BEHAVIOUR OF CURVED STEEL BRIDGE RAILINGS SUBJECTED TO VEHICLE COLLISION

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ABSTRACT

Curved steel railings have been used along curved bridges. Similar to straight railings, the curved ones are prescribed four safety requirements following as: (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. However, the design and construction for the curved railing have not concerned in the current Japanese specifications. On the other hand, some researchers and engineers have suspected that in the same vehicular collision conditions the curved railings are more disadvantageous than straight railings.

Since the Japanese specifications issued in 2004, the railing is lead to design with smaller and slender form, because two new improvement functions of a landscape-friendly appearance and a flow in the road user's view from bridges are represented into this revision. On the other hand, the present study found that the impact angle between the vehicle and railing in some cases of curved bridges may be larger than angle specified in the Japanese specifications.

The objectives of this research are accordingly to study performances of curved railing subjected to vehicular collision loads. The purposes of study are following as: (1) to qualify the suspicion of the researchers and engineers; (2) to develop new-type curved railings satisfied the improvement functions in the current Japanese specifications; (3) to investigate the performances of curved railings under the larger impact angle than hitherto from the vehicle; and (4) to propose the recommendations for the railing design.

Chapter 1 is about introduction in the field of the present study with background, statements, objectives and limitations.

Chapter 2 is verification progress for the collision simulations using in the study. A full scale-test of the impact collision between a heavy truck and straight steel railing which was performed by Japan Public Works Research Institute is simulated by the finite element models using LS-DYNA 3D software.

The numerical results of both railing and truck behaviours are examined and then compared with the experimental results. Those comparisons would verify the numerical simulations. Therefore, the methods and assumed properties used into the simulations are reapplied to analyses in the next parts of the study for performances of the curved steel bridge railings subjected to truck collision loads.

In Chapter 3, the performances of a concave-curved steel bridge railing, which was designed before 2004, under the vehicular impact collision are examined using the numerical analysis. The steel railing is of grade SC, and subjected to 25 ton (245

kN) of truck weight, 50 km/h of truck velocity and 15^o of impact angle. This railing grade was designed to apply for the straight railing installed on straight bridges. To verify whether concave-curved railings are more disadvantage as suspected, this railing is applied for curved railings having a curve radius of 100 m, 150 m, 280 m or 460 m, under the same vehicular conditions. The numerical solutions of concave-curved railings are compared with those of straight one.

The study found that, in cases of curved bridges with a concave-curve radius of 150 m and 100 m, because of human problems the impact angle between the railing and vehicle may occur as 20^o and 25^o, respectively, and are larger than angle of 15^o specified in Japanese specifications. Accordingly, in the next stage of numerical analysis, impact angles of 20^o and 25^o are applied to investigate the performances of those cases of curved steel railing.

Chapter 4 reports the results of development of two new-type concave-curved steel bridge railings. Those types of railing have met two new improvements in railing function prescribed by Japanese specifications issued in 2004. In this chapter, the suspicion from the researchers and engineers about safe situation between curved and straight railings and performances of curved railing under larger impact angle than hitherto are investigated for new-type curved railings.

A combination between partial experimental tests for the new-type posts and numerical analyses is main method using in this chapter with following procedures as: (1) to verify new posts by static and heavy ball experimental tests; (2) to study performances of new posts by numerical simulation and using above experimental results to verify post simulations; and (3) to apply those post simulations to create full impact collision of new-type railings subjected to the heavy truck collision.

Chapter 5 reports the study of performances of a convex-curved railing under the impact of a truck. The models of M-type railing posts, beams and concrete curbs that are successfully created in the previous chapter are adopted into this study. The M-type convex-curved railing has a curve radius of 100 m, and is subjected to the collision conditions that are applied for the railing grade of A as following mentions in the Japanese specifications.

Finally, recommendations and remarks for curved steel bridge railing design, summary and conclusions of the present research and future works are proposed in Chapter 6.

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Chapter 1
INTRODUCTION

1.1 Background

1.1.1 Classification of railing

The safety functions of the railing on bridge have become more challenge for the civil engineers because of the large increase of the vehicular speed, weight and scale and the rapid expansion of traffic road networks nowadays. According to the basic property of the material, the railings are classified into rigid and flexible types. The rigid railing is made of the concrete. The other one is made of the steel or aluminium alloy. The metal railings can undergo large deformation, thus this type of railing can absorb more energy from the vehicular kinetic energy than the rigid ones. From this reason, the flexible railing is required to use along the most of highways and highway bridges.

Curved railings are installed along the curved bridges. Similar to straight railings, the curved ones shall have the same safe functions with the protection requirements for the vehicular occupants and vehicle. The different character between the straight and curved railings is that the beams of curved railings are bended following the curvature of bridge.

1.1.2 Japanese specifications for the railing design

The Japanese specifications for the railing design were established in 1965. An allowance of increase of the truck's weight from 20 ton (196 kN) to 25 ton (245 kN) is lead to change the truck's gravity center. Thus, the behaviours of truck and railing were re-examined by Japan Road Association and the revised specifications were issued in 1999 [1]. The specifications implemented in 2004 [2] have concerned two new improvement functions of a landscape-friendly appearance and a flow in the road user's view from bridges. Those improvements have need of new concepts for the railing design with requirements of smaller and slender form of railing beams and posts.

The latest Japanese specifications for the railing design were implemented in 2008 [3]. Since those specifications, the railings are required an experimental examination before installing on the bridges. Similar to the other country specifications [4], the

Japanese specifications for the railing design require four performances for railings as following: (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.

According to References [2, 3], the grades of railing are obtained based on the impact index levels. This index is functions of the vehicular weight and speed and an impact angle between the vehicle and the railing. The classification of railing grades is presented in **Table 1.1**. For the highways and highway bridges, the railing grades of SC, SB, SA and SS are applied. The other ones are normally used for road or bridge allowed a low vehicular speed. The form and shape of the railing are selected by the engineers on considerations such as cost and topography.

Table 1.1 Classification of the railing grades

Grades	Truck mass (*ton*)	Speed of vehicle (*km/h*)	Collision angle (*deg*)	Impact index (*kJ*)
C	25 (245 kN)	26	15	45
B		30		60
A		45		130
SC		50		160
SB		65		280
SA		80		420
SS		100		650

The flowchart of design for the railing can be proposed as following **Figure 1.1**. The form and features of railing are selected in the pre-design step. Both static and collision load tests are the ideal method to investigate the performances of the railing. If the designed railings can be verified from the experimental tests, the railings are adopted to install along the bridge.

1.2 Rational of the study

Many varieties of the concrete and metal railings have been used over the world together with extensive existing papers reported the performances of railing under the collision loads. The finite element models were created to investigate the collision performance of a pole and a type of roadside under a car impact [5]. The performances of roadside subjected to light and heavy vehicle collision were studied using the numerical analyses [6]. An extruded aluminium alloy truss-work bridge railing was examined to satisfy levels three and four conditions of NCHRP Report 350 [7]. The design of Annisquam river bridge railing which meets requirement of NCHRP Report 350 was introduced [8].

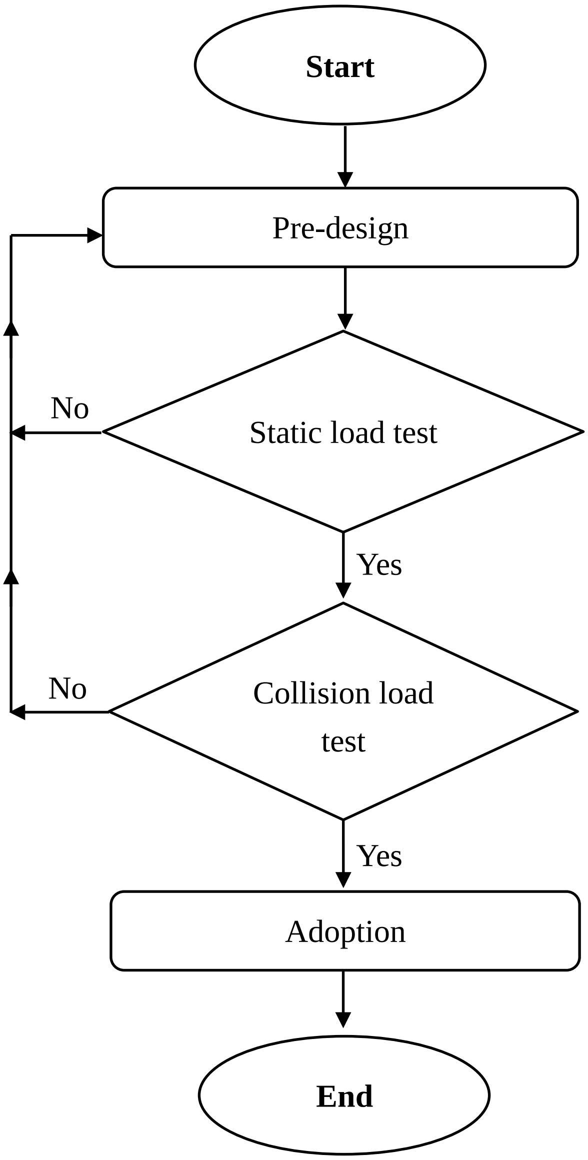

Figure 1.1 Flowchart of the railing design

In our laboratory, the collision performances of some types of railing have been studied and reported in many existing previous papers. The finite element model was created to study the impact collision of various types of railings subjected to truck collision [9]. The steel highway railing under the impact of the truck was investigated by using numerical simulation [10]. The collision performances of the steel and aluminium alloy were investigated using numerical analyses [11]. The performances-based design of a new-type railing was examined using the finite element models [12]. The concrete railing subjected to a heavy truck collision load was studied by numerical simulations [13].

Such researches were performed to study behaviours of steel straight railings subjected to the impact collision loads. In which, the collision problems were simulated by finite element models using the LS-DYNA 3D software. For some studies, the numerical results were compared with experimental ones, by this way the numerical simulations were verified. Since 1992, a series of full scale test for a steel straight railing under the impact of truck was performed by Japan Public Works Research Institute [14]. Recorded results from those tests were used as the reference data to verify the numerical models in our laboratory researches about the impact collision between the railing and the truck.

The curved railings are installed on the curved bridges. Similar to straight railings, curved ones would be required to meet four performance standards. Performances of curved railing in comparing with those of straight one were investigated using finite element models [15]. In this research, numerical analyses were performed to investigate performances of some types of curved and straight railing. Two new-type straight railings that met new improvement functions in the Japanese specifications in 2004 were developed by using numerical study [16]. The behaviours of new-type posts were examined by both static and collision tests. Numerical simulations were developed to study collided performances of those posts. Such simulations are verified by comparing its results with those of experimental test, and then are adopted to study performances of railing under the impact of truck.

The numerical analyses used LS-DYNA 3D can effectively study the collision events and the performances of steel railings subjected to the vehicular collision loads [5-13]. The Japanese Traffic Accidents Analysis Association reported that the number of accidents on curved road sections and bridges exceeded 50,000 over a 4-year period from 2000. Accordingly, the purposes of the present research are to investigate performances of curved steel bridge railings and to improve new-type posts presented in Reference [16] to develop new-type curved steel railings used on the curved bridges.

The numerical analysis using the finite element models is a main method of the present study. The experiences and assuming properties of material and model representation from our laboratory's existing researches [9-16] are adopted into the present study. The existing researches for the railing subjected to truck collision indicate that the performances of railings can effectively study from the numerical solutions following as: the railing displacements; amount of energy absorbed by railing; collision force occurred on railing posts and beams; deformation of railing;

decrement of truck velocity after collision stages; truck movement; and moving acceleration average of the truck's center of gravity.

1.3 Statements of the study

The Japanese Traffic Accidents Analysis Association recorded the number of accidents on curved road sections and bridges exceeded 50,000 over a 4-year period from the year of 2000 as shown in Reference [17]. However, the current Japanese specifications for railing design have referred only to the design of straight railings and some researchers and engineers have suspected that in the same vehicular collision conditions and impact angle the curved railings undergone larger displacement and are more disadvantageous than straight one. Thus, the suspicion of safe situation between curved and straight railing should be qualified.

The Japanese specifications for railing design issued in 2004 improved two new functions for railings. The first is a requirement of a landscape-friendly appearance and the second is to take account of flow in the road user's view from bridges. Those improvement functions have led to changes requirements in the railing design, in which the railing beams and posts would be designed with smaller and slender form and features. Therefore, the new railings should be developed to meet new requirements in current standards.

An impact angle is formed from the direction of the truck and the course of the railing. This angle has a bearing on the performances of railing and the behaviours of the truck. The largest value of impact angle specified in the Japanese specifications is of 15^o. Certainly, the present study finds that in some actual cases of curved bridges together with human problems the impact angle may be larger than hitherto. Accordingly, the performances of curved railing subjected to the collisions of such larger impact angles should be investigated.

The current Japanese specifications for the railing design issued in 2008 require a full-scale test for the railing before it is installed on the bridges. But this test involves a considerable cost and effort, and nowadays computer software used in combination with supercomputer is powerful enough to simulate the collision problems with a full set of properties and boundary conditions. The numerical analyses can reduce the calculation time and allow investigating for multiple cases of impact collision. The numerical results can converge with results from experimental tests [5-13]. Numerical analysis, therefore, is the effective method used for the present study of the performances of curved steel bridge railings under the impact of a heavy truck.

1.4 Objectives of the study

This research proposes to study the performances of curved steel bridge railings under the impact of the heavy truck. The study adopts the successful experiences and assuming properties in the representation of the impact collision models from existing studies performed by our laboratory [9-16]. The results of study are recommendations and remarks proposed in the curved railing design. According to above statements, the objectives of study are following as:

(1) Qualify the suspicion of the researchers and engineers about safe situation between curved and straight railings when they are subjected to the same vehicular collision conditions, impact angle and railing features and grade.
(2) Improve the new-type curved steel bridge railings which satisfy the improvement functions in the current Japanese specifications. The post of those railings is designed with smaller and slender form. Both static and collision behaviours of posts are verified by experimental test. The numerical simulations are developed to investigate the performances of those curved railings.
(3) Investigate the performances of curved steel bridge railings with concave curvature under the collision of larger impact angles than hitherto. This analysis is performed to qualify the safety margin of the concave-curved railings when subjected to the case of large impact angles.
(4) Investigate the collision performances of the curved railing with a convex curvature under the impact of the truck. According to the concave or convex curvature of the curved bridges, a corresponding curved railing is applied to use. However, the current Japanese specifications have not concerned about the curved railing in the design and analysis. Thus, the numerical simulation is created to study the collision performances of such kind of curved railing in the present research.
(5) From the results of study, recommendations and remarks for the curved steel bridge railing in the design and analysis are made.

1.5 Method of study

Figure 1.2 shows the flow of study for the present topic. A full-scale test of curved railing under the collision load would be the ideal methodology for purpose of this topic but this test requires a considerable cost and effort. Nowadays, with powerful computer software and using a supercomputer, the collision problems can be modelled easily with a full set of properties and boundary conditions. Thus numerical analyses are relied on to study the performance of curved steel railings in this topic.

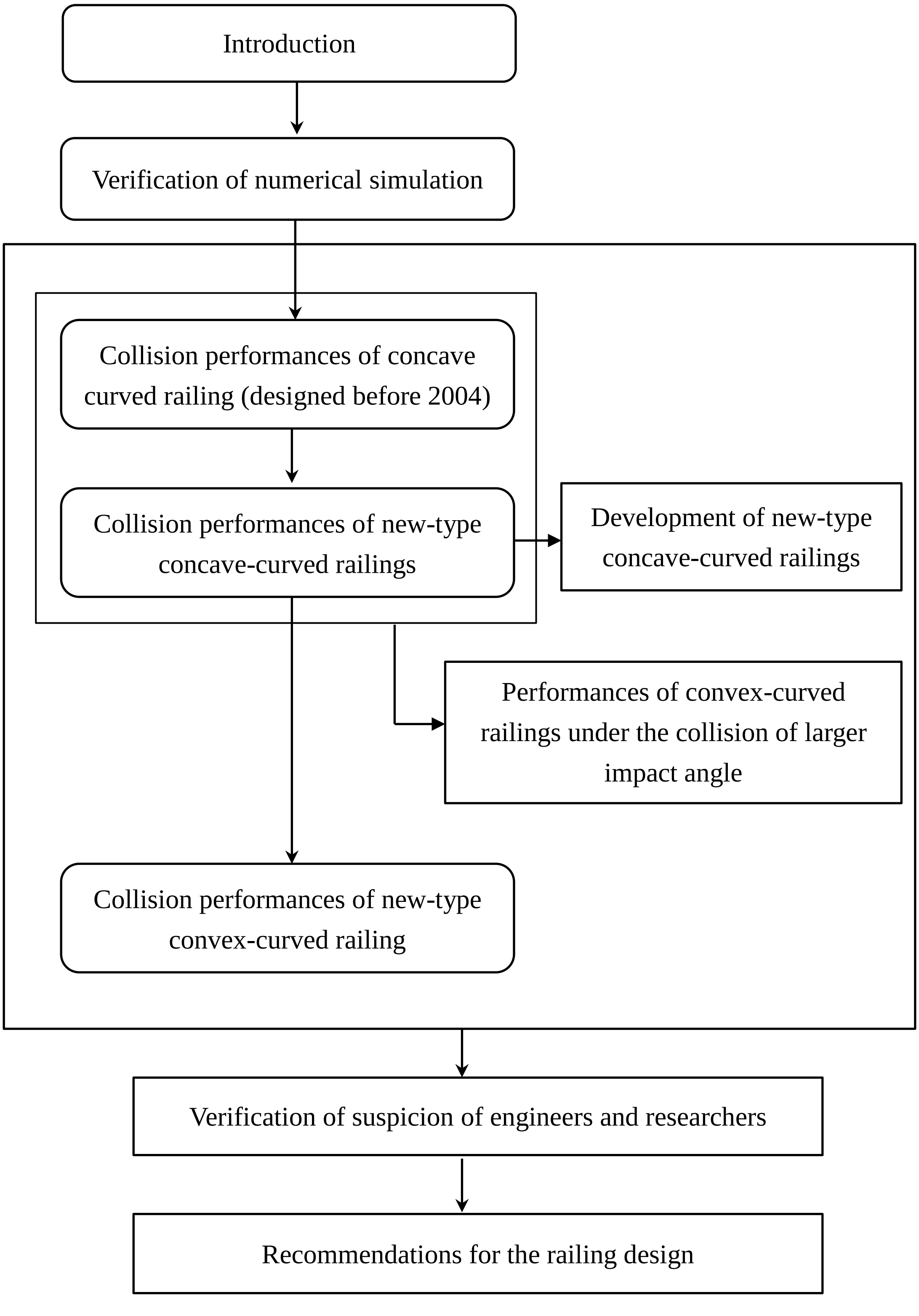

Figure 1.2 Flowchart of the research

The procedures of the study are following as: (1) to verify the numerical simulation by using the experimental results and adopting the experiences and assumed properties from existing researches performed by our laboratory; (2) to study performances of concave-curved railing subjected to the truck collision; (3) to develop new-type concave-curved steel bridge railings under the impact of the heavy truck; and (4) to investigate performances of new-type convex-curved railing subjected to heavy truck collision.

In the second procedure, performances of concave-curved railing are investigated by using only numerical simulations. A combination of partial experimental tests for railing posts and numerical simulations for full curved railings is main method in the third and fourth procedure of study. The LS-DYNA 3D software is engine of numerical analyses in this study.

1.6 Limitation of the study

According to objectives of the present study and limited time of study program, this study is limited into the following scope as:

(1) To investigate the performances of steel bridge curved and straight railings under the impact of a heavy truck with the weight of 25 ton (245 kN).
(2) The railing post investigated in the study is made of flanges and web, and has cross-section of H-shape. The railing beams have a pipe cross-section.
(3) The railing investigated in the study is designed to install on bridges.

1.7 Content of the study

The study consists of six chapters and its organization is shown in **Figure 1.3**. The present chapter explains about the rational, statements, and objectives of the research and the general introduction for the field of impact collision.

Chapter 2 reports the result of the verification of numerical collision simulation. The full-scale test for the collision performances of steel straight railing under the impact of the truck carried out by Japan Public Works Research Institute [14] were simulated by the finite element models. From the comparison between numerical and experimental results, assumed properties of model, mesh size of element, strain rate effect, sleeve connection between beam and beam and so on are adopted into the present study of the collision performances of curved steel bridge railings.

The performances of the concave-curved steel bridge railing subjected to the truck collision load are studied in **Chapter 3**. This type of railing has an H-shape cross section, and was designed before 2004. The concave-curved railing is improved from a straight railing with keeping the same railing features and collision condition. The concave-curved railings investigated have the curve radius of 100 m, 150 m, 280 m and 460 m.

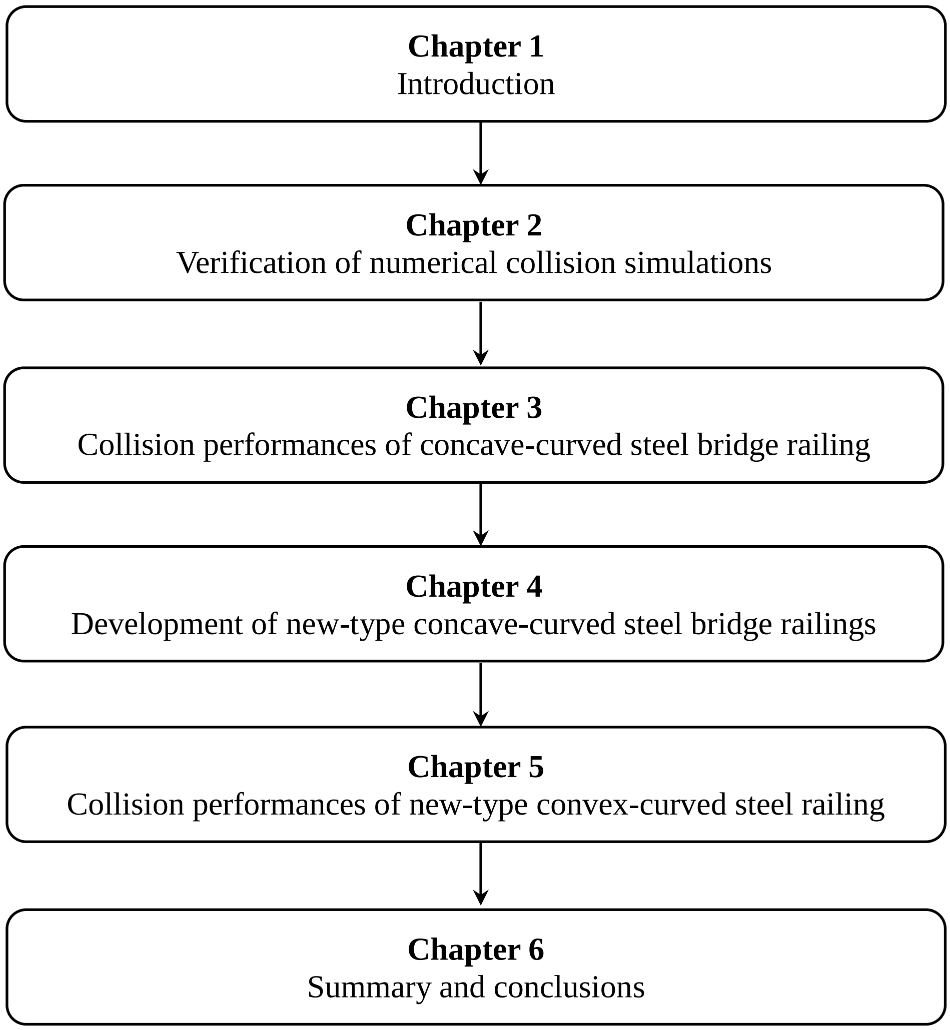

Figure 1.3 Organization of the study content

Chapter 4 reports a development of two new types of concave-curved steel bridge railings. The posts of such railings have a slender form, and meet improvements in the Japanese specifications for the railing design issued in 2004. Performances of those posts are examined by experimental static and collided test and numerical analysis. The numerical simulations of posts are verified by comparing its results with those of experimental test. The verified simulations of posts are adopted to develop impact collision simulations of new-type concave-curved steel bridge railings subjected to the truck collision.

To verify the suspicion of engineers and researchers, the behaviors of concave-curved steel bridge railings investigated in **Chapters 3** and **4** are compared with those of corresponding straight one which is subjected to the same collision conditions of truck and impact angle. As with the discussion in section of statements of the study, the 20^o and 25^o impact angles may occur on railings with a curve radius of 100 m and 150 m. Thus, those railings under the collision of the large impact angles are examined.

Study of performances of a curved railing with convex curvature subjected to heavy truck collision is presented in **Chapter 5**. The convex-curved railing investigated in this chapter names M-type which is one of railing types presented in **Chapter 4**. The convex-curved railing has radius of 100 m, and is subjected to collision conditions for railing grade of A following mentions in the current Japanese specifications for the railing design.

The finite element models of impact collision between the railings and the heavy truck are created by using the LS-DYNA 3D software. The study problems are determined with an executing by supercomputer installed at Information Technology Center of Nagoya University, which has a peak speed of 60 TFLOPS.

Summary and conclusions of the present study and recommendations and remarks for the design of curved steel bridge railing are presented in **Chapter 6**.

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Chapter 2

VERIFICATION OF THE NUMERICAL SIMULATIONS

2.1 Introduction

The Japanese Public Works Research Institute (JPWR) carried out a series of experimental tests for the steel straight railings under an impact of heavy truck in 1992. One of those tests was simulated by finite element models using LS-DYNA 3D software in our laboratory.

The numerical results of the railing and truck are compared with their experimental ones. This comparison would verify the numerical simulation of impact collision between the railing and truck. The methods and assumed properties of such verified simulation are adopted into studies of performances of concave-curved and convex-curved steel bridge railings subjected to truck collision. The flowchart of present study is shown in **Figure 2.1**

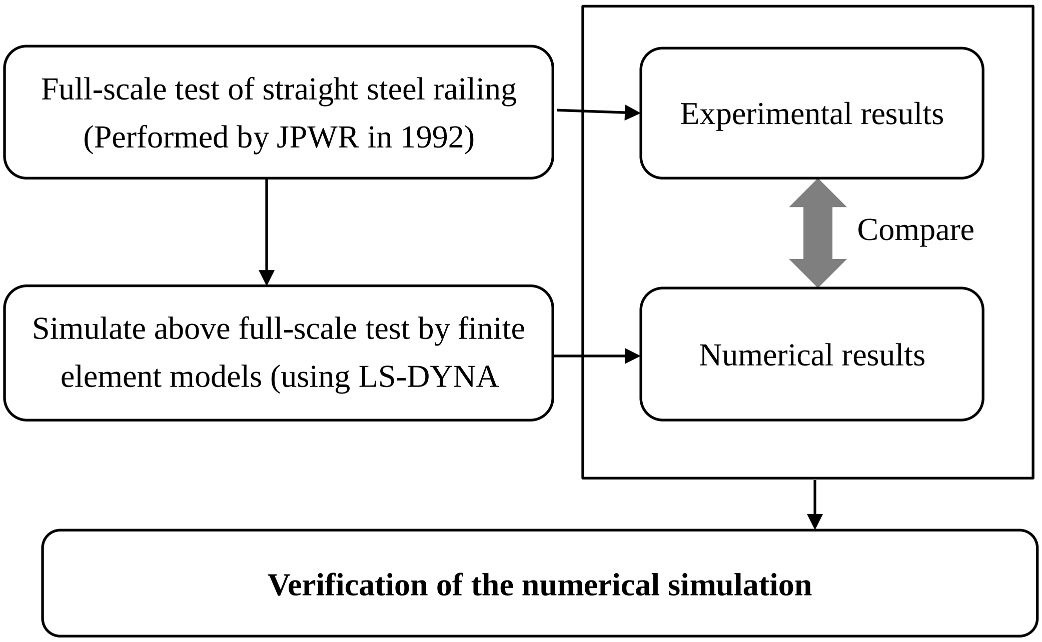

Figure 2.1 Verification of the numerical simulation

The straight steel railing investigated is subjected to the collision conditions of the truck weight and speed of 25 ton (245 kN) and 80 km/h and the impact angle between the railing and truck is 15^{o}. According to Reference [2], the railing has a grade of SA.

2.2 Finite element models

2.2.1 Railing model

The railing is made of steel posts and beams and concrete curb. To connect beam and beam, a pipe sleeve is used. The pipe sleeve is fastened onto the beams using high-strength bolts. The cross-sections of railing post and beam are an H-shape and pipe, respectively. The finite element model of railing is shown in **Figure 2.2**.

