Study on performance of curved guard fences using numerical simulation

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Abstract

Although many traffic accidents occurred at curved roads, a full-scale field collision experiment of a curved guard fence has not been performed so far in Japan. The behavior of colliding vehicles and collided curved guard fences are not well known yet. In this study, some FEM models were developed to confirm the performance of curved guard fences through numerical collision analyses. Numerical analyses are carried out on the straight and the curved guard fences under the same collision conditions, because the results of two types of guard fences are compared. As results of numerical collision analyses, within the impact specified in the design code of guard fences in Japan, both straight and curved guard fences lead the truck safely. Comparing the results of two types of fences, the response displacement of curve guard fence is smaller than that of straight guard fence. It is clarified that curved guard fences lead a truck much safely as well as straight guard fences.

Key Words: curved guard fence, vehicle collision, numerical analysis, LS-DYNA

1. INTRODUCTION

Roads have much importance on human activities. Many traffic accidents have occurred recently as the number of cars in Japan has been increasing. It urgently must be to ensure safety of road.

Guard fences have responsibility on safety of occupants of vehicles. According to the design code of guard fences in Japan, guard fences are required to have the following four performances. 1) Prevention of detail, 2) Safety of occupant, 3) Guiding vehicles to road, 4) Prevention of spreading out the broken pieces. Guard fences that have better efficiency of absorbing a shock of vehicles' collision, safety of occupant, and guiding driver's eye are generally established. But the fatal accidents will be expected to occur, stiffer guard fences made of concrete are established to avoid breakthrough.

In regard to establishment of guard fences, administrators of roads finally make a decision which type of guard fences is adopted. The design code will need to say that cases of accidents must be considered when the guard fences are established, however, such a regulation is not prescribed in it. According to statistics of traffic in Japan, the number of collision with guard fences and central separation fences is over 9000 times a year and it occupies about 37.5% of total single collisions of vehicles. Cases of accidents must be reflected when the guard fences are established at where the accidents are frequently occurred. Then statistics of traffic in Japan also say that the number of traffic accidents at curved roads has reached over 50000 for last 4 years. Guard fences on curved roads (curved guard fences) are generally the same as guard fences on straight roads, however, beams of curved guard fences are bended to meet the radius of roads. According to the design code, if the radius of road is small, guard fences raised a degree can be established. But the field experiments of vehicle collision with curved guard fences have never been performed so far. The behaviors of both guard fences and vehicles need to be clarifying because the behaviors of those are not clarified.

However, the field experiments need a lot of costs and time and detailed inspection cannot be done. If the numerical analysis [4,5,6,7] can complete the field experiments, the performance of guard fences is easily checked and detailed inspection can be done easily too.

In this study, the performance of curved guard fence is verified by numerical analysis, and the behavior of both guard fence and vehicle will be clarified. The analytic results of curved guard fence are compared with those of straight guard fence to consider the problems of the present state of curved guard fences, if any.

2. FEM MODELS FOR NUMERICAL SIMULATION

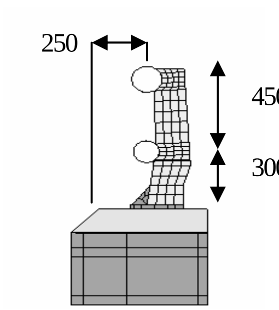
2.1 Guard fence model

Fig.1 shows the FEM models of the steel guard fences. The fence post is made of the H-shape steel whose web and flange are 135mm wide and 6 mm thick, and 125 mm wide and 4.5 mm thick, respectively. Both the main beam and sub-beam are of pipe sections. The pipe diameter and thickness of the main beam are 139.8 mm and 6 mm, respectively. The pipe diameter and thickness of the steel sub-beam are 114.3 mm and 4.5 mm, respectively. Both posts and beams are modeled as isotropic elastic plastic materials following the von Mises yielding criterion. When the analysis of collision is performed, strain hardening and strain rate effect must be considered for steel materials [6]. Stress-strain relationship depended on strain rate effect given from the results of kinetic tests for steel materials is inputted in these FEM models [4]. The base of guard fence is made of concrete curb which has some reinforcement steels. The boundary condition at this concrete curb is considered as a fix end. The posts are joined to concrete curbs by anchor bolts [4]. Both anchor bolts and anchor plates are modeled as elastic materials, and their Young's modulus are 206GPa.

