Study on Steel Railings Installed on Concave- and Convex-Curved Bridge Parapet

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ABSTRACT
This paper reports performance results for steel bridge railings installed on concave- and convex-curved bridge parapet based on new-type posts. Preliminary experimental tests are first conducted to examine the behaviours of these posts when subjected to a collision from a heavy steel ball. The values thus verified are then fed into the LS-DYNA 3D analysis tool to generate improved simulations for the performances of new-type curved steel railings subjected to truck collisions. For some concave road curvatures, it is found that the impact angles between the vehicle and the railings are larger than assumed in the current Japanese specifications. Some researchers and engineers suspect that a curved railing is less effective than a straight one in the same collision conditions. The purposes of this study, in addition to contributing to the further improvement of curved steel railings, are accordingly to test the validity of the said suspicion, and to investigate the performances of these new-type concave-curved steel railings under larger collision impact angles. The performance results for concave- and convex-curved railings are compared against each other as well as with the results for straight railings.

Key words: Impact collision, Dynamic analysis, Curved steel railings, LS-DYNA.

1. INTRODUCTION

In Japan, the first specifications for railing design were established by the Japan Road Associations in 1965. With rapid changes in traffic capacity and in the road network, the specifications were revised in 1972 and 1999, while a third revision [1] in 2004 introduced two entirely new functional standards: a landscape-friendly appearance and continuous flow in the road user's view from a bridge. The latest specifications [2] published in 2008 further require a full-scale test for every railing before it is installed on a road section or bridge.

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Most essentially, however, as in other countries [3], Japanese specifications [1, 2] set four basic performance standards: railings should: (1) prevent vehicles from leaving the road; (2) guide vehicles back to the line of the road; (3) protect occupants; and (4) prevent projection hazard of the railing.

An extensive variety of flexible railing designs has been used on bridges around the world, and there is a wealth of research concerning railing responses to vehicle collisions in various conditions. Numerical analysis has been used to compare collisions of cars with roadside railings [4]. The behaviour of an F-shape bridge railing in response to a collision from a compact car has been numerically simulated [5]. Other numerical analyses have been undertaken for the collision of a heavy truck into a high performance steel railing [6]. Two new types of railing designed to meet raised functional standards in the Japanese Specifications have been developed with the aid of finite element modelling [7, 8]. Performances of a curved railing have been numerically analysed [9]. And behaviours of curved and straight railings have been compared under the same vehicular conditions to identify the respective strengths and weaknesses [10]. The study on the behaviours of new-type curved steel bridge railings has been performed using the numerical analysis [11].

The purpose of the present research is to contribute to the development of concave- and convex-curved railings using two new types of steel post designed to meet the raised functional specification standards. The behaviours of these posts are examined in experimental tests involving collision with a heavy steel ball. These test results are then fed back into a finite element simulation model created with LS-DYNA 3D. The numerical simulations for the posts' responses are verified against the experimental results, and these verified values can then be reused to obtain closer simulations of the responses of the new-type steel railings as employed on curved bridges and subjected to truck impact collisions.

Some engineers and researchers suspect that curved railings are inferior in performance to straight ones under the same collision conditions. However, the Japanese specifications [2] give no consideration to curvature in either design or construction. This study finds that in some conditions on concave-curved bridges the impact angle between the vehicle and the railing may exceed the specification angle of 15°. In addition to testing the experts' suspicions in general, therefore, a more particular purpose of the research is to examine responses of concave-curved steel bridge railings to collisions from trucks at larger impact angles.

The research relies on numerical analysis using finite element models created with the LS-DYNA 3D tool. But the results obtained for the new-type curved railings are not taken alone but compared with others for a previously existing set of railings designed and successfully used for a bridge before 2004. All of the railings investigated meet the specification grade A; that is to say, they meet the required standards of response to a collision from a truck of 25 tonnes (245 kN) at an impact velocity of 45 km/h. In accordance with the Japanese specifications [1, 2], the required railing performance is appraised using results obtained for displacement, energy absorption, and truck responses. These results are presented in chapters 2, 3 and 4. The summary and conclusions follow in the last chapter.

2. DEVELOPMENT OF TWO NEW TYPES OF STEEL RAILING POST

The dimensions and shapes of the two new post types investigated in this study are presented in Figures 1(a) and 1(b) under the names M-type and R-type. These new types are designed to meet raised functional standards in the Japanese Specifications [1]. Specifically, they are expected to withstand a lateral torsional buckling failure in the compression flange during an impact collision. In addition, the R-type post is designed with a deliberate narrowing in the