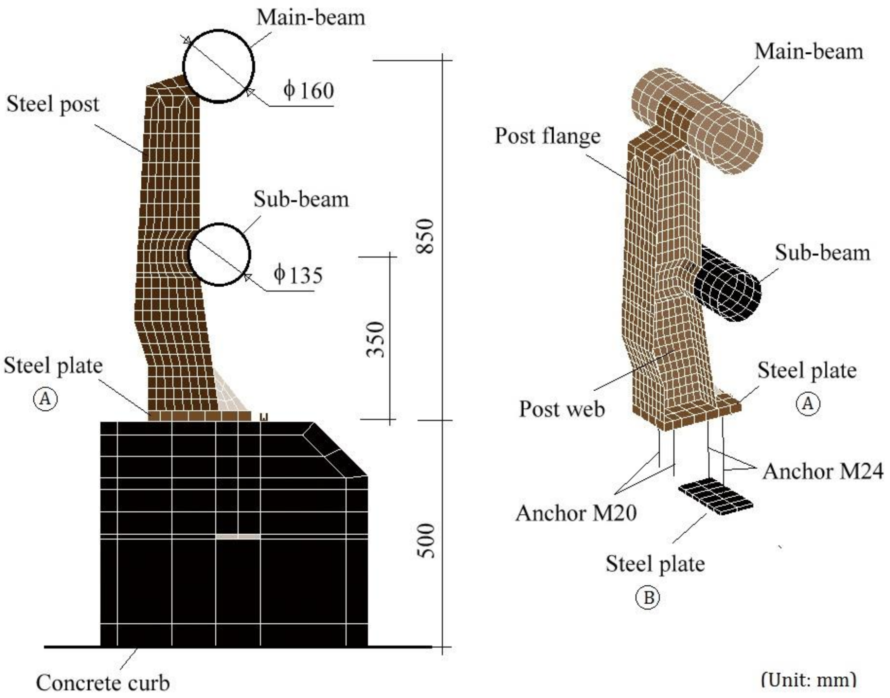

Figure 2.2 Finite element models of the railing

The beams are created by four-node shell elements. The diameters of main and sub beam are 160 mm and 135 mm with thickness are 7 mm and 4 mm, respectively. The post model is created by four-node shell element. The flanges and web of post are 150 mm and 158 mm in wide and 9 mm and 6 mm in thickness, respectively. The concrete curb can be considered as bulk component of railing, thus the simulation of concrete curb is modelled by eight-node solid elements.

The static and dynamic properties of steel are obtained from experimental tests and modelled into the LS-DYNA 3D software. The material model of steel is an isotropic elasto-plastic material following von Mises yielding criterion with properties matched of experimental ones. According to Reference [1], the steel grades used for railing members and their main properties are presented in **Table 2.1**.

Table 2.1 Properties of the steel materials used for the railings

Description	Steel grade	Mass density (kg/m^3)	Poisson's ratio	Young modulus (GPa)	Shear modulus (GPa)	Yield stress (MPa)
Beam	STK400		0.3	206	88	235
Post	SS400	7850	0.3	206	88	235
Steel plate	SS400		0.3	206	88	235

The concrete is simulated as the 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 concrete curb is modelled with the general elasto-plastic condition. This means that the concrete in compressive side comes to yield point and only the cut-off stress is available once the tensile stress increases to the tensile strength. The steel reinforcements are modelled as bar elements. The curb is considered as fixed end. A typical model of railing in three-dimension is presented in **Figure 2.3**

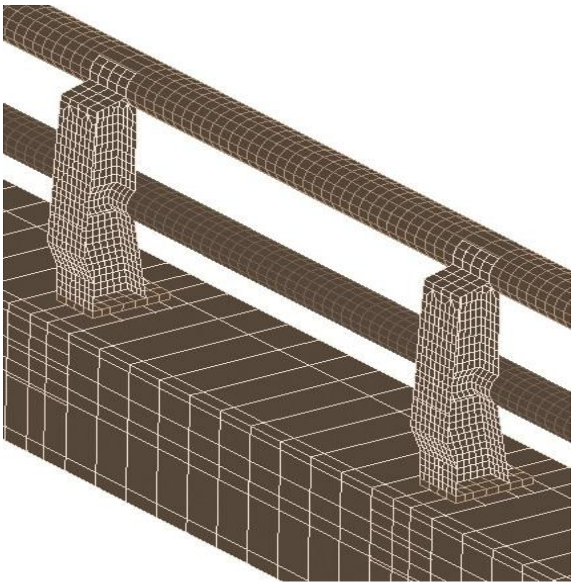

Figure 2.3 The railing model in 3D

A steel plate with thickness of 25 mm is welded into the post at bottom. In fact, this plate is fastened onto the concrete curb by using two anchors of M20 and two anchors of M24. Those anchors are secured to another steel plate that is set in the concrete curb. In the numerical simulation, the steel plates are modelled by eight-node solid elements. The anchors are modelled as bar elements. The connection between the anchors and the steel plates is modelled as a joint connection. The connection between the steel plates and the concrete curb is simulated as a contact of elements to elements in LS-DYNA 3D.

2.2.2 Truck model

The finite element model of truck was successfully developed in Nagoya University with a support from a truck manufacturer and presented in many existing researches performed in our laboratory [3, 4, 5]. The geometry and dimensions of truck model matches those of an actual truck used in the experimental test. The truck components of engine, cargo and transmission are modelled as eight-node solid elements. The four-node shell elements are used to create the truck members of side, frames, cab, and fuel tank. The truck with weight of 25 ton (245 kN) is summed from weights of truck members and cargo. The finite element model of truck is presented in **Figure 2.4**.

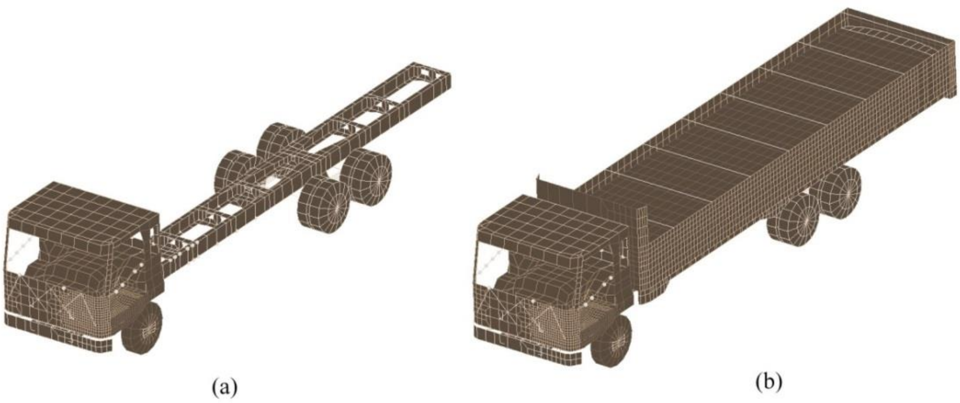

Figure 2.4 Finite element models of the truck (a) Ladder-type truck frame and (b) Whole truck model

The truck has a length of 11,800 mm, height of 3,300 mm and width of 2,500 mm. The truck's gravity center is around a height of 1400 mm from the road pavement. Truck is assumed to travel on a road which has a descending cross slope of 6 percent and the friction coefficient between truck's tires and road pavement is 0.45. The connection between tire and wheel is modelled as a rotation joint.

The side member of truck is thickness of 8 mm and its material is modelled as the general elasto-plastic stress-strain relationship. The steel of truck is modelled as an isotropic elasto-plastic material following the von Mises yielding condition. The aluminium alloy used for cargo body is modelled as a multi-piece linear stress-strain relationship. The properties of truck material are presented in **Table 2.2**. The total numbers of elements and nodes in the truck model are 9,344 and 9,830, respectively.

Table 2.2 Properties of the material used for the truck

Material	Mass density (kg/m3)	Young Modulus (GPa)	Yield stress (MPa)	Poisson's ratio
Aluminium alloy	2720	70	245	0.34
Steel	7850	206	295	0.30

A numerical simulation of impact collision of the present straight steel railing under an impact of the heavy truck in three-dimension is presented in **Figure 2.5**. Posts and beam located from post numbers 5 (P5) to 11 (P11) undergo large collision loads from the truck, thus this area on the railing is called as collision area.

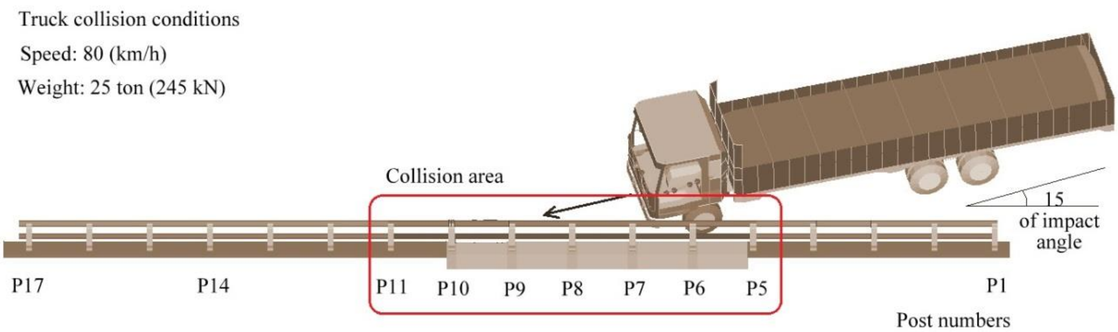

Figure 2.5 Impact collision simulation between the straight railing and heavy truck

2.3 Verification of numerical simulation

2.3.1 Effect of mesh size on numerical result

In the numerical analysis, the mesh size of element affects computation time and approximation of numerical solution in comparison with experimental one. A fine density of element mesh will increase the time of computation and analysis progresses, but a coarse density in element mesh will reduces an accuracy of numerical solution. Therefore, this section reports the option of mesh density which is applied on the railing to study the performances of steel railing under vehicular collision.

Figures 2.6 and **2.7** present two densities of element mesh investigated in this study named 4-4-8 and 8-8-35 models. The first and second figures indicate the numbers of mesh elements on the horizontal grid for flanges and web, respectively. The third figure is indication of the number of elements along the beam each span. For example, in case of 4-4-8 models, the flange and web of all posts are meshed with 4 elements on the horizontal grid and all beams are meshed with 8 elements along each beam span

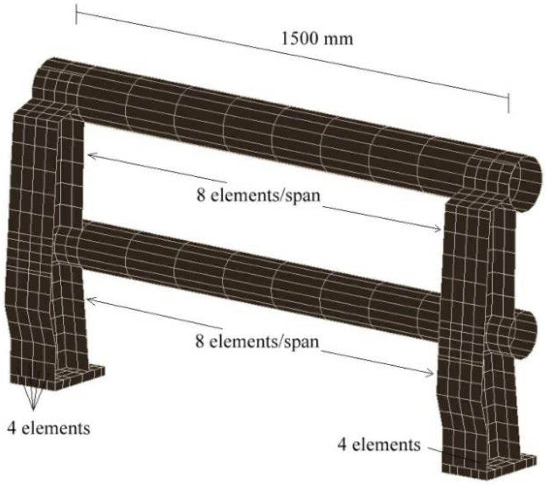

Figure 2.6 Mesh element type of 4-4-8 model (Unit: mm)

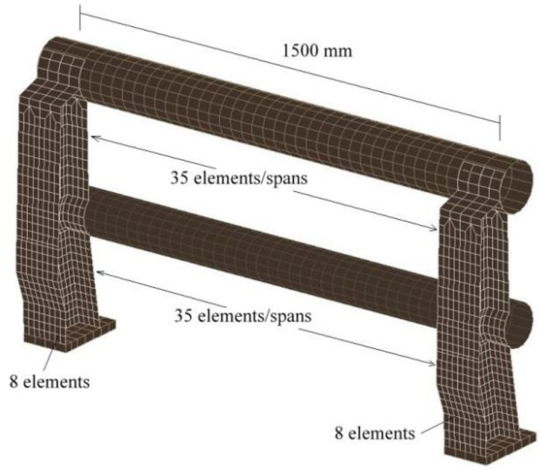

Figure 2.7 Mesh element type of 8-8-35 model (Unit: mm)

For the 8-8-35 model case, only beams and posts closest to the collision area are applied with this density. The element sizes of post flange and web are 18.7x25 mm and 19.8x25 mm, respectively. The element sizes of main-beam and sub-beam are 38.5x30.8 mm and 38.5x26.4 mm, respectively. The other beams and posts along the railing in either direction, the 4-4-8 models of mesh density are applied. The element sizes of flange and web are 37.5x50 mm and 39.8x50 mm, respectively, and main-beam and sub-beam are 168.7x30.8 mm and 168.7x26.4 mm, respectively.

To determine an effective mesh density, the numerical results of both element mesh models are compared with those of experimental one [1] as shown in **Figure 2.8**.

The element mesh sizes of concrete curb, steel plate, and the truck are similar in both cases.

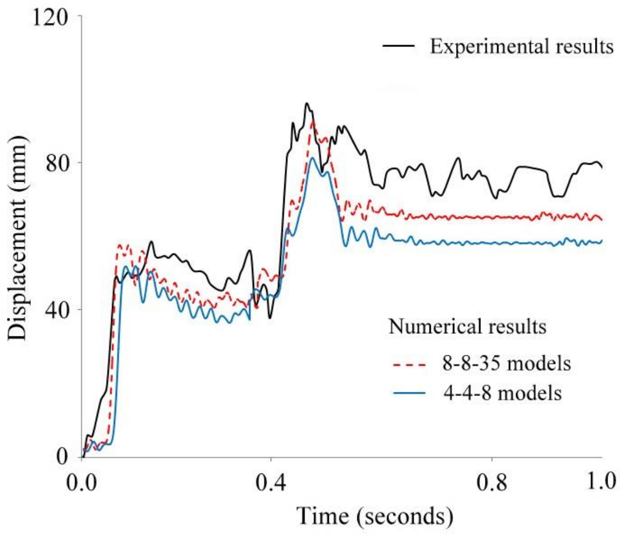

Figure 2.8 Effect of element mesh size on the numerical solution

The displacement-time histories shown in **Figure 2.8** indicate that two stages are occurred during the impact collision. In the first stage, the front bumper of truck crashes into the railing. The maximum numerical displacements caused by the first stage are close to experimental ones. The second stage occurs when the rear part of the truck body hits the railing. For this stage, the maximum and residual displacements of 8-8-35 model are closer to the experimental displacement than the other model. **Figure 2.8** shows that in both collision stages, the 8-8-35 models have approximate solutions to the experimental one, thus this element mesh size is adopted into the study of collision performances of steel bridge railing under the impact of truck.

2.3.2 Effect of strain rate of steel

The numerical analysis considers the effect of strain rate of steel to the behaviours of railing. According to Reference [6], the strain rate effect model for the steel grade of SS400 which is used to make the railing posts and plate is presented in **Figure 2.9**. Such model also was reported in existing previous papers published by our laboratory Reference [7, 8]. For the steel grade of STK400 which is used to make the railing beams, the strain rate effect is presented as that of 0.2% offset yield stress determined following **Equation (2.1)**. Both models, the yield stress increases with the increase of the strain velocity.

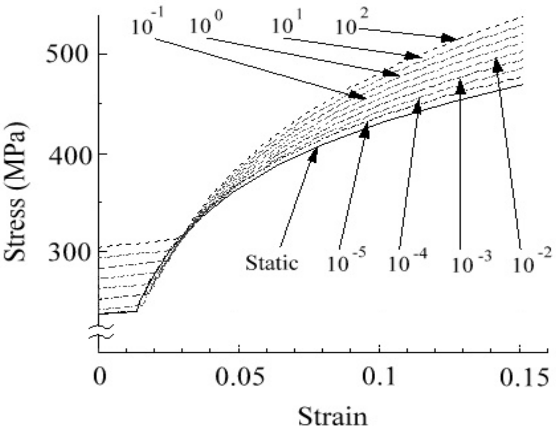

Figure 2.9 Model of strain rate for the steel grade of SS400

$$\frac{\sigma_d}{\sigma_s} = 1.11 + 0.0213 \log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_u}\right) \quad (2.1)$$

Where,

σ_d : is the dynamic stress (MPa);

σ_s : is static stress (MPa); and

$\dot{\varepsilon}$: is the strain velocity (1/s).

In order to compare the numerical results of the strain rate effect on the railing displacements, two types of analysis results follow as

(1) *Without strain rate*: Analysis without any consider of strain rate of steel

(2) *With strain rate*: the increase of yield stress of steel following the increase of the strain velocity is modelled into the numerical analyses.

The comparison between the calculated numerical displacement with or without strain rate effect and the experimental displacement is shown in **Figure 2.10**. The displacement-time history of numerical results is similar to that of experiment one with the first collision stage occurred at time of 0.15 seconds and the second stage at 0.5 seconds. The result of analysis indicates that in the both collision stages the residual and maximum amount of displacements come closest to the experimental one when considering the effect of strain rate into the steel model. Therefore, the effect of strain rate of steel will be counted into the numerical analysis of performances of steel bridge railing subjected to the truck collision.

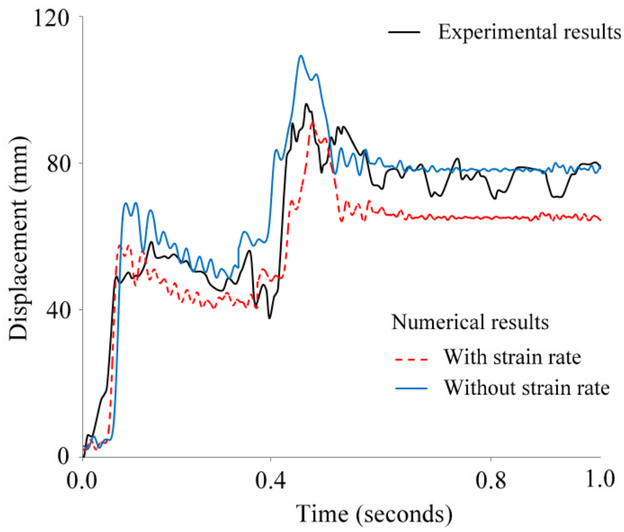

Figure 2.10 Effect of strain rate of the steel on the numerical solution

2.3.3 Sleeve connection between beam and post

A steel pipe sleeve was used to connect beam and beam in fact. The pipe sleeve has 300 mm length and 6 mm thickness. The properties of sleeve steel are similar to those of the railing beams. Accordingly, effects of sleeve connection on the railing displacement are investigated in the numerical analysis.

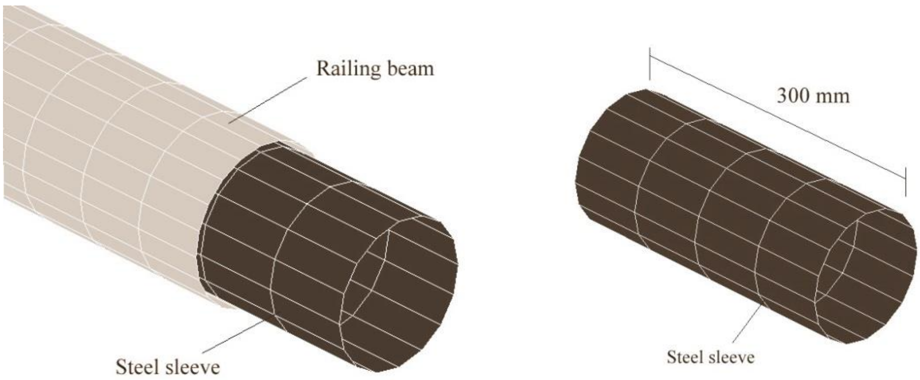

Figure 2.11 Sleeve connection between beam and beam

The finite element model of pipe sleeves is shown in **Figure 2.11**. The pipe sleeves are modelled by four-node shell elements. The contact between pipe sleeve and beam is defined as a surface to surface contact in the LS-DYNA 3D software. The comparison of numerical displacements for the two cases of sleeve and continuous connection with experimental one is presented in **Figure 2.12**.

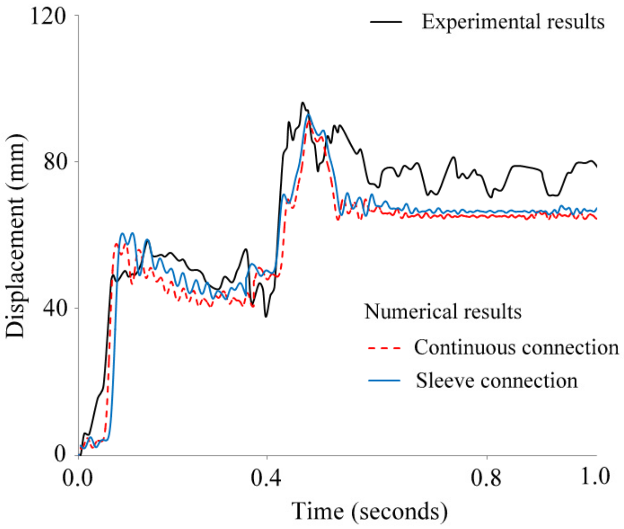

Figure 2.12 Effect of connection types on the numerical solution

The tracks of displacements shown in **Figure 2.12** indicate that the behaviours of both railing cases which are counted with sleeve and continuous connections are similar to experimental ones. In the fact, the sleeve pipes are fastened onto the beams using high-strength bolts. Those bolts can prevent any transposition of the connection joint along the beam center axis. Thus, in order to simplify the representation of numerical model the continuous connection is assumed in the collision simulation of railing subjected to truck collision.

2.4 Conclusion

On the basis of numerical results and comparisons between the numerical and experimental solutions, summaries and discussions of present study can be concluded as following:

(1) From the results of existing researches and current study, they can be seen that the impact collision of steel bridge railing under the vehicular impact can be studied by the finite element model using the LS-DYNA 3D software.

(2) From the comparison of displacement results between two models of element mesh size with experimental one, the results in the case of element mesh of 8-8-35 density are more accurate than those in the other ones. Therefore, this type of mesh density is applied for the next analyses of the study.

(3) The numerical displacements with considering the effect of strain rate of steel are closer to the experimental ones. Thus, the strain rate of the steel material is

counted into the numerical analyses of the steel bridge railing subjected to the heavy truck collision.

(4) The railing behaviours in the cases of continuous and sleeve connections are similar. On the other hand, the high-strength bolts prevent any transposition of the connection joint along the beam center axis. To simplify the model representation and save computation time, the continuous connection is adopted for numerical analysis of the performance of steel bridge railings under the impact of the truck.

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Chapter 3

COLLISION PERFORMANCES OF CONCAVE-CURVED STEEL BRIDGE RAILING

3.1 Introduction

The main objectives of research presented in this chapter are to study the collision performances of concave-curved steel bridge railing subjected to the impact of heavy truck. The type of present railing was successfully designed to install on straight bridge before 2004. The railing has grade of SC, and is subjected to collision of truck speed of 50 km/h, truck weight of 25 ton (245 kN) and impact angle of 15^{o}. The performances of this straight railing were studied by using the numerical analysis and presented by Hirai and Itoh [1].

The procedures of present study are shown in **Figure 3.1** with two main objectives. The first is to verify the suspicion of some researchers and engineers about safe situation between the straight and curved railing. The second is to investigate the performances of concave-curved steel bridge railing under the collision of the impact angles which are larger than angle specified in the Japanese specification for the railing design.

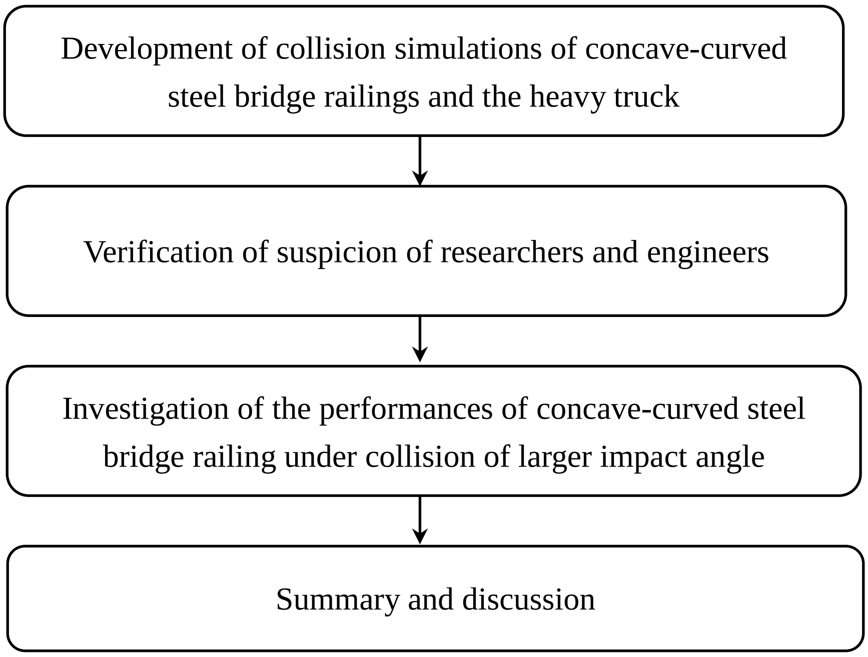


Figure 3.1 Flowchart of the present study on the concave-curved steel bridge railings

For the first objective, the experiences and assuming properties of representation of collision models successfully developed by our laboratory are adopted into the present study of performances of concave-curved steel bridge railings. The models of post, beam and curb successfully simulated for straight bridge railing are used to create simulations of concave-curved bridge railings subjected to truck collision. The numerical results of concave-curved railings are compared with those of corresponding straight one in the same collision conditions of truck and impact angle.

According to Reference [2], the speed of vehicle on curved road sections and bridges are limited by their curvature radius. The relationship of vehicular speed and the radius of road and bridge curvature is presented in **Table 3.1**.

Table 3.1 Road curvature-vehicular speed relationship

Road curvatures (m)	Limitation of speed
460	100
280	80
150	60
100	50

The designed railing grade of SC investigated in the present study under collision of 50 km/h vehicle speed meet speed requirements of all types of curved bridges shown in **Table 3.1**. Accordingly, the present study conducts for railings with the concave curve radius of 100 m, 150 m, 280 m and 460 m. **Figure 3.2** shown procedures for the first objective of present study. The expected results are to demonstrate the performances of concave-curved railings and qualify the suspicion of researches and engineers.

The study finds that by some human reasons the impact angle between concave-curved railings with a curve radius of 100 m and 150 m and the vehicle may be larger than angle which is specified in the Japanese specifications for the railing design. Thus, the next objective of the present study is to examine the performances of such concave-curved railings subjected to the collision of the larger impact angles. **Figure 3.3** presents the procedures of the study. The finite element models of impact collision problems are created by using LS-DYNA 3D software.

3.2 Finite element model of railing and truck

Figure 3.4 presents the 3D model and cross-section of railing post. As for the railing posts, the compression and tension flanges are 150 mm width and 6 mm thickness and the web is 145 mm width and 4.5 mm thickness, respectively. The main-beam and sub-beam are pipe cross-section with diameters of 140 mm and 114 mm and thicknesses of 6 mm and 3.5 mm, respectively. The beams and posts are modelled by using four-node shell elements.

