NUMERICAL ANALYSIS ON VEHICLE COLLISION TO FLEXIBLE PRECAST CONCRETE GUARD FENCE

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Abstract

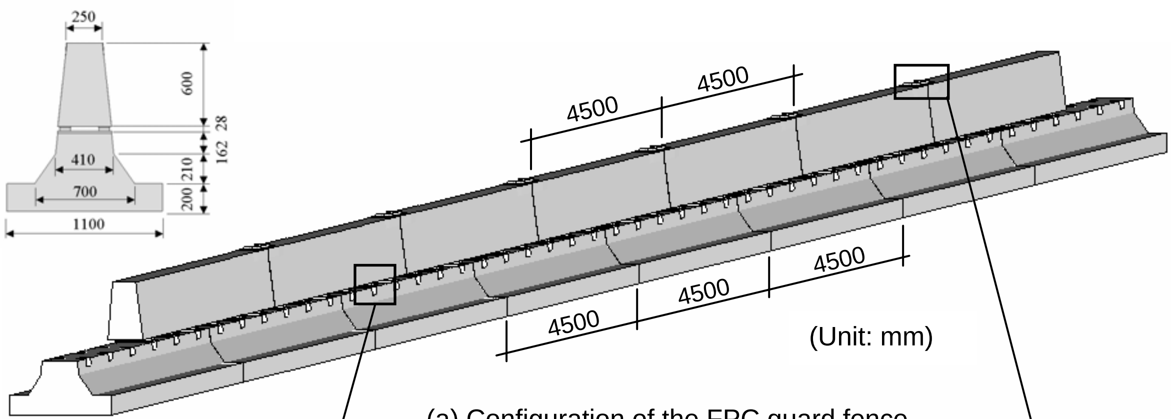
A new type of guard fence named Flexible Precast Concrete (FPC) guard fence has been developed in Japan. In this study, FEM models are established for truck and the FPC guard fence to simulate impact behaviors. Firstly, tension tests on the spring steel (SUP9) for the flat-springs are conducted to obtain the stress-strain relationship and the strain rate effect. Secondly, numerical analysis is carried out using the material parameters obtained from the tension tests. The analytical results are compared with the data of full-scale truck collision experiment, and the FEM models for the FPC guard fence are proved to be valid and practical. As a result, effectiveness for evaluating the performances of the FPC guard fence by numerical analysis results is validated. In addition, the analytical results of the FPC guard fence are also compared with that of the normal type of concrete guard fence.

Keywords: Numerical analysis, FEM, Vehicle collision, FPC guard fence

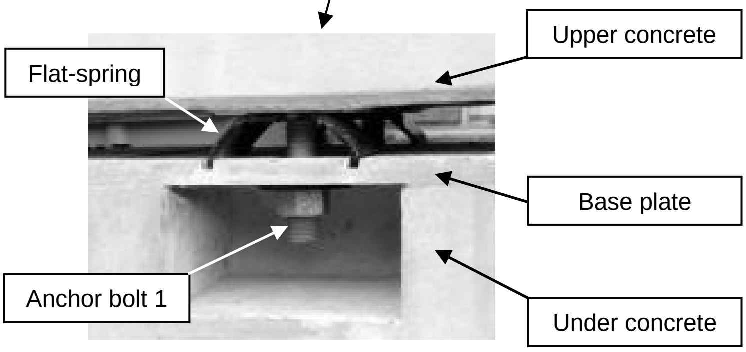
1. Introduction

To meet the rising safety requirements of highways due to the increases in the traffic speed, vehicles' volumes and weights, height of vehicles' centroids and so on, a new code for the design of guard fences was implemented and issued in April 1999 in Japan [1]. In the new code, full-scale collision experiments for performance evaluation of guard fences are required before construction, and the prescribed performances include: i) prevention of vehicles' derail, ii) guiding vehicles to road, iii) safety of occupants, and iv) prevention of spreading out the broken pieces. If a guard fence can be designed to satisfy these performances, any types of materials and shapes for the guard fence are available.

