「材料」(Journal of the Society of Materials Science, Japan), Vol. 62, No. 10, pp. 607-614, Oct. 2013
Original Papers

Performance of New-Type Curved Steel Bridge Railings Subjected to Heavy Truck Collisions†

by

Le Thanh*, Yoshito Itoh**, Seiji Itoh*** and Osamu Takadoh****

Japanese specifications for railing design have introduced two new improvements in functions for railings since 2004. The first is to require a landscape-friendly appearance and the other is to take account of flow in the road user's view from bridges. The concern with these functions has led to changes in design with requirements for more slender forms of railing beams and posts. Current Japanese specifications for railing design are concerned only with straight railings. Some researchers and engineers suspect that curved railings are more dangerous. The purpose of this research is accordingly to contribute to the development of two new types of curved bridge steel railings satisfying the new functional requirements and also to verify the above suspicion. A full-scale test is the ideal methodology for this study but this test involves a considerable cost and effort. Thus a combination between partial experimental tests for the new types of posts and numerical analyses is relied on here to study the performance of the new-type steel curved bridge railings. The procedures followed are : (1) to study performances of new posts experimentally under static and collision conditions ; (2) to develop numerical analyses to study performances of straight railings ; and (3) to apply these analyses to instances of new-type posts in curved railings in order to obtain a comparison with straight ones. The LS-DYNA 3D is engine software used for the numerical analysis. Based on the results of the study, a design recommendation is proposed for new-type curved steel railings.

Key words : *Dynamic numerical analysis, Impact collision, Steel curved bridge railings, LS-DYNA 3D, Finite element model*

1 Introduction

Railings are safety installations along road sections and bridges, and can be classified into rigid and flexible types on the basic of their material properties. Rigid railings are made of concrete and flexible ones of a steel or aluminum alloy. Flexible railings have a higher capacity to absorb collision energy, and can be expected to undergo a larger deformation. For this reason, flexible railings are used on most highways and highway bridges. As in other countries,[1] Japanese specifications[2)~4)] involve four safety performance standards for railings : (1) to prevent vehicles from leaving the road ; (2) to protect occupants; (3) to guide vehicles back to the line of the road; and (4) to prevent penetration of the railing. Since 2004, Japanese specifications[3] have also been improved by introducing two new functions for consideration. One is a landscape-friendly appearance and the other is the continuity of flow in the road user's view from a bridge. The latest specifications[4] issued in 2008 prescribe an experimental method for the determining of grades and forms of railing.

Many varieties of steel railings have been used on roads and bridges around the world and an extensive research literature exists for describing impact collisions between vehicles and railings. Performances of a compact car crashed into a luminaire pole have been verified using a finite element model.[5] Cases of a roadside crash cushion subjected to a vehicle collision have been investigated through a comparison of numerical and experimental results.[6] Performances of an aluminum bridge railing have been tested at collision levels three and four.[7] Those of steel railings subjected to a collision with a heavy truck have been examined with the use of finite element models.[8)~10)] Types of bridge railings satisfying the new Japanese function specifications of 2004 have successfully been developed for use on the straight road sections and bridges.[11] Finally, a full-scale test examining the performances of straight steel railings has been carried out by the Japanese Public Works Research Institute.[12]

The number of accidents on road sections and bridges with curves exceeded 50,000 over a 4-year period from 2000.[13] However, performances of curved road and bridge railings studied from a full-scale test have not been performed in Japan. One investigation has been made by means of numerical analysis for the case of curved railing of 100 m curve radius subjected to truck collisions under a range of different conditions.[14] The current Japanese specifications for railing design have only references to the design of straight railings and some researchers and engineers suspect that curved railings are more dangerous than straight ones. It is certainly also the case that the addition of new functions to the 2004 specifications have led to changes in design requirements with

† Received Jan. 8, 2013
* Dept. of Civil Engineering, Nagoya Univ., Chikusa-ku, Nagoya 464-8603 Japan.
** Member : Dept. of Civil Engineering, Nagoya Univ., Chikusa-ku, Nagoya 464-8603 Japan
*** Dept. of Civil Engineering, Nagoya Univ., Chikusa-ku, Nagoya 464-8603 Japan
**** Seminer Engineering Corporation, Tokyo 136-0071 Japan

smaller and slender forms for railing beams and posts. The purpose of this research is therefore to contribute to the development of two new types of curved railings satisfying the changed functional requirements of Japanese specifications and at the same time to verify the above suspicion.

A full-scale test would be the ideal method for the purposes of this study, but would require a considerable outlay of cost and effort. Nowadays, in any case, computer software is powerful enough to simulate collision problems with a full set of properties and boundary conditions.[5), 6)] Accordingly, the main method for this research will be numerical analysis supported by some partial experimental tests conducted on posts. The procedure followed will be : (1) to study the performances of new posts by means of static tests and experimental tests involving collisions ; (2) to develop numerical analyses for the study of performances in the case of straight railings; and (3) to apply these analyses to the case of the same sort of new posts used with curved railings in order to compare the resulting conditions and performances with those occurring with straight ones.