The radius of curved guard fence models are determined by Table 1 that follows the Road Design Regulations in Japan [8]. The assuming collision speed toward this guard fence model is 50 km/h, so 100m of radius is selected from Table 1. The slope of 6% is considered in Table 1. Slopes at the curved road prevent cars from slipping to outside of the roads. Rigid wall is used as a floor in this model. Leaning the rigid wall in this model represents the slope of 6%.

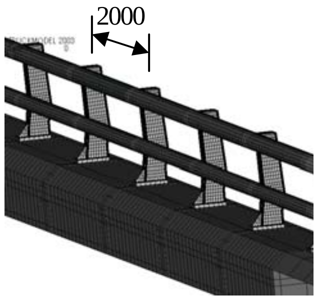
2.2 Truck model

Fig.2 shows the FEM model of a truck used in this study. This truck has been developed in our laboratory having the assistance of automobile engineers [4,5,6,7]. The based weight of truck model was made for 25tf trucks by modeling the truck frame, engine, driving room, cargo, tires and so on. The 14ft and 20tf truck models can be easily developed by modifying the weight of the cargo because the structures of 14ft and 20tf truck are similar to the 25tf truck except the strengthened frame and the loading capacity of the vehicle axles. The steel is assumed to be isotropic elastic plastic materials following the von Mises yielding criterion, and strain rate effect is considered in steel. Cowper & Symonds model representing Eq.(1) is used for steel of a truck [7].

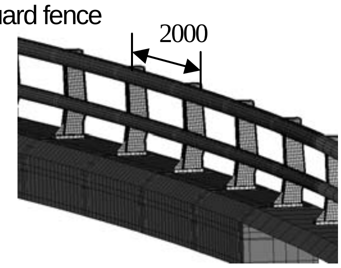


(a)Cross section of the guard fence

Unit：mm



(b) Straight guard fence model



(c) Curve guard fence model

Fig 1. FEM models of guard fence

Table 1 Radius of a curved road

Design speed (km/h)	Radius of a road (m)
100	460
80	280
60	150
50	100

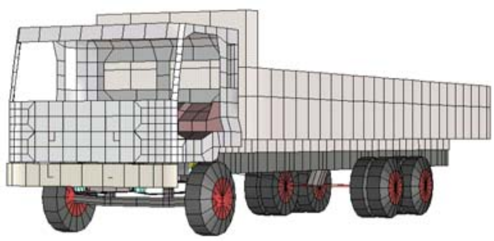


Fig. 2 The FEM model of a truck

$$\sigma_d / \sigma_s = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}} \tag{1}$$

where, σ_d :Kinetic stress (MPa),

σ_s :Static stress (MPa),

$\dot{\varepsilon}$:Strain rate(1/s), and

C, P : Parameters of strain rate.

2.3 Collision conditions

According to the design code of guard fences in Japan, the level of impact shown in Table 2 classifies the strength of guard fences. The level of impact means the index of kinematics energy in the vertical direction of guard fences. In this study, the collision condition is set to meet the level of impact of classification A. To compare the result of collision simulation for the straight guard fence with that for the curved guard fence, the same conditions shown in Table 3 are applied for two types of guard fences. In Table 3, A-s means the result of collision simulation for the straight guard fence, A-c means that for the curved guard fence, and following number shows the collision speed (km/h). The collision angle against the curved guard fence is an angle between a centerline of the truck and a tangent line at the cross point. Fig. 3 shows the FEM model of the collision simulation.

3. RESULTS OF COLLISION SIMULATIONS

3.1 Comparing the results of two types of guard fences

Fig.4 shows the maximum response displacements at the top of each post. The largest response displacement of straight guard fence is 57mm recorded at the Post-9, and that of the curved guard fence is 28mm recorded at the Post-6. The largest displacement of the straight guard fence is twice the measure of that of the curved guard fence. In the case of the curved guard fence, lots of posts were expected to deform because the truck was expected to push against the curved guard fence. However, the truck does not show such a behavior, and only a few posts deform. The truck moves along the curved guard fence, and the curved guard fence leads truck safer than the

Table 2 Classification of guard fences

Impact index(kJ)	Classification
over 45	C
over 60	B
over 130	A
over 160	SC
over 280	SB
over 420	SA
over 650	SS

Table 3 Collision conditions

	As-50	Ac-50
Collsion speed (km/h)	50	50
Collsion angle (deg)	20	20
Mass of vehicle (t)	14	14
Impact index (t)	158	158
Slope (%)	0	6

