure 4. The FEM models of the truck are not detailed in this paper because of the publication of another paper in the same conference proceedings [1].

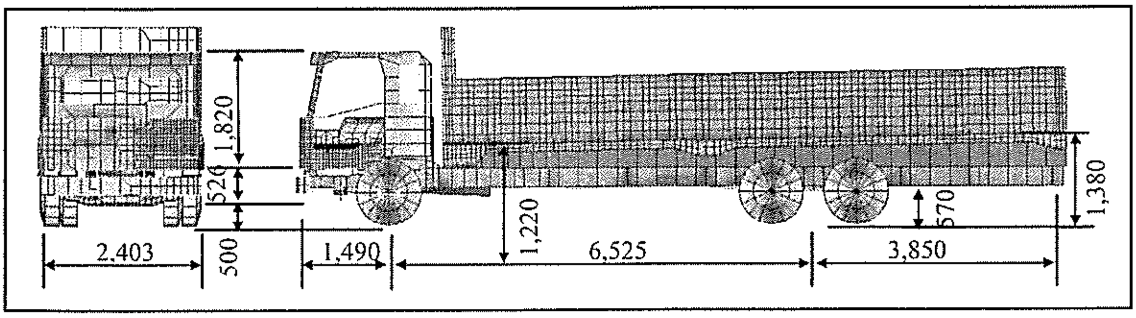


Fig. 4. FEM Models of a Truck (unit: mm)

The mesh size of trucks is diminished at the crash position, which is the left front of the driving cabin. The total numbers of nodes and elements in the FEM mode of a truck are 16,095 and 15,505, respectively. The Young's modulus of steel is 206 GPa, while that of aluminum is 70 GPa. The Poisson's ratios of steel and aluminum are 0.30 and 0.34, respectively. The yield stresses of steel and aluminum are 235 and 248 MPa, respectively. The shear moduli of steel and aluminum are 88 and 26 GPa, respectively.

3.2 Models of the Hybrid Guard Fence

For the purpose of computer simulation, the above hybrid guard fence is modeled in FEM. Figure 5 shows the mesh divisions in three dimensions as well as further size of the guard fence. Both the aluminum alloy posts and beams are modeled on the basis of shell elements. Concrete and reinforcing bars of the concrete base are modeled as solid and beam elements respectively. The boundary condition of the concrete base on the ground is considered as a fixed end.

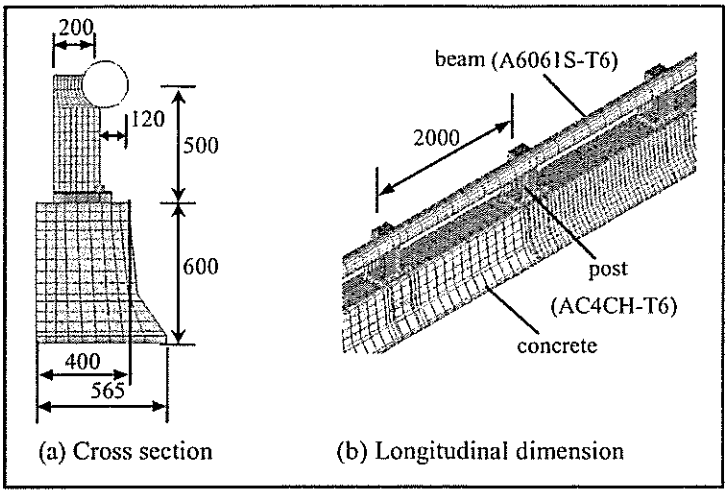


Fig. 5. FEM Models of an Aluminum Alloy-Concrete Guard Fence (unit: mm)

The connections between beams and posts are assumed to be rigid. As shown in Figure 6, the aluminum alloy posts are connected with the concrete base in the form of anchor bolts and plates. The anchor bolts are modeled as beam elements while the anchor plate and nuts are modeled as solid elements. For simplicity, anchor bolts and plates are assumed to be completely cohered with the concrete base. The thicknesses of plates of beams and posts are determined according to design specifications and testing documents, and change according to their locations [3, 6].