The railings investigated in the study are of grade A, suitable for an impact angle of up to 15°, a truck weight of up to 25 t (245 kN) and a truck speed of up to 45 km/h. This railing grade was first introduced for straight railings. To verify whether, as suspected, curved railings are more dangerous, the same grade properties and collision conditions are applied to curved railings having a curve radius of 100 m. The solutions obtained are then compared with the solutions for straight railings and with those obtained from previously existing curved railing designed before 2004 and installed on a bridge in Hokkaido, Japan. In some cases of human problems, the speed of a vehicle may exceed what is allowable on that stretch of road. Accordingly, the ultimate state of the railings is also investigated for higher vehicle speeds.

The numerical research is conducted using the software engine LS-DYNA 3D and the collision problems are solved on the Nagoya University supercomputer which has a maximum speed of 60 TFLOPS. The numerical results for displacements, energy responses and truck behaviors are then taken as basic input for the development of new types of steel railing for curved bridges. The results of the analyses are presented in chapters 2, 3 and 4. A conclusion and remarks are provided in the last chapter.

2 New types of railing post

2.1 Feature of posts

Two newly developed types of steel post are used for the performance investigation undertaken in the study. These new types have the designed names M and R. An earlier existing type N designed for use on a bridge in Hokkaido in 2004, is used as a comparison reference. The two new types have previously been presented by Itoh et al.[11)] and their shapes and dimensions are shown in Figure 1. In accordance with the Japanese specifications,[3)] the new posts have a more slender design than previous types. The main difference between the two new types is that type M has a narrow section in the lower part and in the vicinity of the tension flange.

2.2 Experimental tests of post subjected to a static load

The maximum displacement permitted in the railing by the Japanese specifications is 300 mm. In the tests, therefore, the top part of the post needs to be subjected to a static force sufficient to cause 300 mm of horizontal displacement. The initial shape and section of the post are selected from an equivalent structural model represented as having an ultimate load Pw.[11)] The static load - displacement relationships for the two types of post are shown in Figure 2. The maximum loads of 33.5 kN for M and 35.6 kN for R are larger than the ultimate loads obtained for the equivalent model posts of 29.5 kN for M and 32.3 kN for R. The loads acting posts M and R decrease so as to become smaller than the ultimate loads once the displacement reaches a value of around 200 mm. By the requirements of the Japanese specifications and in accordance with the expectations for post design, the post types M and R are appropriate for use in a study aiming to achieve advances in collision analysis.

2.3 Dynamic tests of posts subjected to a heavy steel ball

Figure 3 presents the overview of a collision test for a post subjected to the impact of a steel ball with 475 kg of mass. The ball is lifted to a specified height using a steel frame. The kinetic energy of the collision will depend on the height of the ball above the top of the post, and is calculated to cause 300 mm of displacement in the post. The collision load is referred from static load. The simulated collision tests, on the other hand, are performed on a finite element model using LS-DYNA 3D software.

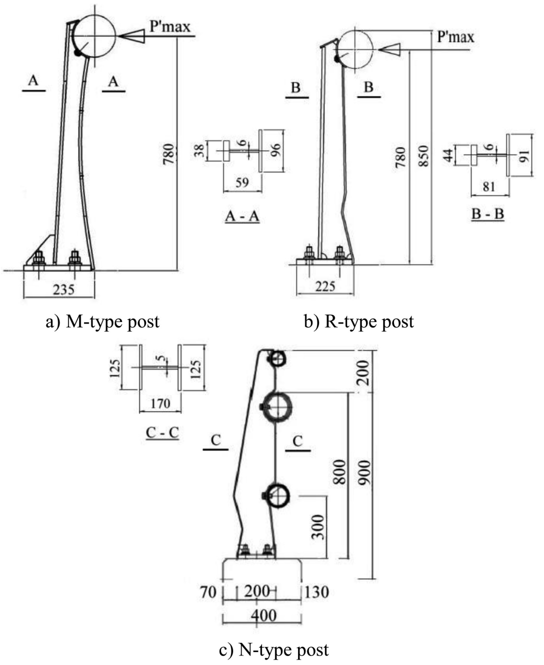
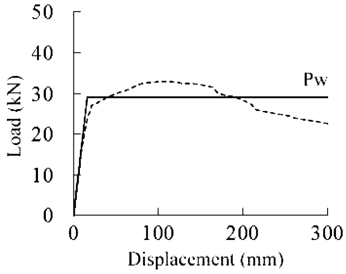
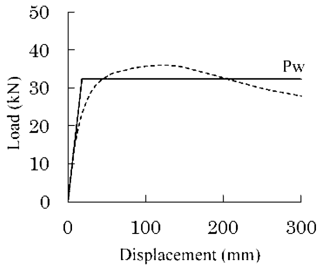


Fig. 1 Features of railing posts. (Unit : mm)



a) M-type post



b) R-type post

Fig. 2 Static load-displacement relationship of posts.