Table 4 Breakaway speed and angle

	As-50	Ac-50
Breakaway speed (km/h)	43.9	43.2
Breakaway angle (deg)	1	1.02

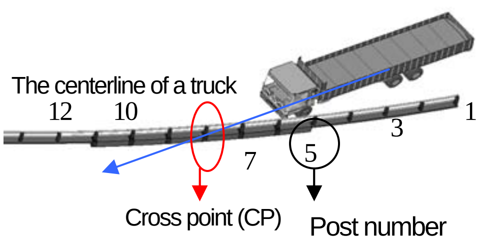


Fig.3 FEM model of collision simulation

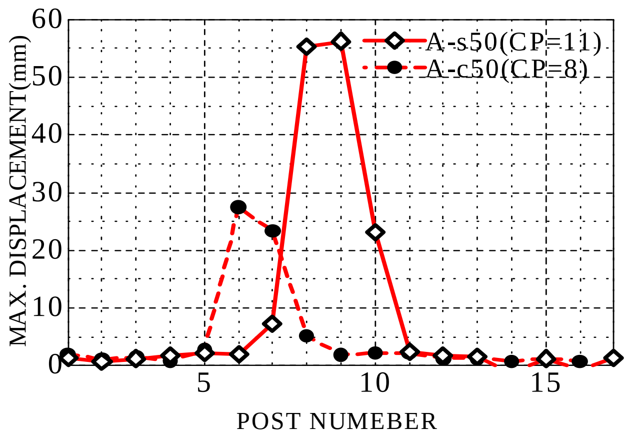


Fig.4 Comparing the maximum response displacement at the top of each post

straight guard fence.

Table 4 shows breakaway speeds and angles about both straight and curved guard fences. The design code of guard fence in Japan specifies that breakaway speed must be over the 60% of collision speed and breakaway angle must be within the 60% of collision angle. From Table 4, these results meet the regulations of the design code. Summarizing these results, making curved guard fences by bending beams of straight guard fences looks like to have no problems, and the present way of setting up the guard fences at the curved roads seem to be fully safe.

However, guard fences are given impacts within the classification of guard fences in these collision simulations. Considering the present state of traffic in Japan, a lot of vehicles seem to be speeding over the speed limit. These cars might be caused by big accidents. It needs to show whether guard fences lead vehicles speeding over the limit or not.

3.2 Considering the extra performance of guard fences

Collision simulations changing collision speeds are done to check the extra performance of both straight and curved guard fences. Table 5 shows the changed collision conditions that only collision speed is increased. Fig.5 shows the response displacement history of the post that records the largest displacement. In the case of 60km/h, the maximum response displacement of straight guard fence is 130mm, and that of curved guard fence is 99mm. In the case of 70km/h, the maximum response displacement of the straight guard fence reaches 322mm, and that of the curved guard fence reaches 215mm. The design code prescribes that the maximum permissible response displacement is 300mm, so the straight guard fence cannot lead the truck safely in the case of 70km/h. However, the curved guard seems to be able to stand larger level of impact. It is clarified that the curved guard fences lead the vehicles safer than the straight guard fences even when collision speed is increased.

Then the collided truck behaves differently comparing the straight guard fence with the curved guard fence. The second collision is occurred in the case of the straight guard fence given 60km/h of collision speed. The second collision means a collision caused by the rear of a truck after a collision caused by the front part of a truck. The rear wheel does not run up onto the concrete curb of the curved guard fence, so the collided truck does not behave such a thing in the case of 60km/h. This seems to be caused by the slope established under the curved guard fence.

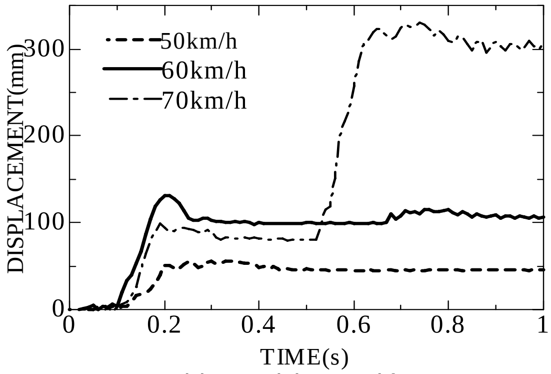
3.3 More detailed comparison between two types of guard fences

In regard to response displacements at the top of each post and behavior of the truck, the results of collision simulation for the curved guard fence are compared with those for the straight guard fence in 3.1 and 3.2. Other detailed data are compared between two types of fences in 3.3.

