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COMPUTER SIMULATION OF ON-SITE FULL-SCALE TESTS OF SINGLE-SLOPE CONCRETE GUARD FENCES

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Abstract

On-site full-scale tests are important to understand what happens to guard fences when vehicles collide with them. However, such tests requiring large inputs of both time and money have not been well modeled through the use of computer simulations. The purpose of the research presented in this paper is to model the full-scale tests conducted for single-slope concrete guard fences struck by heavy trucks. First, the on-site full-scale static loading test is modeled by investigating the ground boundary of the single-slope concrete guard fence. Then, the on-site full-scale crash test is simulated by developing finite element method (FEM) models for both heavy trucks and single-slope concrete guard fences. Comparing the results generated from computer simulations and on-site experiments demonstrates that the developed models can be applied to simulate the collision of heavy trucks with single-slope concrete guard fences and further to provide the data to design new guard fences and analyze existing ones.

Keywords: concrete guard fence, vehicle collision, tests, computer simulations, modeling

1. Introduction

With the improvement of road network and vehicle capacities, heavy trucks have become more important in local and national freight transport in recent years. For instance, the numbers of trucks in Australia and their annually traveled kilometers from 1991 to 2003 have increased 18 and 37 per cent, respectively [1]. Both the function and safety of conventional transportation infrastructures are also challenged by increased allowable vehicle weights and speeds. An example is that about 40 per cent of traffic fatalities in the state of Victoria, Australia have involved collisions with fixed objects such as poles, trees and guard fences in recent years [2]. Safety guard fences are normally required on roads where trucks are permitted to travel at high speed, therefore increasing requirements to design and analyze highway guard fences. Under such circumstances, full-scale vehicle crash tests have been conducted worldwide although they are expensive and time consuming. For example, on-site full-scale tests on single-slope concrete guard fences were conducted in USA and Japan [3, 4].

The use of computer modeling to develop roadside features has become a practical method, especially given the latest development of faster computers and more accurate software. For example, computer simulation of vehicle crashes with roadside hardware has become the subject of much research into steel highway guard fences [5, 6], aluminum highway guard fences [7], and steel railway guardrails [8, 9]. In addition, several researchers have attempted to use computer simulation to solve the problems of vehicle collisions with guardrail posts [10, 11], steel bridge piers [12], and concrete bridge piers [13]. However, few studies have been published on how to investigate the computer simulations of on-site full-scale tests.

The purpose of the research presented in this paper is to study the computer modeling of both static and dynamic on-site full-scale tests of single-slope concrete guard fences using transient simulations and to investigate the collision performance of both heavy trucks and concrete guard fences. The next section briefly describes the typical concrete guard fences currently used in practice. This is followed by a section on computer simulations of static loading tests focusing on modeling the ground boundary of single-slope concrete guard fences. In order to simulate the on-site full-scale crash tests through the use of computers, finite element method (FEM) models are then 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 testing progress of heavy trucks colliding with single-slope concrete highway guard fences [14]. The final section concludes this paper.

2. Concrete Guard Fences

Highway guard fences may be deflective or rigid. The metal beams and posts in deflective guard fences, which are normally made of steel or aluminum, absorb a large portion of the kinetic energy of a colliding truck in the form of residual displacement. This may effectively reduce the energy shift to the interior of the truck, and therefore save the truck driver from a fatal injury. The concrete guard fence is a typical rigid guard fence. It is designed for use at a limited number of places because of its low elastic-deformation capacity. In case of a vehicle colliding with a concrete guard fence, the kinetic energy of a moving truck transfers little to the guard fence, and much to the internal energy of the truck. Therefore, the vehicle may be severely collapsed and the passengers fatally wounded. Concrete guard fences are, however, regarded as appropriate transportation hardware to prevent vehicles from leaving the road. A vehicle involved in an accident and falling from an urban bridge or viaduct may cause further serious traffic accidents. Moreover, concrete guard fences are cheaper than steel fences in construction and require low maintenance [15].