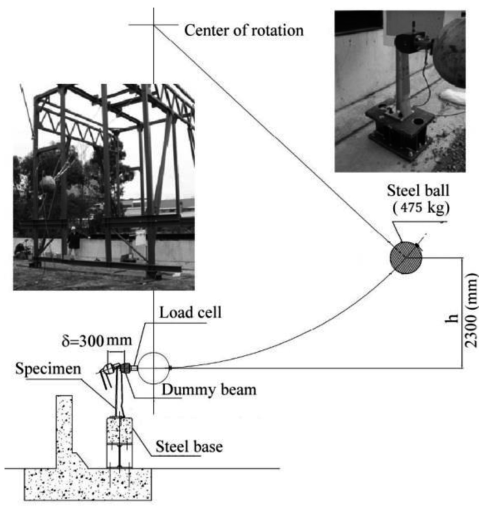
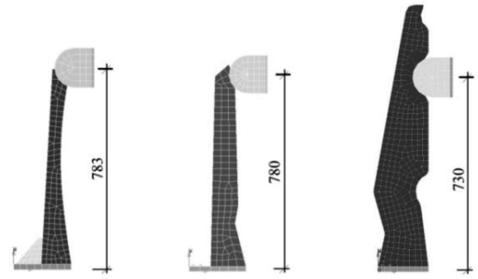


Fig. 3 Collision test for posts using a heavy steel ball.

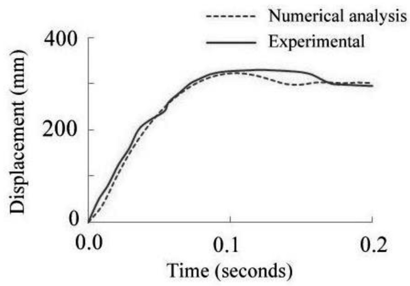
The finite element models of the new and existing posts are presented in Figure 4. The post flanges and web are modeled as four-node shell element. The M-type post has a tension flange 9 mm thick, a compression flange 38 mm in width and 9 mm thick and a web 6 mm thick. With the R-type post, the tension flange is 6 mm thick, the compression flange 44 mm wide and 12 mm thick and the web 6 mm thick. With the previously existing N-type, the tension and compression flanges are 125 mm wide and 6 mm thick, and the web thickness is 5 mm. The steel in the post is modeled as an isotropic elasto-plastic material following von Mises yielding critition. The ball is modeled using a solid element, and is considered to move in a horizontal direction.

The experimental and numerical results for the three kinds of posts subjected to impacts from the heavy steel ball are shown in Figure 5. It can be seen that the numerical behaviors of an M-type post are similar to the experimental ones. Displacement is largest with the M-type of post, and smallest with the N-type. This is because, with the new types of post being designed more slender than the previous one, their material quantity is also smaller, with the result that they can absorb less energy. Figure 6 shows the state of failure of posts with clear signs of lateral torsional buckling at the compression flanges. From the comparison of the numerical and experimental results, it can be found that the performances of the new types of post subjected to heavy ball collision loads meet the requirements of the Japanese specifications, and can be studied by numerical analysis. In other words, these new types can be used to study railing performance, and finite element models of the sort employed here can be used to create viable simulations of collisions between truck and railing.

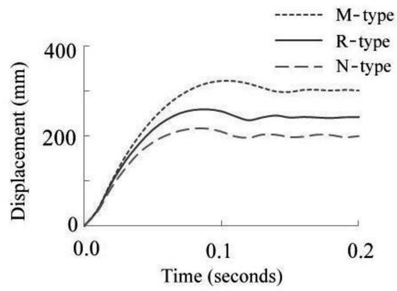


a) M-type post b) R-type post c) N-type post

Fig. 4 Finite element models of posts subjected to collisions from ball. (Unit : mm)



a) Experimental and numerical displacement results for M-type



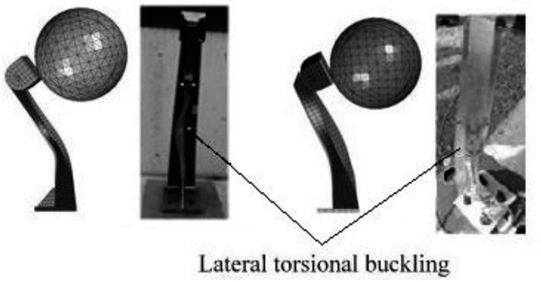
b) Displacement results for M-type, R-type and N-type

Fig. 5 Results of subjecting posts to heavy steel heavy ball collision.

3 Verification of the impact collision model

3.1 Introduction

A series of full-scale tests of impact collisions between trucks and straight steel railings has previously been performed by the Japanese Public Works Research Institute.[12] The railings were of the grade SB, and were subjected to collisions with a truck of weight 25 t (245 kN) and speed



a) M-type post b) R-type post

Fig. 6 Failures of posts subjected to heavy steel ball collisions.

80 km/h at an impact angle of 15°. For comparison, tests involving the same conditions are investigated here by numerical analysis using the LS-DYNA 3D software. From the initial comparisons between the numerical and experimental results, the performances of the railings and the behaviors of the trucks are determined, and the methods and assumed properties of the simulation are then improved as necessary and finally reapplied to analyses of impact collisions between trucks and new-type steel railing on curved bridges.