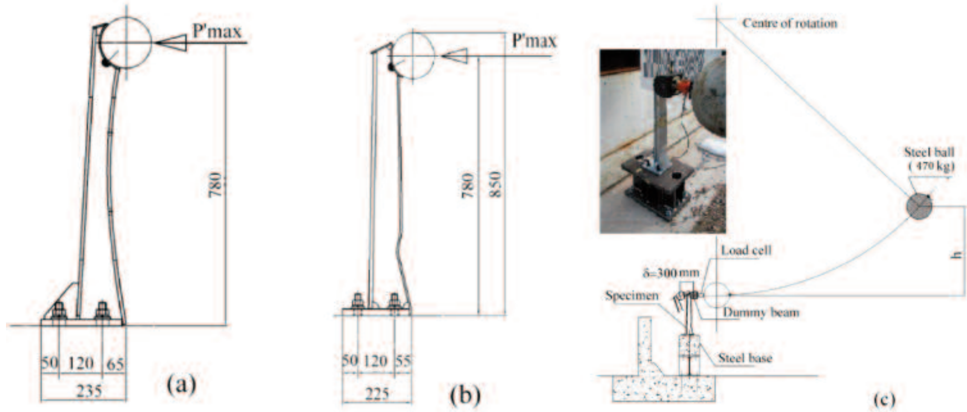

Figure 1. Features of new-type posts: (a) M-type, (b) R-type and (c) Experimental test in which post is subjected to collision with a heavy steel ball (Unit: mm)

cross-section towards the bottom part of the tension flange in order to obtain a more even distribution of energy absorption between the two flanges and the web. The presence or absence of this narrowing is the main difference between the M-type and R-type railing posts.

The initial shape and section of new-type posts are designed according to an equivalent structural model [8]. This model has two spans, and consists of three equivalent columns with rectangular section. The columns and actual posts have an equal area of cross section. The Japanese Specifications [2] request the largest displacement occurred within the railing subjected to collision load is smaller than 300 mm. Therefore, in the equivalent model an ultimate bending moment of the column is determined by assigning 300 mm of displacement at the top of column. According to a relationship curve between ultimate bending moment and load with the railing grade described by the Japanese Specifications, the ultimate load of equivalent column is obtained. Such ultimate load is used to design initial shape and cross section of the railing post.

The behaviours of new-type posts are examined by static load test performed in the laboratory. The post is attached onto the steel beam foundation using the high strength bolts. The static force acts to the top part of the post to cause 300 mm of horizontal displacement. The curve of static load – displacement relationship is compared to the ultimate load obtained by above equivalent structure. The post that has a closed amount of ultimate load and largest load recorded in the experimental test is adopted.

The collision performances of the two types are examined by the experimental test illustrated in Figure 1(c) in which the post is attached onto the steel foundation by high strength bolts, and is subjected to an impact of a heavy steel ball. The collision load comes from the struck of steel ball under the gravity. The kinetic energy of steel ball is controlled by increasing or decreasing its initial height that is measured from the top of post to the center of steel ball. The initial height is determined to cause 300 mm of horizontal displacement at the top part of post. Accordingly to the load in static test, properties and dimension of the post cross-section, the initial height of the steel ball in the tests is 2150 mm for the M-type post and 2300 mm for the R-type one. The steel ball has a mass of 470 kg.

The collision experiment test of posts is also simulated using finite element models created with LS-DYNA 3D as shown in Figure 2. The flanges and web are modelled as four-node shell elements. The element sizes of the flange and web are 19.5×22.6 mm and 20.2×21.5 mm for the M-type post and 23.7×28.7 mm and 23.3x23.4 mm for the R-type one. Both types are made of SS400 steel modelled as an isotropic elasto-plastic material conforming to the von Mises yield criterion with Young's modulus of 206 GPa, Poisson's ratio of 0.3 and yield stress of 235 MPa. The stress-strain relationship of steel considered an effect of strain rate is obtained by the dynamic tensile test by our laboratory is simulated for the steel model in LS-DYNA 3D. The steel plate at the bottom of each post is modelled with eight-node solid elements, and the mesh for the steel ball is made up of tetrahedral solid elements. The simulated shapes and dimensions match those actually occurring in the practical tests. The posts are considered as end-fixed.

Figure 3 compares the numerical and experimental displacement-time histories of posts subjected to collisions with the steel ball. The horizontal displacement is as measured at the top of the post. For the M-type post, the numerically simulated displacement-time history is

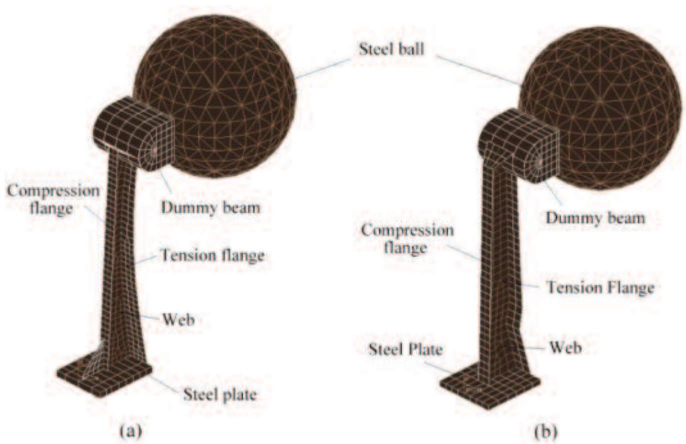

Figure 2. Numerical simulation of collision test for new-type post: (a) M-type, (b) R-type