There exist three major types of concrete guard fences: they are: (a) Florida type, (b) single slope type, and (c) perpendicular-wall type as sketched in Figure 1. The Florida-type guard fences are also called by other names and have minor differences in their configurations. This type of fence has the longest history and widest use among all three types of concrete guard fences. The perpendicular wall is rarely constructed in highways or bridges. The single slope concrete guard fence is relatively new and its primary advantage is that the pavement adjacent to it can be overlaid several times without changing its performance [3]. The single-slope concrete guard fence is also thought to be able to improve the impact performance in comparison to the Florida-type concrete guard fence, especially for small vehicles. The remaining of this paper will simulate the on-site full-scale tests on single-slope concrete guard fence subjected to the collision of heavy trucks.

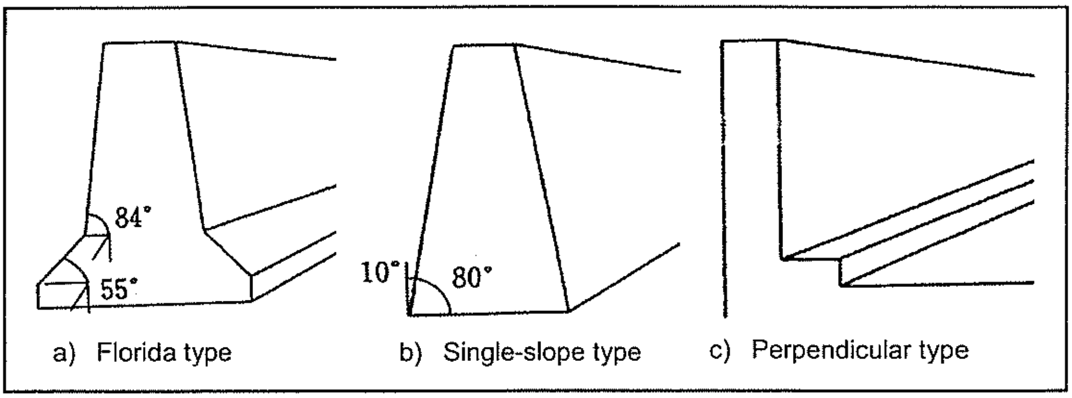


Fig. 1. Typical Concrete Guard Fences

3. Computer Simulations of Full-scale Static Loading Test

3.1 On-site Full-scale Static Loading Tests

In 1998, the Public Works Research Institute in Japan decided to conduct full-scale tests to better understand the strength and deformation characters of concrete guard fences [4]. On the basis of practical utilization, only single-slope and Florida types of concrete guard fences were chosen for full-scale testing that contains static and dynamic loading tests. The static loading experiment is targeted to test the performance of the whole guard fence and to determine its load-displacement relationships.

Figure 2 summarizes the loading location and the places to measure displacements. The four measuring places are labeled as DH1, DS2, DS3, and DS4. The loading direction is horizontal and parallel to the cross section.

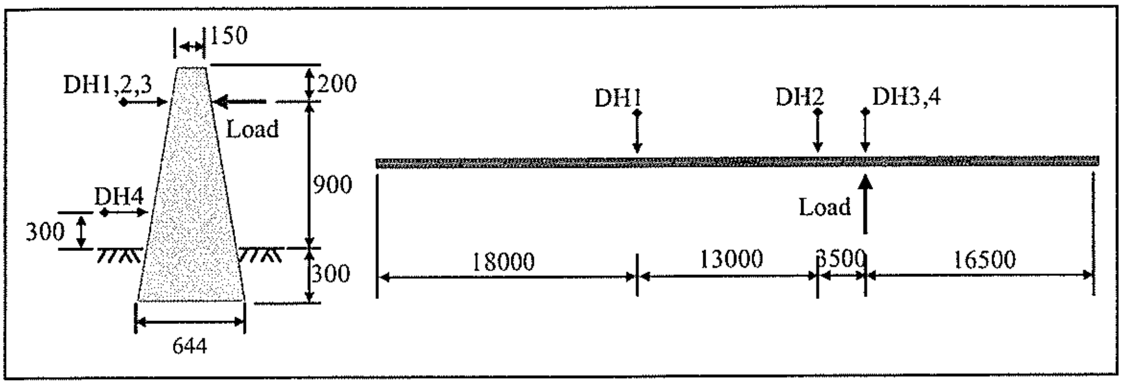


Fig. 2. On-site Full-scale Statistic Loading Tests (unit: mm)