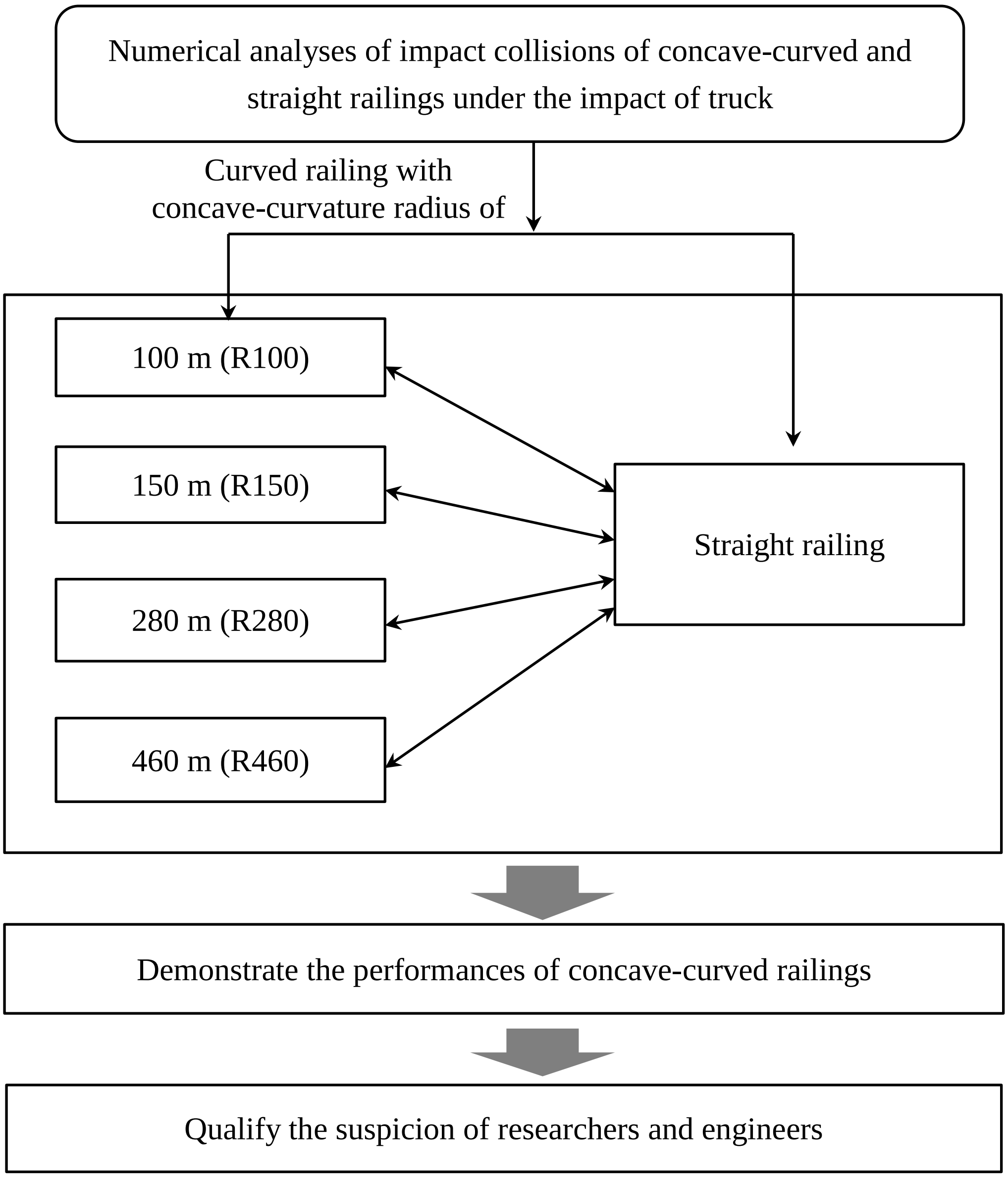


Figure 3.2 Procedures of the present study for the first objective

The beams and post are made of steel grade of STK400 and SS400, respectively. The models of steel and concrete materials are created similar to those in section 2.2.1. Properties of materials used for railing members are shown in **Table 3.2**. The highest mesh density of elements are applied for posts and beams located in the collision area (from post numbers 5 to 11). The other posts and beams along the railing in either direction, larger element sizes of mesh are applied. Span between post and post is around 1500 mm.

The finite element model of the truck represented in section 2.2.2 is again adopted for collision analyses in this chapter. The truck crashes into the railing beams at a point between post numbers 8 and 9. **Figure 3.5** shows the typical simulation of impact collision between concave-curved and straight railings with the heavy truck.

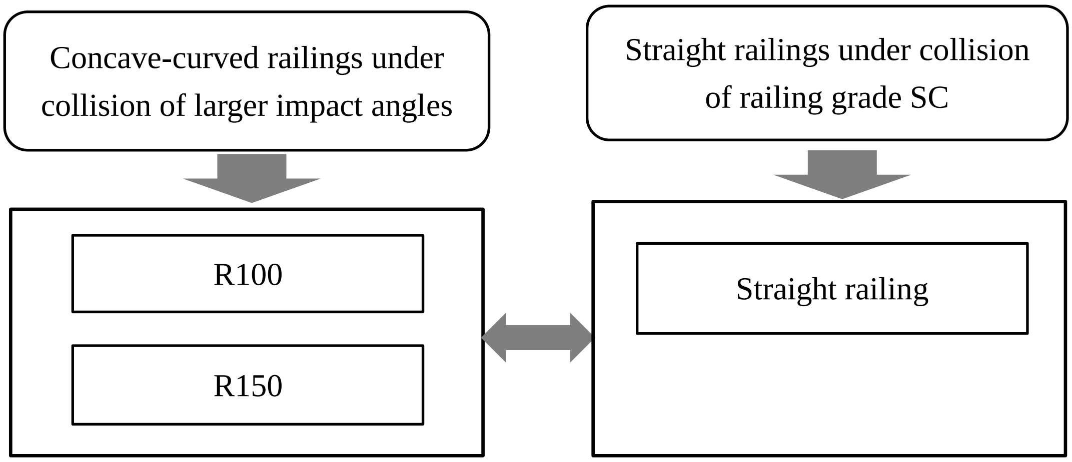


Figure 3.3 Procedures of the present study for the second objective

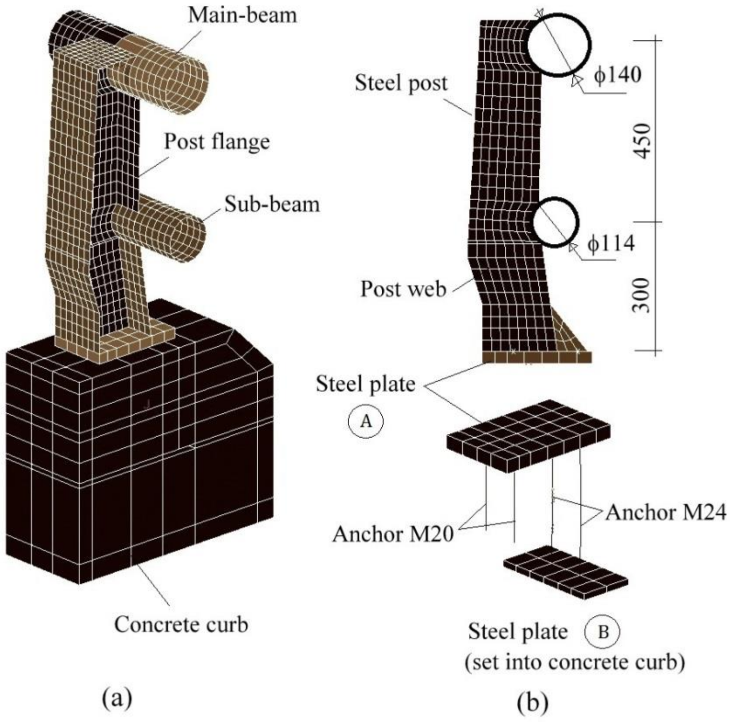


Figure 3.4 Finite element models of the railing (a) 3D model and (b) Cross-section of post (Unit: mm)

Table 3.2 Properties of the steel materials used for the railings

Description	Steel grade	Mass density (kg/m^3)	Poisson's ratio	Young modulus (GPa)	Shear modulus (GPa)	Yield stress (MPa)
Beam	STK400		0.3	206	88	235
Post	SS400	7850	0.3	206	88	235
Steel plate	SS400		0.3	206	88	235

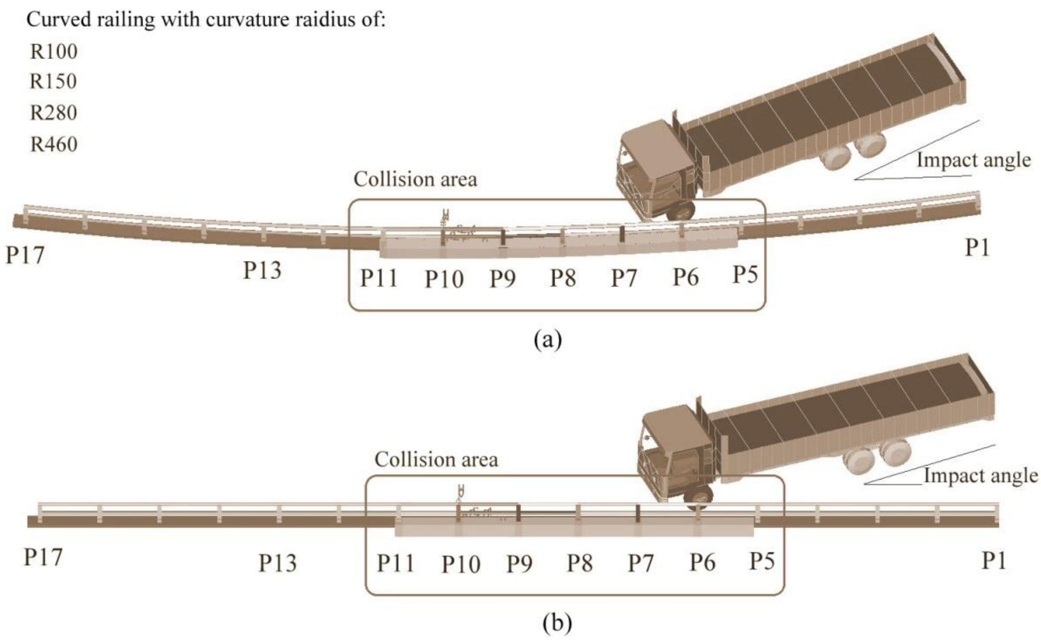


Figure 3.5 Typical collision simulations of railings subjected to the heavy truck collision (a) Concave-curved railings and (b) Straight railing

3.3 Performances of concave-curved railing

According to the purpose of the present study, the models of railing post, beam and curb and material properties and so on which are successfully simulated for straight railing are adopted to create simulations of concave-curved railings with a curve radius of 100 m, 150 m, 280 m and 460 m.

To verify the suspicion of researchers and engineer, all concave-curved and straight railings are subjected to the same collision conditions of truck weight of 25 ton (245 kN), truck speed of 50 km/h and the impact angle of 15^o. The numerical results of concave-curved railings with displacements, absorbed energy and truck behaviours are compared with those of corresponding straight one. The flowchart of the present numerical analysis is shown in **Figure 3.6** and the results of study are presented in the following sections.

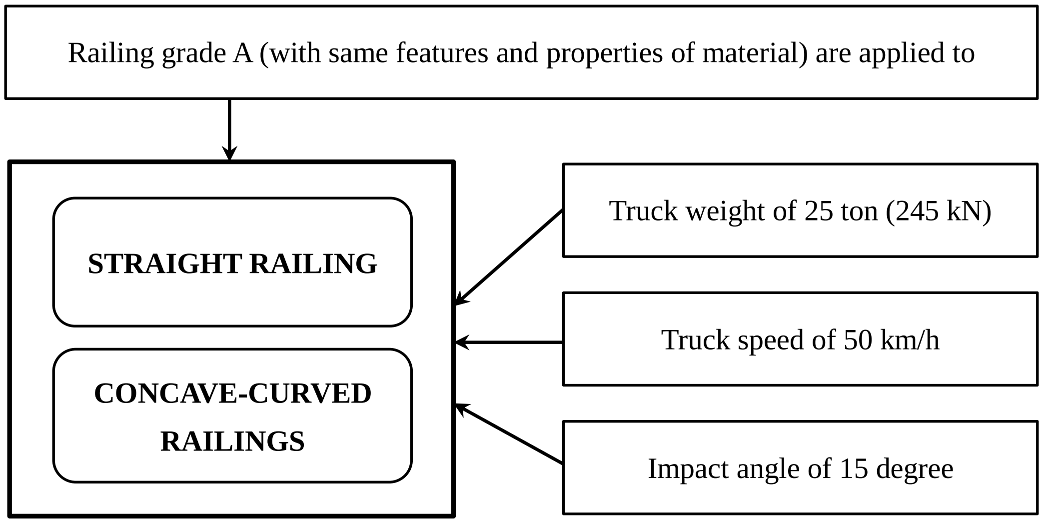


Figure 3.6 Procedures of the verification of the researcher and engineer suspicion

3.3.1 Railing displacements

The current Japanese specifications for the railing design have prescribed that the allowable displacement of railing under the collision loads is not over 300 mm. Accordingly, the numerical displacements shown in here are the largest displacements occurred on the railings. Because, the truck crashes into the railing beams at a point between post numbers 8 and 9, the maximum displacement on the railing normally occurs at the top part of post 8. The displacement-time history of posts in those railings is presented in **Figure 3.7**.

The displacement-time history indicates that the behaviours of straight railing and concave-curved ones with a curve radius of 100 m, 150 m, 280 m and 460 m are similar. There is only one collision stage occurred during the impact collision. This stage is caused when the front bumper of truck crashes into the railing. The second collision stage does not occur. This behaviour is different with results shown in section from 2.2.3 to 2.3.5 which two collision stages are occurred. This difference can be explained that the speed of the present truck is smaller than that of previous case.

The largest displacement on all railing cases occurs at the point where the first collision stage is happened. After this moment, amount of railing displacements becomes a constant. **Table 3.3** shows the summary of the maximum displacements at the top of posts 8 and 9 for all cases of railing.

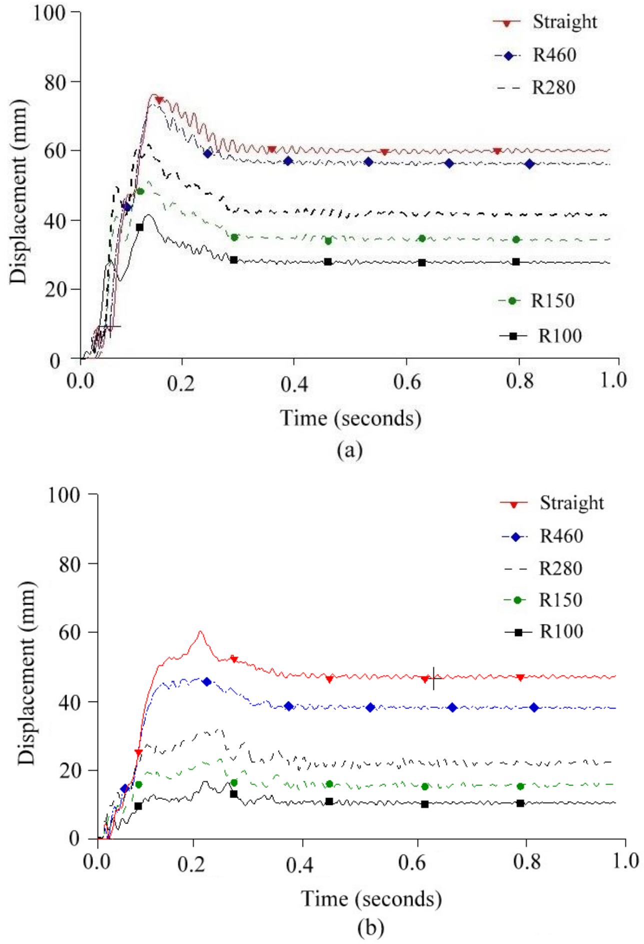


Figure 3.7 Displacement-time histories of the railing posts (a) Post number 8 and (b) Post number 9

Table 3.3 Maximum displacements of the railing posts

Railing types	Displacements (*mm*)	
	Post 8	Post 9
Concave-curved railings		
R100	43	17
R150	53	23
R280	64	37
R460	75	47
Straight railing	79	60

The numerical results can be seen that the displacements of straight railing and concave-curved ones are smaller than 300 mm, and meet requirement of Japanese specifications for the railing design. The largest displacement occurs in post 8 of straight railing with amount of 79 mm and smallest one occurs in the concave-curved railing with the 100 m curve radius. The displacements on railing with the concave curve radius of 460 m are close to those of straight one.

Some engineers and researchers have reasoned that in the same collision conditions of vehicle, properties of railing and impact angle the curved railings undergo larger displacement than straight one, thus the curved railings are more disadvantageous than the straight railings. However, the numerical results shown in **Figure 3.7** and **Table 3.3** indicate that the displacements of all concave-curved railings are in fact always smaller than those of the corresponding straight railing. The displacement on concave-curved railing decreases with any decrease in the radius of railing curvature.

Lateral residual displacements of concave-curved and straight railings are presented in **Figure 3.8**. It can be seen that the impact collision load severely affects the posts and beams which locate in collision area (from posts 5 to 11). The displacements on the other posts along the railing in either direction are insignificant.

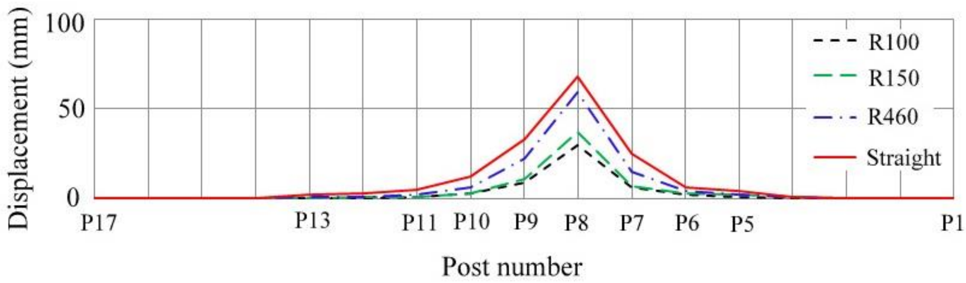


Figure 3.8 Lateral residual displacement pattern of the railings

3.3.2 Energy absorption of railings

During the impact collision, a portion of truck’s kinetic energy will transfer to the railing. Absorbed energy of railing is contributed to beams, posts and concrete curb with insignificant portion. According to the Japanese specifications for the railing design shown in **Table 1.1**, the largest energy which is allowed to transfer for the railing with grade of SC is 160 kJ. On the other hand, the railing beams and posts that undergo large displacement will involve much more energy than the others [3, 4]. The purpose of the study in this section is therefore to examine the energy behaviour of concave-curved railings during impact collision.

The energy absorbed by post number 8 is presented in **Figure 3.9**. The energy transferred to the railing beams is shown in **Figure 3.10**. They can be seen that the energy transferred to beams and posts of straight railing are much greater. For the case of concave-curved railing with a curve radius of 100 m, the amount of absorbed energy of its beams and post is smallest.

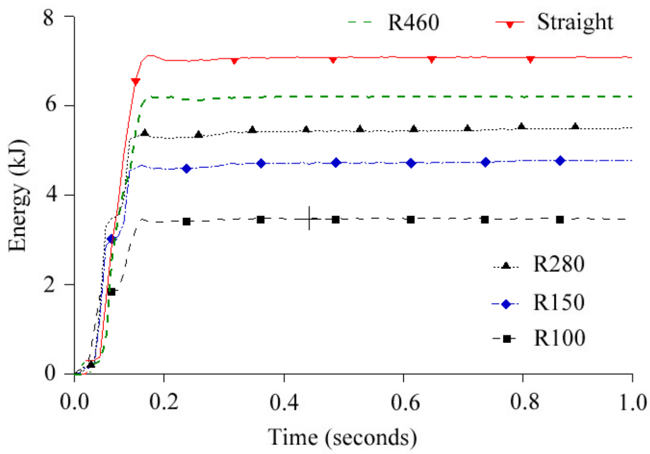


Figure 3.9 Absorbed energy of the post number 8

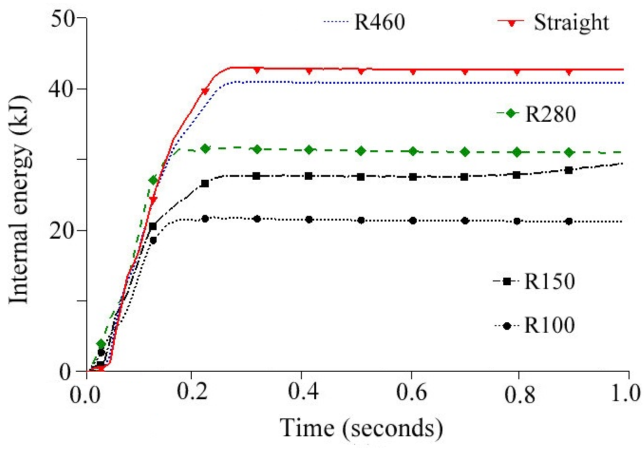


Figure 3.10 Absorbed energy of the railing beams

The energy absorbed by all railing member consisted of beams, posts, concrete curb, steel plates and steel reinforcements is presented in **Figure 3.11** and summarized in **Table 3.4**. They can be shown that the most energy transferred from the truck to the railing is absorbed by the beams. The energy absorbed by the concrete curb is insignificant. The straight railing absorbs the largest amount of transferred energy of 53.6 kJ. The energy transferred to the concave-curved railing with a curve radius of 100 m is smallest with 26 kJ.

According to **Table 1.1**, the energy transferred from the truck to all concave-curved and straight railings is smaller than 160 kJ and meets requirement of

Japanese specifications for the railing design. Because, the second collision stage does not happen during the impact collision, the absorbed energy of all railings does not increase after the point of front bumper of truck crashes into the railing.

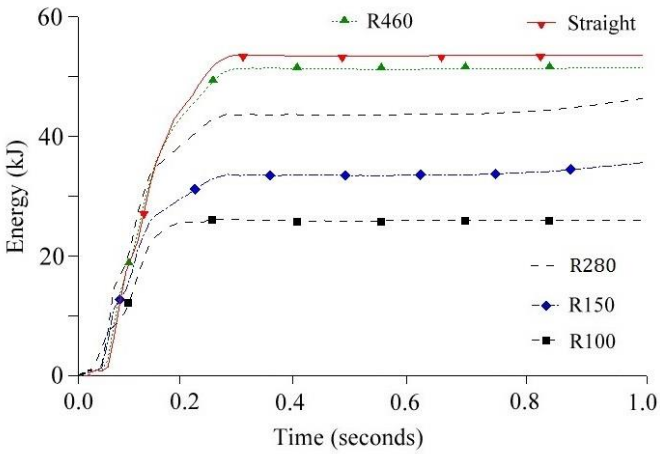


Figure 3.11 Absorbed energy of the all railing cases

Table 3. 4 Absorbed energy of the railing components

Type of railing	Absorbed energy				
	Posts		Beams		Whole railing
	(*kJ*)	(%)	(*kJ*)	(%)	(*kJ*)
Curved railing					
R100	4.3	*17*	21.1	*81*	26.0
R150	6.0	*17*	29.4	*82*	35.7
R280	7.2	*17*	34.2	*81*	42.4
R460	10.4	*20*	40.7	*79*	51.5
Straight railing	10.7	*20*	42.6	*79*	53.6

The numerical results of absorbed energy shown in this section indicate that the amount of energy transferred from the truck to the railing becomes larger with every increase in the radius of curvature of the concave-curved railing and in fact the straight railing always absorbs more energy than any concave-curved ones. The energy absorbed by straight railing may be around double amount of energy absorbed by concave-curved railing which has the smallest curve radius of 100 m.

3.3.3 Collision force on the railing posts

The collided shear force at the base of railing post numbers 8 and 9 is presented in **Figures 3.12** and **3.13**, in which P_y and P_{st} are the yield load and the load at the point where strain hardening appears, respectively. According to References [1, 5], amount of P_y and P_{st} are determined and shown in **Figures 3.12** and **3.13**. For post number 8, the collision force of all concave-curved and straight railings exceeds the yield load and reaches the strain hardening load. For post number 9 which has smaller displacement, the collision force is smaller than the strain hardening load, but reaches the yield load.

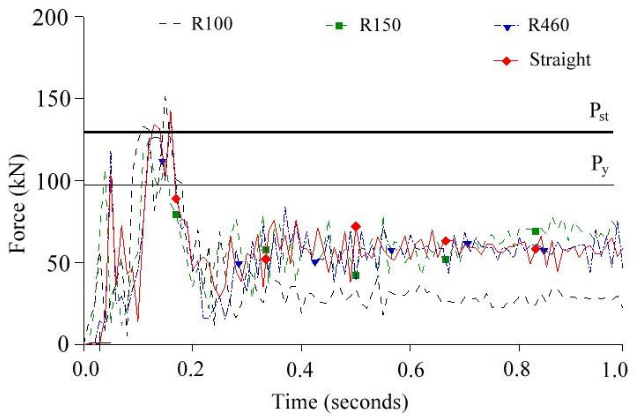


Figure 3.12 Collided base shear force of the post number 8

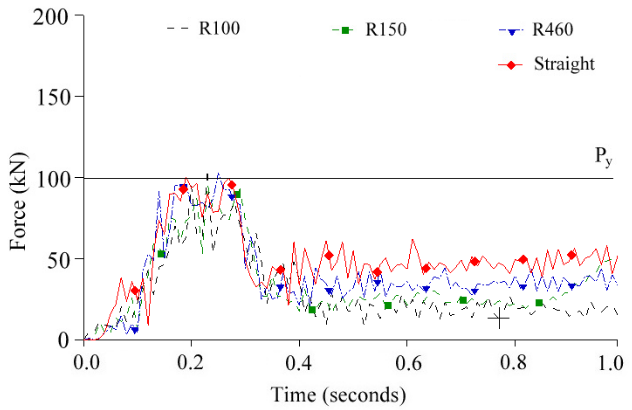


Figure 3.13 Collided base shear force of the post number 9

The above numerical results show that the displacement on post and energy transferred from the truck to the railing increase with increase of the radius of the railing curvature. In the same truck collision conditions and railing properties, the straight railing undergoes largest displacement and absorbs much energy. The maximum displacement on the straight railing is twice as large as that of a concave-curved railing with the smallest curve radius. It can be seen that the steel material of the straight railing posts may become inelastic and enter into the state of strain hardening earlier than those of the concave-curved railing ones.

3.4 Truck behaviours

3.4.1 Movement of truck

One of performance standard requirements for the railing is to guide the vehicles back to the line of the road. **Figures 3.14** and **3.15** present the movements of truck during the impact collision for case of concave-curved railing with a curve radius of 100 m, 150 m, and 460 m and straight railings.

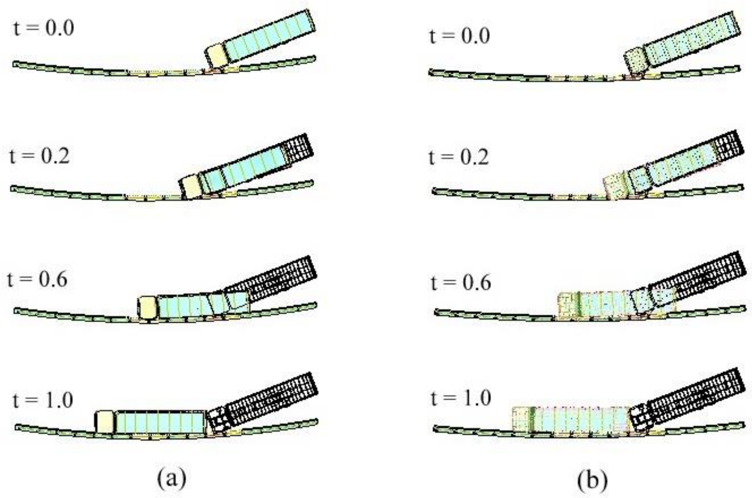


Figure 3.14 Movement of truck crashed into the concave-curved railings (a) Radius of railing curvature of 100 m and (b) Radius of railing curvature of 150 m

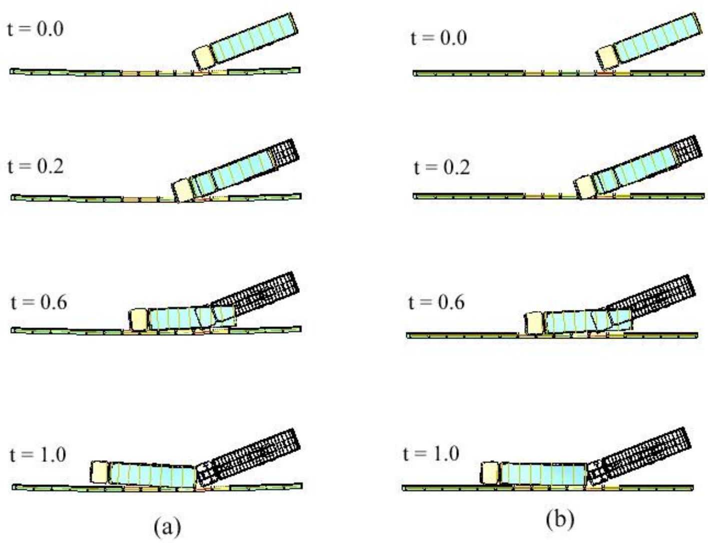


Figure 3.15 Movement of truck crashed into the concave-curved and straight railings (a) Radius of railing curvature of 460 m and (b) Straight railing

The figures of the truck's movement can be seen that after the front bumper of truck crashes into the railing the truck moves parallel to the railing by an orientation of railing beams and then runs toward the end of railing. The truck is guided back to the line of road by the railing. All concave-curved and straight railings meet required performances in the Japanese specifications for the railing design.

3.4.2 Breakaway of truck velocity

According to Reference [6], the remained speed of vehicle after the moment of impact collision must be over 60 percent of initial designed speed. For the railing grade of SC with the collision of truck speed of 50 km/h, the required speed of vehicle after the impact collision has to be larger than 30 km/h.