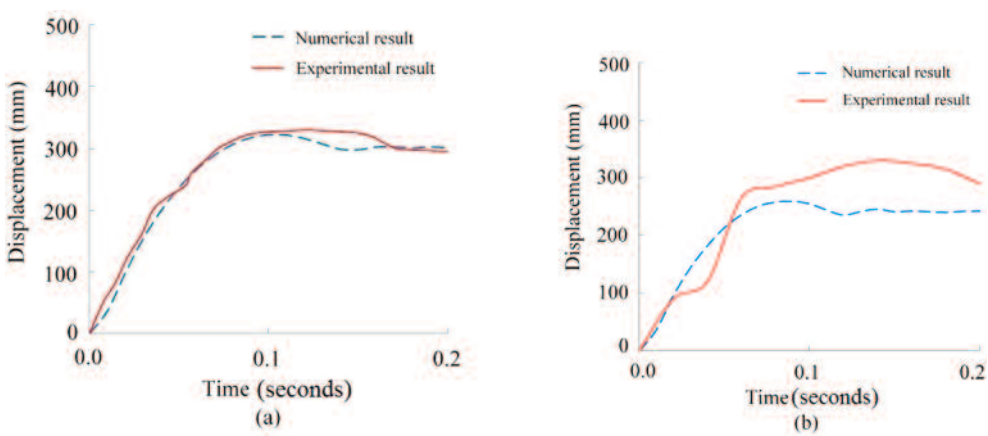

Figure 3. Numerical and experimental displacement-time histories for railing posts subjected to collision with a steel ball; (a) M-type, (b) R-type

close to the experimental test result. The maximum numerical and experimental displacements are 322 mm and 330 mm, respectively. For the R-type post, the experimental displacement is larger than the numerically calculated one for time lengths of between around 0.05 and 0.2 seconds. In the experimental tests, the out-of-plane displacement caused by the lateral torsional buckling failure at the compression flange leads to an increase in the horizontal displacement measured at the top of this R-type post. The maximum experimental and numerical displacements are 330 mm and 259 mm, respectively. It can be seen in Figure 3 that the numerically simulated behaviour of the R-type post is similar to that of the M-type one.

Kinetic energy from the steel ball is transferred to the post during the impact collision. The distribution of the energy absorbed by the post flanges and web is presented in Table 1, where it is clear that a greater amount of energy is absorbed by the compression flange than elsewhere. The R-type post offers a more even distribution of absorbed energy between the two flanges and the web, and is thus superior in meeting the post design requirement. Figure 4 shows examples of post failures from the numerical analysis and the experimental tests. In the M-type post, the lateral torsional buckling is found to occur along the entire compression flange. In the R-type post it is confined more to the vicinity of the narrow part in the cross-section.

For the sake of discussion, similar data are also included for the response behaviour of a previously existing type of post ("N-type"), designed for a bridge in Hokkaido. A finite element model of this N-type post is shown in Figure 5(a). The cross-section is more rigid than in the new-type posts. Figure 5(b) compares the numerical

Table 1. Distribution of absorbed energy in the post members

Post members	M-type (kJ)	R-type (kJ)
Whole post	8.0	8.7
Compression flange	4.3	3.7
Web	2.9	2.0
Tension flange	0.7	3.0

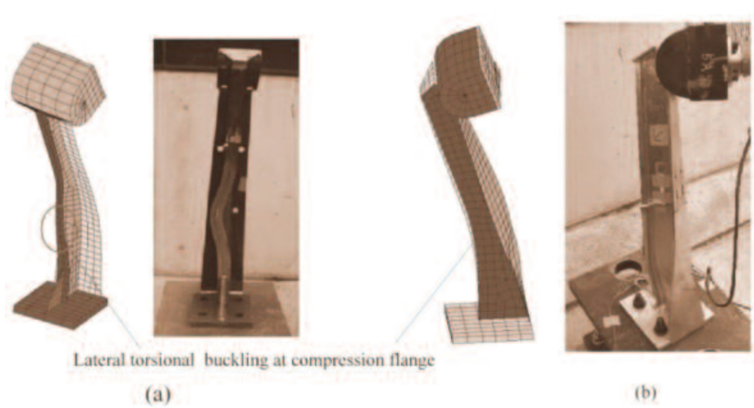

Figure 4. Cases of lateral torsional buckling failure in numerical analysis and experimental tests; (a) M-type, (b) R-type