3.2 Modeling the Ground Boundary of the tested Single-slope Guard Fences

Figure 3 details the cross-sectional sizes of the tested single-slope reinforced concrete guard fences. Their subgrades fences are strengthened by a 200 mm layer of uniformly crushed stone aggregates. The guard fences are constructed at 300 mm under the ground. Their two sides are backfilled by the same crushed stone with a thickness of 200 mm and topped by the 100 mm asphalt pavement.

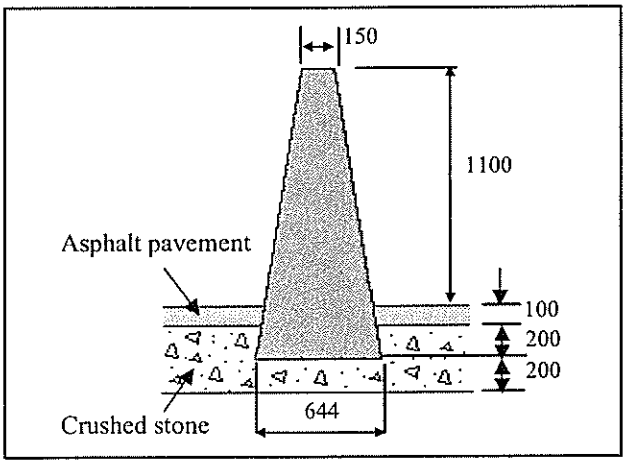


Fig. 3. Cross Section of a Single-slope Concrete Guard Fence

The reaction of the subgrade to the embedded guard fences is modeled in the form of several springs. First, the asphalt pavement at each longitudinal side of the guard fence is equivalently assumed to be connected with the fences at the top of the pavement through a linear compression spring as shown in Figure 4. The spring coefficient is 15 kN/mm per meter at the longitudinal direction of the guard fence. The backfilled crushed stone at each longitudinal side is equivalently assumed to be another linear compression spring to connect with the guard fence at its bottom. The spring coefficient is 5 kN/mm per meter at the longitudinal direction of the guard fence. The subgrade under the guard fence is assumed to be a spring mattress to support the guard fence and prevent it from movement horizontally. Its vertical and horizontal compression spring coefficients are 0.1 kN/mm and 0.016 kN/mm per square meter of fence base respectively. These spring coefficient values are assumed on the basis of previous collision experiments by guard fence makers.

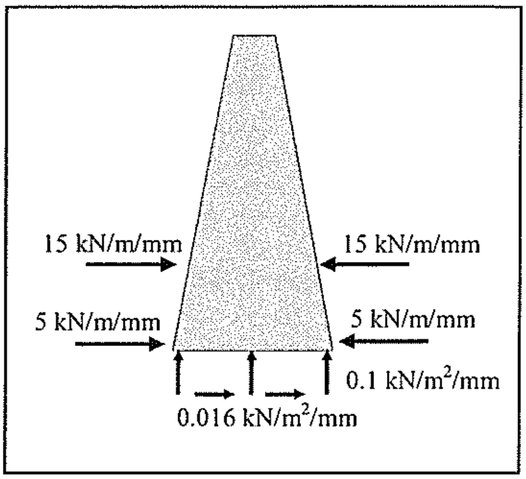


Fig. 4. Spring Models of the Subgrade of a Single-slope Concrete Guard Fence

3.3 Computer Simulation Results

The developed spring subgrade models are verified by comparing the simulation results with the experimental records. According to spring subgrade models, displacements of guard fences at four locations with the increase of load are calculated by considering the concrete guard fence as a completely rigid. Load-displacement relationships at measurement points DH1, DH2, DH3, and DH4 from both experiment and simulation are compared in Figure 5(a), (b), (c) and (d), respectively.