3.2 Finite element models of railing

The finite element model of the railing is shown in Figure 7. Four-node shell elements are used to model the posts and beams. The posts have an H-shaped cross-section with a flange 150 mm wide and 9 mm thick and a web 158 mm wide and 6 mm thick. The diameter and thickness of the main beam are 160 mm and 7 mm, and those of the sub-beam 135 mm and 4 mm, respectively. The steel of the posts and beams is modeled as an isotropic elasto-plastic material following von Mises yielding criterion. The concrete curb is modeled using eight-node solid elements. The typical elasto-plastic material assumed in the model is concrete with a Young's modulus of 24.4 GPa. The curb is considered as end-fixed

3.3 Finite element model of truck

The finite element model of the truck is one developed in Nagoya University with support from a truck manufacturer, as shown in Figure 8. It is a model that has already been used in previous researches.[8)~11)] The geometry and dimensions of the truck are simulated to match those of an actual truck. The body frames, driving cab, side members, fuel tank, and pipelines are modeled as four-node shell elements. Other members such as the engine, transmission and freight load are modeled as eight-node solid elements. The truck is simulated to travel on a road surface having a 6 percent slope.

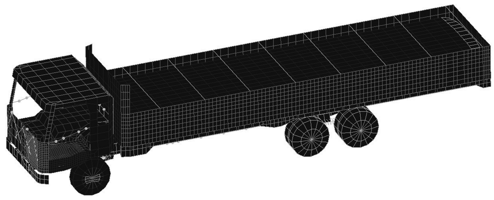


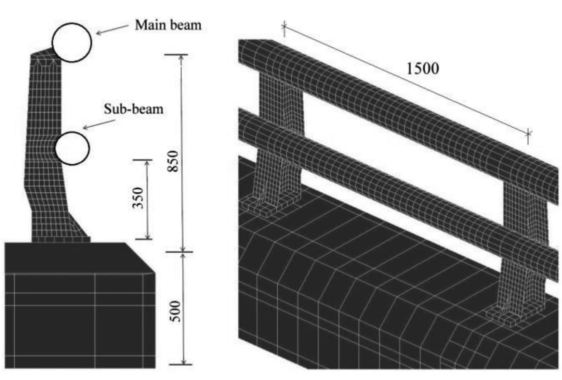
Fig. 8 Finite element model of truck.

An isotropic elasto-plastic material following von Mises yielding criterion is assumed for the steel of the truck, with a Young's modulus of 206 GPa, a Poisson's ratio of 0.3 and a yield stress of 295 MPa. The truck is 11,800 mm long, 3,300 mm high and 2,500 mm wide and its center of gravity is at a height of 1400 mm. The total numbers of elements and nodes in the truck model is 9,344 and 9,830, respectively.

3.4 Verification of numerical analysis

Two densities of element mesh are adopted in the present study, as shown in the 4-4-8 and 8-8-35 models diagrams in Figure 7b). The numbers of mesh elements in the post flange and web on the horizontal grid is indicated by the first and second figures, respectively. The number of elements along the beam spans is indicated by the third figure. The 8-8-35 mesh density is used for the beams and posts closest to the collision area. The other beams and posts along the railing in either direction are applied the 4-4-8 mesh density.

The displacement considered the effect of the mesh size is shown in Figure 9 in which the numerical results are compared with the experimental ones. Both the numerical and experimental paths of displacement indicate that there are two stages to the collision impact. The first stage occurs when the front bumper of the truck crashes into the railing, and this is followed by a second



a) Cross-section b) Railing assemblage

Fig. 7 Finite element models of railing. (Unit : mm)

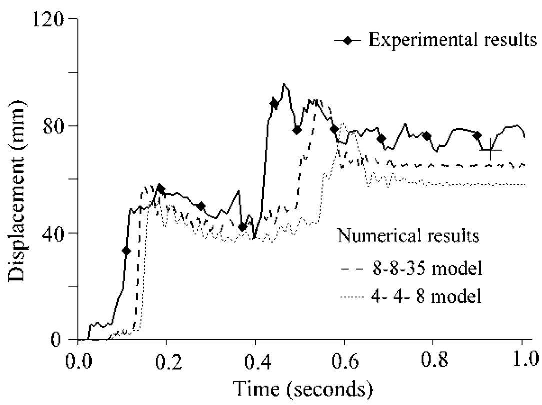


Fig. 9 Effect of element mesh size on numerical results.

stage in which the rear part of the truck body hits the railing. From Figure 9, it can be seen that the displacement shown by the 8-8-35 model comes closer to the experimental result and for that reason this is the element mesh size adopted in this study.

The effect of the strain rate of the steel on the railing displacement is also investigated in the numerical analysis. The strain hardening starts from 0.0014 and an initial strain hardening modulus is 4.01 GPa (2% of the Young's modulus). The stress-strain relationship calculated for the steel is recommended by Itoh et al..[15] Figure 10 shows the calculated displacements in cases where the strain rate effect is or is not taken into account. It can be seen that the calculated results for both the maximum and the residual amounts of displacements come closer to the experimental results when the strain rate is considered. Comparing these numerical and experimental results, therefore, it appears that the performance of new-type steel bridge railings subjected to a truck collision can be studied by numerical analysis using the LS-DYNA 3D software. In this case involving the analysis of curved steel railings, the 8-8-35 element mesh density is the better one to adopt and the strain rate effect of the steel is taken into account.