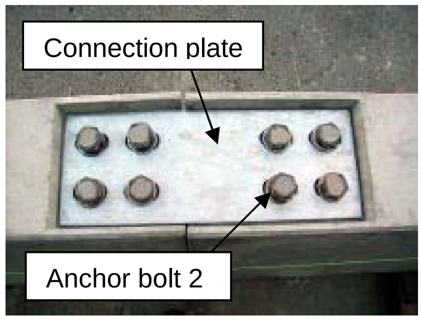
In order to accommodate the severe conditions in the National Highway of Nagoya-Osaka, such as the highly curved layout of roadway and the large traffic amount, and also to satisfy the requirements of the new code, a new type of guard fence named Flexible Precast Concrete (FPC) guard fence has been developed in Japan. The FPC guard fence is made by connecting two precast steel fiber reinforced concrete (SFRC) segments with flat-springs, as shown in Fig. 1, which is much different from the normal type of concrete guard fence (see Fig. 2) in structure and performances. This guard fence was designed to have a high deformation capacity and to enable quick construction as well as easy maintenance after damaged. The full-scale collision experiments for the FPC guard fence were conducted in 1998 at the Public Works Research Center of Japan [2] and it has been shown by the experiments that the FPC guard fence possessed satisfactory performances. However, it is still need to be improved for widespread practical use, such as to optimize its structure and enhance the adaptability to various highways. It is impractical to do all the full-scale collision experiments for the improved FPC guard fences because of the huge time and cost consumption. The numerical simulation is therefore a useful tool and is necessary for evaluations of the performances of the improved FPC guard fences and the behaviors of crashing vehicle.



(a) Configuration of the FPC guard fence



(b) Connection of upper and under concrete



(c) Connection of upper concrete

Figure 1. Structure of the FPC guard fence

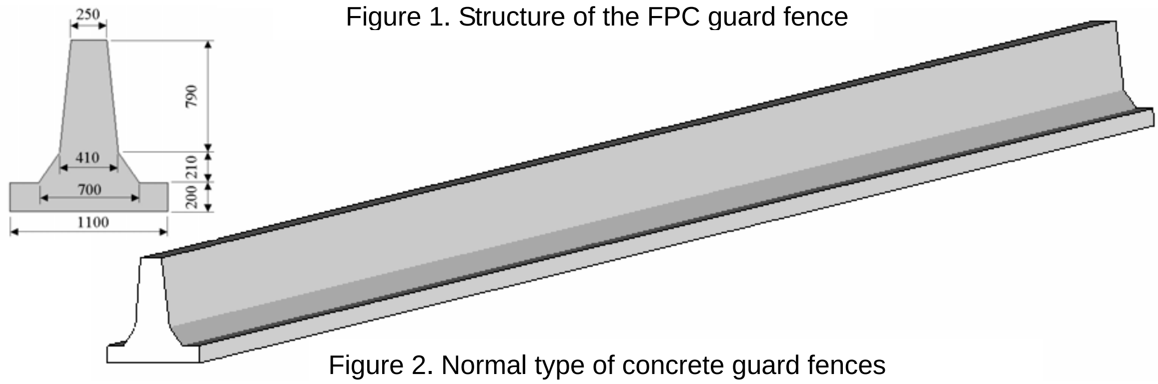


Figure 2. Normal type of concrete guard fences

Table 1. Material for the components of the FPC guard fence

Component	Material
Upper concrete	SFRC (Steel Fiber Reinforced Concrete)
Under concrete	SFRC (Steel Fiber Reinforced Concrete)
Base plate	SS400 (mild steel)
Anchor bolt 1	SS400 (mild steel)
Anchor bolt 2	SS400 (mild steel)
Flat-spring	SUP9 (spring steel)
Connection plate	SS400 (mild steel)

Table 2. Chemical composition of the steels for the FPC guard fence by JIS[3]

Symbol of steel	Chemical composition (%)					
	C	Si	Mn	P	S	Cr
SS400	0.13	0.16	0.63	0.020	0.007	-
SUP9	0.52~0.60	0.15~0.35	0.65~0.95	< 0.035	< 0.035	0.65~0.95

In this study, tension tests on the spring steel (SUP9) for the flat-springs are conducted to obtain the stress-strain relationship and the strain rate effect, and numerical analysis is carried out using the material parameters obtained from the tests. The analytical results are compared with the experimental data, and the FEM models for truck and the FPC guard fence are proved to be valid and practical, the effectiveness for evaluating the performances of the FPC guard fence by numerical analysis results is validated.