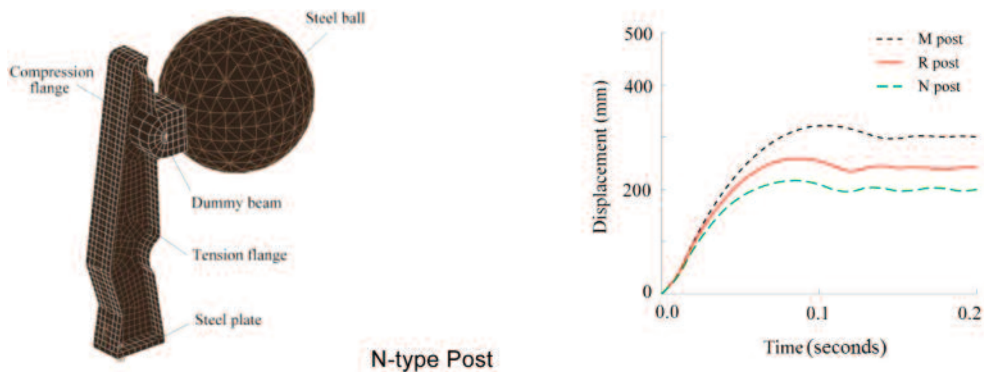

Figure 5. Simulation model of N-type post and comparison of displacements simulated for new and N-type post

displacements for this N-type post and the newer M- and R-types. The pattern is similar for all three, but the largest and smallest displacements occur with the M-type and N-type posts, respectively. The smaller displacement obtained with the N-type post is due to the rigidity of the design.

From these comparisons of the numerical and experiment results, it can be verified that the numerically simulated behaviours of the new-type posts subjected to the collision with the steel ball are close to the ones measured in experimental tests. The response behaviours of these new-type posts meet the current Japanese specifications and the expectances of design, and can be adequately investigated by means of the numerical simulations created by LS-DYNA 3D. Such simulations can also be verified by comparing results obtained from them with real experimental data. Once verified, the models of the new and previous post types can then be effectively used, in particular, to simulate impact collisions for assessing the performance of curved steel bridge railings subjected to a heavy truck collision.

3. PERFORMANCES OF NEW-TYPE CONCAVE-CURVED STEEL RAILINGS

As explained above, the new-type posts meet the requirements of the Japanese specifications for railing design and the adequacy of the numerical simulations for the purposes of this research has been verified. This chapter moves on to an applied use of these posts in roadside railings on curved steel bridge parapets. A concave bridge curvature will first be assumed, with a curve radius of 100 m. The same two new post types, M-type and R-type, are examined as in chapter 2, and the same type of previously existing post, N-type, is also referred to as a comparison reference. All of the railings considered are of specification grade A, for which the collision conditions assumed are of a truck weighing 25 tonnes (245 kN) travelling at an impact velocity of 45 km/h. In some cases, the impact angle between the vehicle and the railing is found to be larger than the 15° assumed in the current specifications. Accordingly, the performances of these concave-curved railings need to be investigated both for the specified impact angle and for larger ones.

3.1. FINITE ELEMENT MODELS OF RAILINGS AND TRUCK

Finite element models of the new and previous railing types are shown in Figures 6(a), 6(b) and 6(c). The railings consist of top, upper and under beams, posts, and a curb. The beams are of tubular cross-section. For the new M-type and R-type railings the top beam is largest,

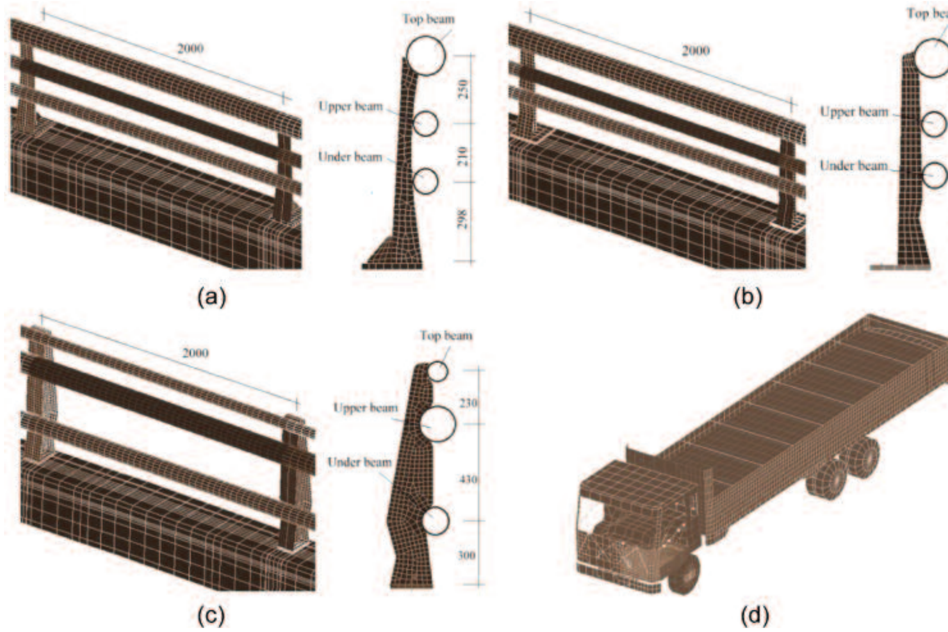

Figure 6. Numerical simulations: (a) M-type railing, (b) R-type railing, (c) N-type railing and (d) Truck (Unit: mm)