Figure 3.16 shows the velocity-time history of the truck's gravity center during the impact collision. It can be seen that in all cases of concave-curved and straight railings the remained speeds of the truck are larger than 30 km/h. Therefore, all concave-curved and straight railings meet requirements of vehicular breakaway speed in Japanese specifications.

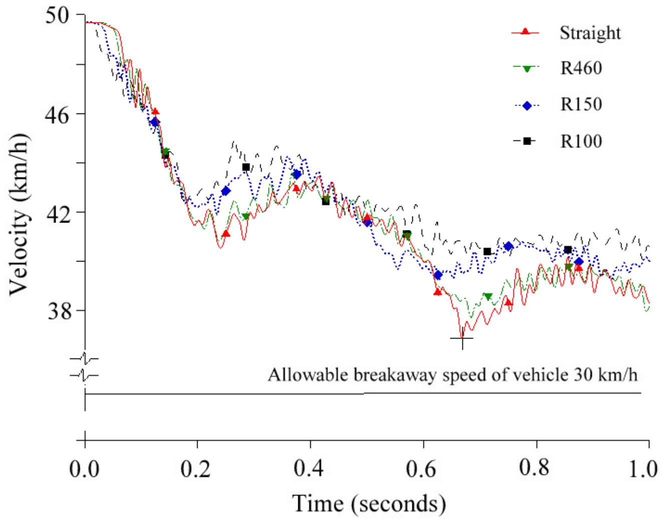


Figure 3.16 Breakaway of the truck velocity

3.4.3 Moving acceleration average

An important factor to ensure the safety for the vehicular passengers and driver is the acceleration of vehicle during the impact collision. This acceleration is measured at the gravity center of body of driver and passengers who are in the drive cabin. In the collision test, sensors can be attached on the human body called a dummy doll to measure that. However, a numerical simulation of human body requires much time and efforts, and is not the main purpose of the present study. Therefore, the study measures the acceleration at the gravity center of truck. This alternative method is also recommended in the Japanese specification for the railing design [6].

According to Reference [6], maximum amount of a moving acceleration average that is safe for driver and passenger for case of truck crashed into railing grade of SC must be smaller than 200 $m/s^2/10ms$. This value is an average of 21 representative acceleration points of 0.5 millisecond interval for each 10 milliseconds. The measured moving acceleration averages at the gravity center of the truck for cases of the concave-curved railing with a curve radius of 100 m and straight one are presented in **Figures 3.17** and **3.18**, respectively.

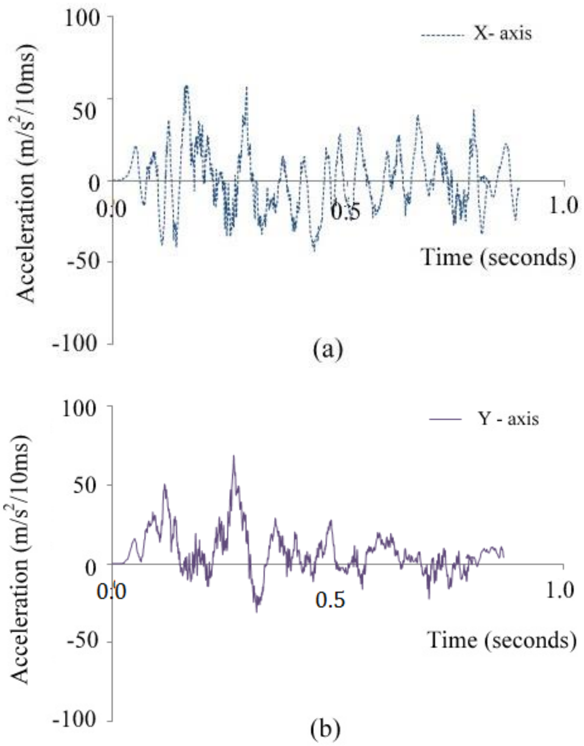


Figure 3.17 Moving acceleration average for the case of concave-curved railing with a curve radius of 100 m (a) X – acceleration and (b) Y – acceleration

In both cases of concave-curved and straight railings which have smallest and largest displacement, their moving acceleration averages at the central gravity of the truck are smaller than the allowable one of 200 $m/s^2/10ms$. Accordingly, it can be seen that the truck driver and passengers are secured from the impact of truck by concave-curved and straight railings investigated in the present study.

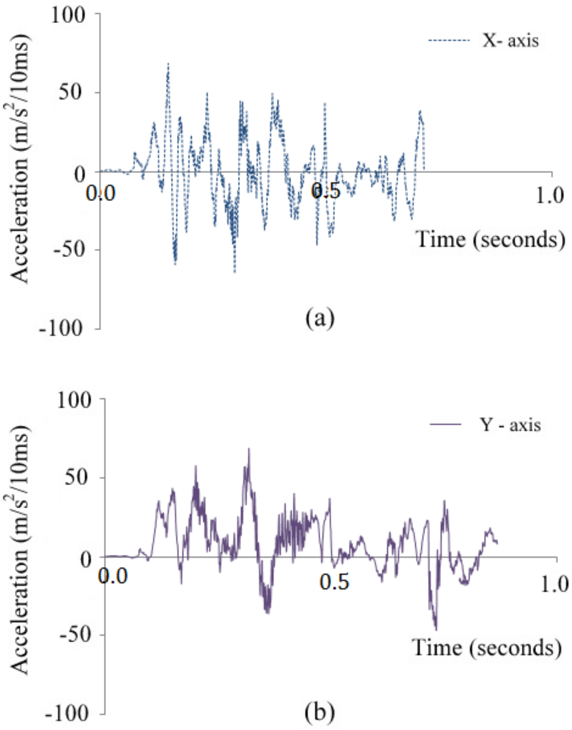


Figure 3. 18 Moving acceleration average for the case of straight railing (a) X – acceleration and (b) Y – acceleration

From the comparisons of numerical results between concave-curved and straight railings, the light of discussions can be shown here that the concave-curved railings with a curve radius of 100 m, 150 m, 280 m and 460 m meet required standards in the Japanese specifications for the railing design. In the same collision conditions of vehicle, railing properties and impact angle, the concave-curved railings are safer than straight one and the railing grade that is designed for the straight bridges can applied to install on the concave-curved ones.

3.5 Performances of concave-curved steel bridge railing under collision of large impact angles

In this section, the research investigates the performances of concave-curved steel bridge railing under the collision of larger impact angles. The numerical simulation of concave-curved and straight railings performed in the above sections is adopted into the study here. All railings are subjected to the collisions of truck weight of 25 ton (245 kN) and speed of 50 km/h.

For the impact angle between the vehicle and railing, the study finds that in some cases of the concave-curved railings this angle is increased accordingly to the curve radius of railing, vehicular movement and position of vehicle on the road lanes. Such increased angle may be larger than angle of 15^o which is specified in the Japanese specifications.

3.5.1 Impact angle on the concave-curved bridges

Considering a case of concave-curved bridge as shown in **Figure 3.19**, the bridge has 100 m radius of curvature and three lanes in one direction. The concave-curved bridge is assumed that both its ends are connected with straight ones. Similar to the above study, the impact angle is measured by angle between the vehicular direction and a tangential to the curved railing at the point where the vehicle crashes into the railing and called as impact point.

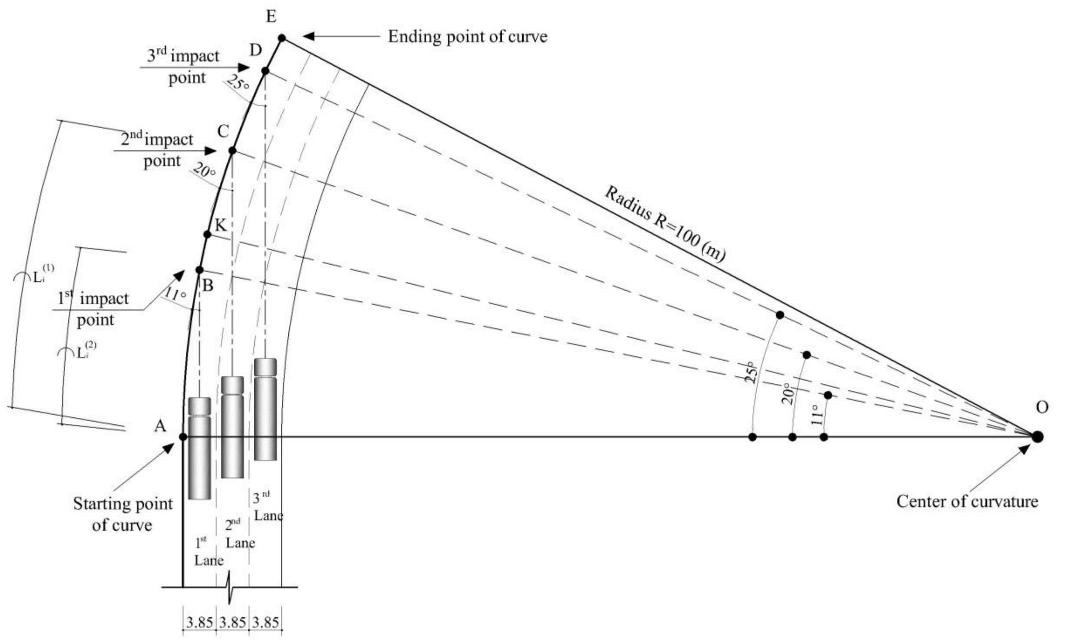


Figure 3.19 Impact angles between the truck and concave-curved railing

It is assumed that by the human problems the truck comes from the straight road section and continues to move in the straight line and to crash into the concave-curved railing as shown in **Figure 3.19**. Points B, C or D are the impact points between the railing and the truck which travels on the first, second and third lane, respectively. In those cases, the impact angle can be determined following **Equation (3.1)** in degree unit.

$$\gamma = 180L_i^{(1)}/nR \quad (3.1)$$

Where,

$L_i^{(1)}$ is the arc length (m) measured from point A which is a starting point of concave-curved railing to impact point B, C or D and i terms to the lane (1, 2 or 3) originally travelled by the truck; and

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

Equation (3.1) can be applied to compute the impact angle for cases of concave-curved railings with a curve radius of 150 m, 280 m and 460 m. Summary of computed impact angle for those cases of concave-curved railing is presented in **Table 3.5** and the relative lengths of the arcs is presented in **Table 3.6**.

Table 3.5 Impact angles between the truck and concave-curved railings

Lanes	Impact angle γ (deg)			
	R100	R150	R280	R460
1^{st} lane	11	9	6	5
2^{nd} lane	20	16	11	9
3^{rd} lane	25	20	14	11

Table 3.6 Relative length of arcs

Lanes	Curved railing length $L_i^{(1)}$ (m)			
	R100	R150	R280	R460
1^{st} lane	20	23	31	40
2^{nd} lane	34	41	54	70
3^{rd} lane	44	53	70	90

The computed angles can be seen that the larger impact angle occur when the truck travels on the second or third lane and crashes into the railing. The largest impact angle of 25^o occurs in the case of curved railing with the concave curve radius of 100 m when truck travels on the third lane. The impact angle of 20^o occurs when the truck travels on the second or third lane and crashes into the concave-curved railing with a curve radius of 100 m or 150 m. The 20^o and 25^o impact angles are larger than angle of 15^o which is specified in the Japanese specifications for the railing design.

Considering an another case, in which by human reasons and others the truck is assumed to travel on straight line and departs from the straight-ahead α_o angle before coming to hit the concave-curved railing as shown in **Figure 3.20**. For this case, the impact angles of the concave-curved and vehicle are determined following **Equation 3.2** in unit of degree.

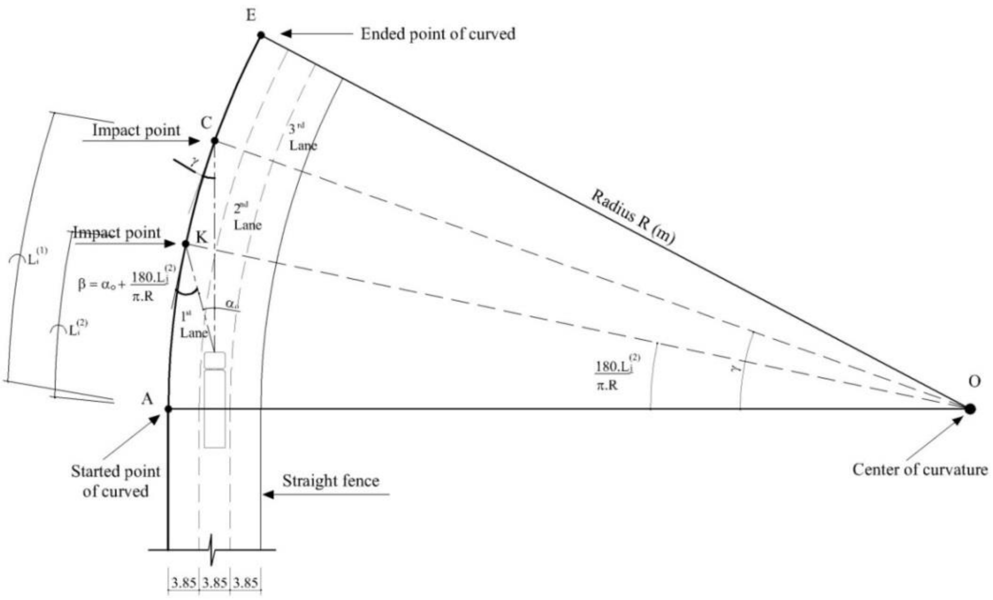


Figure 3.20 Impact angles for the case of truck departed from a straight-ahead α_o angle

$$\beta = \alpha_o + 180L_i^{(2)}/nR \qquad (3.2)$$

Where,

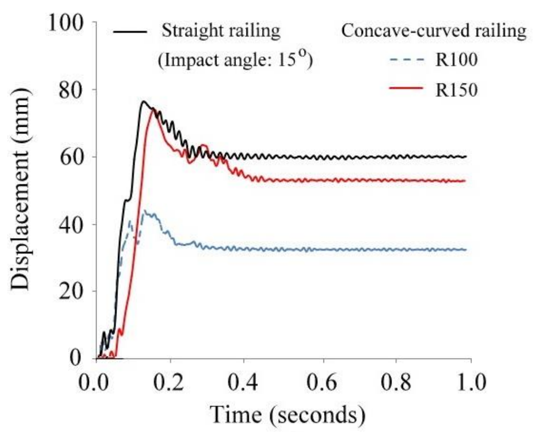
- $L_i^{(2)}$ is the arc length (m) as measured from breakaway point A to impact point K, i terms to the lane (1, 2 or 3) originally travelled by the truck; and
- R is the curve radius of the railing (m).

For an example, using the **Equation (3.2)** to determine the impact angle for case of concave-curved railing with a curve radius of 100 m and truck travelled on the third lane, if the truck departs from the straight-ahead α_o angle then the impact angle is $(25+\alpha_o)^o$. It can be seen that according to the radius of curvature of the railing, the number of lanes on road, and the truck movement and position on road, the greater impact angles may occur when the truck crashes into the concave-curved railings. The purpose of the study in this section is accordingly to examine the performances of concave-curved steel bridge railing under the collision of larger impact angles.

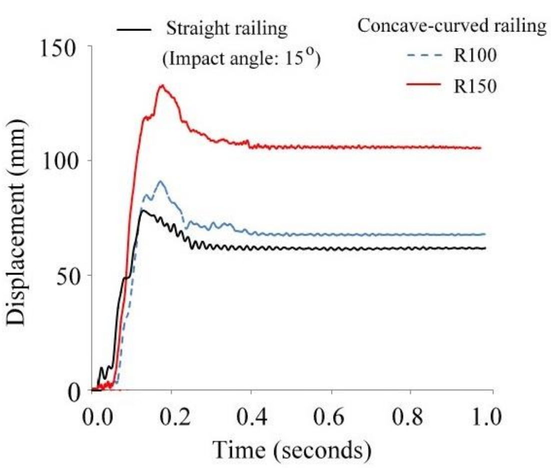
3.5.2 Displacement of concave-curved steel bridge railings under collision of larger impact angles

The impact angle has a bearing on the railing responses and the truck behaviours. Therefore, when the impact angle becomes larger the concave-curved railings may be in more disadvantageous situation than straight one. To qualify the safe situation between the straight and concave-curved railings as the suspicion of researchers and engineers, the numerical results of the concave-curved railings under the collision of the larger impact angles are compared to those of corresponding straight one. The performances of such straight railing were obtained in above sections. The straight railing is subjected to the collision conditions designed for the railing grade of SC with the truck speed of 50 km/h and weight of 25 ton (245 kN) and the 15^o impact angle.

The comparison of numerical displacements of the concave-curved railings with a curve radius of 100 m and 150 m which are subjected to the 20^o and 25^o impact angles and the corresponding straight one is shown in **Figure 3.21**. All cases of railings are subjected to the same truck collision. A summary of maximum displacement of the concave-curved and straight railings is shown in **Table 3.7**.



(a)



(b)

Figure 3.21 Displacements of the concave-curved railings subjected to the collision of large impact angles (a) Angle of 20^o and (b) Angle of 25^o

The displacement-time history shown in **Figure 3.21** indicates that there is only one collision stage during the impact collision similar to the case of railings subjected to the impact angle of 15^o. For the case of 20^o impact angle subjected to concave-curved railings, the displacement on the concave-curved railing with a curve radius of 100 m is larger than that on the same railing subjected to the impact angle of 15^o, but still smaller than that on the corresponding straight one. Both maximum and residual displacement of concave-curved railing with a curve radius of 150 m comes close to that of the corresponding straight railing.

Table 3.7 Displacement on railings under the collision of the larger impact angles

Type of railing	Displacements (*mm*)			
	20 degree		25 degree	
	Post 8	Post 9	Post 8	Post 9
R100	47	46	62	91
R150	82	76	75	132

For the case of the impact angle of 25^o, the displacement on both concave-curved railings is larger than that on the corresponding straight one. For the concave-curved railing with a curve radius of 150 m, its maximum displacement is 132 mm, and is greater than that of the corresponding straight one with 79 mm. According to the numerical results and above discussions, it can appear here that with the increases of the impact angle the concave-curved railings undergo the greater displacement than the corresponding straight one.

3.5.3 Energy absorption of concave-curved railings under collision of larger impact angle

In the cases of the larger impact angles the truck weight and speed do not change, thus the kinetic energy of the truck is similar to that in the previous cases with the impact angle of 15^o. The present study finds that the energy transferred from the truck to the concave-curved railings increases with the increase of the impact angles. The comparison of the absorbed energy of concave-curved and straight railings is shown in **Figures 3.22** and **3.23**. The summary of energy distributed among the railing components is presented in **Tables 3.8** and **3.9**.

For both cases of the 20^o and 25^o impact angles, the energy transferred from the truck to the concave-curved railings with a curve radius of 100 m and 150 m is smaller than the designed energy level of 160 kJ for the railing grade of SC and larger than that in the case of the same railing subjected to the collision of the impact angle of 15°. The concave-curved railing with a curve radius of 100 m subjected to the 25° impact angle its absorbed energy is larger than that of the corresponding straight one subjected to the same the truck collision with the 15° impact angle.

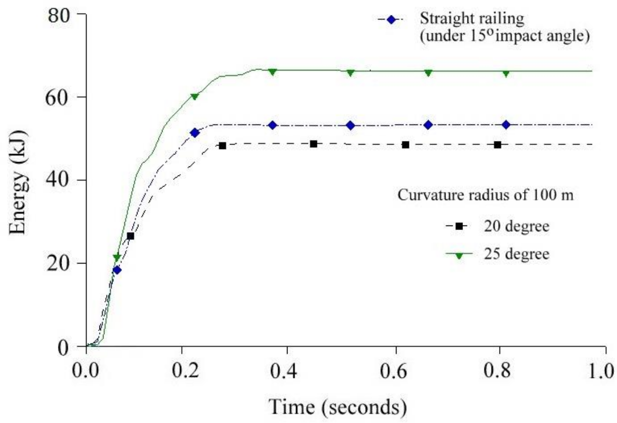


Figure 3.22 Absorbed energy of the concave-curved railing with a curve radius of 100 m

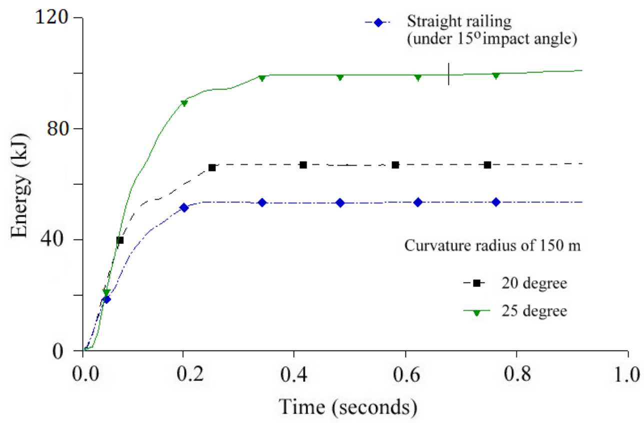


Figure 3.23 Absorbed energy of the concave-curved railing with a curve radius of 150 m

Table 3.8 Absorbed energy of the railings under the collision of the 20° impact angle

Type of railing	Absorbed energy				
	Posts		Beams		Railing
	(kJ)	*(%)*	*(kJ)*	*(%)*	*(kJ)*
R100	6.8	*15*	41.8	*84*	49.0
R150	11.9	*17*	55.5	*82*	67.6

In the case of the concave-curved railing with a curve radius of 150 m under the collision of the impact angle of 20° and 25°, the energy transferred from truck to concave-curved railing is greater than that of the corresponding straight one. For an example, for the case of the impact angle of 25^o the energy absorbed by the concave-curved railing is 101 kJ, and is twice as large as that of the corresponding straight railing with 53.6 kJ.

Table 3.9 Absorbed energy of the railing under the collision of the 25^o impact angle

Type of railing	Absorbed energy				
	Posts		Beams		Railing
	(kJ)	*(%)*	*(kJ)*	*(%)*	*(kJ)*
R100	12.1	*18*	54.4	*81*	66.5
R150	18.1	*18*	82.9	*81*	101.0

A light discussion can appear here that the increase of the impact angle increases the energy transferred from the truck to the concave-curved railings. In some cases of concave-curved bridge with the human problems, the concave-curved railing is more disadvantageous than the corresponding straight railing which is subjected to the same truck collision and the impact angle of 15^o.

3.5.4 Movement of truck crashed into concave-curved railings with larger impact angles

The movements of truck in the cases of the 20^o and 25^o impact angles are shown in **Figures 3.24** and **3.25**. It can be seen that the truck is guided by railing back to the line of road after the impact collision.

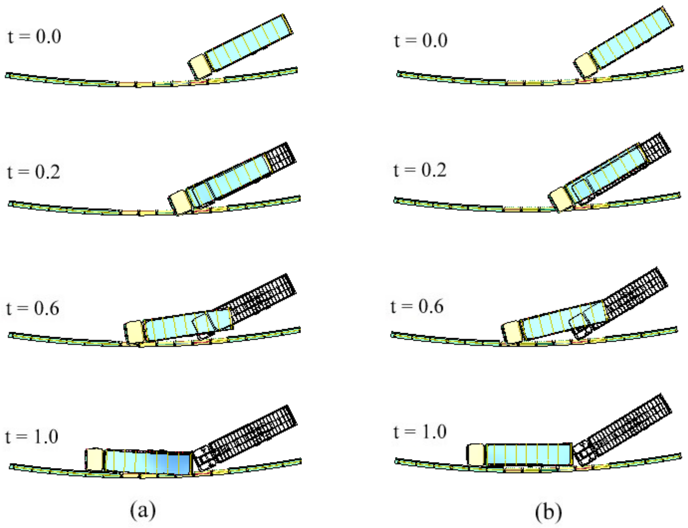


Figure 3.24 Movement of the truck crashed into the concave-curved railing with a curve radius of 100 m (a) Impact angle of 20^o and (b) Impact angle of 25^o

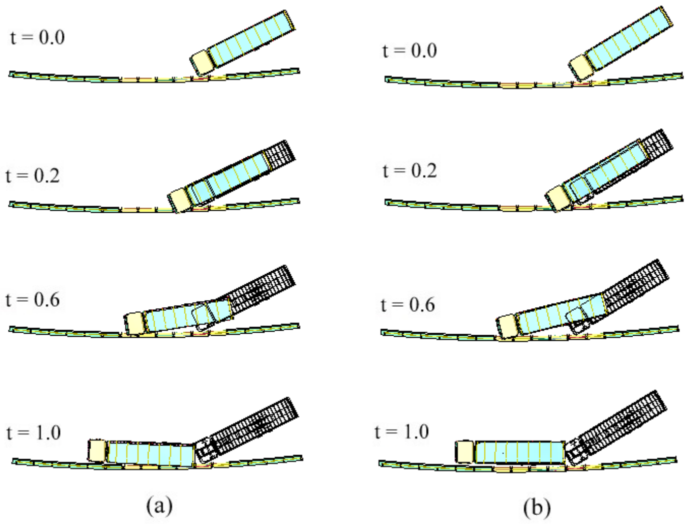


Figure 3.25 Movement of the truck crashed into the concave-curved railing with a curve radius of 150 m (a) Impact angle of 20^o and (b) Impact angle of 25^o

3.5.5 Breakaway speed of truck crashed into concave-curved railing with larger impact angle

The decrement of truck speed is shown in **Figure 3.26** and a summary of the remained velocity of the truck after the impact collision is presented in **Table 3.10**. It can be seen that in all cases the remained velocity of truck is larger than 60 percent of initial designed speed of 30 km/h. The concave-curved railings subjected to the collision of the impact angle of 20^o and 25^o meet requirements in the Japanese specifications for the railing design.

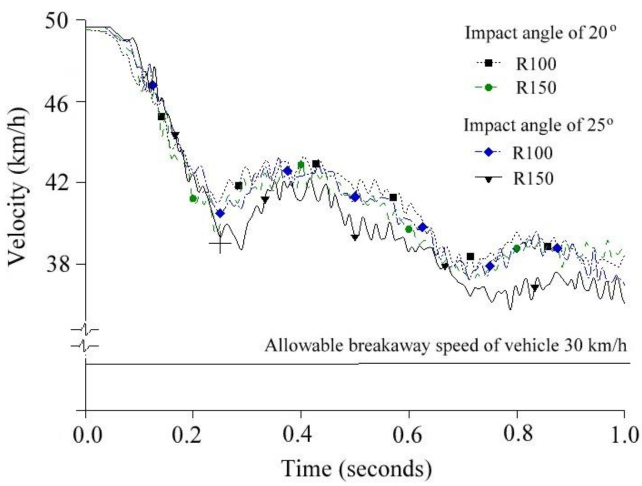


Figure 3.26 Breakaway of the truck speed for the cases of the impact angles of 20^o and 25^o

Table 3.10 Remained speed of the truck crashed into the railing with the larger impact angles

Type of railing	Breakaway speed of the truck (%)		
	15^o	20^o	25^o
R100	83.5	78.5	79.2
R150	81.4	78.5	77.0

3.5.6 Limitation state of concave-curved railing caused by large impact angles

As discussions in Section 3.5.1, because the truck may depart from the straight-ahead α_o angle, the largest impact angle may occur on concave-curved railing with a curve radius of 100 m is $(25+\alpha_o)^o$. The great increase of the impact angle will increase the displacement and absorbed energy in the concave-curved railing, thus the performances of such railing may not meet requirement standards in Japanese specifications. Accordingly, the present study increases the impact angle to investigate a limit state on the concave-curved railing at which its performances will not meet requirement standards.

This analysis deals in the concave-curved railing with a curve radius of 100 m. The study finds that the limited impact angle in which such railing does not meet requirement standards is 30^o. **Figure 3.27** shows the displacement-time history for the railing post number 8. The largest displacement on this post is around 620 mm and over the displacement of 300 mm specified in the Japanese specifications. **Figure 3.28** presents the truck movement. It can be seen that the railing cannot guide the truck back to the line of the road after the impact collision.