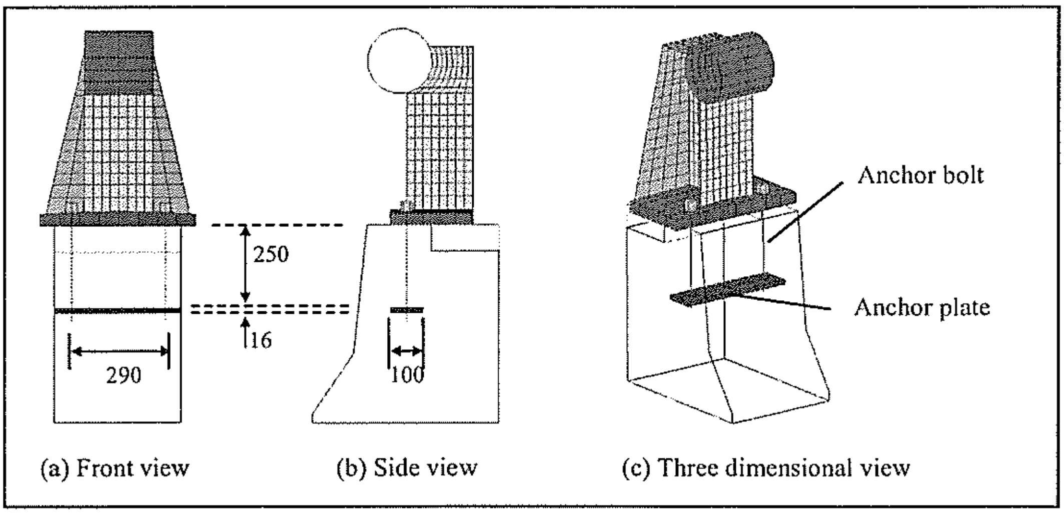


Fig. 6. Connections between a Post and the Concrete Base (unit: mm)

As shown in Figure 7, the mesh sizes of the upper metal and the lower concrete base are diminished for five spans around the crash point from post 5 to 11 (inclusive) to better understand the performance within the collision process. Totally, there are 20,979 nodes and 19,617 elements in the aluminum alloy-concrete guard fence.

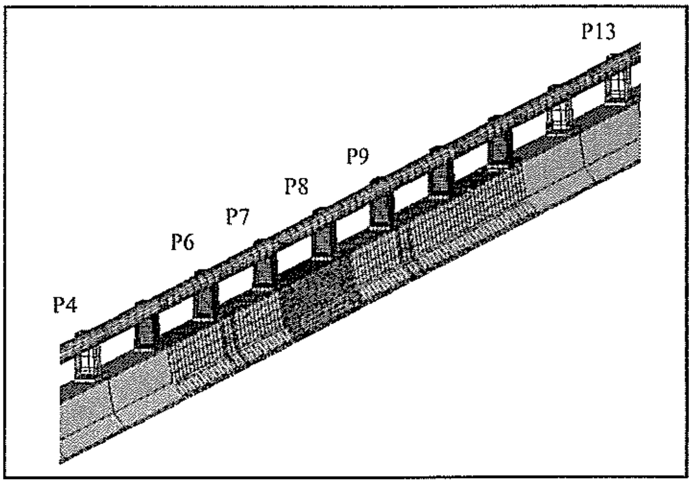


Fig. 7. Mesh Division of Guard Fences

4. Computer Simulation of Heavy Trucks during the Collision Process

The above-developed FEM models are applied to simulate what happen during collisions between a heavy truck and the hybrid guard fence. The collision conditions for computer simulation are made the same as the on-site full-scale tests. Figure 8 snapshots the collision behaviors of a heavy truck at 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 seconds (s) after the collision starts. When the truck's driving cabin collides with the aluminum alloy beams and posts, the left-front wheel rises onto the concrete base of the guard fence. Then, the rear part of the truck crashes into the guard fence. After several turns in collisions between the front and rear of the truck, it goes away from the guard fence. Although the truck frame rises and inclines after about 0.6 second of the collision, the guard fence can prevent the truck from overturning and control the moving angle from the guard fence. The calculated departing speed and angle are 62.9 km/h and 0.0^0 respectively, which are very close to 64.3 km/h and 0.0^0 generated from the on-site full-scale tests. Moreover, the movement track of each truck wheel during the collision generated from the computer simulation is also very similar to the result observed from the tests [3, 6, 8].