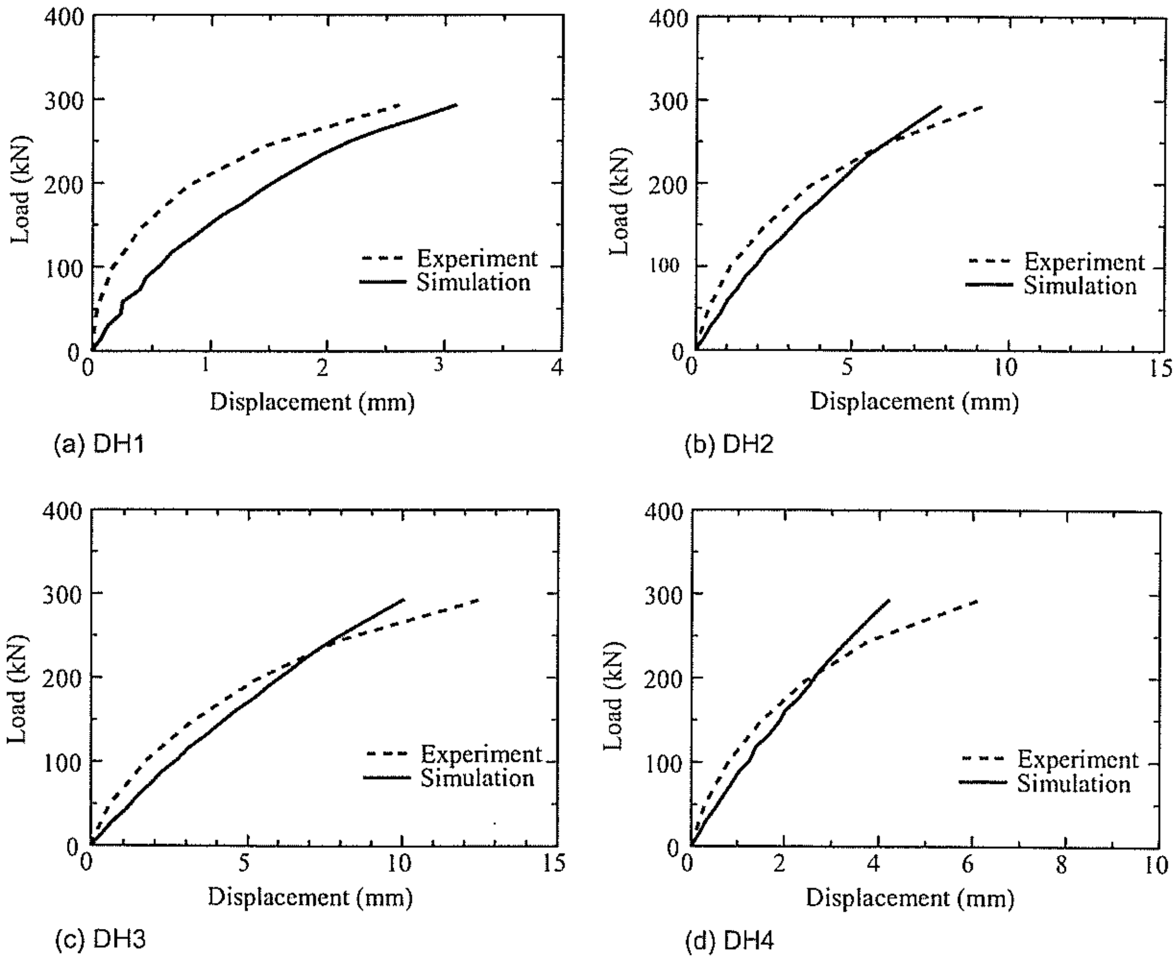


Fig. 5. Load-displacement Relationships at Four Measurement Points

Before the loading achieves about 250 kN, the calculation results at each measurement point are higher than the experimental records. This is mainly because of the neglect of deformation of the concrete guard fences in the simulations under the assumption of complete rigidity. At the initial loading stage, the concrete is an elastic material, and the increase of calculated displacement is more than the tested value. As the plastic performance of concrete becomes evident, the calculated displacement is the same as or less than the testing figure. In addition, there is no doubt that the assumed spring subgrade models do not exactly match the real boundary conditions, which makes the calculated results different from the experimental data.