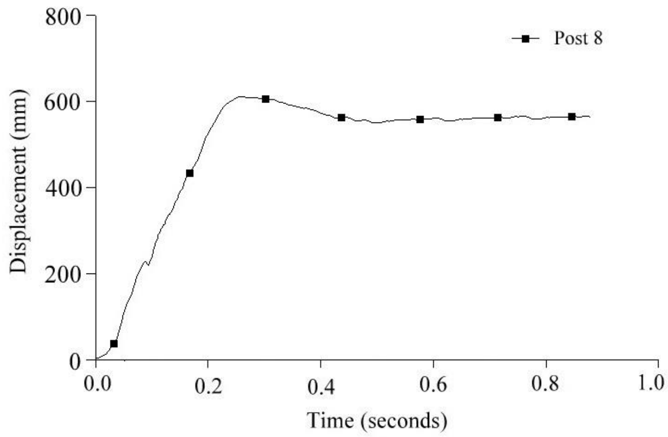


Figure 3.27 Displacement of the concave-curved railing with a curve radius of 100 m subjected to 30^o impact angle

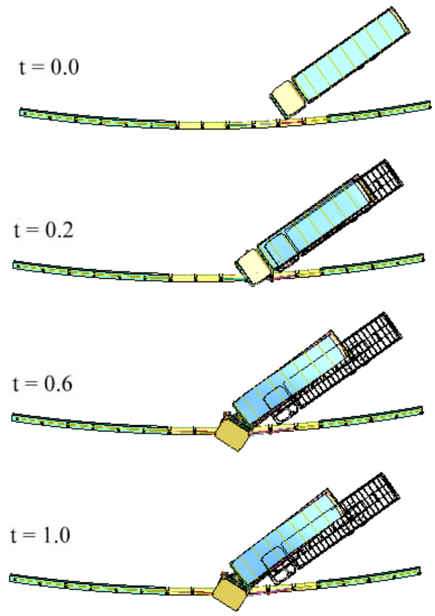


Figure 3.28 Movement of the truck crashed into the concave-curved railing with a curve radius of 100 m subjected to 30^{o} impact angle

3.6 Summary and discussion

The study in this chapter is performed to investigate the performances of concave-curved steel bridges railing. The study successfully develops the numerical collision simulations with using the LS-DYNA 3D software. Those simulations adopt the experiences and properties of the model representation from existing researches that were successfully performed by our laboratory and verified by using experimental results. The research deals with the concave-curved steel bridge railing with several different curvatures.

The study finds that according to the radius of concave curvature of railing, numbers of lane on road, and the vehicular position and movement direction on road the impact angle may become larger than hitherto. The examination of collision performances of concave-curved steel bridges railings under the collision of larger impact angles therefore is other objective of study in this chapter. The conclusions of study can be summarized following as:

(1) From the comparison of numerical results between the concave-curved and straight railings, it indicates that when concave-curved and straight railings are subjected to the same vehicular collision and impact angle the performances of all concave-curved railings meet requirement standards in the Japanese specifications

for the railing design. The displacement and absorbed energy of concave-curved railings always are smaller than those of the corresponding straight one. The railing features and grade designed for straight bridges can apply to install on the concave-curved ones.

(2) The displacement and the energy transferred from the truck to railing increase with the increase in the radius of concave curvature of railing. In the same truck collision and railing grade, the concave-curved railings have smaller displacement and absorbed energy. The straight railing is more disadvantage than the corresponding concave-curved railings.

(3) According to the radius of railing curvature, numbers of lane on road, position and movement direction of vehicle on road and human problems, the impact angle may be larger than angle of 15^o that is specified in the current Japanese specifications. In some case, the amount of displacement and absorbed energy of concave-curved railing are greater than those of the corresponding straight one that is subjected to the same vehicular collision with the 15^o impact angle. In such cases, it is necessary to increase the safety margin of concave-curved railing or control the speed of vehicles for reducing their kinetic energy.

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Chapter 4

DEVELOPMENT OF NEW-TYPE CONCAVE-CURVED STEEL BRIDGE RAILINGS

4.1 Statement of study

The first standards for the railing design were established in 1965 by the Japan Road Association. In the next years, the rapid increase in the Japan road network and a truck's weight from 20 ton (196 kN) to 25 ton (245 kN) are main reasons to increase the vehicular speed and scale, and change the height of the truck gravity center. Those increases have challenged engineers in the analysis and design of railing. Accordingly, the revision of specifications for the railing design was implemented by Japanese Road Association in 1999 [2] to take account such increases into the railing design and construction.

The Japanese specifications issued in 2004 [3] have been prescribed two new requirements that are a landscape-friendly appearance and a flow in the road user's view from bridges for the railings. Those improvement functions lead to change some concepts in the railing design, in which the beam and post of railing are required to design with slender in form and feature. Accordingly, the purpose of the present study in this chapter is to develop new-type concave-curved steel bridge railings that satisfy such improvement functions. As discussions in Chapters 1 and 3, the Japanese specifications have not mentioned about the design of curved railings and some engineers and researchers have suspected about the safety situation of the curved railings. Therefore, the verification of the engineer and researcher suspicion and the proposal of recommendations for the curved railing design are performed in this study.

The latest Japanese specifications issued in 2008 [4] have prescribed a full-scale test for the railing before installing it on the bridges. However, such test involves much time and huge cost. Two new-type of railing posts investigated in this study were successfully developed to use for a straight railings. Their study results were reported in the existing our laboratory papers [5, 6]. In those studies, the behaviours of posts were examined by experimental tests of static load and a heavy steel ball collision and the finite element models. This study uses such verified models of posts to develop the collision simulation of new-type concave curved railings. The study methodology is depended following procedures:

(1) To design the form and feature of two new-type posts. This work was also successfully performed and presented in existing papers of our laboratory [5, 6].
(2) To examine the performances of new-type posts by the experimental tests of the static load and the heavy steel ball collision.
(3) To develop the finite element model to study the performances of new-type railing posts. Those models are verified by comparing their numerical results with the experimental ones. Some results in the second and third procedure were also presented in References [5, 6].
(4) To improve such verified models of posts to develop the collision simulation of new-type concave-curved steel bridge railings under the impact of the heavy truck.
(5) To propose the recommendation for the concave-curved railing design and qualify the engineers and researchers suspicion.
(6) Similar to the discussions in Chapter 3, the larger impact angle may occur on some cases of concave-curved railings, thus this study also performs investigation of behaviours of the new-type concave-curved railings under the collision of the larger impact angles again.

The numerical results of the new-type posts and the concave-curved railings are compared to those of existing one that was successfully designed and installed for a bridge in Hokkaido, Japan before 2004. All railings investigated in the present study has the grade of A, and is subjected to the collisions of truck speed of 45 km/h, truck weight of 25 ton (245 kN) and the impact angle of 15^{o}. A flowchart of the study is presented in **Figure 4.1**.

4.2 New-type steel railing posts

4.2.1 Shape and feature of posts

The shape and dimensions of posts investigated in the present study are presented in **Figure 4.2**. The new-type posts have name of M and R. An existing previous post installed on a bridge in Hokkaido in 2004 names N. Those posts were designed by a railing factory in Japan and reported in the existing previous papers performed by our laboratory [5, 6]. **Table 4.1** is a summary of dimensions for all types of posts. It can be seen that the form and weight of new-type posts are slender and lighter than those of existing one.

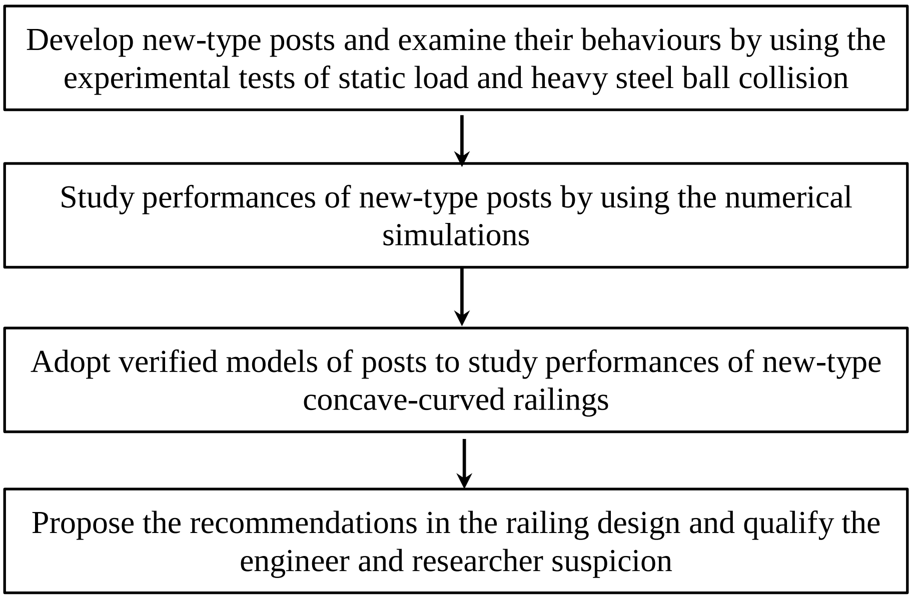


Figure 4.1 Procedures of the present study

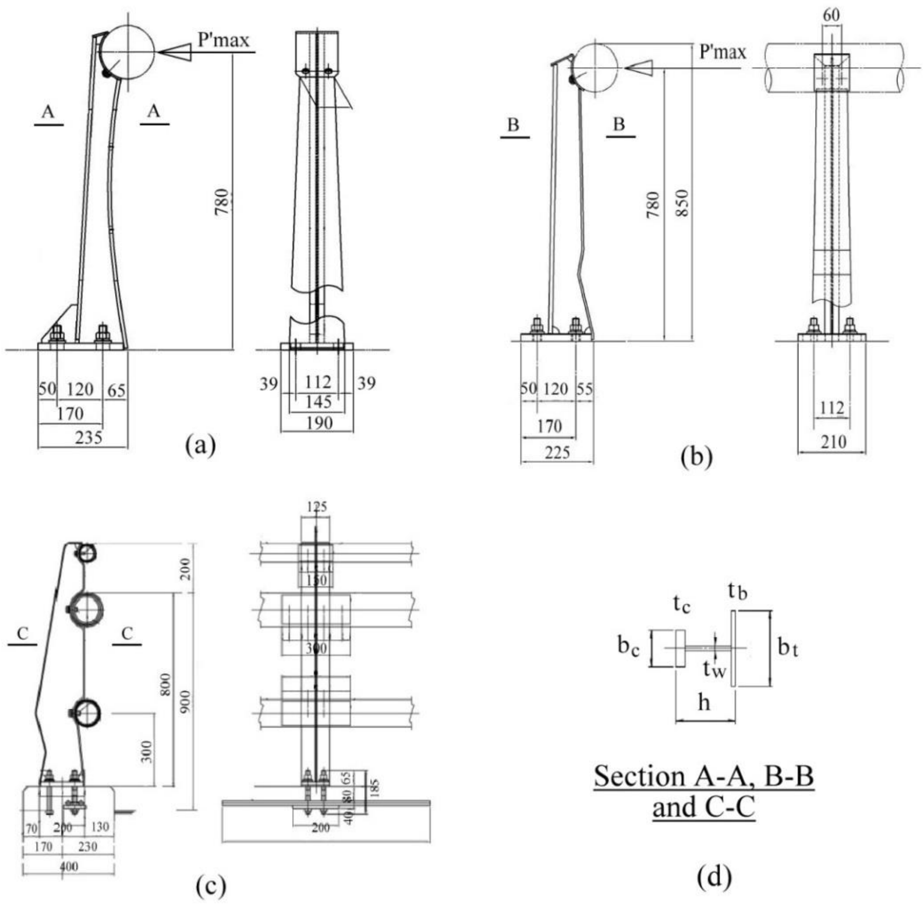


Figure 4.2 Shape and feature of the posts (a) M-type post, (b) R-type post, (c) N-type post and (d) Cross-section of the posts (Unit: mm)

Table 4.1 Summary of dimensions of the new-type railing posts

Type of post	Tension flange		Compression flange		Web	
	b_t (mm)	t_b (mm)	b_c (mm)	t_c (mm)	t_w (mm)	h (mm)
M-type	96	9	38	9	6	59
R-type	91	6	44	1.2	6	81
N-type	125	6	125	4.5	5	170

The N-type post was designed with an expectance of a local buckling failure occurred at the compression flange. Therefore, the N-type post has a narrow cross-section towards the bottom part in the compression flange and the other cross-sections around the narrow one are enlarged as shown in **Figure 4.2 (c)**. The new-type posts were designed to expect a lateral torsional buckling at compression flange. Thus, the new-type posts have a slender and smaller form than the existing one. Accordingly, the expected failures of local or lateral torsional buckling are main different between new and existing posts.

In the R-type post, a narrow section is designed towards the lower part in the tension flange. Purpose of this narrow section is to expect a better energy distribution between post flanges and web and an occurrence of the lateral torsional buckling failure. For M-type railing post, the failure of lateral torsional buckling is also expected to occur in the compression flange toward the lower part without the narrow section. Accordingly, with or without narrow section is main different between M-type and R-type railing posts.

4.2.2 Examination of post behaviours using the static load test

A static load test was carried out to verify behaviours of the new-type posts and its diagram is shown in **Figure 4.3**. This test is performed in the laboratory of the railing factory. The post is fastened onto a steel beam by anchors and considered as fixed-ends. According to the Japanese specifications for the railing design, the allowable displacement on the railing under the impact of the vehicle collision is 300 mm, thus the new-type posts are subjected to the static load that causes a transversal displacement of 300 mm at its top. The static load is transferred to the top part of post via two transverse steel bars as shown in **Figure 4.4**, and considered as concentrated force.

The static test will stop when the displacement at the top of post reaches the amount of 300 mm in the horizontal direction. Relationship of the experimental static load and displacement for new-type posts which was reported in Reference [5] is shown in **Figure 4.5**.

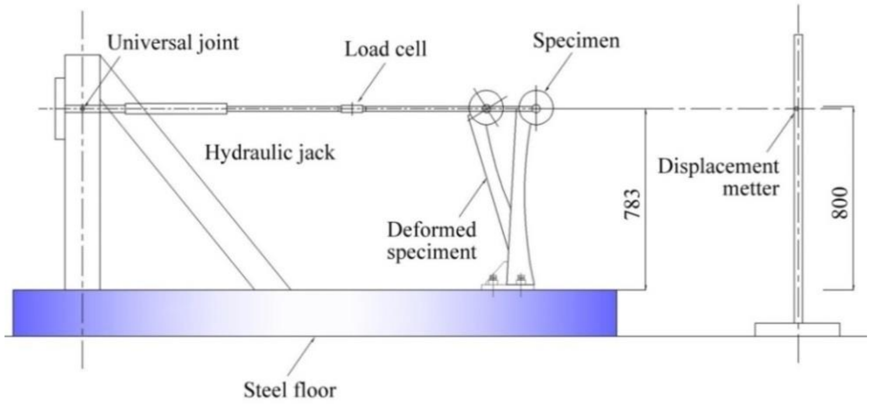


Figure 4.3 Outline of the static load test (Unit: mm)

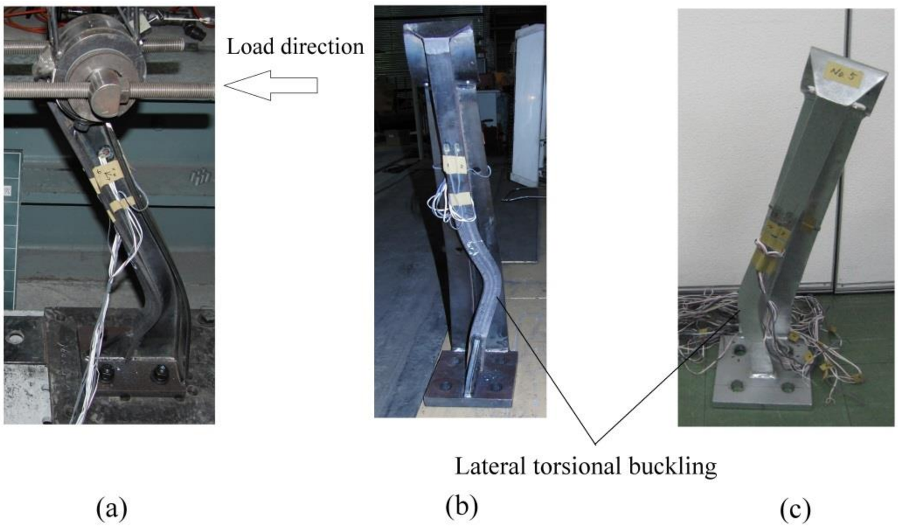


Figure 4.4 Static load test (a) Post specimen, (b) Failure of M-type post and (c) Failure of R-type post

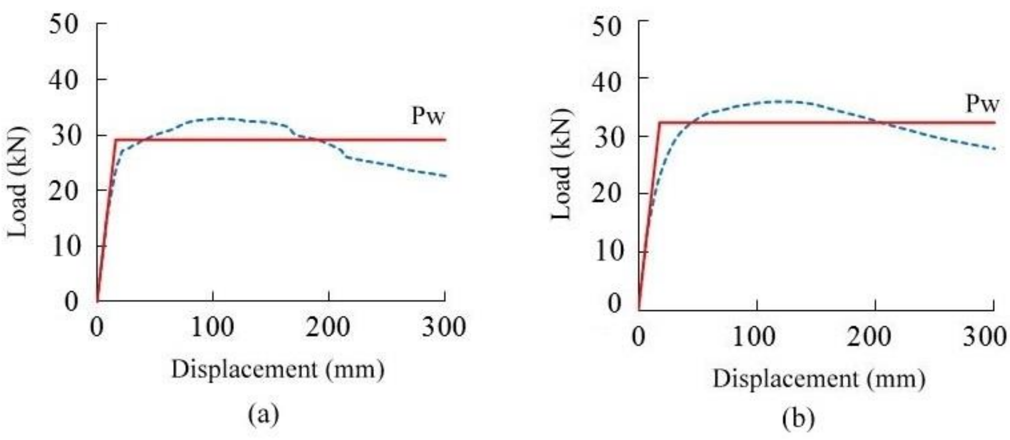


Figure 4. 5 Load-displacement relationship (a) M-type post and (b) R-type post

An equivalent railing structure that has two spans with three posts as shown in **Figure 4.6**. This structural model is used to obtain an ultimate load of P_w as shown in **Figure 4.5**. The equivalent posts have a rectangular cross-section. The cross-section of equivalent posts and actual ones are of equal area. The beams in equivalent structure have the same diameter and properties as the actual beams that will be used for the railing in fact.

To determine the ultimate load of P_w, the top of equivalent post is assumed to deform with a displacement of 300 mm as shown in **Figure 4.6**. A limited bending moment of M_o in the equivalent beam is computed from this structural deformation. According to diagram in the Japanese specifications [4] that describes a relationship between the limited bending moment of M_o, the ultimate load of P_w and the railing grade, with the amount of limited bending moment and the railing grade of A the ultimate load of P_w is obtained. The solutions of P_w for M-type and R-type of posts are reported in Reference [5, 6].

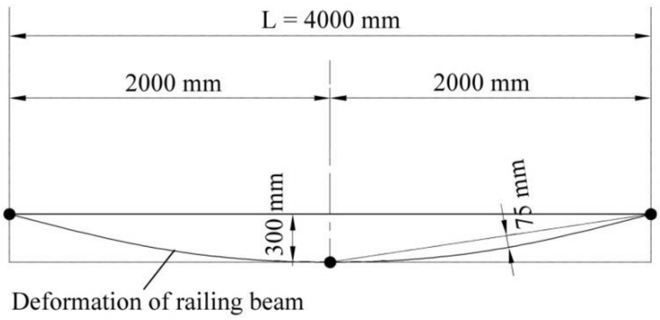


Figure 4. 6 Equivalent structure for the design of an initial shape of the post

Figure 4.5 shows that the maximum static loads on M-type and R-type posts are 33.5 kN and 35.6 kN, and are larger than the ultimate loads of 29.5 kN and 32.3 kN, respectively. However, in all new-type posts the area that is taken from the ultimate load and the static load with the 300 mm displacement axis is close. According to the Japanese specifications for the railing design and the purpose of the study, they indicate that both M-type and R-type posts meet the required standards. Such posts are adopted to use for the examination of collision behaviours.

4.2.3 Collision behaviours of new-type posts

The collision performances of new-type steel posts are examined by subjected to the impact of the heavy steel ball. The outline of this test is presented in **Figure 4.7**.

The post specimen is fastened onto the steel foundation by anchors. Under the gravity, the steel ball swings to strike the post specimen. The kinetic energy of steel ball is controlled by an increase or a decrease in its initial height, and is determined to cause a displacement of 300 mm on the post in the horizontal direction. The amount of collision load arisen from the steel ball kinetic can be referred from the static load. Accordingly to the properties and dimension of the post cross-section, the initial height of the steel ball for M-type and R-type posts are 2150 and 2300 mm, respectively. The steel ball used in the test has a mass of 470 kg (4.6 kN).

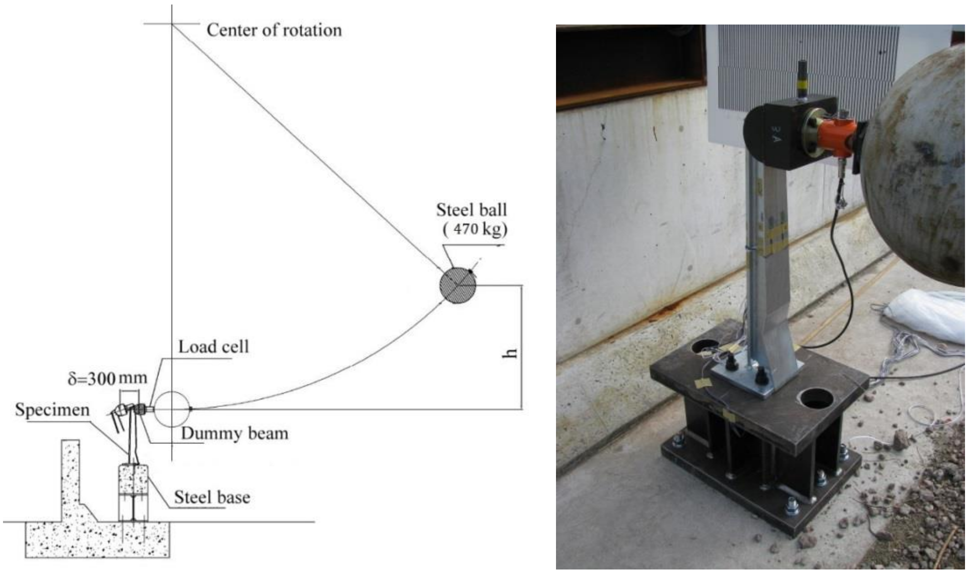


Figure 4.7 Steel heavy ball collision test (a) Outline of test and (b) Test set-up

As for the above discussions, the study also develops the finite element models to study the performances of new-type railing posts under the impact of the heavy steel ball. The numerical simulations of M-type and R-type posts that are created by using LS-DYNA 3D software are presented in **Figure 4.8.** The form and dimensions of numerical posts match those of one that is used in the experimental test as summarized in **Table 4.1**.

The post flanges and web are created by using four-node shell elements. For the M-type post, the element sizes of flange and web are 19.5x22.6 mm and 20.2x21.5 mm, respectively. For R-type post, the element sizes of post flange and web are 23.7x28.7 mm and 23.3x23.4 mm, respectively. The steel of post is the grade of SS400, and is modelled as the isotropic elasto-plastic material following von Mises yielding criterion with its characteristic properties as shown in **Table 2.1**. As for the discussions in **Chapter 2**, the effect of strain rate of steel is taken into the numerical analysis of the collision performances of posts. The steel plate is modelled by the eight-node solid elements. The post is considered as fixed at end.

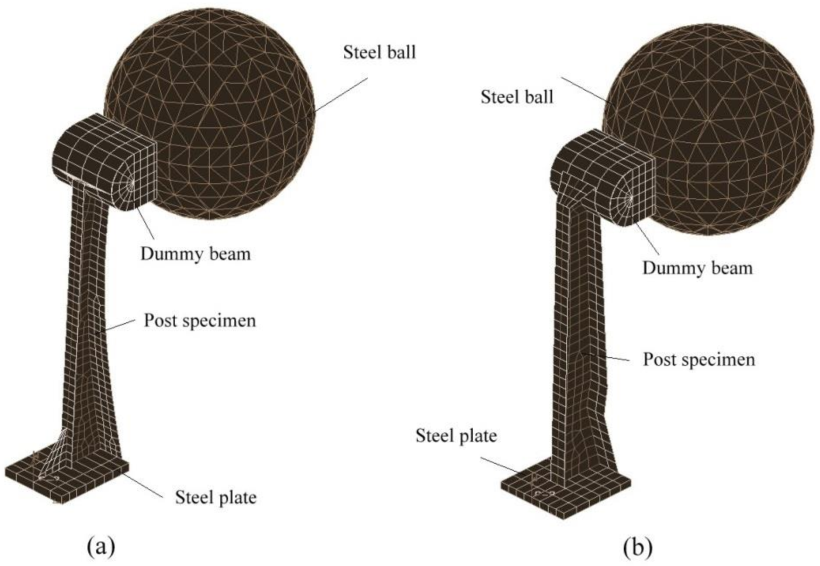


Figure 4.8 Finite element models of posts subjected to the heavy steel ball collision (a) M-type post and (b) R-type post

The steel ball is simulated by using the tetrahedral solid element. The element mesh size of ball is created by using the ball mesh function in LS-DYNA 3D software. The ball steel material is modelled as elastic material with Young's modulus of 206 GPa and yield stress 235 MPa. In the numerical analysis, the steel ball is considered to move in a horizontal direction to strike the post. The velocity of ball is similar to that of experimental one, and is 6492 mm/s and 6714 mm/s for the case of M-type and R-type posts, respectively.

4.2.3.1 Displacement responses

Similar to the studies in **Chapters 2** and **3**, to verify the numerical simulation of new-type steel railing posts subjected to the heavy steel ball load, its solutions are compared with the experimental ones. The comparison of the displacement results for M-type and R-type posts is presented in **Figure 4.9**. The displacement shown in this figure is a transverse displacement at the top part of post in the horizontal direction. It can be seen that for the M-type post, the numerical displacements are close to the experimental ones. The largest amounts of the numerical and experimental displacement are 322 mm and 330 mm, respectively.

For the R-type post, the largest amount of experimental displacement is 330 mm, and is larger than that of numerical one with 259 mm. There is small difference in the track of the numerical and experimental displacement during the impact collision from point of 0.02 seconds to 0.04 seconds as shown in **Figure 4.9 (b)**. Because the lateral torsional buckling occurs at the compression flange of R-type post in experimental test, the out-of-plane displacement increases the displacement in horizontal direction. Thus, from the point of 0.05 seconds to 0.2 seconds, the experimental displacement is larger than numerical one. **Figures 4.9** shows that the track of numerical displacement of the R-type post is similar to that of the M-type one.

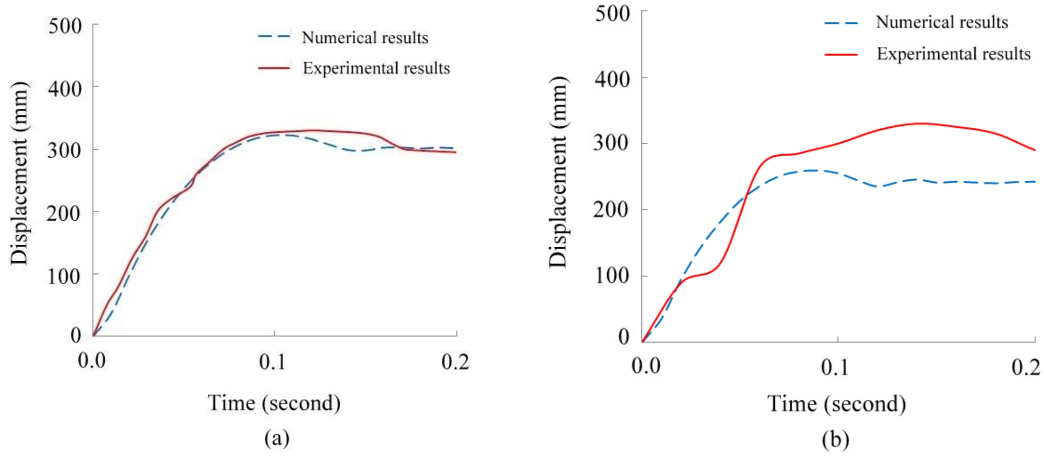


Figure 4.9 Displacement-time histories of the posts subjected to the heavy steel ball collision (a) M-type post and (b) R-type post

4.2.3.2 Collision force of the post

In the experimental test of post subjected to the steel ball collision, strain gauges were attached onto the compression and tension flanges and web of post. The collision force in the post is computed by using those strain data. **Figure 4.10** shows the comparison of the experimental and numerical collided shear force at the base of post. It can be seen that the maximum collision force in the numerical analysis is close to that in the experimental test.

For the M-type post, the largest amounts of experimental and numerical force are 40 kN and 46 kN, respectively. For the R-type post, there is a smaller difference between the tracks of experimental and numerical collision forces. The out-of-plane displacement caused by the lateral torsional buckling is the main reason of this difference. The largest amounts of experimental and numerical force are 59 kN and 68 kN. In both types of post, their collision forces are larger than the load that is subjected in the static test.