4 Performances of new-type curved steel railings

4.1 Introduction

This chapter concerns the development of impact simulations for curved steel railings subjected to truck collision loads. The three types of railing investigated will be denoted as M, R or N, according to the type of post used in each case. To verify the suspicion that curved railings may be more dangerous than straight ones, the same dimensions and material grade as well as the same collision conditions will be applied to cases of curved railings. The Japanese specifications[16] describes that the minimum curve radius permitted for a curved road section or bridges assuming a truck speed of 45 km/h is 100 m. Accordingly, 100 m is the curve radius assumed for the railing in the present analysis. The results obtained for the new-type curved railings are compared with results for straight and previously existing railings with respect to their performances under the impact of a truck collision.

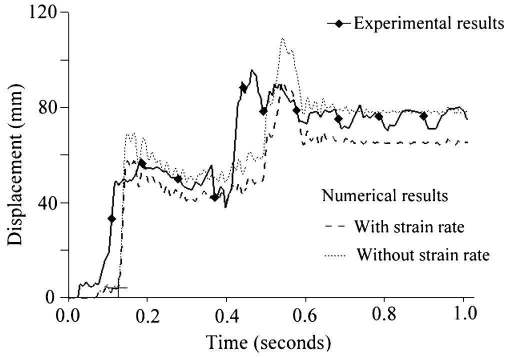


Fig. 10 Effect of steel strain rate on railing displacement.

4.2 Finite element model

The finite element model of railings is presented in Figure 11. The railings are built up from beams and posts, and for the posts the models proposed in the previous chapter are adopted. In both new railing types, the top beam is a pipe of diameter 140 mm, and thickness 6.6 mm. There are two other beams as the middle and bottom beams, which have the same pipe diameter 89 mm and thickness 2.8 mm. For the N-type railing, the pipe diameters for the top, middle and bottom beam are 76 mm, 140 mm and 114 mm, and their thickness are 2.8 mm, 4.5 mm and 3.5 mm, respectively.

The railing posts and beams are modeled as four-node shell elements. The model material for the beams and posts is an isotropic elasto-plastic material following von Mises yielding criterion, with a Young's modulus is 206 GPa and a yield stress is 408 MPa. The concrete curb is created as an eight-node solid element, made of a typical elasto-plastic material having a Young's modulus of 24.4 GPa. The same truck simulation as in chapter 3 is again adopted for this analysis. Figure 12 shows typical simulations of impact collisions for cases of straight and curved railings.

4.3 Displacement response

The railings are subjected to a collision with a truck weight of up to 25 t (245 kN) traveling at a speed of up to 45 km/h, at an impact angle of 15°. The truck crashes into the railing beams at a point between posts 8 and 9.

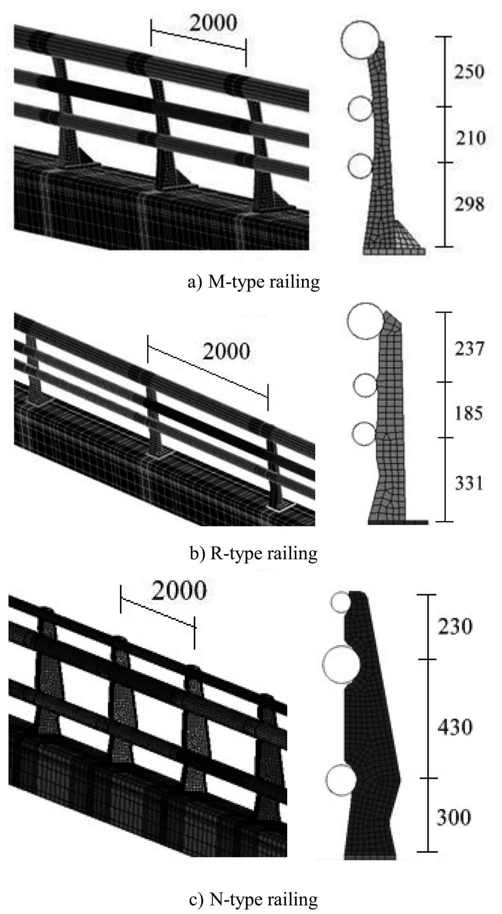
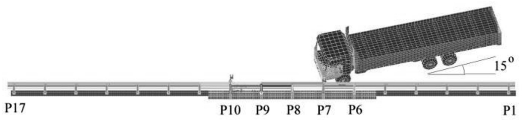
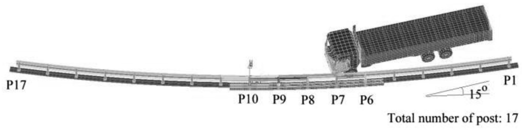


Fig. 11 Finite element models of railings. (Unit : mm)