with a diameter of 140 mm and a thickness of 6.6 mm, while the upper and under beams have the same diameter of 89 mm and thickness of 2.8 mm. For the N-type railings, the upper beam is largest, with a diameter of 140 mm and a thickness of 2.8, while the corresponding dimensions for the top and under beams are 76 mm and 2.8 mm (top) and 114 mm and 3.5 mm (under).

The beams are made up from four-node shell elements, of steel modelled as an isotropic elasto-plastic material conforming to the von Mises yield criterion with Young's modulus of 206 GPa, Poisson's ratio of 0.3 and yield stress of 235 MPa. The stress-strain relationship of the steel is obtained from dynamic tensile test measurements with due account taken of the effect of the strain rate of steel. The strain rate steel model used in this research is adopted from the model that is verified and recommended by the author's laboratory papers [12, 13]. The strain hardening starts from 0.0014 and an initial strain hardening modulus is 4.01 GPa (2% of the Young's modulus).

The concrete curb is made up of eight-node solid elements, with the concrete modelled as a general elasto-plastic material with Young's modulus of 24.4 GPa, shear modulus of 10.5 GPa, compressive strength of 23.5 MPa, and tensile strength of 2.3 MPa. The curb is considered as end-fixed.

The finite element model of the truck is shown in Figure 6(d). This model, originally created with support from a truck manufacturer, has proved itself in previous research [6–10]. The truck has a length of 11,800 mm, a height of 3,300 mm and a width of 2,500 mm. The sides, frame, cab, fuel tank and so on are made up from four-node shell elements. Eight-node solid elements are used for the engine, freight load and transmission. The total weight is 25 tonnes (245 kN), representing the sum of the vehicle components and the load. The steel for the truck is modelled as an isotropic elasto-plastic material conforming to the von Mises

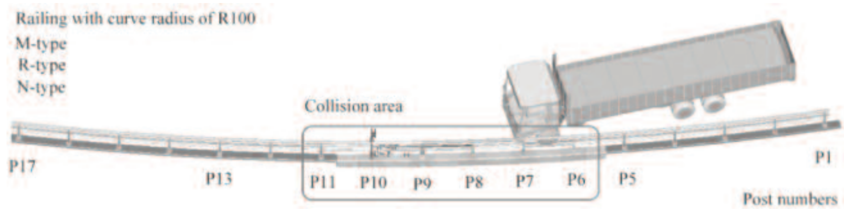

Figure 7. Set of simulations for truck colliding into concave-curved railings

yield criterion and the aluminium alloy representing the load is in a multi-piece linear stress-strain relationship. The total numbers of elements and nodes in the truck model are 9,344 and 9,830, respectively. A set of simulation examples for this truck in collision with the three types of concave-curved steel bridge railings is presented in Figure 7.

3.2. COLLISION PERFORMANCES OF CONCAVE-CURVED RAILING

All discussions in this section are for railings subjected to the collision conditions assumed in the Japanese specifications for railing design [2], that is to say, a truck of weight 25 tonnes (245 kN), an impact velocity of 45 km/h and an impact angle of 15°. Figure 8 shows some displacement responses for M-type and R-type railings. Here, the displacements in these concave-curved railings are compared with those in straight railings under the same collision conditions. For both the concave-curved and the straight railings, it can be seen that there are two distinct stages to the impact collision. The first stage occurs at a time around 0.2 seconds from first impact when the front bumper of the truck collides with the railing. The truck is then guided to run along the railing towards the leading end. The second collision stage occurs around 0.8 seconds after first impact when the rear part of the truck hits the railing.

The largest displacements in the new-type railings all fall within the 300 mm tolerated in the Japanese specifications. Figure 8 also shows that the displacement in the concave-curved railings is always smaller than in the straight ones. Otherwise, the behaviours are similar. The