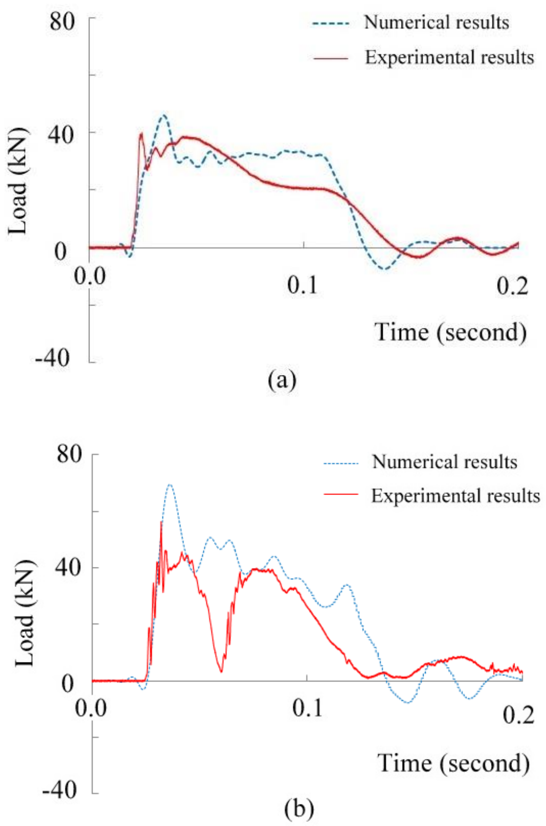


Figure 4.10 Collided base shear forces of the post (a) M-type post and (b) R-type post

4.2.3.3 Lateral torsional buckling failures

Because, the M-type and R-type posts are designed to meet the new improvement functions in the current Japanese specifications issued in 2004, those posts have a smaller and slender form. The occurrence of the lateral torsional buckling failure is the expected result in the design of those posts. **Figure 4.11** presents the failure of M-type and R-type posts after the collision test. It can be seen that the lateral torsional buckling occurs on the entire compression flange in both types of post. For the R-type post, the location where the lateral torsional buckling occurs is at the narrow cross-section.

Figure 4.12 presents the absorbed energy of the post flanges and web and its summary is shown in **Table 4.2**. It can be seen that the energy transferred from the heavy steel ball to the compression flange is larger than the others. In the R-type post, the absorbed energy of flanges and web is close. The narrow section towards the lower part of R-type post is main factor of such distribution. This distribution also is a difference between M-type and R-type posts.

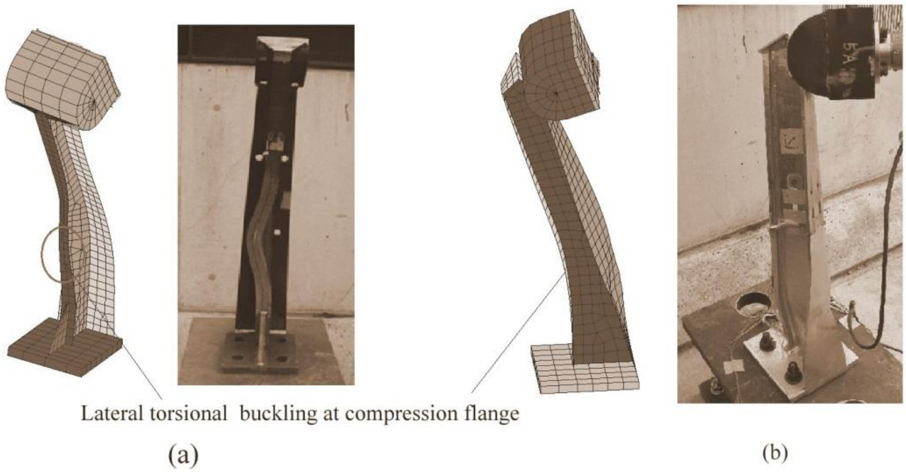
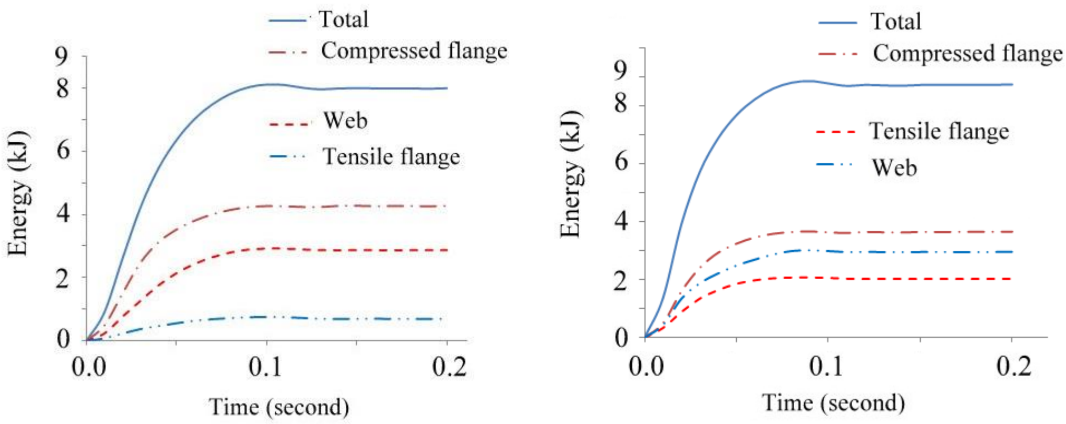


Figure 4.11 Lateral torsional buckling failure (a) M-type post and (b) R-type post

From the comparisons of numerical and experiment results of the new-type posts subjected to the steel ball collision, it can thus appear that the numerical results are close to the experimental ones. In the numerical analyses, the lateral torsional buckling occurs on the compression flange in both types of post, and is similar to that of the post specimen in the experimental collision test.



(a) (b)

Figure 4.12 Energy absorption of the post (a) M-type post and (b) R-type post

Table 4.2 Summary of the absorbed energy of post members

Component of post	M-type (kJ)	R-type (kJ)	N-type (kJ)
Whole post	8.0	8.7	10.3
Compression flange	4.3	3.7	2.6
Web	2.9	2.0	6.2
Tension flange	0.7	3.0	1.4

The results of the present study indicate that the numerical simulations using finite element models can effectively study the collision performances of railing posts. The verified models of posts are effectively adopted to create the simulations of impact collision of new-type concave-curved steel bridge railings under the impact of the heavy truck.

4.2.3.4   Behaviours of new-type and existing posts

As the discussion, to qualify the improvements of new-type posts, the numerical results of such posts are compared with those of an existing post that was successfully designed and installed on the bridge in Hokkaido, Japan before 2004. The existing post names of N-type. The finite element model of N-type post is shown in **Figure 4.13**.

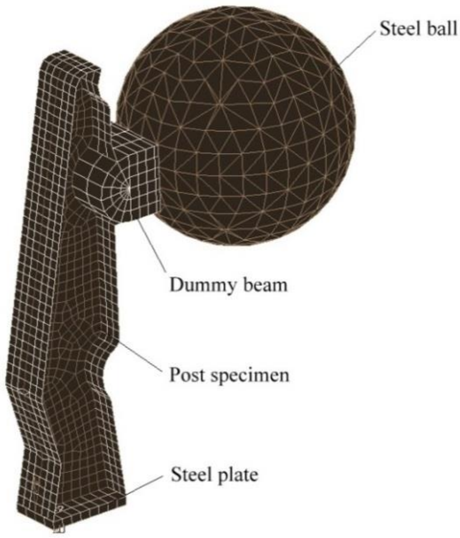


Figure 4.13 Finite element models of the N-type post subjected to the heavy steel ball collision

Similar to the new-type posts, the N-type post is modelled to match its actual shape and dimensions. Again, the post flanges and web are modelled by four-node shell elements and the steel ball is tetrahedral solid elements. The element sizes of post flange and web are 20.8x20.8 mm and 19.5x20.8 mm, respectively. The steel material of post is grade of SS400 and modelled as an isotropic elasto-plastic material following von Mises yielding criterion with properties as shown in **Table 2.1**. A rubber plate attached at the top part of post has a function to reduce a shock load from the steel ball, and is called as a dummy beam. The steel plate and dummy beam are simulated as eight-node solid elements and their materials are plastic material models.

The comparison of displacement between the new and existing posts is shown in **Figure 4.14**. It can be seen that the displacement tracks of new and existing posts are similar. The largest displacement occurs on the M-type post and N-type post has the smallest one. Because the stiffness of N-type post is larger than that of the new-type posts, the displacement occurred on the N-type post must be smaller.

Figure 4.15 presents the collision force on three types of post. The largest amounts of collision load on the M-type, R-type and N-type posts are 46.0 kN, 56.4 kN and 104.7 kN, respectively. Because the N-type post has a larger cross-section area, it can absorb more energy than the M-type and R-type posts that have a smaller cross-section one. In the all types of post, their collided force behaviours are close. The maximum collision force occurs at the point of 0.02 seconds when the ball strikes the post, and then those forces are reduced to become insignificant.

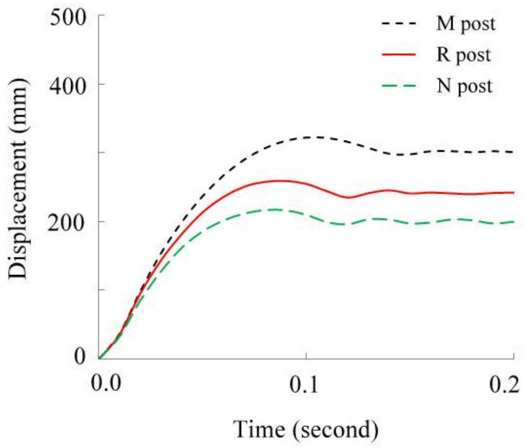


Figure 4.14 Comparison of the displacement between the new and existing posts

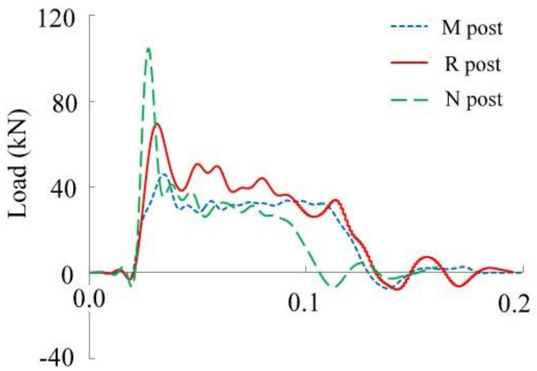


Figure 4.15 Comparison of the collided base shear force on the new and existing posts

From the comparison of numerical results between the new and existing posts it can be shown that the numerical analysis can effectively study the performances of the railing posts subjected to the heavy ball collision. In the same collision conditions of the steel ball, the displacements occurred on the new-type posts are larger than those of the existing post. The energy transferred from the steel ball to the existing post is larger than that of the new-type posts. The numerical simulation of all posts can be adopted to create the simulation of the corresponding railings under the impact of the heavy truck.

4.3 Collision performances of new-type concave-curved steel bridge railings

4.3.1 Purposes and progress of the present study

According to the study statements of required improvement functions for the railing, the suspicion of engineers and researchers and the larger impact angles than hitherto occurred in the some cases of the concave-curved railings, the purpose of the present study is following as:

(1) Develop the new-type concave-curved steel bridge railings which are named as M-type and R-type by using the corresponding M-type and R-type posts.
(2) Verify the engineer and researcher suspicion, in which the curved railings are suspected that to be more disadvantageous than the straight one when they are subjected to the same collision conditions.
(3) Qualify the improvement functions of the new-type concave-curved railings. Those railings are designed with the slender form of post than the existing one. Thus, the comparisons of results between the new and existing concave-curved railings would qualify the improvements of new-type railings.
(4) Investigate the performances of the new-type concave-curved steel bridge railing under the collision of the larger impact angles.

According to above purposes of the present study, the full-scale test is the ideal method for this study. However, such test requires considerable cost and effort. Thus the numerical simulations using the finite element model are relied on this study. The research is performed by following procedures:

(1) Develop the numerical simulations of the M-type, R-type and N-type concave-curved and straight railings subjected to the heavy truck collision.

(2) The numerical results of the concave-curved railings are compared with those of the straight one in the same type and properties of railing and the truck collision conditions. This progress obtains the answer for the suspicion of engineers and researchers, and its outline is presented in **Figure 4.16**.

(3) The numerical results of the new-type concave-curved and straight railings are compared with those of the existing corresponding railings. This comparison qualifies the improvements in the new-type railings. The outline of this progress is shown in **Figure 4.17**.

(4) Investigate the performances of M-type, R-type and N-type concave-curved railings under the collision of the larger impact angles. In this study, the performances of the concave-curved railings subjected to the larger impact angle are compared with those of ones under the higher energy level of truck. The outline of study is presented in **Figure 4.18**.

(5) Propose the commendations and remarks for the development and design of new-type concave-curved bridge railing.

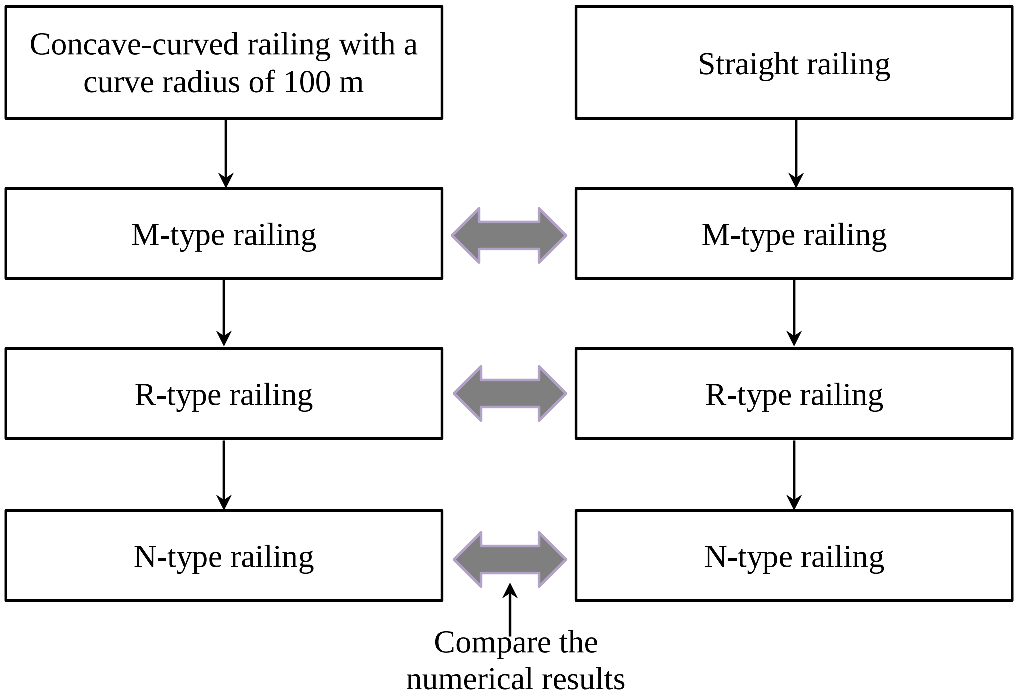


Figure 4.16 Outline of the verification of engineer and researcher suspicion

All new and existing railings have grade of A. Similar to the case of curved bridges as shown in **Figure 3.19** and the summary of large impact angles in **Table 3.5**, the 20^o and 25^o impact angles occur when the truck impacts to the concave-curved railings with a radius of 100 m. Thus, the present study investigates the performances of the M-type, R-type and N-type concave-curved railings with a curve radius of 100 m.

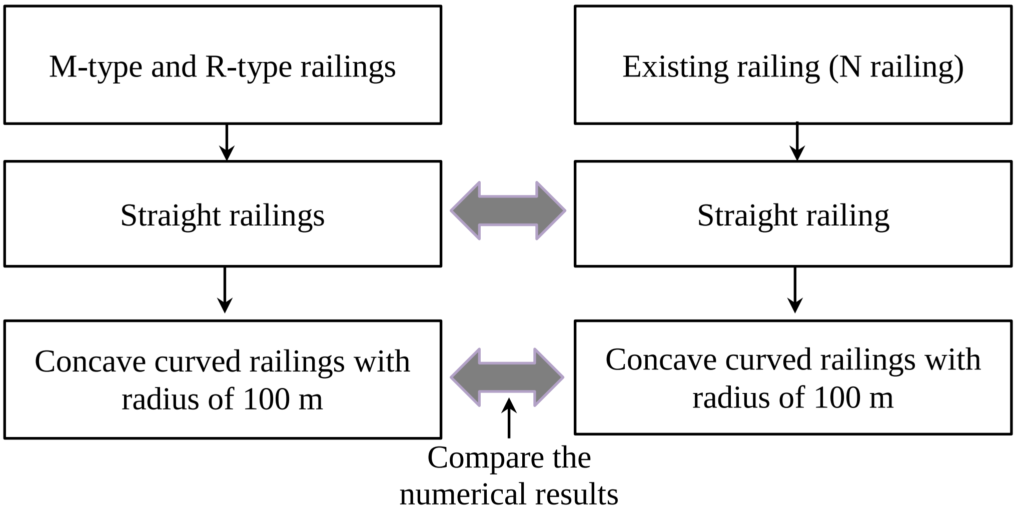


Figure 4.17 Outline of the qualification of improvements of the new-type concave-curved railings

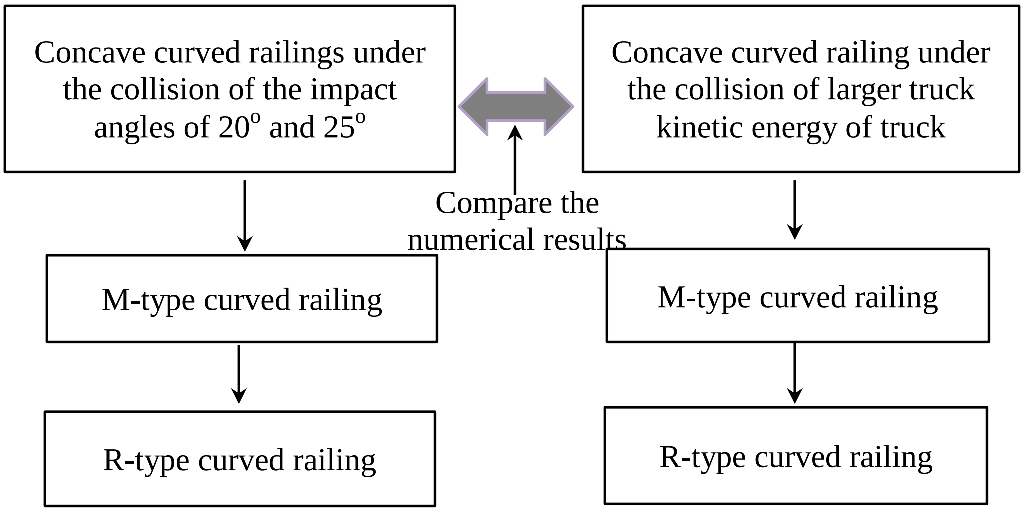


Figure 4.18 Performances of the new-type concave-curved steel bridge railings subjected to the collision of large impact angles

4.3.2 Finite element model of new and existing railings

The finite element models of M-type, R-type and N-type railings are presented in **Figures 4.19**, **4.20** and **4.21**, respectively. The railings are built up from top, upper, and lower beams, posts and the curb. The post models that were successfully created in the previous section are adopted to build the corresponding railing simulations. All beams have the pipe cross-section. Both M-type and R-type railings, the diameter of top beam is 140 mm with thickness of 6.6 mm. The upper and lower beams have the same 89 mm diameter and 2.8 mm thickness. The diameter and thickness of beams are designed depended on the limited bending moment of M_o that is obtained from the equivalent structures as shown in **Figure 4.6**.

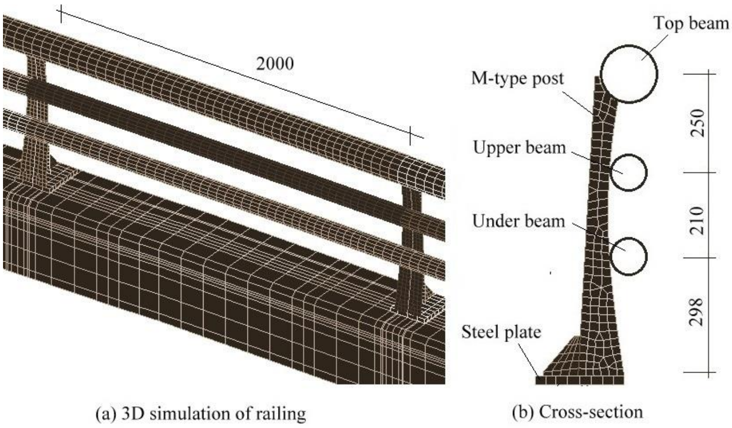


Figure 4.19 Finite element models of the M-type railing (Unit: mm)

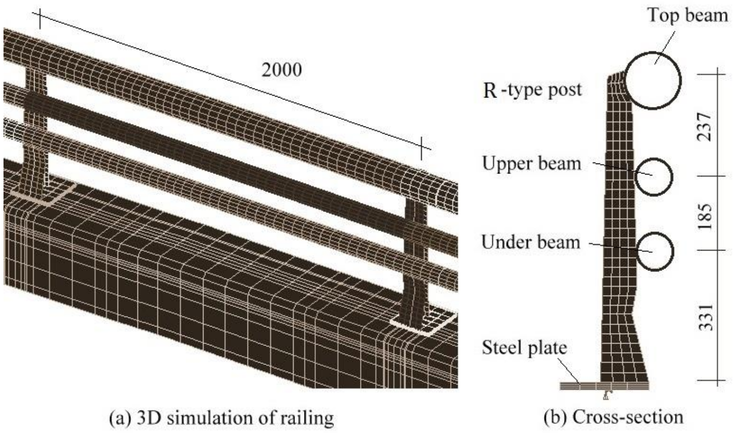


Figure 4.20 Finite element models of the R-type railing (Unit: mm)

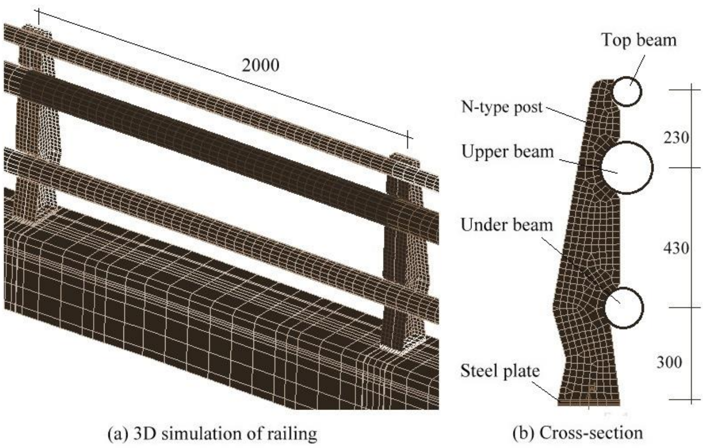


Figure 4.21 Finite element models of the N-type railing (Unit: mm)

The beams of the N-type railing have the pipe cross-section, and are made of the steel grade of STK400. In the N-type railing, the upper beam has the largest diameter and is a difference in arrangement of beams between new and existing railings. The diameter of top, upper and lower beams are 76 mm, 140 mm and 114 mm with their thickness of 2.8 mm, 4.5 mm and 3.5 mm, respectively. In all railings, the span between two posts is 2000 mm.

As with the studies in **Chapters 2** and **3**, the beams investigated in the present study are modelled by using the four-node shell elements. The beam steel is modelled as an isotropic elasto-plastic material following von Mises yielding criterion. The characteristic properties of the steel of railing members are presented in **Table 4.3**. The same truck model successfully used in the previous chapters is again adopted into the impact collision simulations in this study.

The typical simulation for case of truck crashed into the new-type straight railing is presented in **Figure 4.22** and a case of concave-curved railing is shown in **Figure 4.23**. The truck is assumed that to crash the point on beam located between post numbers 8 and 9. The collision area on the railing consists of the beams and posts from numbers 5 to 11.

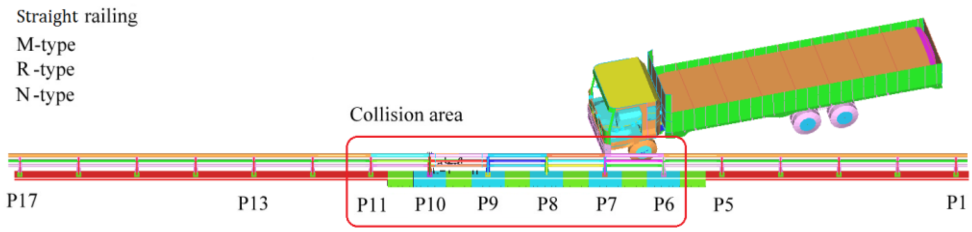


Figure 4.22 Typical simulation of the impact collision between the new-type straight railings subjected to the heavy truck collision

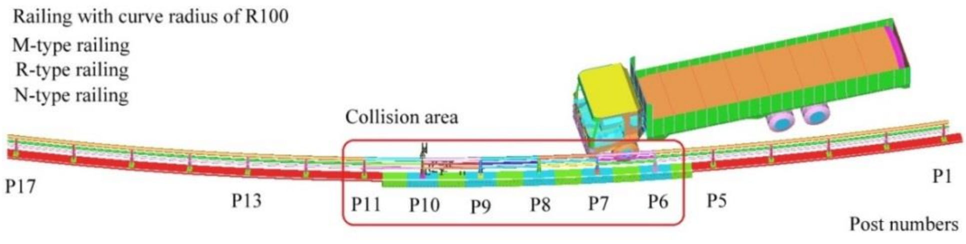


Figure 4.23 Typical simulation of the impact collision between the new-type concave-curved railings subjected to the heavy truck collision

Table 4.3 Properties of the steel materials used for the new and existing railings

Description	Steel grade	Mass density (kg/m^3)	Poisson's ratio	Young modulus (GPa)	Shear modulus (GPa)	Yield stress (MPa)
Beam	STK400		0.3	206	88	235
Post	SS400	7850	0.3	206	88	235
Steel plate	SS400		0.3	206	88	235

4.3.3 Performances of new-type curved railing

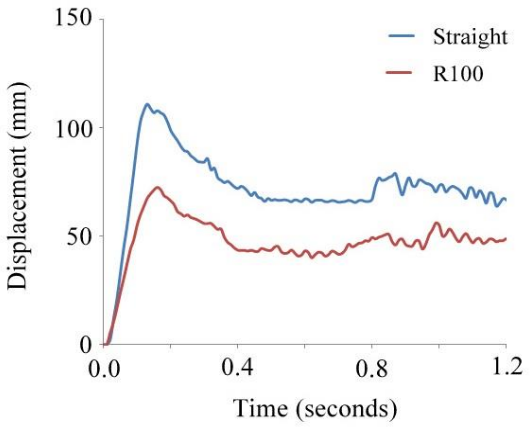
4.3.3.1 Displacement responses

In the all cases of the concave-curved and straight railing, the largest displacement occurs at the top of the post number 8. Their displacement-time history is presented in **Figure 4.24**. It can be seen that the behaviours of railing investigated here are not similar to those of the railing cases in the **Chapter 3**, because two collision stages occur during the impact collision.

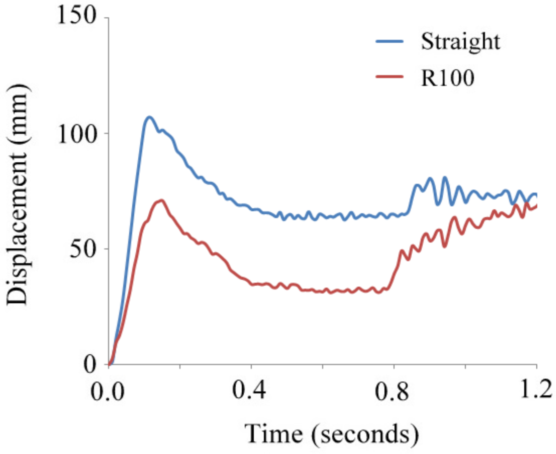
The first stage occurs when the front bumper of truck crashes into the railing. This stage is represented by the maximum displacement at time point around 0.2 seconds. After this moment, by the guide of the railing beams the truck continues to move towards the end of railing and the displacement is decreased. The second collision stage occurs when the rear part of the truck body hits the railing. This stage is represented by an increase of displacement at time point around 0.9 seconds. The increase of displacement in this stage is not larger than that in the first one. After the second stage, the truck is still guided by the railing back to the line of the road.

