Performances of Curved Steel Bridge Railing Using the Numerical Analysis

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Abstract
Railing on the bridges has safe functions to against vehicle collision loads. The impact angle is one of factors to affect impact index and design of railing grade. Impact angle mentioned in Japanese specifications is 15 degree. However, this study found that in some cases of curved bridges, its impact angles are larger than such mention. In addition, engineers suppose that in the same railing grade and truck conditions, curved railing is dangerous than straight railing. Therefore, this research is performed to study on performances of curved bridge railings subjected to larger impact angles, and verifies performances of curved railing. A full-scale test is an important methodology in the field. So, such test requires high cost and much effort. Therefore, the numerical analysis is main method of research based on the following procedures: (1) impact collision simulations are created by FE model using LS-DYNA 3D software; (2) to verify the performances of curved railing; and (3) to apply larger impact angles to curved railings. Numerical results are obtained, and give understand on performances of steel curved railings and proposal in design of curved railing on bridges.
Keywords: Curved Bridge Railing, Impact Collision, LS-DYNA, Numerical Analysis

1. INTRODUCTION

There is extensive type of railing using on the curved bridge. According to material, the railing can be classed into rigid or flexible type. Rigid railing has been made from reinforced concrete. Another has been made from steel or aluminum alloy. An important property of flexible railing is to absorb a large portion of the truck kinetic energy. This response reduces the vehicle impact energy, as the result, vehicle and driver are safer in the collided accident. In Japan, specifications of railing design were published since 1965 by Japan Road Association. Revised specifications were implemented in 1999 to count changes of truck weight from 20 t (196 kN) to 25 t (245 kN) [1]. Latest specifications were published in 2008 [2], since this revision, the railing is required experimental tests in design. Both United State and Japanese specifications in railing design [1,2,3] require four performances to railing as: (1) to prevent vehicles from leaving the road; (2) to defend occupants; (3) to guide vehicles to the road; and (4) to prevent separations of railing.

In this field, a large number of researches carried out to study on behaviors of railing subjected impact collision load. Vehicle simulation is developed by finite element model, and investigated with an impact collision in which compact car crashed into a luminaire pole [4]. The numerical analysis investigates the impact of roadside crash cushion subjected to the vehicle collision [5]. Performances of bridge railing subjected to vehicle collision are carried out by numerical study [6]. Impact collisions of steel and aluminum alloy railings subjected to truck load are simulated to study on their behaviors [7]. Collided performances of high capacity steel railings are investigated with impact of heavy truck [8]. Effects of strain rate are investigated on performances of steel railing in impact collision [9]. Characteristics of such studies are that using computer software to create the impact simulations of straight railing subjected to vehicle collision load. In some researches, numerical results are compared to experimental results. In addition, a full-scale test to study on performances of straight railing was carried out by Public Works Research Institute [10].

Similar to straight railing, curved steel railings on bridge have to meet above required performances. However, curved railings have not investigated fully. Up to now, the full-scale test studying on curved railing performances has not carried out and investigating with limited research as performances of curved railing subjected to vehicle load are studied by using the numerical analysis [11]. According to Japanese specifications [1,2], railings are designed based on the impact index that represents energy of impact collision. This index is obtained by a formulation of vehicle mass and velocity and impact angle. For curved railing, impact angle is formed by truck movement and tangent of curved railing at point which locates on railing and truck crashes into. Maximum value of impact angle in Japanese specifications is mentioned as 15 degree. However, this study found that in some case of curved bridges, their impact angles are larger than such mention. In addition, some engineers suppose that in the same railing grade and collided conditions, curved railing is dangerous than straight railing. Therefore, this research is performed to study on performances of curved bridge railings subjected to truck collision load with larger impact angle, and verifies performances of curved railing in comparing to performance of straight railing.

