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Dynamic simulation of collisions of heavy high-speed trucks with concrete barriers

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Abstract

Real vehicle collision experiments on full-scale road safety barriers are important to determine the outcome of a vehicle versus barrier impact accident. However, such experiments require large investment of time and money. Numerical simulation has therefore been imperative as an alternative method for testing concrete barriers. In this research, spring subgrade models were first developed to simulate the ground boundary of concrete barriers. Both heavy trucks and concrete barriers were modeled using finite element methods (FEM) to simulate dynamic collision performances. Comparison of the results generated from computer simulations and on-site full-scale experiments demonstrated that the developed models could be applied to simulate the collision of heavy trucks with concrete barriers to provide the data to design new road safety barriers and analyze existing ones.

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1. Introduction

Safety barriers are normally required on roads where vehicles are permitted to travel at a high speed. In recent years, heavy trucks have become more important in local and national freight transport with the improvement of road network and vehicle capacities. Both the function and safety of conventional transportation infrastructures are challenged by increased allowable vehicle weights and speeds. Therefore, there have been increased requirements to design and analyze road safety barriers.

Safety barriers are generally of two types: deflective or rigid. The metal beams and posts in deflective barriers, which are normally made of steel or aluminum, absorb a large portion of the kinetic energy of 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 barrier is a typical rigid barrier. 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 barrier, the kinetic energy of a moving truck transfers little to the barrier, and a great deal to the internal energy of the truck. Therefore, the

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vehicle may severely collapse and the drivers and passengers are seriously injured. Concrete barriers are, however, regarded to be appropriate to prevent vehicles from leaving the road. A vehicle involved in an accident from an urban bridge or viaduct may cause further serious traffic accidents. Moreover, concrete barriers are cheaper than the steel ones and require little maintenance [1].

Because full-scale vehicle crash tests are time consuming and expensive, the use of computer modeling to develop roadside features is a more practical method, especially given the development of faster computers and more accurate software. Therefore, computer simulation of vehicle impact loading has become the focus of extensive research on steel highway guard fences [2,3], aluminum highway guard fences [4], and steel railway guardrails [5]. In addition, several researchers attempted to use computer simulation to solve the problems of vehicle collisions with guardrail posts [6], and steel and concrete bridge piers [7,8].

The research presented in this paper used transient simulations to investigate collisions of heavy trucks with concrete road barriers. Finite element method (FEM) models were developed for both vehicles and barriers with a consideration of the nonlinear performances of materials used in barriers and heavy trucks as well as the boundary conditions. A nonlinear and large deformation FEM analysis package, LS-DYNA3D, has also been used to simulate the progressive impact of a heavy truck on a concrete barrier [9]. The accuracy of the FEM models for both truck and barrier was evaluated with full-scale on-site testing by comparing the damage developed and the ultimate collapse of trucks and concrete road barriers.

2. On-site full-scale tests of concrete barriers

Three major types of concrete barriers are in use: (a) the perpendicular-wall shape, (b) F shape, and (c) single-slope shape as sketched in Fig. 1. Each type of concrete barrier may also be known by a different name and have minor differences in the configurations [10]. The F shape concrete barrier has the longest history and widest use among the three types of concrete barriers. Only the F shape concrete barriers were the focus of this research.

The F shape concrete barrier was chosen for full-scale testing to better understand its strength and deformation characteristics by the Public Works Research Institute of Japan [11]. Fig. 2 shows the cross-section and longitudinal sizes of the tested F shape reinforced concrete barriers. The locations of out-of-plate displacement measurements are laid out, and indicated as DH1, DH2 and DH3. The subgrades of barriers are strengthened by a 200 mm layer of compacted uniformly crushed rock. The concrete barriers are bedded at 300 mm under the ground, and the two sides are backfilled using the same crushed rock to a thickness of 200 mm and topped by the 100 mm asphalt pavement. The length of the F shape concrete barrier is 50 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 in the design specification of road barriers in Japan [12]. Due to the limitation of power of the pulling facility, a 20,000 kg truck was used for collision tests instead of the maximum design truck weight of 25,000 kg.