2. Dynamic Tension Tests

2.1 Objective and procedure of tests

According to the researches in the past, the stress-strain relationship and the strain rate effect of the materials used in the guard fence have a considerable influence on the performances of the guard fence, such as the displacement of the guard fence [4][5]. Therefore, in this study the dynamic tension tests are conducted to obtain the stress-strain relationship and the strain rate effect of spring steel (SUP9) used in the flat-springs mentioned above. The servo-valve-type material test machine (MTS) is used in the tests. The strain rate of dynamic tension tests is from about 10^{-5} (1/s) to $10^{-0.5}$ (1/s).

For the stress-strain relationship and the strain rate effect of SS400 steel, the results of dynamic tension tests in the past research [6] are used in this study.

2.2 Results of steel coupon tests

Figure 3 shows the test results of static equivalent stress-plastic strain relationship of SUP9 steel for the analysis. The square points indicate the test data, and the solid line indicates the model curve for the analysis, which is defined by Eqs. (1) and (2) with parameters shown in Table 3 [7].

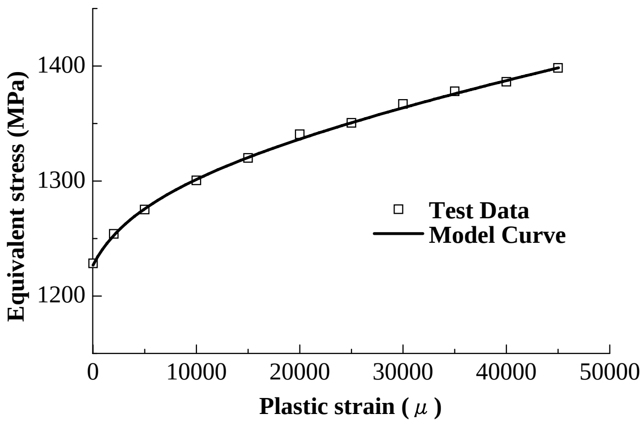


Figure 3. Static stress-strain relationship of SUP9

Table 3. Parameters for Eqs. (1)&(2)

Symbol	Value
$\sigma_{0.2}$	1226.8 MPa
$\varepsilon_{0.2}$	0.002
σ_u	1398.5 MPa
ε_u	0.047048

$$\sigma = \sigma_u \varepsilon^P + \sigma_u (1 - \varepsilon_u)(\varepsilon^p / \varepsilon_u)^m \quad (1)$$

where,
$$m = \frac{\ln\{\sigma_u (1-\varepsilon_u)/(\sigma_{0.2} - \sigma_u \varepsilon_{0.2})\}}{\ln(\varepsilon_u / \varepsilon_{0.2})} \quad (2)$$

σ : equivalent stress, ε^P : plastic strain,
$\sigma_{0.2}$: stress of 0.2% offset, $\varepsilon_{0.2}$: strain of 0.2% offset,
σ_u : ultimate stress, and ε_u : ultimate strain.

Figures 4 and 5 show the strain rate effects on yield stress of 0.2% offset and ultimate stress of SUP9 steel, respectively. The vertical axis of Fig. 4 is the dynamic response factor σ_d / σ_s, where σ_d is the dynamic yield stress and σ_s is the static yield stress. Similarly, the ordinate of Fig. 5 is the dynamic response factor of the ultimate stress. In order to calculate dynamic response factor σ_d / σ_s, it is assumed that σ_s is of the case under the strain rate of 10^{-5}(1/s). The solid lines in these figures indicate logarithmic functions that are recurred with the least square method. In the case of 10^0(1/s) the strain rate effect on the yield stress of 0.2% offset is about 5%, and the strain rate effect on the ultimate stress is about 3%, both strain rate effect is small due to the high yield stress and high ultimate stress.