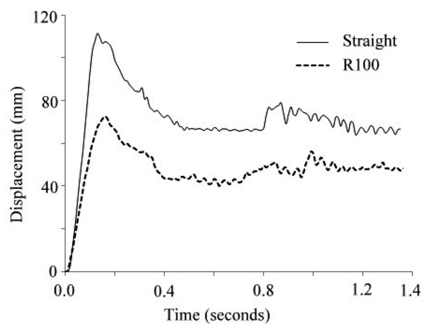
a) Straight railings



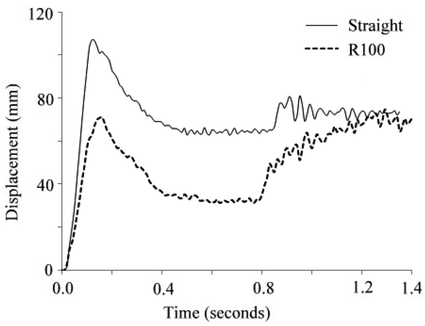
b) Curved railings

Fig. 12 3D simulations of impact collisions.

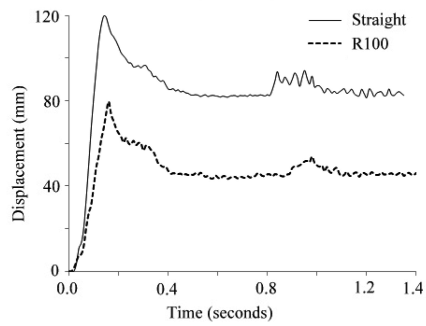
Figure 13 shows the displacement-time histories for both straight and curved railings of types M, R and N. Similarly to the collision problem presented in chapter 3, there are two stages to the collision impact for all types of railings. For a curved railing of type R, the second stage begins at time point 0.8 s when the rear end of the truck body hits the railing and then leaves the railing after time point 1.24 s. Thus there is an increase in the railing displacement between the beginning and end of the second collision stage. The behavior for the curved railings is similar to that for the straight ones. The residual displacements of the M and R-type railings are shown in Figure 14. The results here satisfy the requirements of Japanese specifications for railing design, in the case of both the straight and the curved railings. In each case the displacement is smaller with the curved railing than with the straight ones.



a) M-type railing



b) R-type railing



c) N-type railing

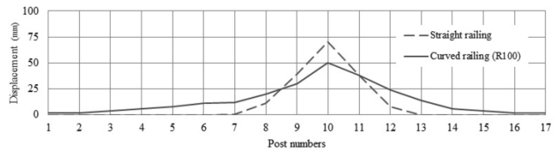
Fig. 13 Displacement-time history of railing posts.

4.4 Energy response

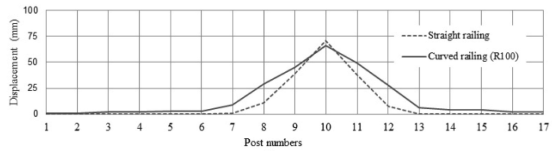
A part of the truck's kinetic energy gets absorbed by the railing. Figure 15 shows the impact energy of the collision from the truck in the M and N types of railing. Most of the energy transferred from the truck is absorbed by the beams and posts. An insignificant part is transferred to other members such as the steel plates, the bolts and the concrete curb. Figure 15 shows that the amount of energy absorbed is larger in the case of the straight railing. This has to do with the greater amount of displacement. Because, the posts and beams undergo the most displacement, they naturally also consume the most energy.

4.5 Truck behavior

According to the Japanese specifications for railing design,[3), 4)] the speed of a vehicle and the impact angle after the point of impact are required to be over 60 per-

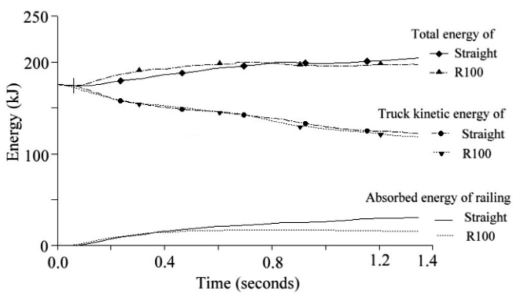


a) M-type railing

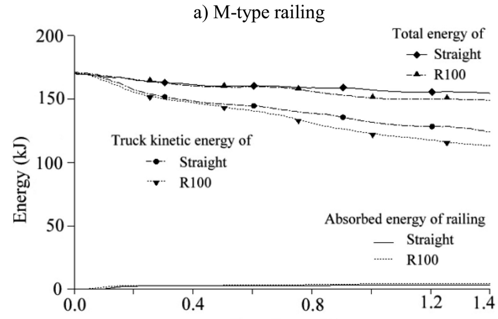


b) R-type railing

Fig. 14 Residual displacement.