Comparisons of these static load-displacement relationships indicate however that the developed spring subgrade models can be used to simulate the performance of concrete guard fences under external loads, in particular if an appropriate concrete material model is applied to represent its elastic and plastic characteristics. Based on the similarity of simulation and testing results, it can also be concluded that the on-site full-scale static loading test of a single-slope concrete guard fence has been successfully modeled through the use of computer simulations in this research.

4. Computer Simulations of On-site Full-scale Crash Tests

4.1 On-site Full-scale Crash Tests

Figure 6 describes the collision transience and longitudinal features of concrete guard fences. The length of a single-slope guard fences is 51 m. The crash point is at 20 m from the truck approaching side, and the speed of the crash truck is 100 km/h which is currently the maximum design speed [16]. 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, 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. To generate this maximum design impact energy in tests, the impact angle of crash trucks was increased to 17^0, and the actual impact energy was 660 kJ.

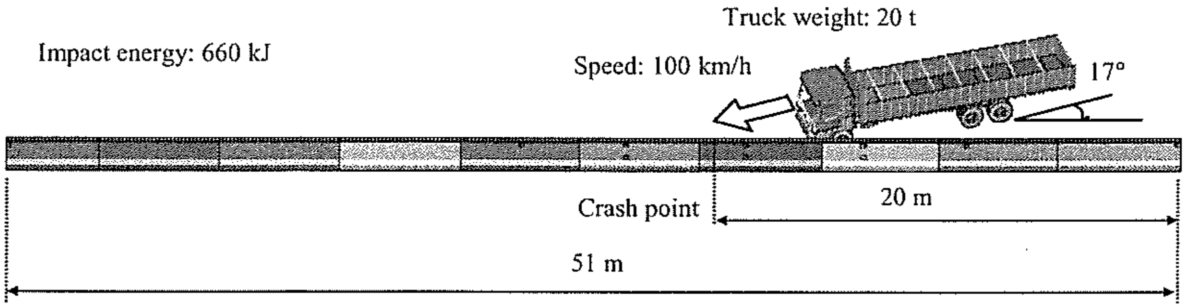


Fig. 6. On-site Full-scale Crash Tests

4.2 FEM Models of Heavy Trucks and Single-slope Concrete Guard Fences

4.2.1 FEM Models of Heavy Trucks

FEM models of the 20 tf truck used in the on-site full-scale crash tests are developed from early FEM models of a 25 tf truck [6, 12]. The structure of the 20 tf truck is similar to the 25 tf truck except for the strengthened frame and the loading capacity of the vehicles' vertical axles. The majority of the modeling objects are 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 length, width and height of the modeled truck are approximately 11.8, 2.5 and 2.9 m, respectively. Figure 7 represents the FEM models of a heavy truck that is used in the research presented in this paper. As shown in Figure 7(a), the truck is modeled according to the ladder-type truck frame with two side members of channel sections. The thickness of the side member is 8 mm, and the yield stress is 295 MPa. The general elasto-plastic stress-strain relationship is adopted for steel, and the steel strain-rate effects are also taken into account in the truck model [12]. The solid element with the same shape and volume is modeled for the engine and transmission. The tiers, wheels, and gears of a truck significantly influence its behaviors during the collision impact. The connection of the tier and the wheel is assumed to be a rotation joint so that the movement of the wheel can be simulated. A constant value of 0.45 is used for the friction coefficient between the tier and the road pavement. The driving cabin and other small portions are also modeled for the purpose of the numerical simulation. Figure 7(b) shows the FEM models for the whole truck.