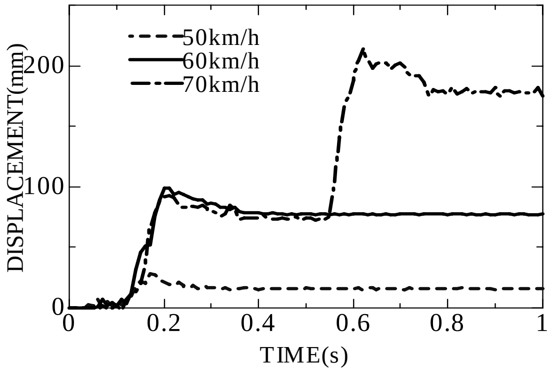
Fig 6 shows the response displacement histories of lower beams, which are collided under 50km/h of collision speed. In 3.1, the maximum response displacement at the top of the post of the straight guard fence is twice as large as that of the curved guard fence. However, there is little difference between the straight guard fence and the curved guard fence in Fig.6. This also seems to be caused by the slope established under the curved guard fence.

Table 5 Changed collision conditions

	As-60	Ac-60	As-70	Ac-70
Collsion speed (km/h)	60	60	70	70
Collsion angle (deg)	20	20	20	20
Mass of vehicle (t)	14	14	14	14
Impact index (t)	227	227	309	309
Slope (%)	0	6	0	6



(a) Straight guard fence



(b) Curved guard fence

Fig. 5 Response displacement history of the post that records the largest displacement

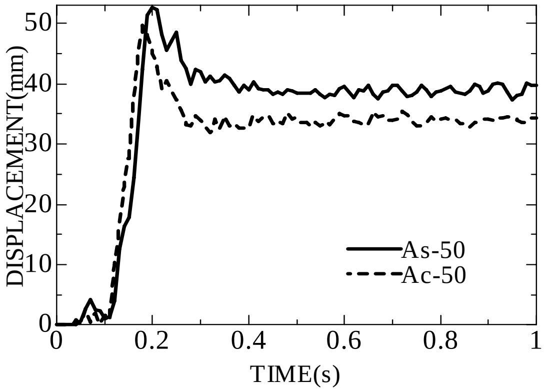
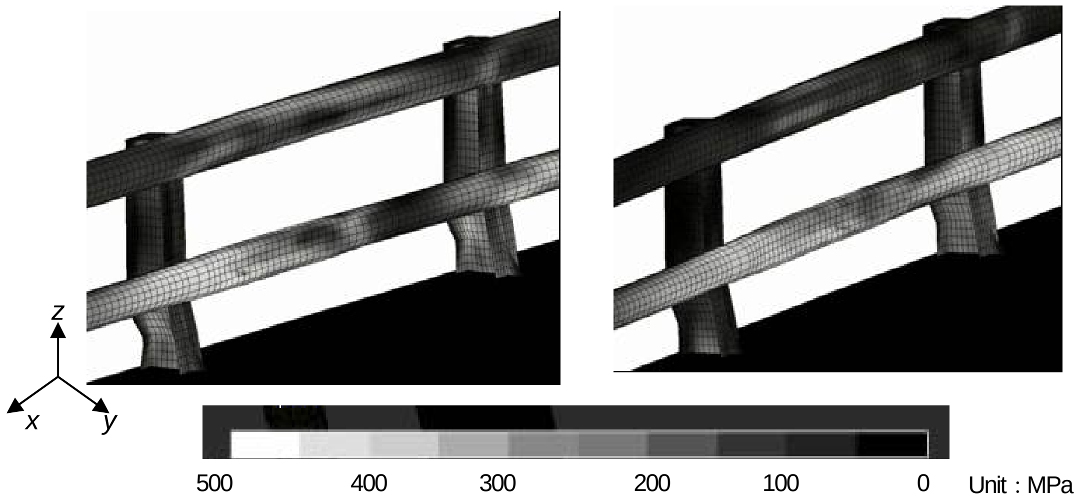


Fig. 6 History of response displacement of under beams



i) Straight guard fence ii) Curved guard fence

Fig. 7 Distribution of equivalent Mises stress after 0.25s passed since collision

The stress distribution shown in Fig.7 tells such a thing as well. Fig.7 shows the distribution of equivalent Mises stress after 0.25s passed since collision, and it is computed by Eq. (2).

$$\sigma = \frac{1}{\sqrt{2}}\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} \quad (2)$$

where, σ_{eq} : Equivalent Mises tensile stress,
σ_X : Stress for X axis,
σ_Y : Stress for Y axis,
σ_Z : Stress for Z axis,
τ_{XY} : Sheering stress for XY direction,
τ_{YZ} : Sheering stress for YZ direction, and
τ_{ZX} : Sheering stress for ZX direction.