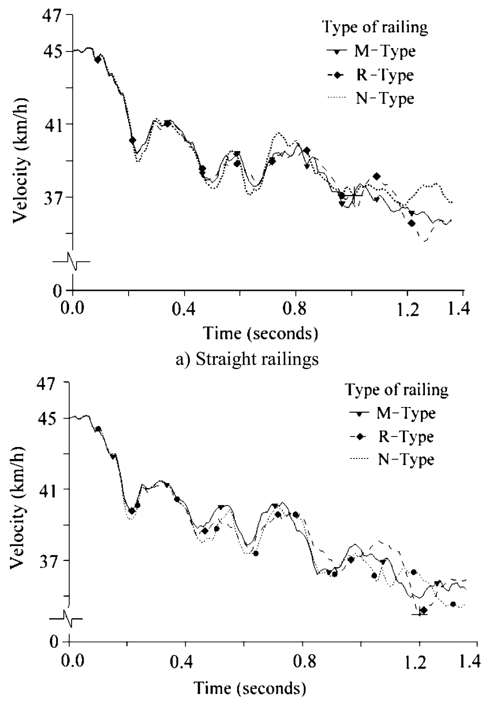


a) M-type railing



b) R-type railing

Fig. 15 Energy of impact collision.

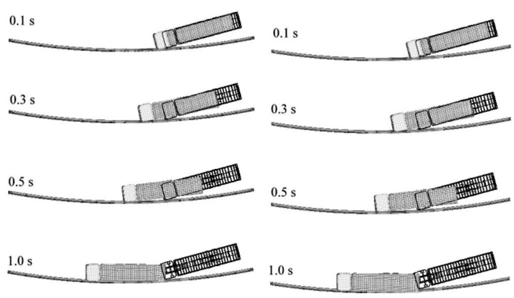


b) Curved railings

Fig. 16 Decrease in speed of truck.

cent of the design speed and under 60 percent of initial impact angle, respectively. The truck's speed at its center of gravity in the actual direction of movement is shown in Figure 16. The truck movement is presented in Figure 17. From these results it can be seen that the decreases in the truck speed and in the impact angle are sufficient to meet the requirements. In other words, the new-type curved railings are capable of guiding the vehicle back to the line of the road.

Another representative factor of truck behavior is acceleration. The Japanese specifications stipulate that the moving acceleration average secured for drivers and passengers should not exceed 180 $m/s^2/10ms$ in the case of a grade A railing. The moving acceleration average is determined at the truck's center of gravity using 21 acceleration points of 0.5 millisecond interval for each 10 milliseconds of movement as shown in Figure 18. It can be seen that the moving acceleration averages in cases of both new-types railings lie within the allowable limit of what is considered safe for driver and passengers.



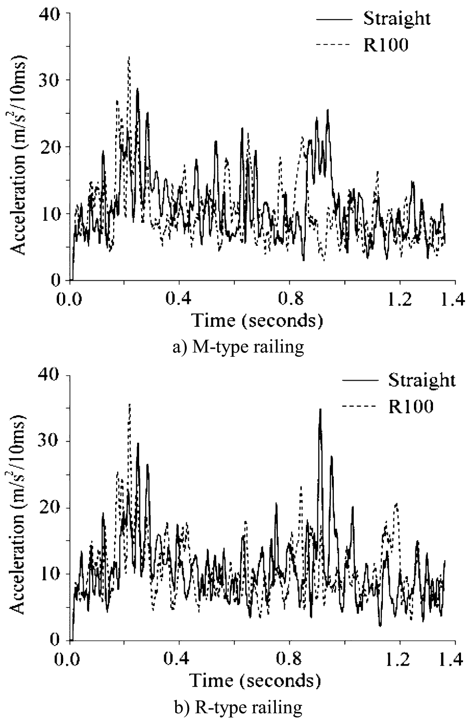
a) M-type railing b) R-type railing

Fig. 17 Movements of truck during collision into curved railings.

The main purpose of this research as has been said is to study the performances of new-type curved steel railings by means of numerical analysis. Thus, the performances of these railings are compared with those of straight ones, and of previously existing types in the same grade and under the same collision conditions. The curve radius chosen for the analysis is 100 m. As has been mentioned, it is suspected by some researchers and engineers that curved railings might be more dangerous than straight ones in the same collision condition because they are expected to undergo more displacement. In fact, however, the analyses show that the displacement of all types of curved railings is always smaller than in the corresponding straight railing. Since the amount of energy transferred from the truck to the curved railing is smaller than it would be for a straight railing, the curved railing is better able to guide the vehicle. Thus, the design grade stipulated for straight railing can safety be adopted for curved ones. Finally, the performances of new-type curved railings can certainly be investigated by numerical analysis using LS-DYNA software.

4.6 Curved railings subjected to higher speed truck

The displacements in the railing and the amount of energy transferred from the truck to railing are depended on the truck's initial kinetic energy. Because of human problems, the actual speed of truck on bridges may be over the allowable speed. To cover cases of this sort, and to investigate the resulting ultimate state of the railings, this section will deal with the performances of railings subjected to collisions from trucks traveling at higher speed, up to a point at which the railing displace-



b) R-type railing

Fig. 18 Moving acceleration average of truck's center of gravity.

ment reaches 300 mm. In the Japanese specifications,[3), 4)] the increment steps in the truck's speed requiring one or two upgrades in the railing design are the increase to 65 km/h and 80 km/h, respectively. In this study it is found that the displacements in M and N-type straight railings and in N-type curved railing exceed the allowable limit of 300 mm when the truck's impact speed increases to 80 km/h shown in Figure 19.