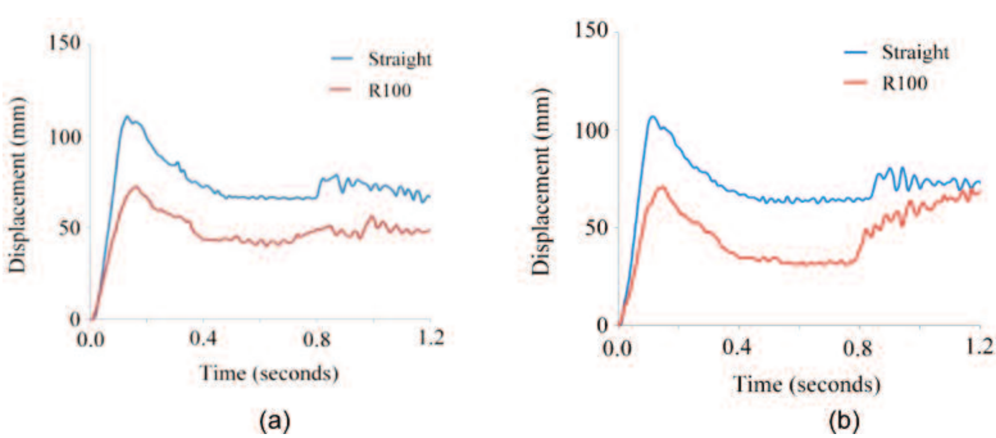

Figure 8. Displacement-time histories of new-type railings: (a) M-type, (b) R-type

Table 2. Energy transfer from truck to railing (Unit: kJ)

Type of railing	Concave-curved	Straight
M-type	29	35
R-type	26	28

energy transfer from the truck to the railing during the impact collision is shown in Table 2. For the M- and R-type railings, the amount of energy transferred and absorbed is smaller than in the case of the straight railing.

Figure 9 makes a comparison of displacements between the new M-type and R-type railings and the previous N-type, showing that the displacement occurring with the new-type railings is always smaller than with the previous type, given the same collision conditions. Figure 10 shows the successive movements of the truck colliding into concave-

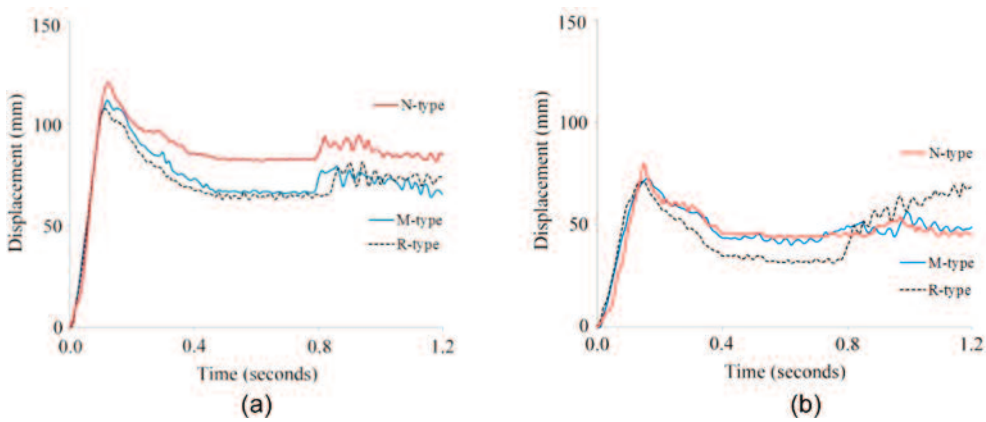

Figure 9. Displacement and railing curvature: (a) straight, (b) concave-curved

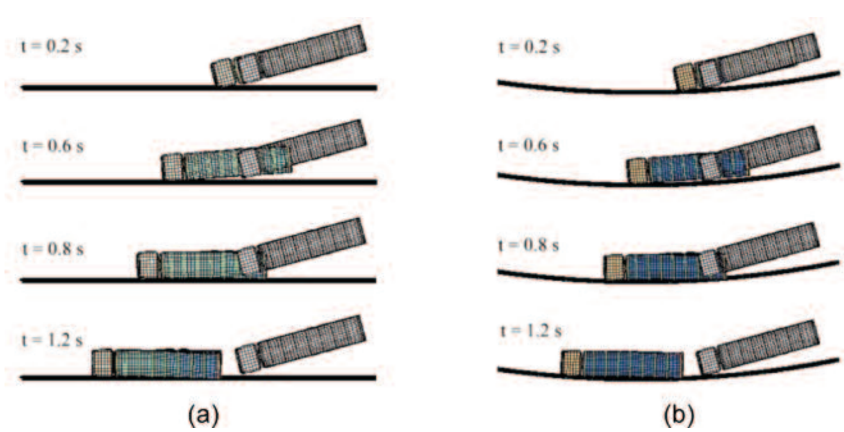

Figure 10. Movements of a truck colliding into M-type railings: (a) straight, (b) concave-curved

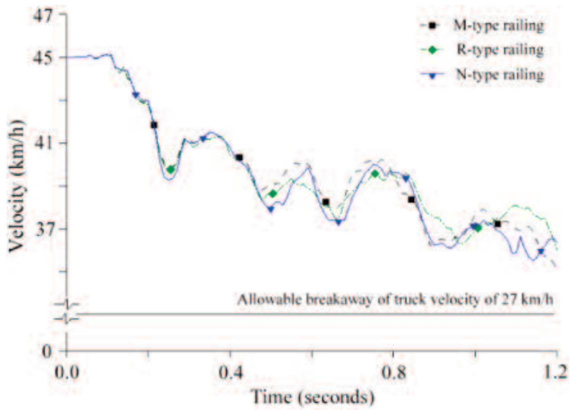

Figure 11. The decremental speed loss of truck

curved and straight railings of the M-type. This confirms that the truck is guided to run on towards the end of railing and back to the line of road following the first and second collision stages.