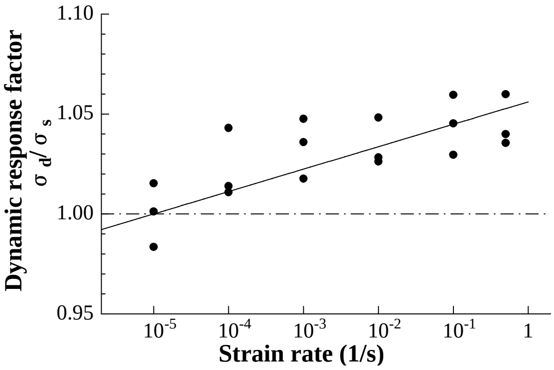


Figure 4. Strain rate effect on yield stress of 0.2% offset of SUP9

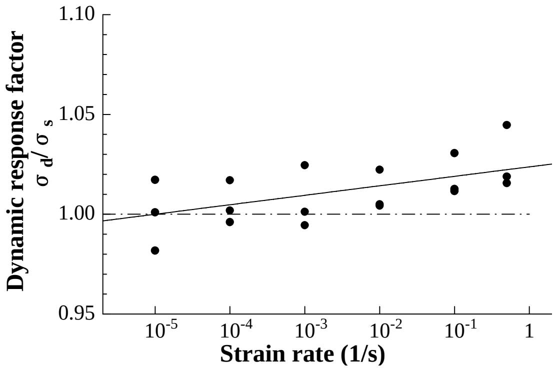


Figure 5. Strain rate effect on ultimate stress of SUP9

3. FEM Models

3.1 Truck model

The numerical analysis for simulating the truck-to-fence collision is carried out using the nonlinear dynamic analysis software LS-DYNA. Figure 6 represents the FEM truck model that is used in this study, which is constructed by the second author in the past research [8] and modified in this study to agree with the truck that was used in the field experiment. In this model, the number of nodes and elements are 9,838 and 9,342, respectively. The weight of the truck is 25 t and the most parts such as the truck-frame, the driving room, the cargo and the tiers are mechanically and geometrically characterized in the model. The length, width and height of the model are 11,800 mm, 2,500 mm and 3,300 mm, respectively. The height of gravity center is 1,400 mm. The Young's modulus of steel is 206 GPa, and 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 and aluminum are 235 MPa and 248 MPa, respectively. In order to simulate the damage of the cabin in detail, very fine mesh is assigned to the cabin. By adjusting the cargo, the weight of the truck model, position of the centroids of the model can be set to the same as those of the truck used in the full-scale collision experiment.

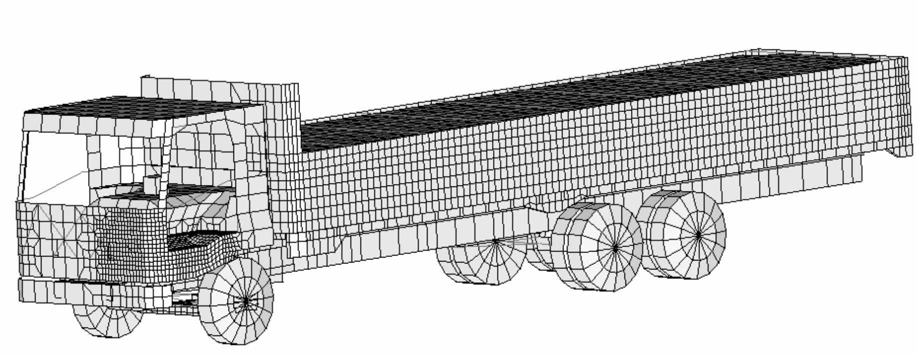
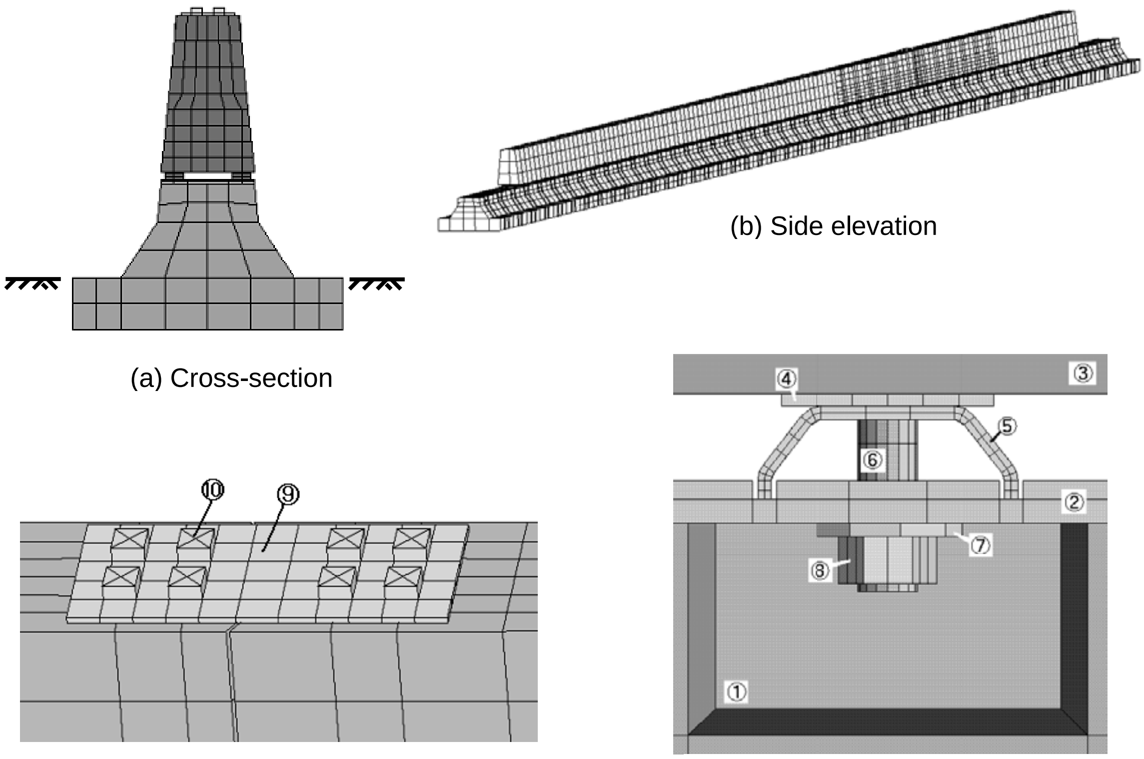