Thus, Figure 19 shows that M and N-type straight railings and N-type curved railing do not met the specification requirements. The displacement occurring with the N-type railing is larger in every case then that occurring with the M and R types. In this sense, it can be said that the new-type railings have a greater margin of safety capacity than the type of railing designed before 2004.

5 Summary and conclusions

This paper deals with two new types of railings developed by the authors used on curved bridges on a basic of numerical analysis. The conclusions can be summarized as follows :

(1) The finite element models represented the impact collision of a truck into a curved steel bridge railing have been successfully applied in a study of the performances of new-type curved railings using LS-DYNA 3D software.

(2) From comparisons of numerical results for curved and straight railings of M, R and N types, it is found that the railing displacement is smaller in cases of curved railing than in cases of straight ones. The truck's kinetic energy transferred to curved railings is less than straight ones. The curved railings are better able to guide the vehicle safety back to the line of road. The grade designed for a straight railing can equally be applied for curved ones.

(3) From the comparisons of the results it can also be said that the amounts of displacement and energy absorption are smaller with the new-type railings than with the previously existing one. The new-type railings thus satisfy the requirements for bridge railing design.

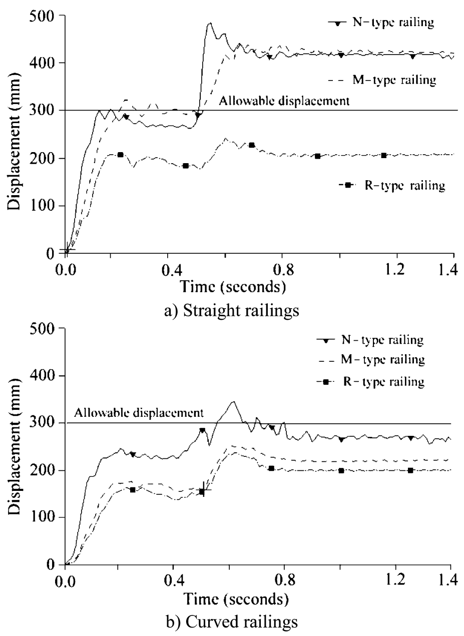


Fig. 19 Displacement- time history of railing posts subjected to collisions from a truck at speed 80 km/h.

References

1) Transportation Research Board, "Recommended procedures for the safety performance evaluation of highway features", Washington, National Cooperative Highway Research Program Report 350 (1993).
2) Japan Road Association, "The specifications of railing design" (1999) Maruzen Press, Tokyo (in Japanese).
3) Japan Road Association, "The specifications of railing design" (2004) Maruzen Press, Tokyo (in Japanese).
4) Japan Road Association, "The specifications of railing design", (2008) Maruzen Press, Tokyo (in Japanese).
5) J. W. Wekezer, M. S. Oskard, R. W. Logan and E. Zywicz, "Vehicle impact simulation", Journal of Structural Engineering, ASCE , Vol.119, No.4, pp.598-617 (1993).
6) P. Miller and J. F. Carney, "Computer simulations of roadside crash cushion impacts", Journal of Transportation Engineering, ASCE, Vol.123, No.5, pp.370-376 (1997).
7) M. H. Ray, E. Oldani and C. A. Plaxico, "Design and analysis of an aluminum F-shape bridge railing", International Journal of Crashworthiness, Vol.9, No.4, pp.349-363 (2004).
8) Y. Itoh, M. Mori and S. Suzuki, "A study on behavior of bridge guard fences subjected to vehicle collision using numerical analysis", Journal of Structural Engineering, Vol.45A, pp.1635-1643 (1999) (in Japanese).
9) Y. Itoh and C. Liu, "Nonlinear collision analysis of heavy trucks onto steel highway guard fences", Journal of Structural Engineering and Mechanics, Vol.12, No.5, pp.541-558 (2001).
10) B. Liu and Y. Itoh, "Numerical analysis on vehicle collision for performances-based design of a new type of guard fences", 1st International Conference on Construction Information Techniques, Beijing, China, pp.476-483 (2004).
11) Y. Itoh, S. Itoh, Y. Kitane and O. Takadoh, "Study on collision performance of new bridge railing guard fences allowing for the view", Journal of Structural Engineering, JSCE, Vol.48, No.2, pp.413-426 (2012) (in Japanese).
12) Public Works Research Institute (PWRI), "A study of the steel railing", Research Report No. 74, Tsukuba, Japan (1992) (in Japanese).
13) Japanese Traffic Accidents Analysis Association, "Statistics of traffic in Japan 2000-2003" (in Japanese).
14) T. Hirai and Y. Itoh, "Study on performance of curved guard fences using numerical simulation", 6th Asia Pacific Conference on Shock & Impact Load on Structures, Perth, W. Australia, pp.259-265 (2005).
15) Y. Itoh, B. Liu, K. Usami, R. Kusama and S. Kainuma, "Study on strain rate effect and performance examination of steel bridge guard fences subjected to vehicle collision", Journal of Structural Mechanics and Earthquake Engineering, JSCE, Vol.759, No.I-67, pp.337-353 (2004) (in Japanese).
16) Japanese Road Association, "Explanation and applications of road regulations" (2004) Maruzen Press, Tokyo (in Japanese).