According to first two required standard performances for railing in the Japanese specifications, the truck responses of residual speed and reflected impact angle should be considered. The first is the residual speed of the truck after the first two collision stages should still be more than 60 percent of the initial impact speed. For a specification grade A, therefore, the residual speed of the truck needs to remain above 27 km/h. Figure 11 shows that the decremental loss of speed following the truck's collision into any of the new-type concave-curved railings meets this requirement. The second is a reflected impact angle of the truck and railing after the first collision stage should still be more than 60 percent of the initial impact angle.

These numerical results for the new-type concave-curved railings subjected to a truck collision indicate that both the M-type and R-type of railings satisfy the specification requirements. The performances of these new-type concave-curved railings under particular impact conditions can be studied more closely using the numerical simulations made possible by the LS-DYNA 3D tool.

For the same truck collision conditions, the amounts of displacement and energy absorption will be smaller in concave-curved railings than in straight ones. In other words, the concave-curved railing is superior in performance to the straight one. A similar comparison of results between the new-type and previous railings show that the new type is superior.

3.3. PERFORMANCES OF CONCAVE-CURVE RAILINGS IN COLLISIONS AT LARGER IMPACT ANGLES

Figure 12 shows a case from a concave-curved bridge with a curve radius of 100 m. The road section has three lanes, and connects with straight sections at both ends. As a result of human error, it is assumed that a truck entering from the lower straight section continues in the same straight line and collides into the concave-curved bridge railing. The impact angle between the vehicle and the railing can thus be determined by Eq. (1) (unit: degrees).

$$\gamma = 180L_i/\Pi R \qquad (1)$$

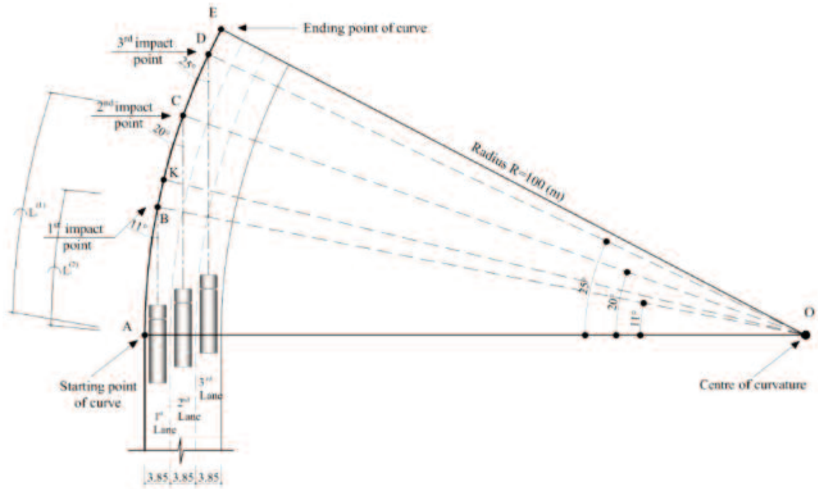

Figure 12. Larger impact angles on concave-curved railings

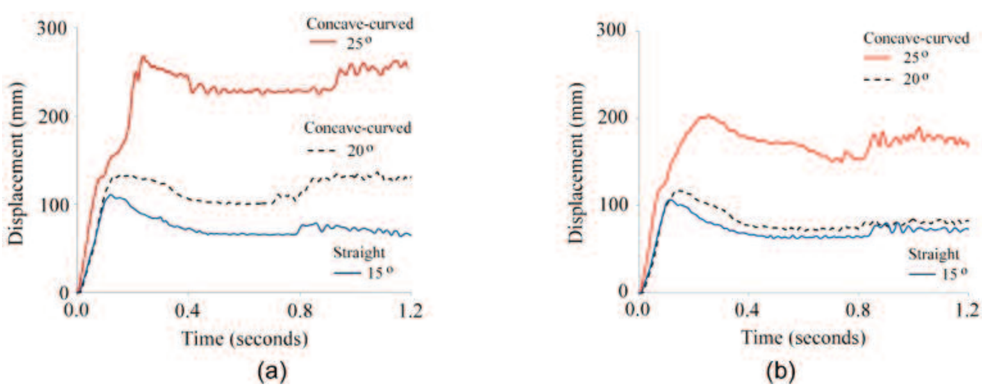

Figure 13. Displacements in concave-curved railings for larger impact angles: (a) M-type, (b) R-type

Where:

L_i is the arc length (m) measured from point A to impact point B, C or D

R is the curve radius of the railing (m).