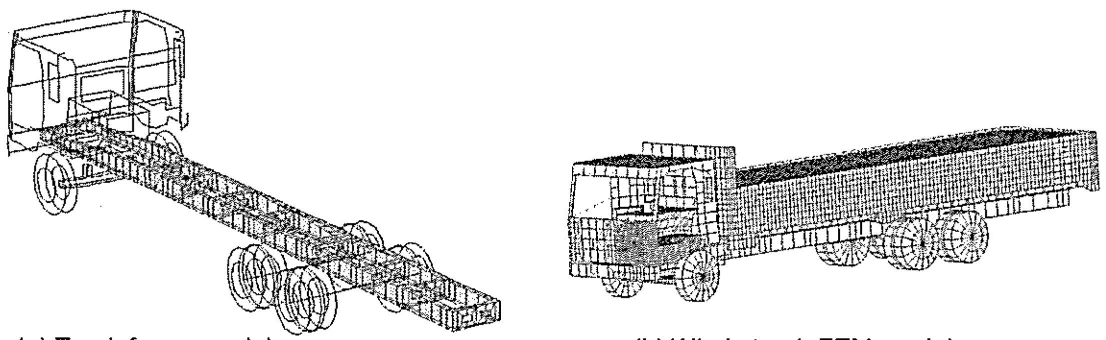
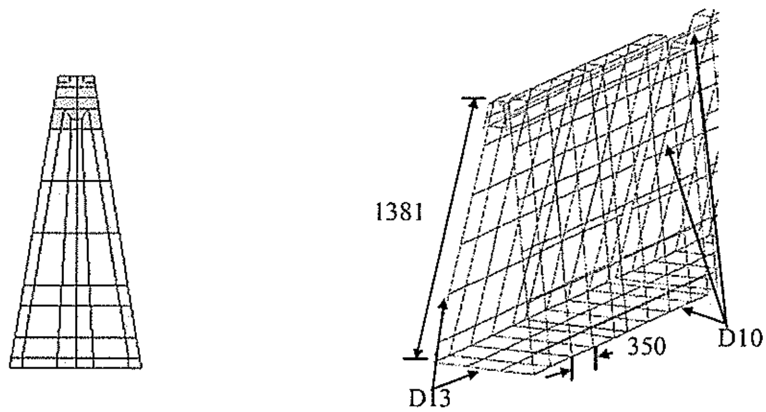

(a) Truck frame model (b) Whole truck FEM model

Fig. 7. FEM Models of a Truck

The face-to-face automatic touch type in LS-DYNA software is used to represent the contact of a moving truck with the guard fence at the collision transient [14]. The mesh size of trucks is diminished at the crash position, which is normally the left front of the driving cabin while driving on the left side. The total numbers of nodes and elements in the FEM model 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.

4.2.2 FEM Models of Concrete Guard Fences

The concrete guard fences used in the on-site tests are also modeled in FEM for the purpose of computer simulation. Figures 8(a) and (b) represent the FEM mesh layout from the cross-sectional direction and the reinforced framing of a single-slope type of concrete guard fence, respectively. The D10 reinforcing bars are used as the trapezoid frame, and the D13 reinforcing bars are used in all other places.