The displacement results shown in **Figure 4.24** are the comparisons of the largest displacement on the concave-curved and straight railings. The curved and straight railings are built up from the same features and dimensions of posts and beams, and are subjected to the same vehicular collision conditions. The track of displacement indicates that the behaviours of the concave-curved railing are similar to those of the straight one. For all railing cases, both residual and maximum displacements of the concave-curved railings are smaller than those of the straight one.

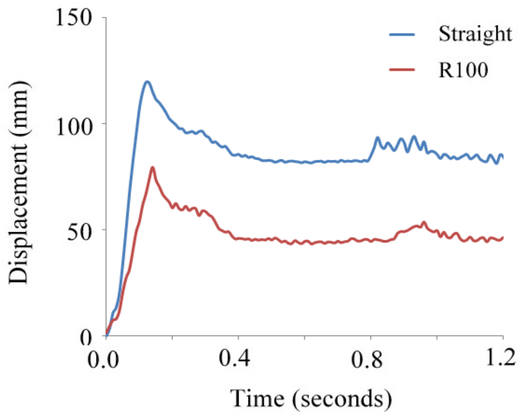
Figure 4.25 is a comparison of lateral residual displacement occurred on the new-type concave-curved and straight railings. It can be seen that the posts located in the collision area have severe deformation due to the impact of truck than the other posts toward the both ends of railing. The lateral displacements of the new-type concave-curved steel bridge railings are smaller than those of the straight one. The concave-curved railings thus guide the truck back to the line of road better than straight ones.



(a)



(b)



(c)

Figure 4.24 Displacement of the new-type railings (a) M-type, (b) R-type and (c) N-type

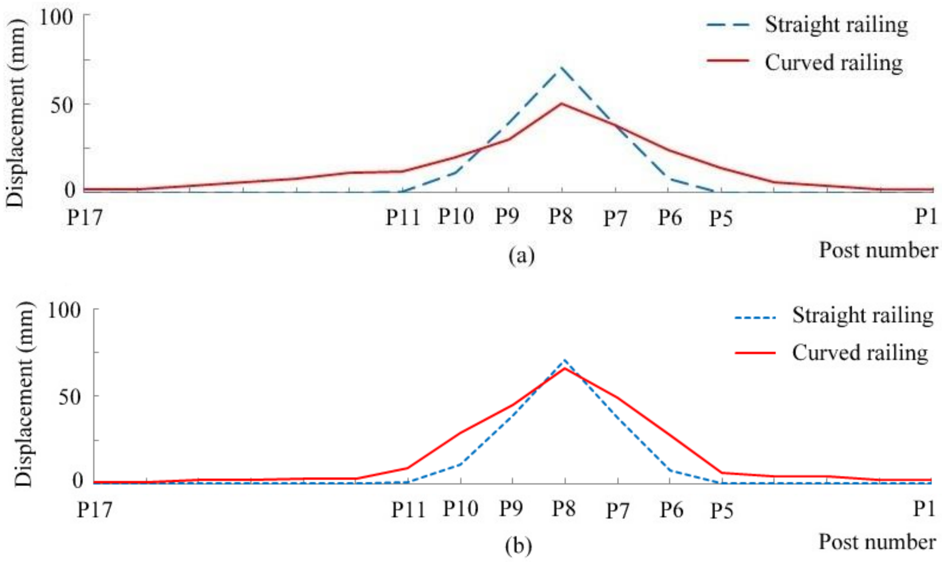


Figure 4.25 Lateral residual displacement patterns of the new-type railings (a) M-type railings and (b) R-type railings

The numerical results indicate that the displacements of all concave-curved railings are smaller than 300 mm that is specified in the Japanese specifications, thus the new-type concave-curved railings meet requirement standards. Comparisons of displacement between the new-type and existing railings are presented in **Figure 4.26**. In both cases of the straight and concave-curved railing, the displacement on the N-type railing is larger than that on the other ones.

4.3.3.2 Absorbed energy of new-type concave-curved railing

The absorbed energy of railing is summarized in the **Table 4.4**. For all cases of railing, the energy transferred from the truck to railing is smaller than the impact energy level of 130 kJ for the railing grade of A which is specified by the Japanese specifications. The M-type railing absorbs more energy than the R-type one. Because the displacement on M-type railing is larger, such railing absorbs much energy. The M-type straight railing is transferred the largest amount of energy with 35 kN and R-type curved railing is the smallest with 26 kN.

Table 4.4 Absorbed energy of the new-type railings

Type of railing	Curved railing (kJ)	Straight railing (kJ)
M-type	29	35
R-type	26	28

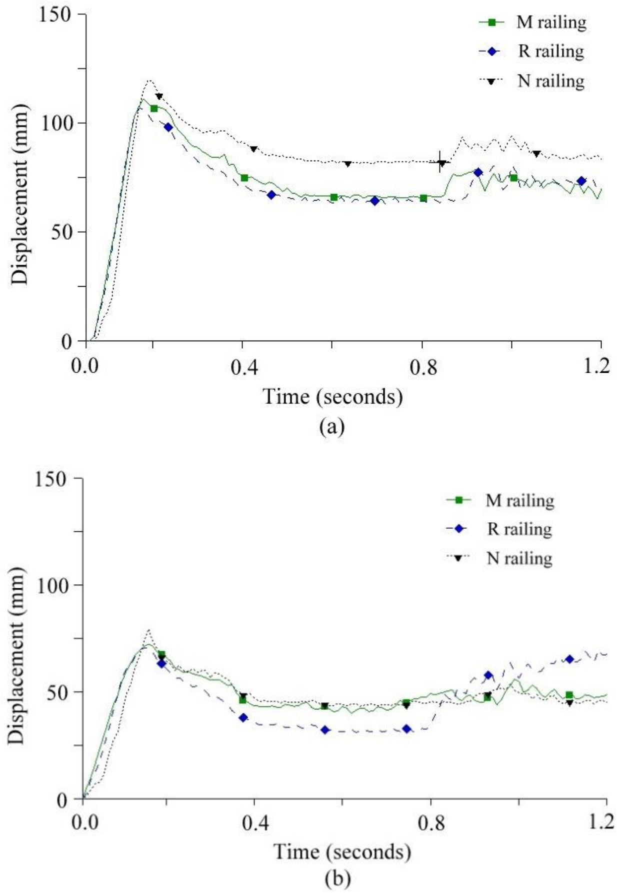


Figure 4.26 Comparison of the displacement results for the new-type and existing railings (a) Straight railings and (b) Concave-curved railings

The total energy and the truck kinetic energy for the case of M-type railing are shown in **Figure 4.27** and for the case of R-type railing is **Figure 4.28**. In those figures, the energy responses of the new-type concave-curved railing case are compared with those of the corresponding straight one and the existing railing also.

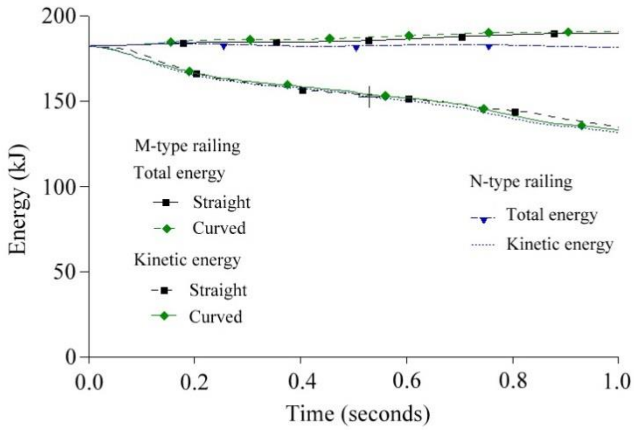


Figure 4.27 Energy response of the impact collision for the M-type railing

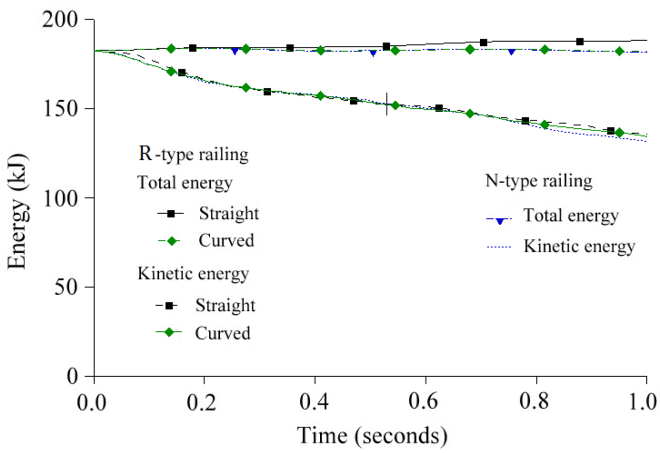


Figure 4.28 Energy response of the impact collision for the R-type railing

Figures 4.27 and **4.28** show that the energy results of the new-type concave-curved railing case are close to those of the corresponding straight one. The energy responses of new-type railing case are similar to those of existing one. Because a part of the truck's kinetic energy is transferred to the railing, the truck energy is decreased during the impact collision.

4.3.3.3 Movement of truck crashed into the new-type railings

As with the studies in previous chapters, the movement of truck is important consideration to verify the performances of the new-type concave-curved railings. **Figure 4.29** shows the movement of the truck crashed into the M-type concave-curved railing with a curve radius of 100 m. This movement is compared with the other one drawn for the case of M-type straight railing. Both curved and straight railings are subjected to the same truck velocity and speed and impact angle.

Figure 4.29 shows that after the first and second collision stage, the truck continues to move along the railing towards the end of railing and then back to the line of road. Accordingly, it indicates that the M-type concave-curved steel bridge railing effectively meet the required standards in the Japanese specifications for the railing design.

By the same way, the movements of truck crashed into the R-type and N-type concave-curved and straight railings are shown in **Figures 4.30** and **4.31**, respectively. It can be seen that by both types of railing, the truck is guided back to the line of road successfully.

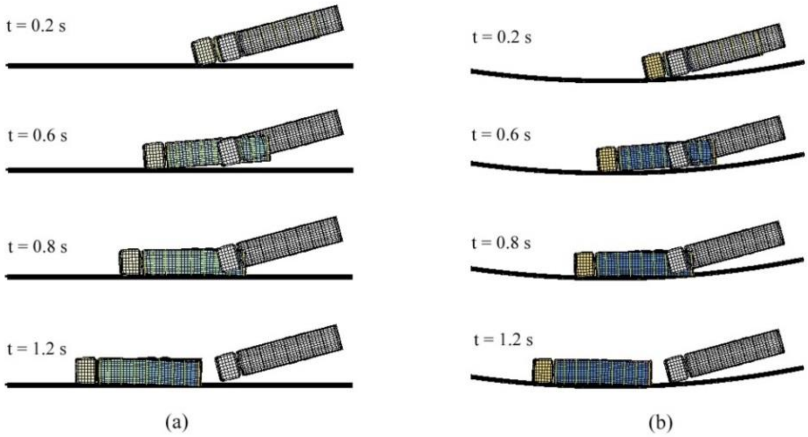


Figure 4.29 Movement of the truck crashed into the M-type railing (a) Straight railing and (b) Concave-curved railing

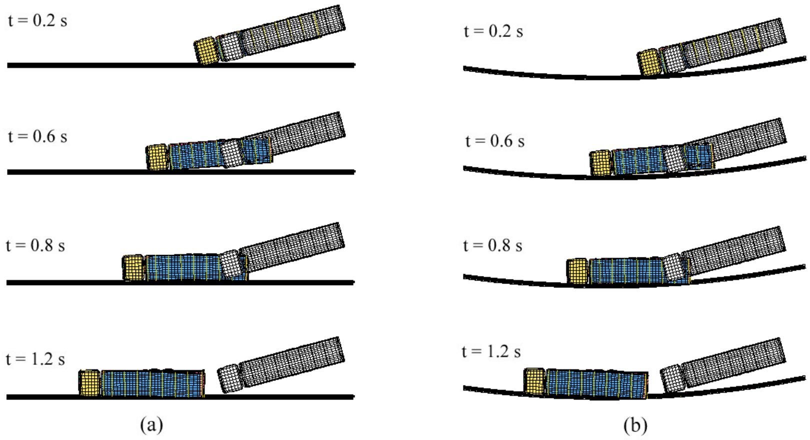


Figure 4.30 Movement of the truck crashed into the R-type railing (a) Straight railing and (b) Concave-curved railing

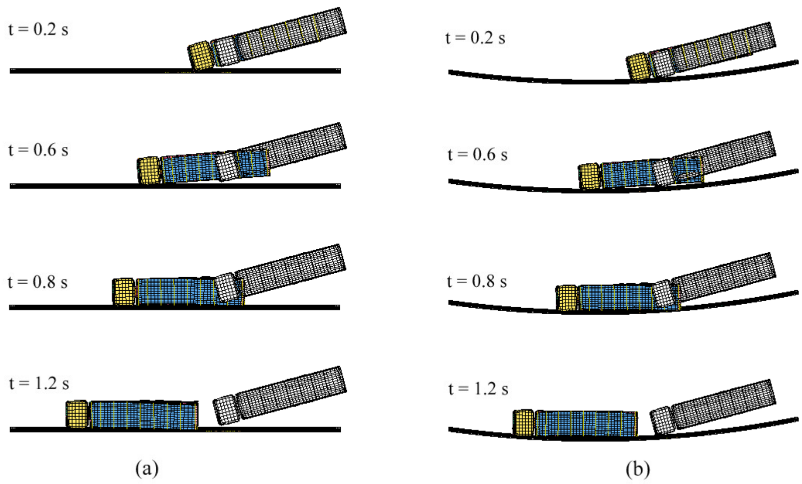


Figure 4.31 Movement of the truck crashed into the N-type railing (a) Straight railing and (b) Concave-curved railing

4.3.3.4   Decrement of truck velocity

The velocity-time history of the truck for both cases of the new and existing railings is presented in **Figures 4.32** and **4.33**. Such velocity is obtained at the point of the truck gravity center in the movement direction. The track of velocity shows that the decrement of truck speed in the case of new-type railings is close to that in the case of existing ones.

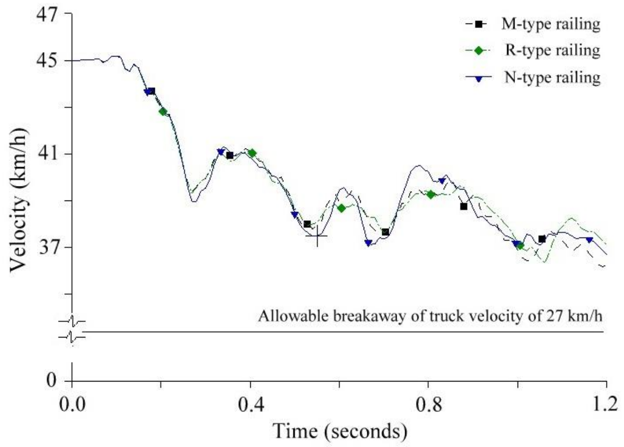


Figure 4.32 Velocity-time history of the truck crashed into the new-type and existing straight railings

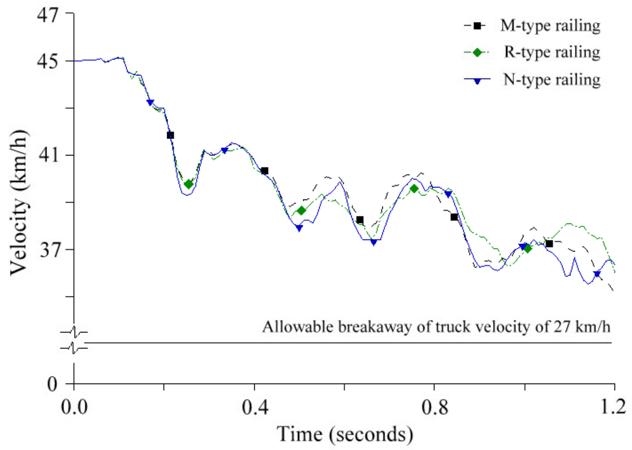


Figure 4.33 Velocity-time history of the truck crashed into the new-type and existing concave-curved railings

For all railing cases, the remained velocity of truck after the impact collision is larger than 60 percent of its initial speed that is specified as 27 km/h. It thus indicates that all new-type concave-curved railings meet required standards in the current Japanese specifications for the railing design.

4.3.3.5 Moving acceleration average of truck crashed into new-type railings

As with the discussions in **Chapter 3**, the acceleration at the point of the truck's gravity center can be considered to ensure the safety for the vehicular passengers and driver. The moving acceleration average of the truck gravity center for the cases of concave-curved and straight railings is presented in **Figures 4.34** and **4.35**. This type of acceleration is solved by using 21 acceleration points of 0.5 millisecond interval for each 10 milliseconds of movement.

The moving acceleration average results indicate that the acceleration behaviours of the truck crashed into the concave-curved railing is quite similar to that in the case of straight railing. All railings investigated in the present study, the moving acceleration average is less than a limit amount of 180 $m/s^2/10ms$ specified by the Japanese specifications for the railing grade of A. Thus, the truck's driver and passengers are secured in the impact with those railings.

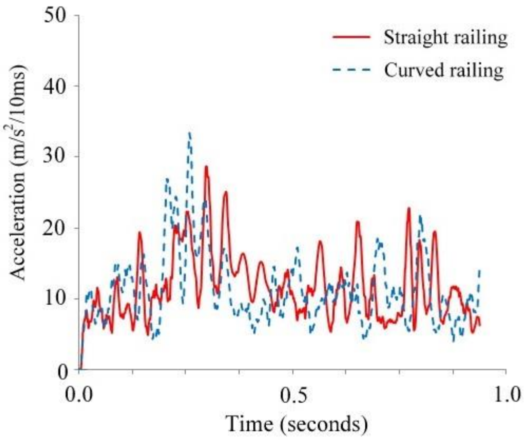


Figure 4.34 Moving acceleration average of the truck gravity center for the M-type railing case

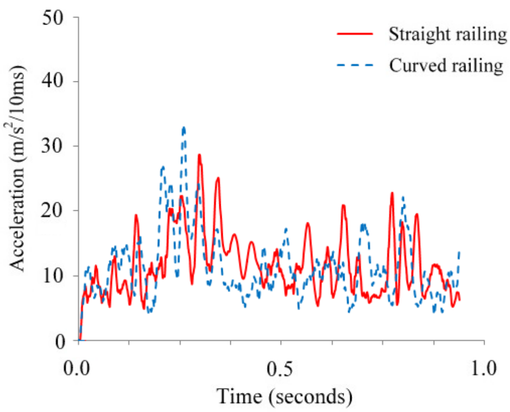


Figure 4.35 Moving acceleration average of the truck gravity center for the R-type railing case

As with above discussions, the purpose of the present study is to develop the new-type concave-curved steel bridge railings and verify the suspicion of the engineers and researchers. Accordingly, the results of the new-type concave-curved railings are compared with those of the straight one, and of existing type successfully used on the bridge in Japan. In the comparisons of each railing type, both straight and concave-curved railings are built up from the same features and dimensions of beams, posts and curb, and are subjected under the same vehicular collision conditions and impact angle.

The curve radius of railing investigated is 100 m. The analytical results show that the displacements occurred on the concave-curved railing are always smaller than those on the corresponding straight one. The energy transferred from the truck to the straight railings is larger than that in the case of concave-curved one. The concave-curved railing can effectively guide the truck back to the line of road after the impact collision. Thus, the numerical analysis using the LS-DYNA 3D software can certainly be adopted to study the performances of new-type concave-curved steel bridge railings. Finally, the grade and features designed for straight railing is safely used for the railing on the concave-curved bridges.

4.4 Performances of new-type concave-curved railings under larger impact angle

A last study in this chapter is to perform an investigation for the performances of the new-type concave-curved railings under the collision of larger impact angles. As has been mentioned above, because of human problems the impact angle between the concave-curved railing that has a curve radius of 100 m and the truck may occur with angles of 20^o and 25^o. The displacement and the energy transferred from the truck to the railing increase with any increase of the impact angles. Thus, the concave-curved railing in such cases may be in more disadvantageous situation than the other concave-curved and straight ones.

However, the current Japanese specifications for the railing design have not mentioned about the cases, in which the impact angle is larger than 15^o. To concern whether the concave-curved railings under the collision of the impact angles of 20^o and 25^o are in safe or not, such new-type concave-curved railings are examined by subjected to those angles. To qualify the disadvantageous or advantageous situation of those concave-curved railings, their results are compared with those of corresponding straight and concave-curved ones under the impact of the truck collision with higher speeds of 65 km/h and 80 km/h.

4.4.1 Responses of new-type and existing curved railings

The displacement on M-type concave-curved railing subjected to impact angle of 20° and 25° are presented in **Figures 4.36** and **4.37**. For the case of 20° impact angle, the displacement of concave-curved railing are compared with that of the corresponding straight one subjected to the same vehicular conditions but the impact angle is 15° and of the other corresponding concave-curved and straight ones which are subjected to the impact angle of 15° and the truck speed of 65 km/h.

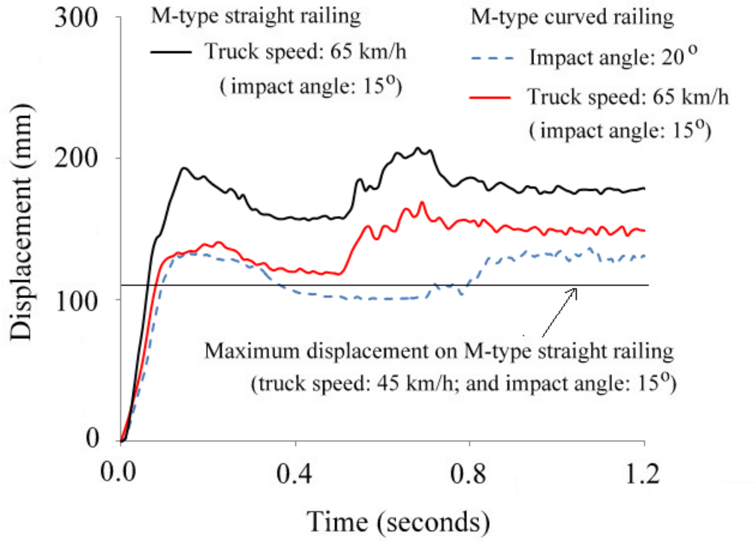


Figure 4.36 Displacement of the M-type concave-curved railing under the collision of the 20° impact angle

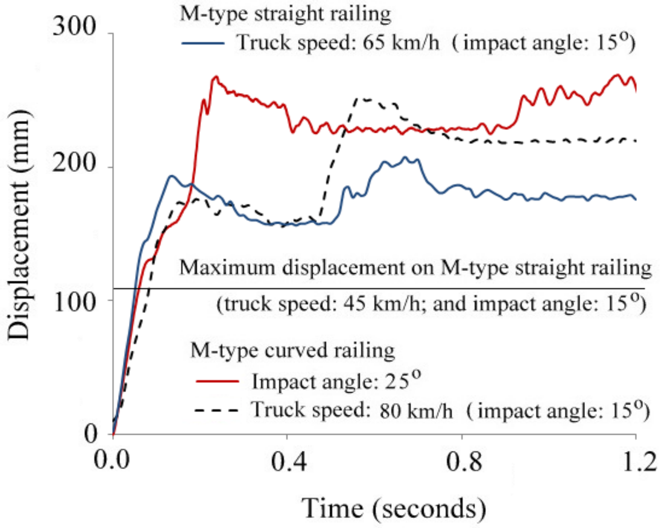


Figure 4.37 Displacement of the M-type concave-curved railing under the collision of the 25° impact angle

All railings have the same features and dimensions of beams, posts and curb, and are subjected to the collision of the truck weight of 25 ton (245 kN). **Figure 4.36** shows that when the impact angle is of 20^o, the maximum displacement on the concave-curved railing is larger than that of the corresponding straight one which is subjected to the same truck collision but the impact angle is 15^o, and is close to that of the same concave-curved railing where the collision of the 65 km/h truck speed with the impact angle of 15^o is applied.

For the case of the 25^o impact angle, **Figure 4.37** indicates that the maximum displacement of the concave-curved railing is larger than that occurred on the corresponding straight and concave-curved ones where the collision of the truck speed of 65 km/h with the impact angle of 15^o is applied. According to **Table 1.1**, the collision of the truck weight of 25 ton (245 kN) and speed of 65 km/h with the impact angle of 15^o is applied for the railing grade of SB. It thus appears here that the displacement of the M-type concave-curved railing under the collision of the impact angles of 20^o and 25^o may reach for that of railing that has two more higher grade.

By the same way, the displacement of the R-type concave-curved steel bridge railing when subjected to the impact angles of 20^o and 25^o is shown in **Figures 4.38** and **4.39**, respectively. For the case of the 20^o impact angle, the maximum displacement on the R-type concave-curved railing occurs in the first collision stage, and is close to that of the corresponding straight one which is subjected to the collision of the truck speed of 45 km/h and the impact angle of 15^o.

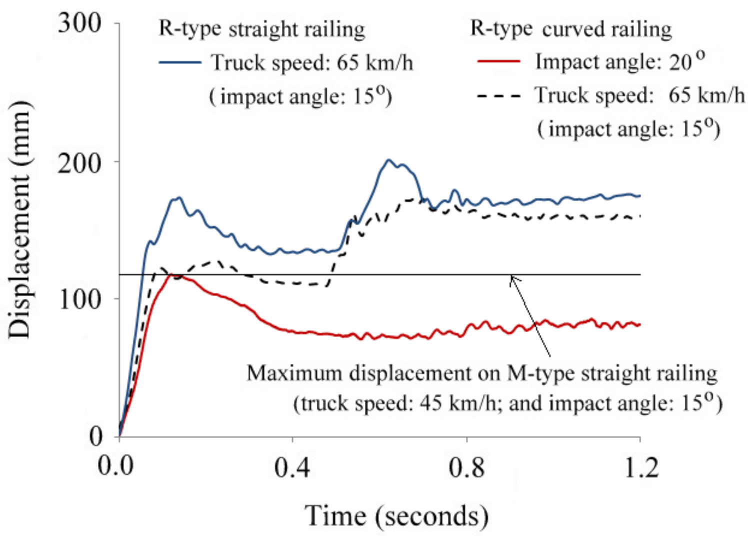


Figure 4.38 Displacement of the R-type concave-curved railing under the collision of the 20^o impact angle

Figure 4.39 shows that in the case of the 25° impact angle the displacement on the R-type concave-curved railing is close to that of the corresponding straight and concave-curved ones which are subjected to the truck speed of 65 km/h with the impact angle of 15°. Both cases of impact angles investigated the maximum displacement on R-type concave-curved railing occurs in the first collision stage.

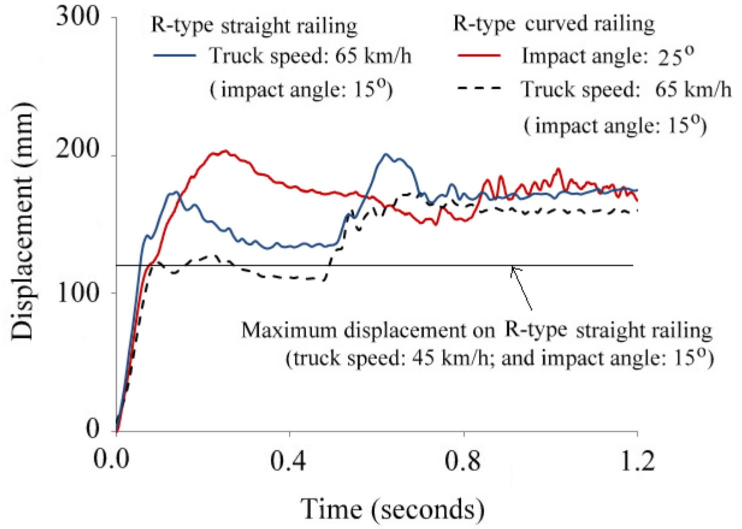


Figure 4. 39 Displacement of the R-type concave-curved railing under the collision of the 25° impact angle

The displacement results of the N-type concave-curved railing subjected to the impact angle of 20° and 25° are shown in **Figures 4.40** and **4.41**, respectively. In the case of the impact angle of 20°, the largest displacement is close to that of the corresponding straight one. For the 25° impact angle case, the largest displacement is larger than that of the corresponding straight and concave-curve ones where the truck speed of 65 km/h is applied, and is over the 300 mm limit displacement specified in the Japanese specifications. It can thus appear that the N-type concave-curved railing did not meet requirement standards when the impact angle is up to 25°.

The results of displacement indicate that both new-type concave-curved steel bridge railings under the collision of the larger impact angles than hitherto meet the displacement requirements prescribed in the current Japanese specifications for the railing design. The displacement on the N-type concave-curved railing is over the limit displacement of 300 mm when the impact angle is up to 25°.