From Fig.7, stress acted to the curved guard fence mainly concentrates on the lower beam compared with the straight guard fence. Caused by the slope, the truck collides the curved guard fence as the body of truck is leaned. It means that influence of collision with curved guard fence mainly appears to the lower beam. However the response displacement of the lower beam of the curved guard fence largely differ from that of the straight guard fence, if the collision speed is increased. As the collision speed is increasing, the slope less influence the behavior of the guard fence.

Fig.8 shows the history of collision impact load toward posts in the vertical direction of the guard fence. The result of strongly deformed three posts under 50km/h of collision speed is shown in Fig.8. In these figures, yield load is computed by the following Eq. (3) for reference. Eq. (3) assumed that the joining point to upper beam is concentrically loaded.

$$P_y = \frac{2\sigma_y I_z}{dL} \tag{3}$$

where, P_y : Yield load (kN),

σ_y : Yield stress（MPa）,

I_z : Moment of inertia (mm^4),

d : Width of web (mm), and

L : Distance from the basin of post to the joining point to upper beam (mm).

Then load coming to appear strain hardening is obtained from Eq.(5). Eq.(4) written in [10] calculates bending moment of rectangular section when strain hardening comes to appear. The right side of Eq.(4) can approximate 1.5.

$$\frac{M_{st}}{M_y} = \frac{3}{2} - \frac{1}{2(\phi_{st}/\phi_y)^2} + \frac{E_{st}}{E}\left[\frac{\phi_{st}}{\phi_y} - \frac{3\varepsilon_{st}}{2\varepsilon_y} + \frac{(\varepsilon_{st}/\varepsilon_y)^3}{2(\phi_{st}/\phi_y)^2}\right] \tag{4}$$

$$P_{st} = \frac{M_{st}}{L} \tag{5}$$

where, M_{st} : Bending moment of rectangular section when strain hardening comes to appear,

M_y : Yield bending moment,

Φ_{st} : Curvature when strain hardening comes to appear,

Φ_y : Yield curvature,

E_{st} : Modules of initial strain hardening,

E : Young's modules,

ε_{st} : Strain when strain hardening comes to appear,

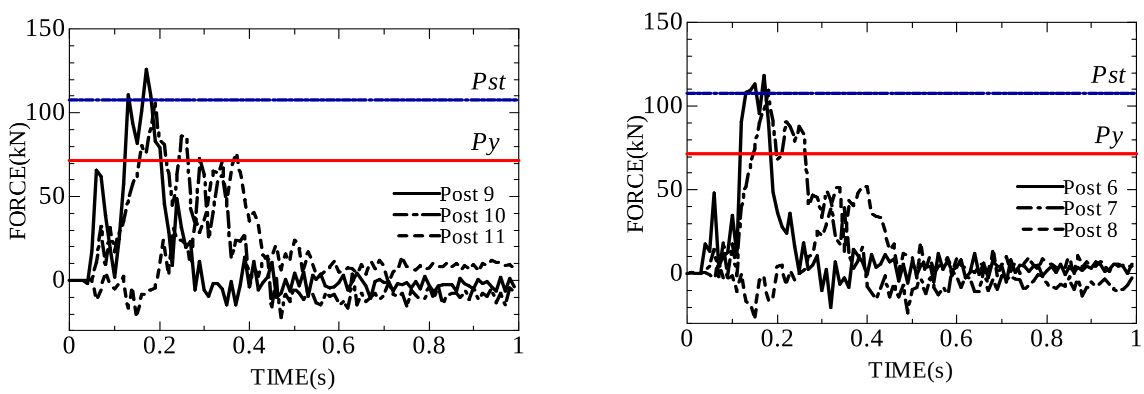
ε_y : Yield strain,

P_{st} : Load when strain hardening comes to appear, and

L : Distance from the basin of post to the joining point to upper beam.

The largest response displacement is generated at the Post-9 of the straight guard fence and the Post-6 of the curved guard fence. Comparing the collision impact load between these posts, the maximum load of the Post-9 is about 10kN larger than that of the Post-6. The difference of the collision impact load between these two posts is relatively smaller than the difference of the response displacement. This seems to be caused that the section of the post fully enters the state of plastic.