According to the design specifications of road barriers in Japan, the impact energy of a truck is determined by its crash speed and angle, and weight [12]. The maximum design impact energy is 650 kJ while the crash truck speed and angle, and its weight are 100 km/h, 15°, and 25,000 kg, respectively. To generate this maximum design impact energy in tests, the impact angle of the colliding truck was increased to 17°, and the actual impact energy was 660 kJ.

3. Modeling concrete barriers and trucks

3.1. Subgrade model

The reaction of the subgrade to the embedded concrete barriers is modeled in the form of several springs. The asphalt pavement at each longitudinal side of the barriers is assumed to equally connect barriers at the top of the pave-

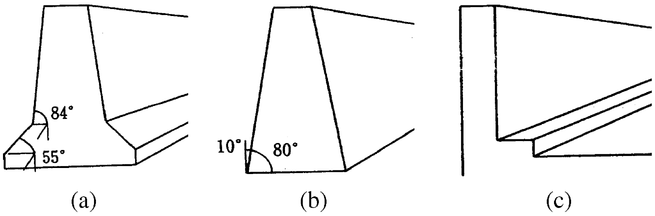


Fig. 1. Typical concrete barriers.

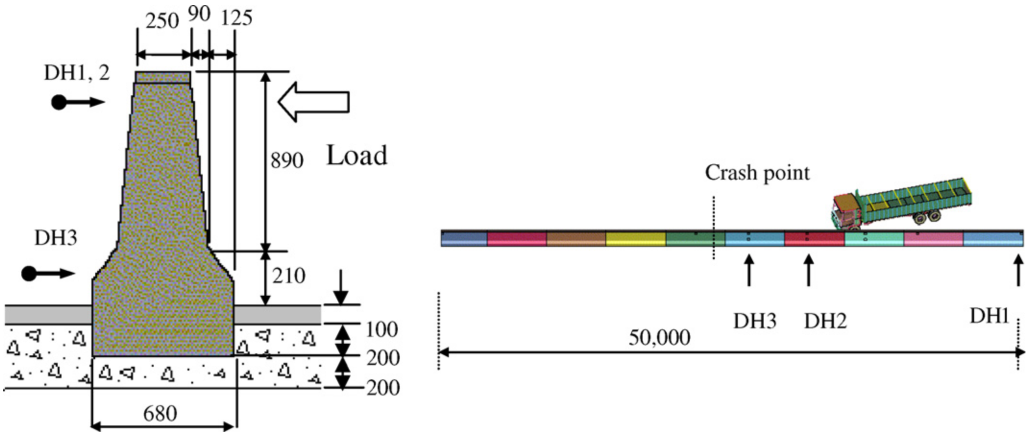


Fig. 2. The F shape concrete barrier used for the on-site full-scale crash test (mm).

ment by a linear compression spring. The spring coefficient is 15 kN/mm per meter at the longitudinal direction of the concrete barrier. The backfilled crushed rock at each longitudinal side is similarly assumed to be another linear compression spring to connect with the concrete barrier at its bottom. The spring coefficient is 5 kN/mm per meter at the longitudinal direction of the barrier. The subgrade under the concrete barrier is assumed to be a spring mattress to support the barrier. Its vertical and horizontal compression spring coefficients are 0.1 kN/mm and 0.016 kN/mm per square meter of barrier base, respectively. These spring coefficient values were assumed on the basis of previous collision experiments by barrier makers.

3.2. FEM models of heavy trucks

The FEM model of the 20,000 kg truck used in the on-site full-scale crash tests is developed from an early FEM model of a 25,000 kg truck [3,7]. Their structures are similar apart from the strengthened frame and the loading capacity of the vehicle's vertical axles. The modeling is targeted to the truck frame, engine and transmission, driving cabin, cargo, and tires. Their weights are 2470, 1600, 640, 1670, and 2570 kg, respectively. The total weight of the modeled truck structure is 8950 kg and the remaining 11,050 kg 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.

Fig. 3 represents the FEM models of the truck as outlined in this paper. As shown in Fig. 3(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 [7]. The solid element with the same shape and volume is modeled for the engine and transmission. The axles, wheels, and gears of a truck significantly influence its behavior during the collision impact. The connection of the axle 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 tire and the road pavement. The driving cabin and other small portions are also modeled for the purpose of the numerical calculation. Fig. 3(b) shows the FEM model for the whole truck.