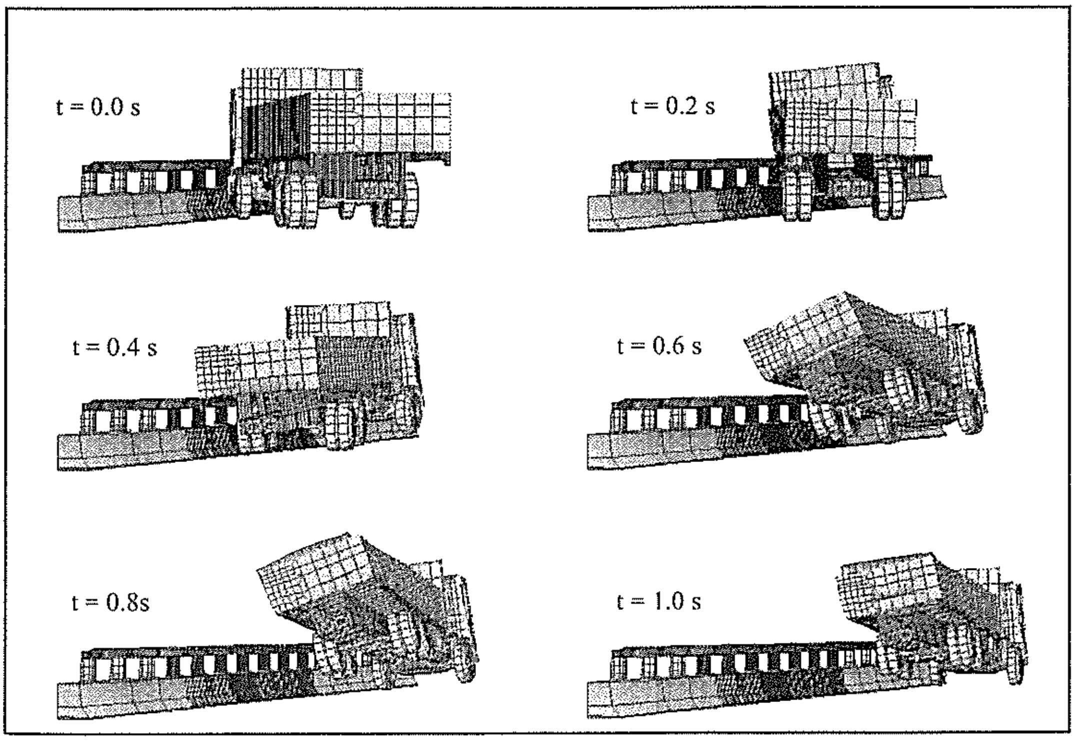


Fig. 8. Collision Behavior of a Truck

5. Computer Simulation of Guard Fences during the Collision Process

5.1 Out-of-plane Displacements

During the on-site full-scale collision tests of high-speed heavy trucks with hybrid guard fences, the out-of-plane displacements at several places are fully recorded. This has made it possible to evaluate the simulation results by comparison. Figures 9(a) and 9(b) compare the time-displacement relationships obtained from tests and computer simulations at the top of post 7 and the concrete base of post 8 respectively. The computer simulation stops at 1.2 seconds after the impact when the second collision, which is the rear part of the truck with the hybrid guard fence, completes.

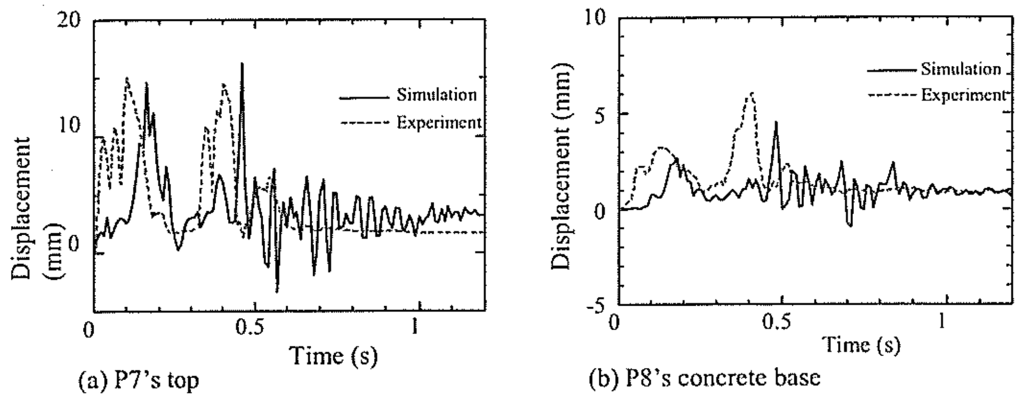


Fig. 9. Out-of-Plane Displacements of Hybrid Guard Fences

At the post's top at P7, the maximum out-of-pane displacements during the first and second collisions are quite similar no matter from tests or computer simulations. The maximum out-of-plane displacement generated from the computer simulation is 16.2 mm (in the second collision), which is slightly bigger than the maximum testing value 14.9 mm (in the fist collision). Moreover, the time period from the first to second collision of the front and rear of the truck in simulation is also same as that recorded in tests. In addition, the maximum out-of-plane displacement appears later in the computer simulation compared with the on-site tests and this may be caused by the difficulty to exactly set up the same commencement times.

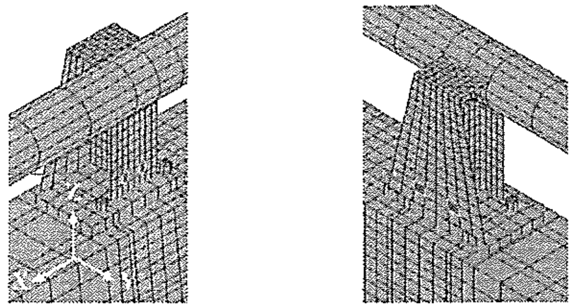
At the concrete base at P8, the maximum out-of-plane displacements are rather small in both simulation and experiment because of the bottom position. Obviously, the maximum displacement of either computer simulation or experiment during the first collision is smaller than that during the second collision. This is because the front-left wheel collides with the bottom of the concrete base during the first collision, but the rear-left wheel crashes the top of the concrete base during the second collision. The assumption that the concrete base is completely fixed on the ground reduces the out-of-plane displacements generated from the computer simulation, and this may be why the maximum displacements in both first and second collisions are obviously smaller than those recorded in tests.