Behaviors of steel railing subjected to vehicle collision load are studied from a full-scale test is an important methodology. However, such experimental test requires high cost and much time. A numerical analysis by using computer software to simulate impact collision of the curved steel railing and truck can reduce time and cost. Their numerical results can be close to experimental results by powerful developing of computer and software. The numerical analysis has become another important method in the field of study [4,5]. Therefore, the numerical analysis is selected to be main method in this study based on the following procedures as: (1) Impact collision of curved steel railing and truck are modeled as finite element models by using LS-DYNA 3D software, (2) to verify performances of curved railings by comparing their results to straight railing results; and (3) performances of curved railing is analyzed with larger impact angle. Impact collision problems are executed by supercomputer of Nagoya University. Results of study are presented in result section. Study conclusions are discussed in the last section of paper.

2. CLASSIFICATION OF RAILINGS

According to Japanese specifications [1,2], railing grades are selected depend on the impact index that is presented in Eq.(1) and their summaries are shown in Table 1. Form and shape of railing are not prescribed within Japanese specifications and they are selected by engineer according to cost, landscape and others.

$$I_s=0.5m(V\sin\theta/3.6)^2 \tag{1}$$

where I_s is impact index (*kJ*); *m* is mass of vehicle (*t*); V is speed of vehicle (*km/h*); and θ is impact angle (*deg*).

Table 1 Classification of the railing

Railing grade	Vehicle mass (*t*)	Vehicle speed (*km/h*)	Impact angle (*deg*)	Impact index (*kJ*)
C	25	26	15	45
B		30		60
A		45		130
SC		50		160
SB		65		280
SA		80		420
SS		100		650

The radius of curved roads and bridges is designed based on permissive speed of vehicle on this road. Such relations are prescribed by Japan Road Association [12], and presented in Table 2. It can be seen that if radius of curved road is designed as 100 m, then the permissive speed of vehicle is not over 50 km/h. Therefore, the railing on curved bridge must meet those relations.

Table 2 Classification of the radius of road and vehicle speed

Radius of curved road (*m*)	Maximum speed of vehicle (*km/h*)
460	100
280	80
150	60
100	50

3. FINITE ELEMENT MODEL OF IMPACT COLLISION SIMULATIONS

3.1 Railing model

Railing shape of study is successfully designed and used on straight bridge site at Japan. This railing meet grade SC with collided conditions as: 25 ton (245 kN) of truck mass; 50 km/h of vehicle speed; and 15 degree of impact angle. Finite element model of railing is presented in Fig. 2. Bridge railing is combined from posts, beams and concrete curb. Cross-section of railing posts is H-shape and beams are pipe sections. The post is modeled by four-node shell elements with flange is 150 mm of wide and 6 mm of thick and web is 145 mm wide and 4.5 mm thick. Railing beams include main and sub-beams and their positions are shown in Fig.1. Diameters of main and sub-beams are 139.8 mm and 114.3 mm, respectively. Both beams are created by four-node shell elements. Element thicknesses of main and sub-beam are 6 mm 3.5 mm, respectively. Spans of posts are around 2000 mm.

Steel material of both beam and post are modeled as isotropic elastic plastic material following the von Mises yielding criterion. Effects of strain rate of the steel material on the railing displacements are considered in the numerical study. Relation of stress-strain is adopted following recommended relation by Itoh et al. [9,13]. Young's modulus of steel is 206 GPa and yield stress is 281 MPa. Post is connected with concrete curb by steel plate with 25 mm of thickness that is joined to the concrete curb by two anchor bolts of M20, and two of M24. Steel material of anchor bolts and plate is modeled as elastic material with Young's modulus is 206 GPa and yield stress is 281 MPa. The concrete curb is crated as solid element, and considered as fix at end. Shear modulus of concrete is 10.6 GPa.

3.2 Truck model

The finite element model of the truck is shows in Fig.2. This model has been developed in our laboratory with supporting from truck fabrication company, and presented in some previous study [6,7,8,11]. The total weight of truck is 25 t (245 kN) by modeling the truck frame, engine, driving cabin, tires, cargo and so on. Shell elements are used to model for truck facilities as: side member; driving room; fuel tank; pipelines; and so on. Truck engine and transmission are modeled as solid elements. Performances of tires, wheels and gear are not considered in this study. The truck movement can be simulated by assuming the connection between tires with wheels is a rotation joint. Steel of the truck is modeled as isotropic elastic plastic material following the von Mises yielding criterion with Young's modulus is 206

GPa, and Possoin's ratios is 0.3. Aluminum material is modeled for the cargo body, and considered as multi-piece linear stress-strain relationship with Young's modulus is 70 GPa, and Possoin's ratios is 0.34.