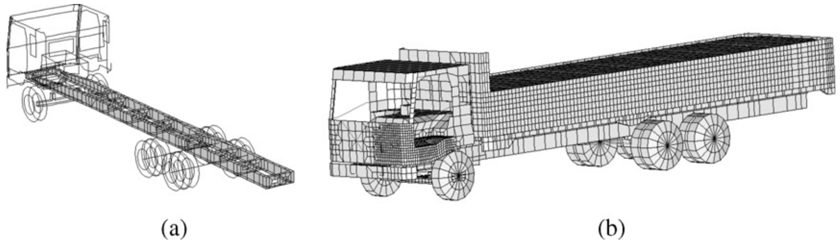


Fig. 3. FEM model of the truck. (a) Truck frame model and (b) whole truck FEM model.

The face-to-face automatic touch type in LS-DYNA software is used to represent the contact of a moving truck with the concrete barrier at the collision transient [9]. 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. Fig. 4 enlarges the driving cabin with diminished mesh sizes.

The total numbers of nodes and elements in the FEM mode of a heavy 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 stress of steel is 235 MPa, while that of aluminum is 248 MPa. The shear moduli of steel and aluminum are 88 and 26 GPa, respectively.

3.3. FEM models of concrete barriers

The concrete barriers used in the on-site full-scale tests are modeled in FEM for the purpose of computer simulation. Fig. 5(a) represents the FEM mesh layout from the cross-sectional direction. Fig. 5(b) represents the reinforced framing of concrete barriers. The D10 reinforcing bars are used as the trapezoid frame, and the D13 reinforcing bars are used in all other places.

The material parameters of steel and concrete used in the actual truck tests are considered in 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 11,845 nodes and 15,703 elements in an F shape concrete barrier.

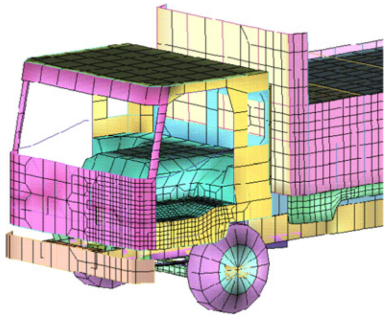


Fig. 4. Mesh division of the driving cabin.

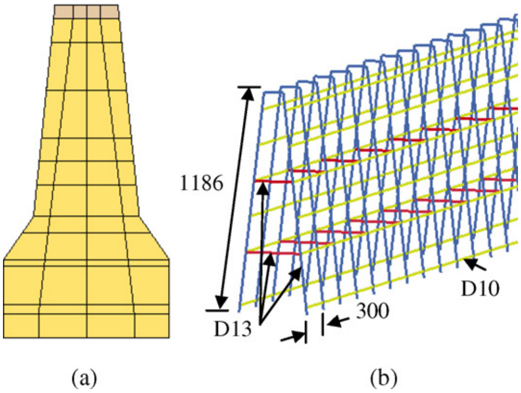
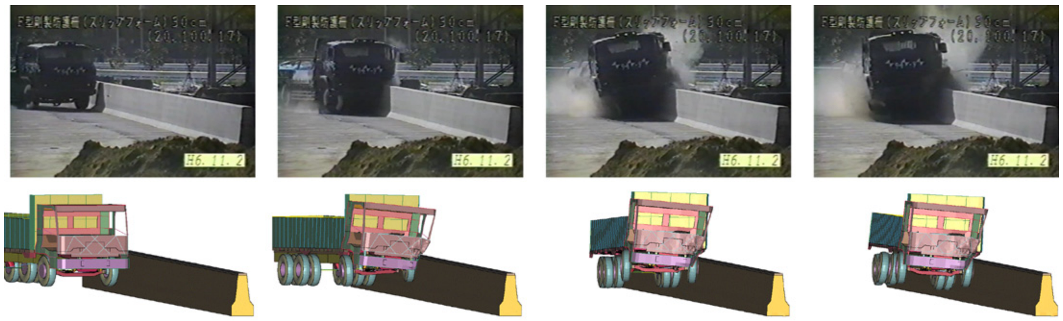


Fig. 5. FEM model of the concrete barrier (mm). (a) FEM model and (b) reinforced framing.