For all cases of the concave-curved railings investigated with the larger impact angles, their displacements are larger than that of the corresponding straight one which is subjected to the same vehicular collision but the impact angle is 15°, and is close to those of the corresponding concave-curved and straight railings where the higher vehicular collision with the increase of the truck velocity is applied.

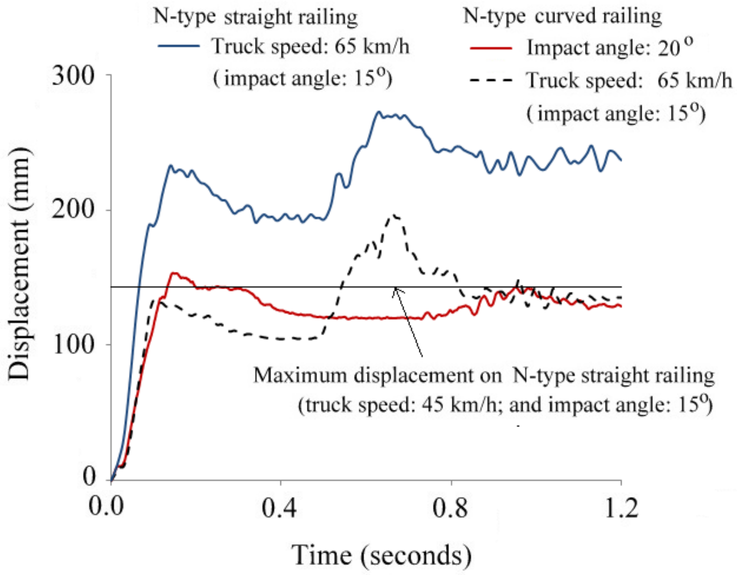


Figure 4.40 Displacement of the N-type concave-curved railing under the collision of the 20° impact angle

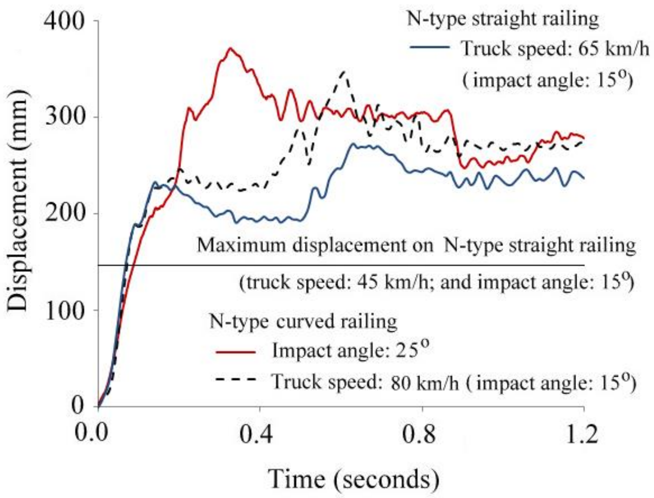


Figure 4. 41 Displacement of the N-type concave-curved railing under the collision of the 25° impact angle

4.4.2 Response of truck

The movements of the truck crashed into the concave-curved steel bridge railings with the impact angle of 25° are presented in **Figures 4.42**, **4.43** and **4.44**. For the M-type and R-type concave-curved railings, the truck is guided back to the line of road after the second collision stage. **Figure 4.44** shows that the N-type concave-curved railing cannot guide the truck when the truck crashes into this railing with the impact angle of 25^o.

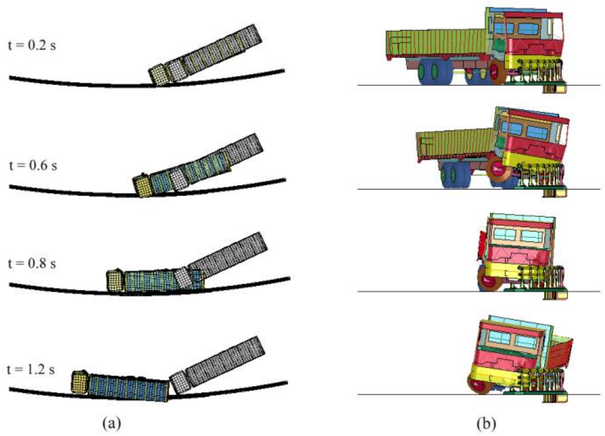


Figure 4.42 Truck movement for the case of M-type concave-curved railing with the 25^o impact angle (a) Top view and (b) Front view

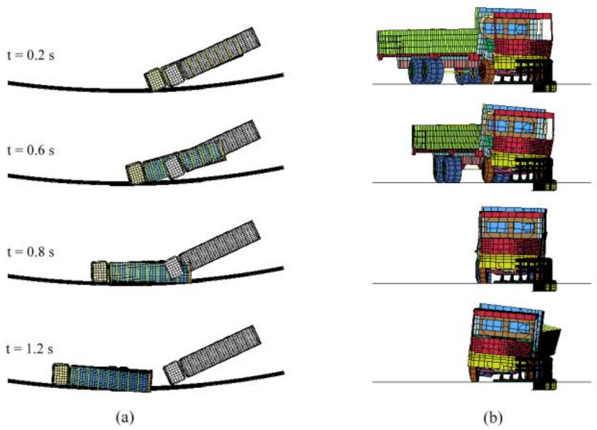


Figure 4.43 Truck movement for the case of R-type concave-curved railing with the 25^o impact angle (a) Top view and (b) Front view

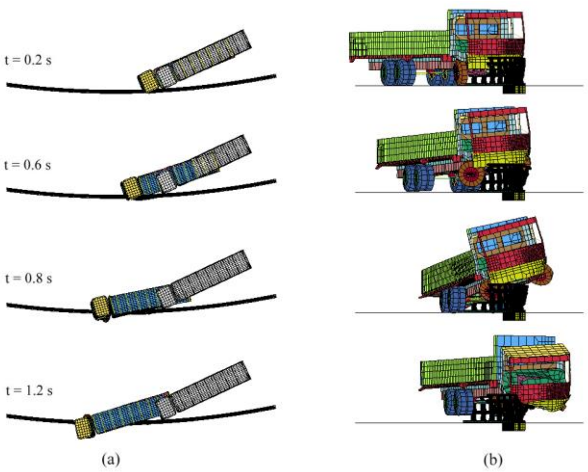


Figure 4.44 Truck movement for the case of N-type concave-curved railing with the 25^o impact angle (a) Top view and (b) Front view

4.5 Summary and discussion

The study successfully develops two new-type concave-curved steel bridge railings by the numerical analyses using the LS-DYNA 3D software. The study deals with the concave-curved railings with a curve radius of 100 m. The numerical simulations of the new-type concave-curved railings under the impact of the heavy truck are successfully created. The conclusions are summarized as follows:

(1) The collision performances of the new-type concave-curved steel bridge railings can be studied by using the numerical simulation created by LS-DYNA 3D software.

(2) From the comparisons of numerical results between the straight and concave-curved railing, it shows that in fact the displacement and absorbed energy of the concave-curved railing always smaller than those of the corresponding straight one when both railings are subjected to the same collision conditions of truck and the impact angle. The concave-curved railings is thus to be more advantageous than the straight one.

(3) From the comparison of numerical results between the new-type and existing steel bridge railings, in the same collision conditions the new-type railings have smaller displacement, and absorb less energy than the existing ones.

(4) The impact angle between the concave-curved railing and vehicle may be greater than hitherto because of some reasons of the human and vehicles. In those cases, the displacement and absorbed energy of the new-type concave-curved railing are larger than those of the corresponding straight railing which is subjected to the same collision of the truck and impact angle.

(5) The performances of new-type and existing railings are examined with the larger impact angles of 20^o and 25^o and the higher kinetic energy of truck with the increase of its speed of 65 km/h. The analysis results show that the displacement on the new-type concave-curved railings under the collision of the 20^o and 25^o impact angle are close to those of the corresponding straight and concave-curved ones where the truck collision for higher grade railing of SB is applied. For the safety, the concave-curved railings used on such kind of concave-curved bridges would be designed with lager safety margin.

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Chapter 5

PERFORMANCES OF NEW-TYPE CONVEX-CURVED STEEL BRIDGE RAILING

5.1 Numerical simulation of convex-curved railing

According to the concave or convex curvature of the curved bridges, a corresponding curved railing is applied. However, the current Japanese specifications have not concerned about the railing with convex curvature in the design and construction. In this study, a numerical simulation of an impact collision between the convex-curved railing and truck is thus created to investigate the collision behaviours of such railing. The objectives of the present study are to propose remarks and recommendations for the design and analysis of the convex-curved steel bridge railing in Japan.

The models of the M-type concave-curved railing beams, posts and curb successfully developed in **Chapter 4** are adopted into this study to create the simulation of M-type convex-curved railing. The convex-curved railing has a curve radius of 100 m and its numerical simulation is presented in **Figure 5.1**. Similar to the concave-curved railing, the impact angle in the case of convex-curved railing is measured by an angle between the vehicular direction and a tangential to the curved railing at the point where the vehicle crashes into. The truck is assumed to crash into the railing at point on the beam located between post numbers 7 and 8.

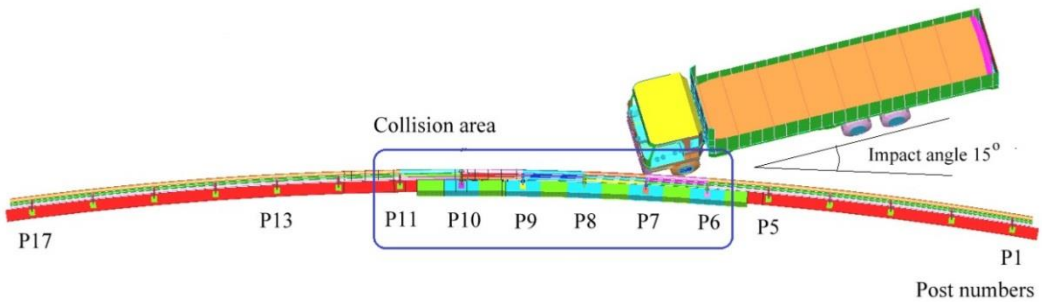

Figure 5.1 Simulation of the impact collision between the M-type convex-curved steel bridge railing and the heavy truck

As with the study in **Chapter 4**, the M-type convex-curved railing has the grade of A, and subjected to the collision of the truck speed of 45 km/h and weight of 25 ton

(245 kN). The performances of convex-curved steel bridge railing are examined with the impact angle of 15^{o} that is specified in the Japanese specifications for the railing design.

5.2 Displacement on convex-curved railing

The numerical results of the M-type convex-curved railing are compared with those of the corresponding concave-curved and straight ones which are successfully investigated in **Chapter 4** as shown in **Figure 5.2**. The largest displacement on the convex-curved railing occurs on post number 8, and is greater than that of the corresponding concave-curved and straight ones. Similar to the other railings, in the case of convex-curved railing, two collision stages are occurred during the impact collision.

The track of displacement shows that the M-type convex-curved railing has smaller displacement than the limit one of 300 mm specified in the Japanese specifications. Thus, the M-type convex-curved railing investigated in this study meets the displacement requirements. However, an amount of the maximum displacement of the convex-curved railing is around twice as large as that occurred on the concave-curved railing.

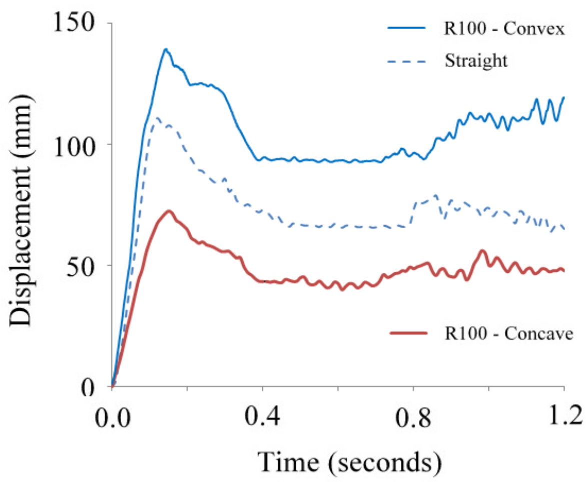

Figure 5.2 Displacements of the M-type convex-curved, concave-curved and straight railings

Figure 5.3 shows the lateral residual displacement on the M-type convex-curved, concave-curved and straight railings. It indicates that only the posts and beams located in the collision area effective undergone the collision load of the truck.

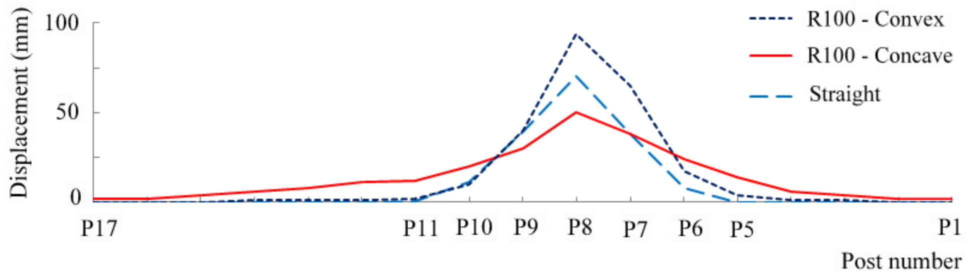

Figure 5.3 Lateral residual displacement of the M-type convex-curved, concave-curved and straight railings

5.3 Truck response

Similar to the concave-curved and straight railing, the truck behaviours of the movement, the velocity decrement and moving acceleration average at the truck gravity center and the breakaway of impact angle during the impact collision are investigated to verify the performances of M-type convex curved railing that meet the requirement standards or not.

5.3.1 Movement of truck

The movement of the truck crashed into the convex-curved and concave-curved railing is presented in **Figure 5.4**. **Figure 5.4 (b)** shows that after the first collision stage, the truck moves towards the end of railing by guiding the beam. The second collision stage occurs when the rear part of the truck body hits the railing. This stage is represented by the increase of displacement at the time points around 0.9 seconds. After two stages of the impact collision, the truck is back to the line of road.

5.3.2 Decrement of truck velocity

The velocity-time histories of the truck gravity center for the cases of the convex-curved, concave-curved and straight railings are shown in **Figure 5.5**. It shows that the decrement velocity of the truck crashed into the convex-curved railing is similar to that of the corresponding concave-curved and straight ones. The remained velocity of truck in all cases is larger than the allowable breakaway speed of 27 km/h. According to the current Japanese specifications for the railing design, it indicates that the M-type convex-curved steel bridge railing meets required standards.

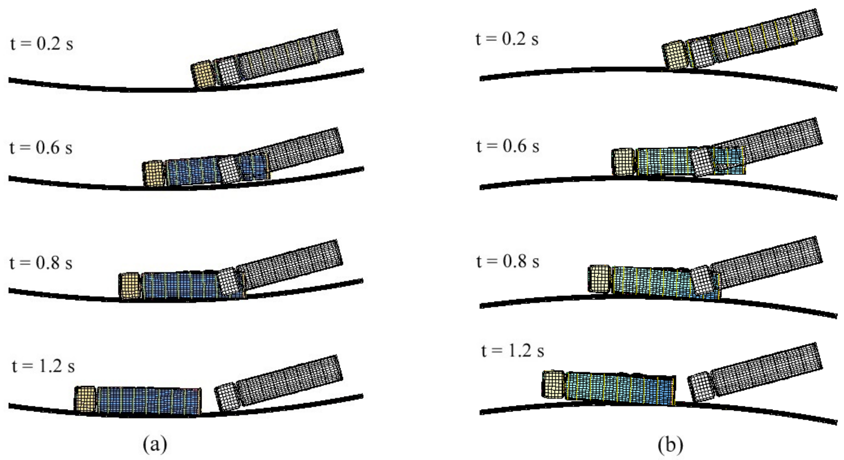

Figure 5.4 Movement of the truck crashed into the M-type railings (a) Concave-curved railing and (b) Convex-curved railing

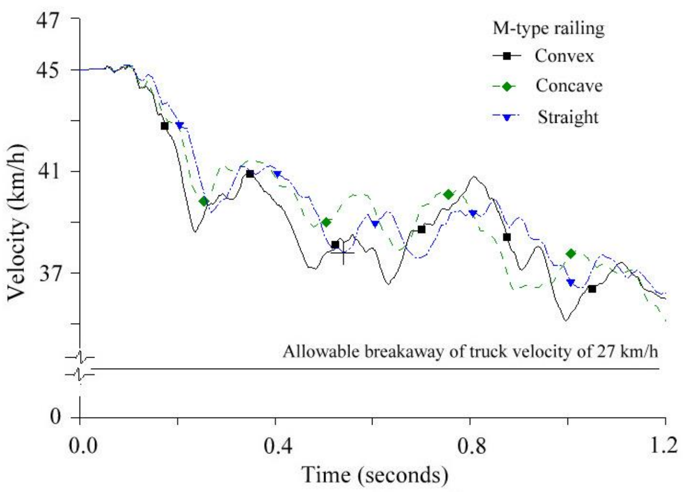

Figure 5.5 Decrement of the truck velocity for the case of M-type concave-curved, convex-curved and straight railings

5.3.3 Moving acceleration average of truck gravity center

The moving acceleration average of the truck gravity center for three cases of railing is presented in **Figure 5.6**. The largest amount of the moving acceleration in the case of convex-curved railing is larger than that of the concave-curved and straight ones. However, all moving acceleration averages are smaller than the limit amount of 180 m/s^2/10ms for railing grade of A that is specified by the Japanese specifications. Thus, the truck's driver and passengers are secured in the impact with the M-type convex-curved railing.

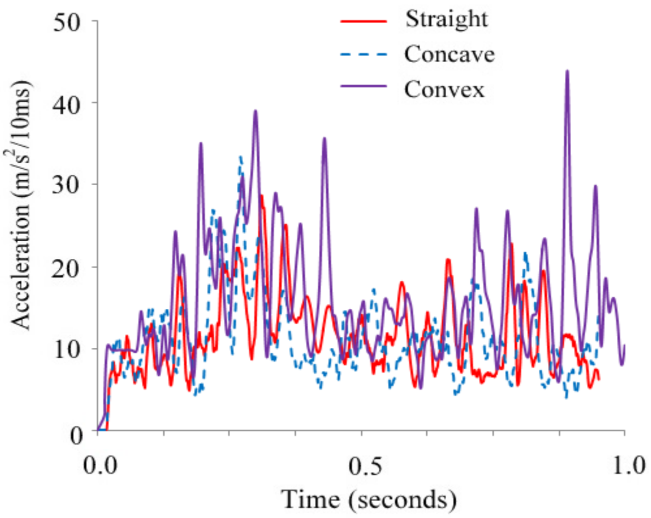

Figure 5.6 Moving acceleration average of the truck gravity center for the M-type concave-curved and convex-curved curved and straight railings

5.3.4 Breakaway of impact angle

According to the current Japanese specifications for the railing design, the impact angle after the point of impact collision is required to be smaller than 60 percent of the initial impact angle of 15°. **Figure 5.7** draws the angle between the railing and the truck before and after the first and second collision stages. A summary of the breakaway of the impact angle during the impact collision is shown in **Table 5.1**.

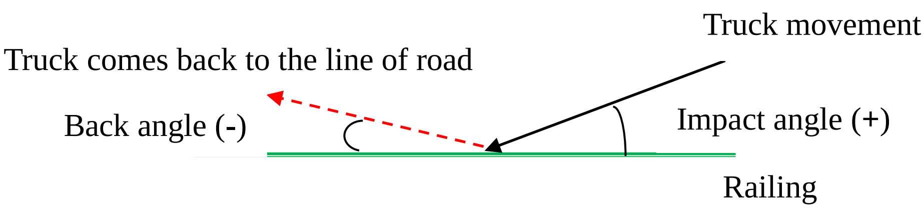

Figure 5.7 Impact angle and back angle of the truck in the impact collision

Table 5.1 Breakaway of impact angle during the impact collision

Time (seconds)	0.0	0.2	0.3	0.4	0.6
Remained angle (deg)	15	13.7	10.6	8.8	7.1

It can be seen that the decrement of the impact angle for the case of M-type convex-curved railing meets the requirements of the Japanese specifications. This railing can guide the truck back to the line of road during the impact collision.

5.4 Summary and discussion

The finite element models are successfully created to study the performances of the M-type convex-curved railing subjected to the truck collision. The numerical results of this railing are compared with those of the corresponding concave-curved and straight railings which are successfully examined in **Chapter 4**. The study deals with the railing with the convex curve radius of 100 m. On the basis of study results, the important observations can be concluded as following:

(1) From the numerical results, it can be seen that the collision performances of the convex-curved steel bridge railings can be studied by using the finite element model with LS-DYNA 3D software.
(2) The collision performances of M-type convex-curved steel bridge railing meet the required standards in the current Japanese specifications for the railing design. This M-type convex-curved railing can be adopted to install on the convex-curved bridges.
(3) From the comparison of results between the convex-curved railing with the concave-curved and straight ones in the same collision of the truck speed and weight and impact angle, the displacement occurred on the convex-curved railing is larger than that of the correspond straight one. It indicates that the convex-curved railing is more disadvantageous than the straight one. In the view point of safety, in the same collision conditions the convex-curved railing should be designed with a larger safety margin than the others.

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Chapter 6
SUMMARY AND CONCLUSIONS

Many varieties of steel railings have designed and installed on curved bridges in the Japan. The curved railings secure the vehicular driver and passenger during the event of impact collision. Similar to the straight railings, the curved ones are also required to meet four performance standards of the Japanese specifications for the railing design.

The objectives of this study are to qualify the researcher and engineer suspicion, in which the curved railings are more disadvantageous than straight ones when they are subjected to the same collision conditions, to develop the new-type curved steel bridge railings that meet two improvement functions in the Japanese specifications for the railing design issued in 2004, and to examine the performances of curved railing under the impact of the heavy truck with the lager impact angles.

The numerical simulations of the curved and straight railings subjected to the truck collision are successfully developed by using the LS-DYNA 3D software. The thesis consists six chapters. In which, **Chapter 1** presents the introduction, the history of development of railing specifications in Japan, the literature of impact collision, and the statements and objectives of the study. The important conclusions from **Chapters 2** to **5** are summarized as following paragraphs:

Chapter 2 reports the study of the performances of the straight steel bridge railing subjected to the truck collision. The numerical simulation is developed to simulate the full-scale test of such railing under the impact of the truck. This test was carried out by the Japan Public Works Research Institute in 1992. On the basis of the study results, the important observations can be concluded as following:

(1) The comparison of the numerical and experimental results indicates that the numerical simulation of the straight steel bridge railing under the vehicular impact is successfully created, and is verified by using the experimental results. The collision performances of the straight steel bridge railing can be studied by the finite element model with using the LS-DYNA 3D software.

(2) The numerical results in the case of the element mesh size of 8-8-35 model and the count of the strain rate effect of the steel are close to those of the experiment test. Thus, such experiences of model representation are applied into the study of the collision performances of the curved steel bridge railings.

(3) The numerical results in both cases of continuous and sleeve connection between beam and beam are very close. In fact the high-strength bolts are used to fasten the pipe sleeve onto the beam. This kind of contact prevents any transposition of the connection joint along the beam center axis. Thus, to simplify the representation and save computation time, the continuous connection type is modelled into the numerical simulation of the curved steel bridge railings under the impact of the heavy truck.

Chapter 3 is the study of the performances of concave-curved steel bridge railings subjected to the heavy truck collision. The study deals with the concave-curved railing with various curve radiuses of 100, 150, 280 and 460 m and the straight one. All railings have the grade of SC, and are built up from the same beams, posts and curb. The collision of the truck weight of 25 ton (245 kN) and speed of 50 km/h with the impact angle of 15^o is subjected to all railing cases. To qualify the suspicion of engineers and researchers, the results of concave-curved railings with a curved radius of 100 m, 150 m, 280 m and 460 m are compared with those of the corresponding straight one.

According to the curvature of railing, the truck position on road and direction movement, and the human problems the angle between the concave-curved railing and truck in the impact collision may be larger than the angle of 15^o that is specified in the Japanese specifications. The study finds that the angles of 20^o and 25^o may occur in the cases of concave-curved railings with a curve radius of 100 m and 150 m. The study is thus to examine the performances of such railings under the impact of truck with larger impact angles. The important conclusions of this study can be summarized following as:

(1) The numerical results show that the performances of all concave-curved railings meet the requirement standards in the Japanese specifications for the railing design. In the same collision conditions, the railing designed for the straight bridge can apply to use on the concave-curved ones.

(2) From the comparison of results between the concave-curved and straight railings when they are subjected to the same collision conditions. It shows that the displacement on the concave-curved railing and energy transferred from the truck to the concave-curved railing increase with any increase in the railing curvature. The concave-curved railing undergoes smaller displacement, and involves less energy than straight one. The concave-curved railing is more advantageous than straight railing when they are subjected to the same collision conditions.

(3) The amounts of displacement and absorbed energy of the concave-curved railings that are subjected to the collision of the impact angles of 20^o and 25^o are greater than those of the corresponding straight one that is subjected to the same vehicular condition but the impact angle is 15^o. In the viewpoint of safety, for the concave-curved bridges where the larger impact angles occur, it is necessary to increase a larger margin for their concave-curved railing or control the speed of vehicle for reducing its kinetic energy.

Chapter 4 reports the development of new-type concave-curved steel railings used for the bridges. The railings are designed with smaller and slender form to meet improvement functions of a landscape-friendly appearance and a flow in the road user's view from bridges required in the Japanese specifications issued in 2004. The experimental tests of static load and the heavy steel ball collision are performed to examine the performances of new-type railing posts.

The finite element models are successfully developed to study performances of the new-type railing posts under the impact of the steel ball. Those post models are adopted to build the simulation of the new-type concave-curved and straight railings under the impact of the truck. The railings investigated in the present study have the grade of A and the radius of concave curvature of 100 m. The conclusions are summarized as follows:

(1) The numerical simulations represented the impact collision of the new-type concave-curved steel bridge railings subjected to the truck collision are successfully developed. The results of the study show that the collision performances of the new-type concave-curved railings can be studied using the numerical simulation with LS-DYNA 3D software.
(2) From the comparisons of numerical results between the straight and concave-curved railings, it shows that in fact the displacement and absorbed energy of concave-curved railings always smaller than those of the corresponding straight one when both railings are subjected to the same collision of the truck weight and speed and the impact angle. The concave-curved railings is thus to be more advantageous than the straight one.
(3) The comparison of numerical results between the new-type and existing railings shows that the new-type railings have smaller displacement, and absorb less energy than existing ones.
(4) Because of the human and other problems, the impact angle between the concave-curved railing with a curve radius of 100 m and the truck may be larger

than one that is specified in the Japanese specifications. The displacement and absorbed energy of this concave-curved railing are larger than that of the corresponding straight one which is subjected to the same collision of truck with the impact angle of 15^o.

(5) The performances of new-type and existing concave-curved railings under the collision of the impact angles of 20^o and 25^o are compared with that of the corresponding straight and concave-curved ones where the higher kinetic energy of truck by increasing the truck speed up to 65 km/h is applies. It can be seen that the displacement on the concave-curved railings under the 20^o and 25^o impact angle are close to that of the corresponding straight and concave-curved ones that are subjected to the higher truck collision for the railing grade of SB. In the viewpoint of safety, the concave-curved railings installed on such kind of concave-curved bridges would be designed with lager safety margin.

Chapter 5 reports the study of the performances of M-type convex-curved railing subjected to the truck collision. The numerical results of such railing are compared with those of the corresponding concave-curved and straight ones which are successfully examined in **Chapter 4**. The study deals with the railing with a convex curvature of 100 m. On the basis of study results, the important observations can be concluded as following:

(1) From the numerical results, it can be seen that the collision performances of the convex-curved steel bridge railings can be studied by using the finite element model with LS-DYNA 3D software.

(2) The collision performances of M-type convex-curved railing meet the required standards in the current Japanese specifications for the railing design. This M-type convex-curved railing can be adopted to install on the convex-curved bridges.

(3) From the comparison of results between the convex-curved railing with the concave-curved and straight ones in the same collision of the truck speed and weight and impact angle, the displacement occurred on the convex-curved railing is larger than that of the correspond straight one. It indicates that the convex-curved railing is more disadvantageous than the straight one. In the view point of safety, in the same collision conditions the convex-curved railing should be designed with a larger safety margin than the others.

With background and knowledge in the impact collision studied from the doctoral research, some studies in the future shall be performed as following:

(1) To model crack and breaks of the structural members into the numerical simulations of the curved steel bridge railing under the impact of the heavy truck to investigate its performances.
(2) To study the impact collision of steel railings under the impact of an automobile collision. For this impact collision, the vehicular driver and passengers are created by using the finite element model to investigate their behaviours.