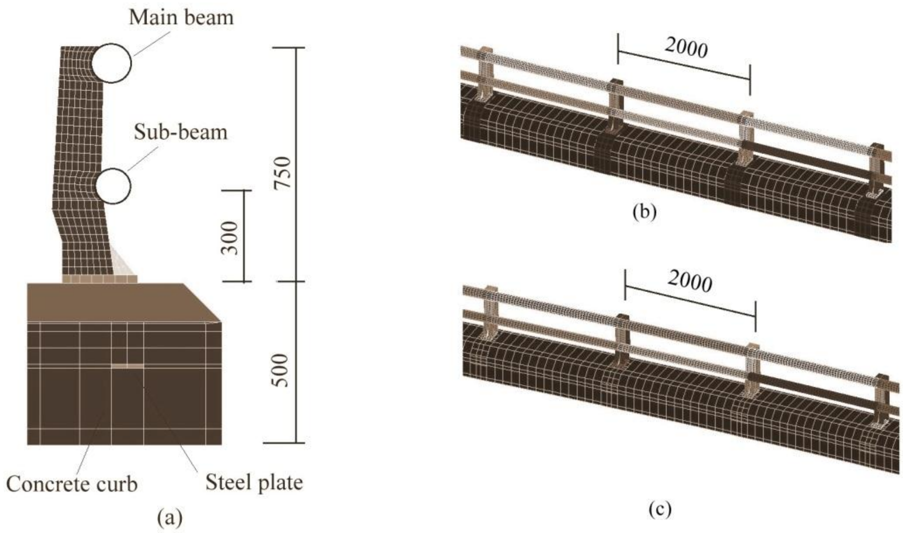

Fig.1 FE models of railing (Unit: mm), (a) Cross section, (b) Straight railing, and (c) Curved railing

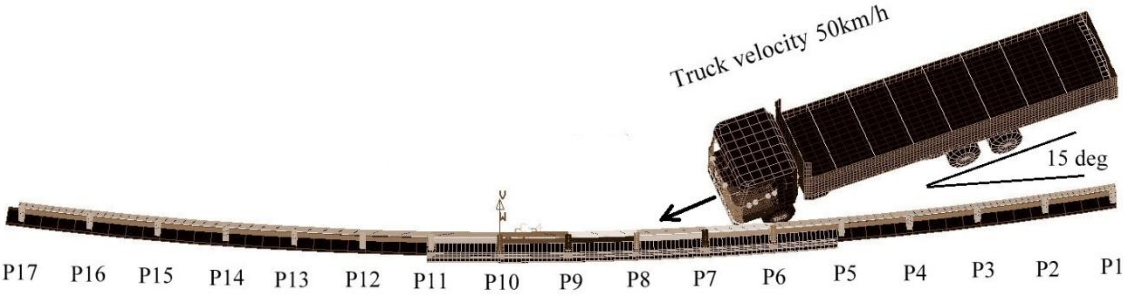

Fig.2 The 3D model of impact collision between truck and railing

4. RESULTS OF NUMERICAL ANALYSES

4.1 Performances of curved railing

Based on Japanese specifications, collision conditions, classifications of railing and so on are described for designing the straight railing, and have not mentioned on the curved railing design. In addition, as above discussion, some engineers have supposed that in the same conditions, curved railing is not safer than straight railing and higher railing grades may be applied for curved railing. Therefore, this study verifies performances of curved railing in comparing with straight railing. A successful designed railing that was installed at the existing bridge in Japan is adopt for curved railings with radius as 100, 150, 460 m. All railings are subjected to the same truck collision conditions with 50 km/h of velocity, 25 ton (245 kN) of mass and 15 degree of impact angle. Numerical results of curved railings are compared to results of straight railing such as: railing displacement and energy response; truck behavior to purpose verified on performance of curved railings.