(a) FEM model (b) Reinforced framing

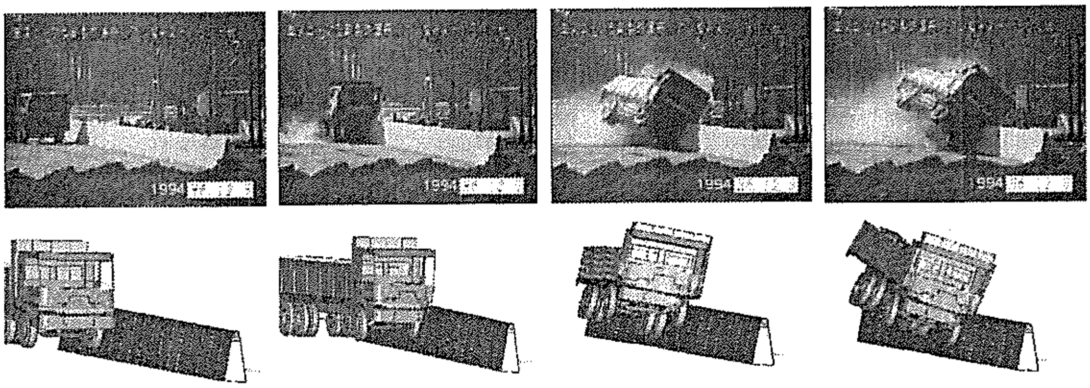
Fig. 8. FEM Models of a Single-slope Concrete Guard Fence

The material parameters of steel and concrete used in the actual truck tests are taken into the simulation. The yield stresses of D10 and D13 reinforcing bars are 373.8 and 407.6 MPa, respectively. The compressive strength of concrete is 34.2 MPa. The Young's moduli of concrete, D10 and D13 are 18.4, 167, and 170 GPa, respectively. Concrete and reinforcing bars are modeled as solid and Hughes-Liu beam elements, respectively. There are 16,179 nodes and 20,579 elements in the single-slope concrete guard fence.

It is widely accepted that concrete strength is highly sensitive to loading procedure, especially in the range of high strain rates. The strain-rate magnitude may be affected by various parameters including the initial elastic modulus, the peak stress, the sharpness of the stress peak and inertial effects [17, 18]. In previous research, various formulae were proposed on the basis of experiments and statistical analyses. Therefore, it is imperative that strain rates are included for numerical simulation, especially for the damage features of structures. However, the strain-rate effects of materials are not considered in the Drucker-Prager failure criteria in the current version of LS-DYNA software. In this research, a sub-routine is coded to take into account the concrete's strain-rate formulae recommended in [17]. The sub-routine and strain-rate formulae are verified by simulating the dynamic compressive analysis of a concrete test specimen and comparing the analysis results with the experimental results.

4.3 Computer Simulation Results

For demonstrating the above FEM models, the tested single-slope concrete guard fences are analyzed using LS-DYNA. Figure 9 shows in detail the performance of the truck at several collision conditions, which are 0, 0.1, 0.5, and 0.7 seconds (s). The graphs from the full-scale experiment carried out by the Public Works Research Institute in Japan and the simulation in the present research are compared. The left-front wheel of the moving truck and the left front of the drivers' cabin first collide with the guard fence, and the left front wheel then runs onto the slope of the guard fence. Shortly, the truck frame inclines, and the left rear wheel runs onto the slope of the concrete guard fence. Finally, the rear part of the truck runs up higher than the driving cabin and rotates over the concrete guard fence. Both the experiment and simulation show the same progresses of collisions, and the same final results that the truck falls down the single-slope concrete guard fence because of the overturn of its rear part. The calculated speed when the truck finally exits from the guard fence is 79.4 km/h, which is quite similar to the tested final speed of 84.7 km/h.



(a) 0.0 s (b) 0.1 s (c) 0.5 s (d) 0.7 s

Fig. 9. Impact Performance of a Truck with a Single-slope Concrete Guard Fence

By comparison between experiments and simulations in the research presented in this paper, it is obvious that computer simulation enables the replication of the whole process of a real collision. The simulation results based on the models in this research may be used to analyze the collision performances of trucks as well as of concrete guard fences.

5. Conclusions

In this paper, computer models, including the FEM models of heavy trucks and single-slope concrete guard fences and the spring subgrade models of guard fences, were developed for simulating on-site full-scale static loading and crash tests. This research fills the gap in the literature on modeling the on-site full-scale tests on single-slope concrete guard fence struck by heavy trucks. Based on this research, it was possible to replicate the collision testing process of heavy trucks with single-slope concrete guard fences through the use of computer simulation. Similar to full-scale tests, computer simulations can also determine the capabilities of single-slope concrete guard fence under static and dynamic loading conditions.

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