Figure 6. Truck Model

3.2 FPC guard fence model

Figure 7 shows the FEM model of the FPC guard fence used in full-scale collision experiment. Almost all components are modeled by hexahedron SOLID elements, as shown in Table 4, except the anchor bolt. The segments of anchor bolt, which are out of concrete, are modeled by SOLID elements, but the segments into concrete are modeled by BEAM elements, because it is difficult to model them by SOLID elements. The formulation of the BEAM elements is based on Hughes-Liu theory, while the hexahedron SOLID elements use one-point-integration, constant stress formulations [9]. Connection components of upper and under concrete are modeled in detail because of its importance for carrying the collision and adsorption of impact energy. To consider the resistance of the foundation elastic and inelastic SPRING elements are also used. In this model, the number of nodes and elements are 91,590 and 45,466, respectively, for the total length of 54,000mm. To reduce computing time, only the parts near by the close point (length: 31,500mm) are intercepted for the simulation computing, in respect that the effect of the parts far from the close point is very small relatively.



(a) Cross-section

(b) Side elevation

(c) Connection components between upper concrete blocks

(d) Connection components between upper and under concrete

Figure 7. FPC guard fence model

Table 4. Material type and mesh type of FPC guard fence model

Part Id.	Name	Material Type	Mesh Type
①	Under concrete	Mat5 (SFRC)	SOLID
②	Base plate	Mat24 (SS400)	SOLID
③	Upper concrete	Mat5 (SFRC)	SOLID
④	Bearing plate	Mat24 (SS400)	SOLID
⑤	Flat-spring	Mat24 (Sup9)	SOLID
⑥	Anchor bolt1	Mat24 (SS400)	SOLID+BEAM
⑦	Gasket	Mat24 (Sup9)	SOLID
⑧	Nut	Mat24 (SS400)	SOLID
⑨	Connection plate	Mat24 (SS400)	SOLID
⑩	Anchor bolt2	Mat24 (SS400)	SOLID+BEAM

Note: Mat5 and Mat24 are material type 5 and 24 of LS-DYNA, respectively.

In this study, SFRC is assumed to be an isotropic elastic-plastic material following the Drucker-Prager yielding criterion with material type 5 of LS-DYNA, and strain rate effect of concrete is not considered because it is known by calculations using user-subroutines that the results with and without strain rate effect of concrete are very approximate in this case. On the other hand, SS400 and SUP9 are assumed to be isotropic elastic-plastic materials following the von-Mises yielding criterion with material type 24 of LS-DYNA, considering the respective strain rate effect.