According to the changes of out-of-plane displacements over time at these two positions, it can be concluded that the computer simulation can replicate an on-site full-scale truck collision with hybrid guard fences.

5.2 Measurement and Simulation of Forces at the Bases of Posts

In addition to the deformation, the stresses at the bases of posts caused by the truck are simulated and compared with the experimental results. As shown in Figure 10(a), two positions are chosen to determine the average Von Mises stress at the front flange at the base of a post according to their three nominal stresses in X, Y and Z directions and three shearing stresses in XY, YZ and ZX planes. Similarly, the Von Mises stress at the rear flange at the base of a post is also the average of Von Mises stresses at two points shown in Figure 10(b).

Table 2 summarizes the Von Mises stresses at the front and rear flanges at the bases of posts 6, 7 and 8, which are generated from computer simulations and on-site full-scale tests. Because of the difficulty in measuring the real stresses during the on-site tests and modeling the full-scale guard fence through the use of computers, there are some gaps between the simulation and testing results at the front flange of post 8 and the rear flange of post 7. Apparently, these stresses are so small and represent that the posts deform within the elastic extents of materials and the hybrid guard fence can be considered as a completely rigid body.



(a) Front flange (b) Rear flange

Fig. 10. Locations of Stress Measurements

Table 2. Von Mises Stresses at the Bases of Posts (MPa)

	Front flange		Back flange	
	Simulation	Experiment	Simulation	Experiment
Post 7	77.5	N/A	69.8	51.9
Post 8	86.6	64.3	72.0	70.1
Post 9	59.6	N/A	50.5	53.3

5.3 Measurement and Simulation of Stresses and Strains of Anchor Bolts

Further studies have been carried out to investigate the strains and stresses of anchor bolts during the collision process. The maximum average strains and stresses of two anchor bolts of posts 7, 8 and 9 among the first and second collisions are compared between simulations and tests in Table 3. With regard to the first collision, the simulation results are smaller than the respective testing results. There are, however, no big differences in either maximum strains or stresses generated from computer simulations and tests during the second collision. In addition, changes of average strains of two anchor bolts of post 8 over time are compared between computer simulations and tests in Figure 11.

Table 3. Maximum Strains and Stresses of Anchor Bolts

		The first collision			The second collision		
		P7	P8	P9	P7	P8	P9
Strain (μ)	**Simulation**	1206	1461	965	970	1076	1184
	Experiment	1632	1818	1555	1051	1151	N/A
Stress (MPa)	**Simulation**	237.6	287.8	190.1	191.1	212.0	233.2
	Experiment	321.7	358.6	305.6	207.0	226.7	M/A

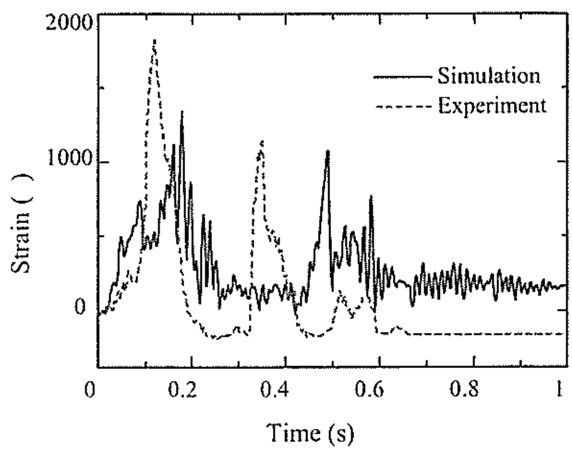


Fig. 11. Time-strain Relationships of Anchor Bolts of Post 8

6. Conclusions

In this paper, computer simulation models were developed for investigating the dynamic collision behaviors of both heavy trucks and aluminum alloy-concrete hybrid guard fences. The usefulness of these models are demonstrated via numerical examples by comparison with on-site full-scale testing measurements.

This research made it possible to simulate the collision process, visualize the movement of the truck, and investigate the performance of hybrid guard fences, including the concrete base, upper metal beams and posts and their connecting anchor bolts, through the use of computers.

The aluminum alloy-concrete hybrid guard fence could prevent the high-speed truck from overturning, and meet the requirements of safe guard fences to guide the movement of a truck after the impact by controlling its leaving speed and angle.

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