The displacements – time history of railing post is presented in Fig. 3. This shows for displacement of post number 7 where records largest value in railing. Summary for large post displacement is presented in Table 3. Peaks of displacement curves relate to the moment in which head of truck crashes into the railing. After this moment, the post displacement becomes down stable state. Minimum displacement is occurred at smallest radius railing with 43 mm. Maximum displacement is occurred at straight railing with 79 mm, and is around twice value than above curved railing. It can be seen that railing displacements is acted by the railing radius. Railing displacements are increased with rising of railing radius. In the same collision conditions and railing features, straight railing is unsafe than curved railings.

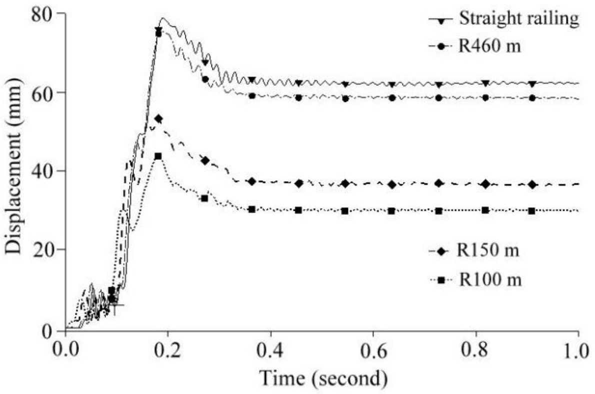

Fig.3 Displacement-time history of post

Table 3 Maximum displacement of railing posts

Type of railing	Displacements (*mm*)	
	Post 7	Post 8
R100	43	17
R150	53	23
R460	75	47
Straight	79	60

Energy distributions to curved and straight railings are presented in Table 4. This shows that in the same truck energy level, truck energy shifted to straight railing is largest, and is around twice value of absorbed energy by smallest curved railing. It is impossible to seen that the railing that has large radius is shifted more kinetic energy than railing with small radius. However, a great shifted energy to railing is leading cause of exceeding displacement of railing beams and posts, as the results, penetrations may happen in railing.

Table 4 Distribution of absorbed energy of railings

Type of railing	Designed impact energy (kJ)	Truck kinetic energy (kJ)	Absorbed energy of railing (kJ)
R100	161	1260	26.0
R150			35.7
R460			51.5
Straight			53.6

The railing design specifications in Japan prescribed that breakaway speed of vehicles must be over 60 percent of designed speed. The truck velocity – time history is presented in Fig. 4. It shows that above requirement of Japanese specification is met by all curved and straight railings. In conclusion, for the same impact energy level, railing grade that is designed for straight railing can adopted for curved railings. Largest displacement and energy that is shifted from truck energy to railing are occurred at straight railing. Penetration happened in straight railing may be higher probability than curved railings.