4. Results of numerical analysis

In the new code, the prescribed performances include: i) prevention of vehicle's derail, ii) guiding vehicles to road, iii) safety of occupants, and iv) prevention of spreading out the broken pieces. The performance i) (i.e. prevention of vehicle's derail) can be evaluated by the horizontal maximum displacement of the guard fence, and the performance ii) (i.e. guiding vehicles to road) can be evaluated by the behaviors of the collision truck. The performance iii) can be evaluated by the acceleration of centroids of the collision car. In this study the collision vehicle is not a car but a large truck, so the safety of occupants is not discussed in this study. It is difficult to evaluate the performance iv) quantitatively, so it is not discussed in this study either.

4.1 Collision conditions

There are 3 cases in the full-scale collision experiments for the FPC guard fence, in this study one of these experiments is analyzed, in which the collision vehicle is a large truck. The collision conditions of numerical analysis are shown in Fig. 8, which are set so as to be the same as those in the experiment. The truck weight is 20 t, the impact velocity is 90.4 km/h and the impact angle is 15.5 degree.

The performance of a guard fence is usually defined by the impact energy, which is a quantitative criterion to reflect the strength of the guard fence in the viewpoint of energy. The design impact energy can be defined as

$$Is = \frac{1}{2} \cdot m \cdot (\frac{V}{3.6} \cdot \sin\theta)^2 \tag{3}$$

where Is is the design impact energy, m is the quality of the impact vehicle, V is the impact velocity of the vehicle and θ is the impact angle. In the case of fore-mentioned condition, the design impact energy is 450 kJ.

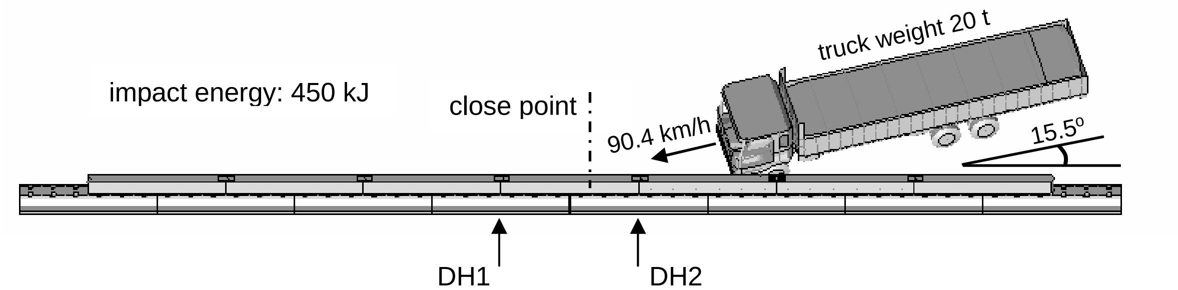
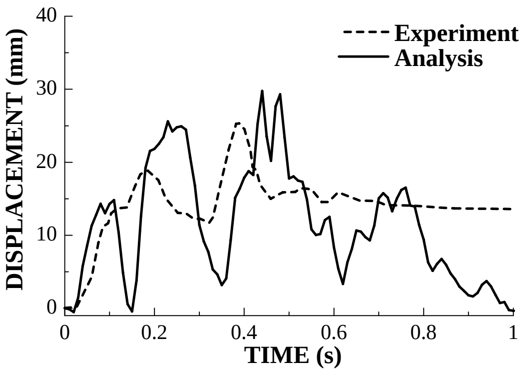


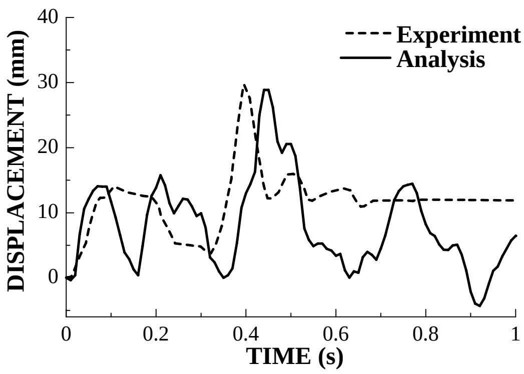
Figure 8. Collision conditions

4.2 Response displacement of guard fence

Figure 9 shows the time histories of the horizontal displacement of the top part of upper concrete in the monitor positions DH1 and DH2, which are around the close point (see Fig. 8), where the horizontal displacements were maximum in the experiment. As shown in Fig. 9, the peak displacements of the experiment and that of simulation appeared twice at the time of the primary collision (about 0.2 second) and the secondary collision (about 0.4 second). The peak displacements of the experiment and that of the simulation are almost in agreement in the position DH2, and the peak displacement of the simulation is 20% larger than that of the experiment in the position DH1. The time when the peak displacement occurred in the simulation delay a little comparing with the experimental result. However, it always can be said that the numerical simulation in this study is useful and effective to evaluate the maximum response displacement of the FPC guard fence.