(a) (b) (c) (d)

Fig. 6. Impact performance of a truck with the F shape concrete barrier. (a) 0.0 s, (b) 0.2 s, (c) 0.4 s, and (d) 0.5 s.

4. Collision simulation of heavy trucks

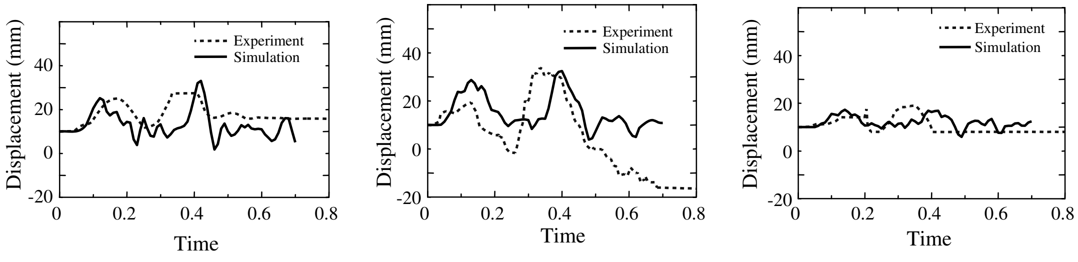
To demonstrate the above FEM models, the tested F shape concrete barriers are analyzed using LS-DYNA. Fig. 6 shows in detail the performance of the truck at several collision points, which are 0, 0.2, 0.4, and 0.5 seconds (s). The graphs from the full-scale experiment carried out by the Public Works Research Institute of Japan and the simulation in the present research is compared. When the truck cabin collides with the concrete barrier at the 84°-angle slope (the first collision), the left-front wheel rises onto the 55°-angle slope. Then, the rear part of the truck crashes into the barrier (the second collision). After several collisions between the front or rear of the truck and the barrier, the truck moves away from the safety barrier. Although the truck frame rises and inclines during the collision, the rear part of the truck is never higher than its front. Therefore, the F shape concrete barrier can prevent the truck from derailing from the road and control the moving-away angle from the barrier. The calculated departing speed and angle of the truck are 77.0 km/h and 1.4° respectively, compared with 78.6 km/h and 1.9° in the on-site full-scale experiment.

By comparing experiments and simulations in these examples, it is obvious that computer simulation enables 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 barriers.

5. Collision simulation of concrete barriers

During the on-site full-scale collision experiments of high-speed heavy trucks with concrete barriers, the out-of-plane displacements of F shape concrete barriers were fully recorded. This has made it possible to evaluate the simulation results by comparison.

Fig. 7(a)–(c) compare the time–displacement relationships obtained from experiment and simulation at DH1, DH2, and DH3, respectively. The computer simulation stops while the second collision is completed at about 0.7 second after collision commencement. According to these graphs, it can be concluded that the computer simulation replicates an on-site full-scale truck collision with concrete barriers. At all these three locations, the maximum out-of-plane displacements at the second (rear) collision are bigger than those at the first (front) collision. The time period from the first



(a) (b) (c)

Fig. 7. Comparisons of displacement responses of the concrete barrier. (a) DH1, (b) DH2, and (c) DH3.

to second collision of the front and rear of the truck in simulation is slightly longer than that recorded in experiments. This may be due to the current simulation assumptions on the distribution of truck weights and no consideration of the local deformation of concrete barriers during the collision process. The maximum displacements at DH3, a bottom position, are rather small in both simulation and experiment. The waves of these out-of-place displacement curves represent the vibration of concrete barrier and the minor collisions of the major front and rear collisions.

6. Conclusions

In this paper, computer analysis models were prepared for simulating the dynamic collision behaviors of both heavy trucks and concrete barriers. The usefulness of these models was demonstrated via numerical examples by comparison with on-site full-scale experiment records.

This research made it possible to simulate the collision process, visualize the movement of the truck, and investigate the performances of concrete barriers through the use of computers.

The F shape concrete barrier could prevent the high-speed truck from derailing from the road, and achieve the requirements to guide the movement of a truck after the impact by controlling its moving-away speed and angle.

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