Larger impact angles of 20° or 25° will occur when the truck is travelling on the centre or right-hand lanes prior to the collision into the railing. Accordingly, the response behaviours of these concave-curved railings also need to be investigated for collisions at these larger impact angles. The numerical results are presented in Figure 13, in comparison with results for straight railings. Here, the displacement in the concave-curve railings is larger than in the straight ones and this difference is more pronounced at the high impact angle of 25°. That is to say, the concave-curved railings are inferior in these circumstances to straight ones.

4. PERFORMANCES OF NEW-TYPE CONVEX-CURVED STEEL RAILINGS

This chapter considers performances of the same new-type railings on convex-curved bridge parapets when subjected to heavy truck collisions of the same sort as described above. A simulation example for this kind of collision is shown in Figure 14. Figure 15

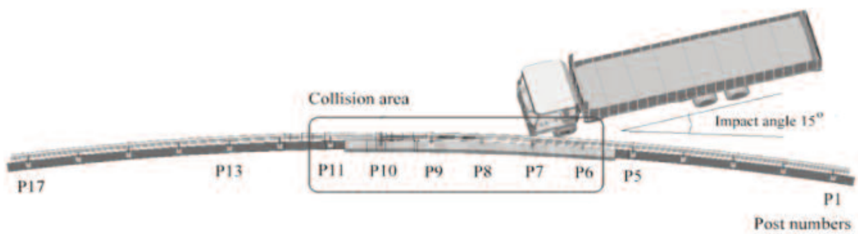

Figure 14: Simulation of the collision of a truck into convex-curved railings

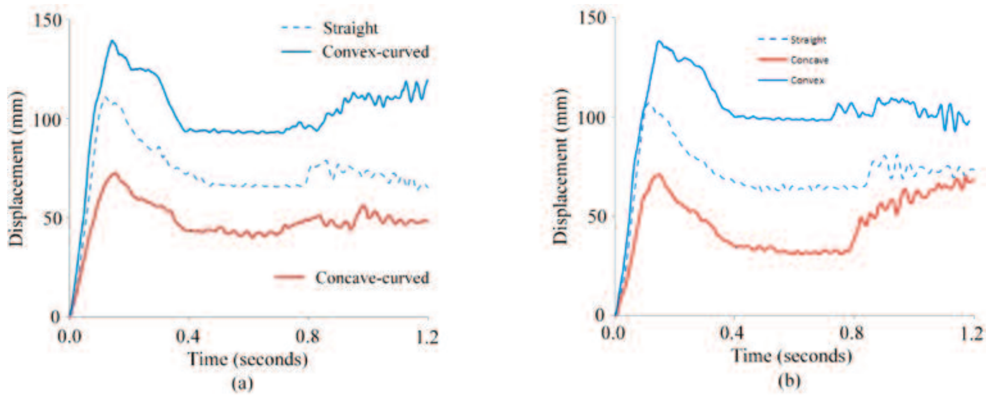

Figure 15. Displacements in convex-curved railings: (a) M-type, (b) R-type

shows displacement results for convex-curved railings compared with concave-curved and straight ones. The same two collision stages occur in each case, whether the railings are of the M- or the R-type. But for the same collision conditions and impact angle, the displacements in the convex-curved railings are larger than in either the concave-curved or the straight ones.

The numerical results further indicate that for impact angles of 20° and 25°, convex-and concave-curved railings are both inferior to straight ones. In the interests of safety, the capacity of these curved railings can be increased by using a higher-grade of railing. Alternatively, the kinetic energy of the vehicles using the bridge can be reduced by controlling the traffic speed.

5. CONCLUSIONS

This paper reports a numerical study of the collision performances of new-type concave- and convex-curved steel railings installed on bridge parapet using the LS-DYNA 3D analysis tool. Finite element models of the impact collision of a truck into concave-curved, straight and convex-curved railings are successfully developed. The conclusions are summarized as follows.

The performances of these new-type curved steel railings can be studied by numerical analysis using LS-DYNA 3D. The concave-curved railings meet the required standards for the Japanese specifications, and are superior in performance to previously existing types.

From a comparison of the numerical results for concave-curved and straight railings, it is shown that for the same collision conditions, the concave-curved railings are superior.

However, for cases involving concave-curved railings and a collision impact angle of more than the specified 15°, as well as for all cases involving convex-curved railings, curved railings are found inferior to straight ones. To obtain the same safety margins as with straight railings, the capacity of these curved railings would need to be increased by using a higher grade of railing. Alternatively, the kinetic energy of the vehicles using the bridge could be reduced by controlling the traffic speed.

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