(a) Response displacement of DH1

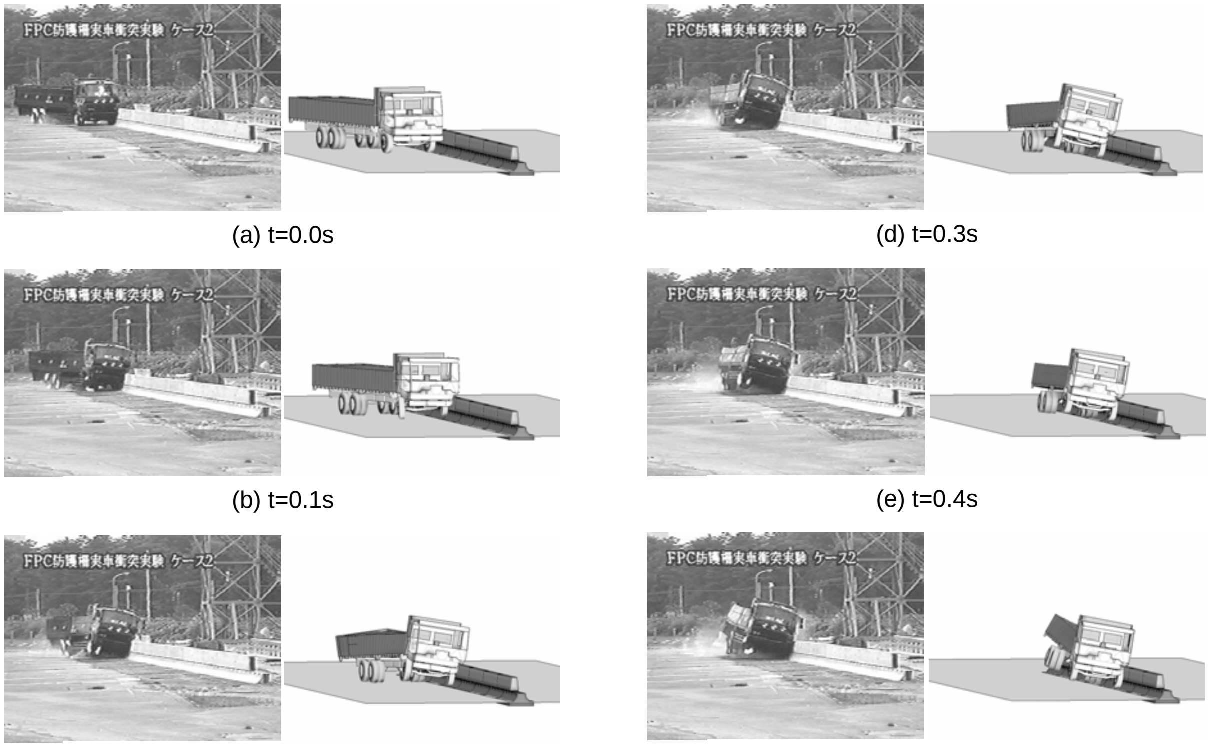


(b) Response displacement of DH2

Figure 9. Comparison of response displacement of the guard fence

4.3 Behaviors of collision truck

Firstly the photographs taken at the experiment are shown in the left-hand side, and the results of the simulation are shown in the right-hand side in Fig. 10. At first the left side of cabin of the truck collide with the upper concrete of the guard fence (primary collision). Then left front wheel run on to the under concrete of the guard fence, and the loading platform of the truck lean to the guard fence, and after about 0.4 second the loading platform collide with the upper concrete of the guard fence (secondary collision). After the secondary collision, the truck run along with the guard fence, and the gradient angle of the truck recovers gradually. As shown in Fig. 10, the behaviors of the collision truck obtained by the simulation agree well with the experimental result.