The maximum loads of the Post-9 of straight guard fence and the Post-6 of the curved guard fence are instantaneously about 10kN beyond the load when strain hardening comes to appear. Eq. (4) and Eq. (5) are equations that assume force of a post statically loaded, and they do not consider strain rate effect. So the plots of P_{st} may rise in the case that strain rate effect is considered and the maximum forces are expected to be almost equal to P_{st}. Considering that the maximum response displacement of the Post-9 of the straight guard fence is twice as large as that of the Post-6 of the curved guard fence, however the difference of the maximum collision impact load is much small, the section of the Post-9 may fully become plastic and enter the state of strain hardening. Fig.8 shows the result of guard fences collided within the impact index prescribed in the design code. In this case, it



(a) Straight guard fence (b) Curved guard fence

Fig.8 History of collision impact load (Collision speed with 50km/h) is thought that the materials of guard fences may reach the stage of strain hardening. However, in the case of collision with the level of impact exceeding the impact index of the guard fence, the materials of guard fences probably reach the stage of strain hardening.

From these results, curved guard fences satisfy the regulated performance prescribed in the design code of guard fences in Japan within the impact specified in the code or twice impact specified in that. Then curved guard fences lead a truck much safely compared with straight guard fences. It is clarified that when a truck collides with a guard fence at curved road whose radius is specified in regulations of roads, a guard fence leads a truck safely. But some fatal accidents by trucks seem to occur at the curved road. These cases are expected to occur at the exceptional sharp bended road. Drivers are required to operate a steering wheel complicatedly at the sharp bended road. So the collision angle is expected to be much larger in the case that a vehicle collides with a guard fence at the sharp bended road. In future, behaviors of both a curved guard fence at sharp bended road and a colliding truck should be clarified.

4. CONCLUSUIONS

The following conclusions can be stated from these researches.

1) Within the impact specified in the design code of guard fences in Japan, it is shown that curved guard fences satisfy the regulated performance and they lead a truck safely using numerical collision analysis.
2) There must be that the curved guard fence leads a truck safely compared with the straight guard fence.
3) Within the twice impact, it is clarified that the curved guard fences satisfy the regulated performance and they lead a truck safely using numerical collision analysis.

Reference

[1] Japan Road Association: The Specifications of Guard Fence Design, Maruzen Press, 1999 (in Japanese).

[2] Japan Traffic Accidents Analysis Association: Statistics of Traffic in Japan, 2000-2003 (In Japanese).

[3] Public Works Research Institute: A Study on the Steel Guard Fences, Research Report No.74, Tsukuba, 1992 (in Japanese).

[4] Itoh, Y., Liu, B., Usami, K. and Kusama, R.: A Study on the Strain Rate Effect and the Performance of Steel Guard Fences, Journal of Civil Engineering, No.759/I-67, pp.337-353, 2004 (in Japanese).

[5] Itoh, Y., Liu C. and Usami K.: Nonlinear Collision Analysis Of Vehicles Onto Bridge Guard Fences, The Seventh East Asia-Pacific Conference on Structural Engineering & Construction, pp.531-536, 1999.

[6] Itoh, Y., Mori, M. and Suzuki, S.：Study on Behavior of Bridge Guard Fences Subjected to Vehicle Collision Using Numerical Analysis, Journal of Structure, No.45A, pp.1635-1643, 1999 (in Japanese).

[7] Liu, B., and Itoh, Y.: Numerical Analysis on Vehicle Collision to Flexible Precast Concrete Guard Fence, 5th Asia-Pacific Conference on SHOCK & IMPACT LOADS ON STRUCTURE, pp.265-272, 2003.

[8] Japan Road Association: Explanation and Application of Regulations on Roads, 2004 (In Japanese).

[9] Public Works Research Institute：A Report on Forms of Guard Fences at Sharpe Bended Roads and Reinforcement for Posts, 1992 (In Japanese).

[10] Fukumoto, Y., and Nishino, F.: Materials of Steel Structure and Frame Strength and Design, Maruzen, pp116-120, 1972 (In Japanese).

[11] NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features: National cooperative highway research program, NATIONAL ACADEMY PRESS,1993.

[12] Wekezer J.W., Oskard M.S., Logan R.W. and Zywicz E.: Vehicle impact simulation, Journal of transportation engineering, Vol.119, No.4, pp.598-617, 1993.