(a) t=0.0s (d) t=0.3s

(b) t=0.1s (e) t=0.4s

(c) t=0.2s (f) t=0.5s

Figure 10. Comparison of collision truck behavior
(left: experiment; right: analysis)

There are two quantitative criterions to evaluate the performance ii) (i.e. guiding vehicles to road) in the new code for the design of guard fences. One is that the breakaway velocity of the truck is over 60% of the impact velocity, and another is that the breakaway angle of the truck is under 60% of the impact angle. Table 5 shows the breakaway velocity and breakaway angle of simulation results and that of the experiment. The results of simulation and that of the experiment are in good agreement, and indicate that FPC guard fence possessed the performance for guiding vehicles to road.

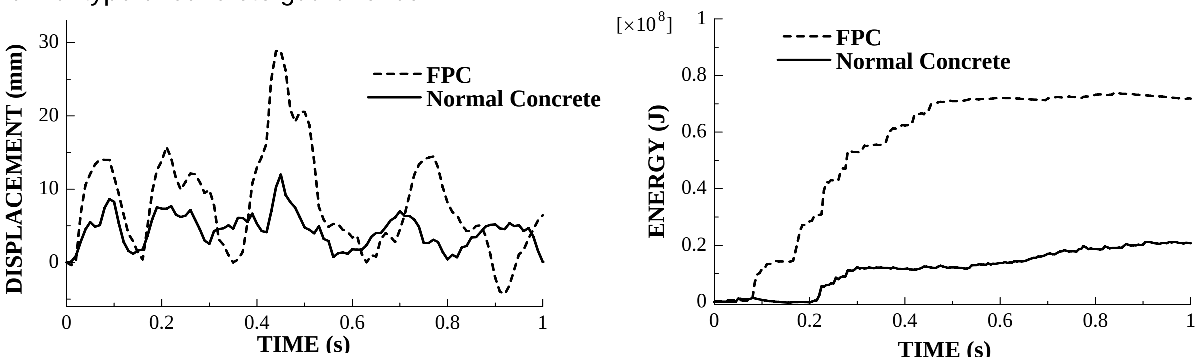
Table 5. Comparison of experiment and numerical analysis

	Velocity			Angle		
	Impact velocity (km/h)	Breakaway velocity (km/h)	Breakaway velocity (%)	Impact Angle (degree)	Breakaway angle (degree)	Breakaway angle (%)
Experiment	90.4	73.7	82	15.5	1.6	11
Analysis	90.4	77.3	86	15.5	1.4	9

As discussed above, the performance i) (i.e. prevention of vehicle's derail) is evaluated by the response displacement of the guard fence, and the performance ii) (i.e. guiding vehicles to road) is evaluated by behaviors of the collision truck. By these discussions the effectiveness for evaluating these performances of the FPC guard fence by numerical analysis results is validated. This approach of numerical analysis is therefore a useful tool for prediction and evaluation of the performances of the improved FPC guard fences in the future. For the evaluation of the performances iii) and iv) we will discuss in the intending researches.

5. Review of the FPC guard fence

As mentioned in the introduction the FPC guard fence is much different from the normal types of concrete guard fence in structure and performances, and FPC guard fence was designed to have a high deformation behavior and high adsorption capacity for impact energy. In order to verify the characteristics of the FPC guard fence, we also analyzed the normal type of concrete guard fence, and the FEM mesh of the concrete, boundary condition and the collision conditions was set to the same as the FPC guard fence, as shown in Fig. 8. The analytical results of the normal type of concrete guard fence are shown in Fig. 11, compared with that of the FPC guard fence, and it was verified that the FPC guard fence has higher deformation behavior and higher adsorption capacity for impact energy than the normal type of concrete guard fence.



(a) Response displacement

(b) Adsorption of impact energy

Figure 11. Comparison of the FPC guard fence and the normal type of concrete guard fence in analytical results

6. Conclusions

In this study, the numerical analysis was carried out for simulating the behaviors of both truck and the FPC guard fence due to the truck-to-fence collision. The following conclusions can be made.

(1) The stress-strain relationship and the strain rate effect of spring steel SUP9 used in the flat-springs of the FPC guard fence were obtained by the dynamic tension tests.
(2) The FPC guard fence was originally modeled, and the numerical analysis was carried out using the material parameters obtained from the tension tests.
(3) The analytical results were compared with the data of full-scale collision experiment, and the effectiveness for evaluating the performances of the FPC guard fence by the numerical analysis results was validated.
(4) The analytical results of the FPC guard fence were compared with that of the normal type of concrete guard fence, and the design concepts of the FPC guard fence were verified.

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