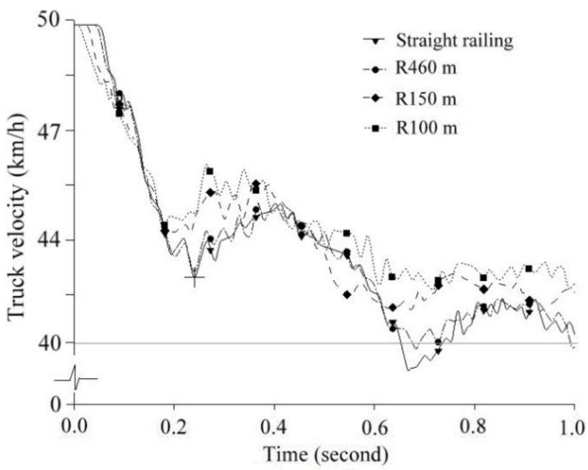

Fig.4 Truck velocity – time history

4.2 Performances of curved railing subjected to higher impact angles

The impact angle is formed by two rays. First is vehicle movement ray and another is tangent of railing at position where head of truck crashed into the railing. This angle is mentioned in Japanese specifications with value as 15 degree. However, considering impact angles of the truck and curved railing as show in Fig.5, in where, the straight road are connected to the curved road or bridge. The road has three lanes. Assume that the truck runs on lane from straight road to crash into the curved railing. Fig. 5 shows impact angles for case of curved railing with 100 m of radius. For other curved railings, the same way is used to obtain value of impact angle. Study found that larger impact angles occur at curved railings with 100 and 150 m of radius. Its summary is shown in Table 5, in where, larger impact angles as 20 and 25 degree occur in 100 m of railing radius and 20 degree occurs in railing with 150 m of radius. Therefore, in this chapter, larger impact angles are applied to study on the performances of curved railings with following progress: 20 and 25 degree of impact angle are applied for 100m; and curved railing with 150 m of radius is subjected to impact angle as 20 degree. According to Eq.(1), replacing 20 and 25 degree of impact angle into the equation, impact energies are computed as 282 and 480 kJ. It means that new impact energy levels are equivalent to one and two higher grade of railing.

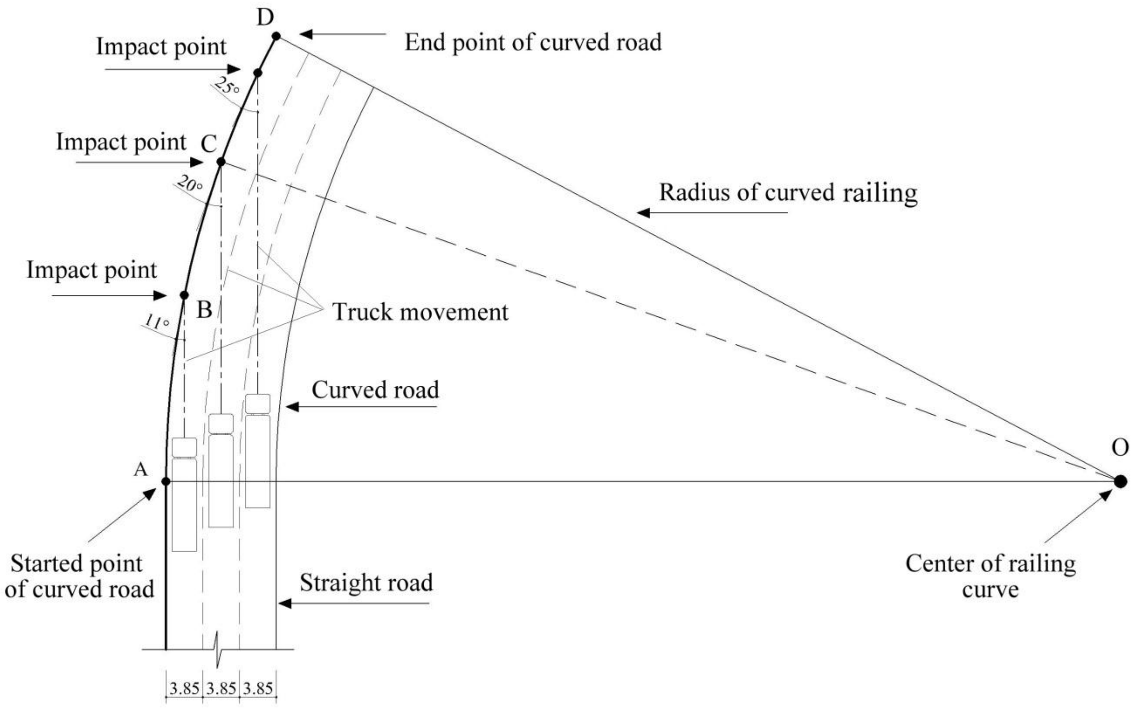

Fig. 5 Impact angle of truck and railing on the curved roads and bridges

Table 5 Impact angle on the curved roads and bridges

Lanes	Impact angle θ (deg)	
	R100	R150
1st lane	11	9
2nd lane	20	16
3rd lane	25	20

The largest displacement – time history on post of railings with 100 and 150 m of radius is presented in Figs. 6 and 7, respectively. For curved railing with 100 m of radius, maximum displacement occurs in case of 25 degree of impact angle and the peak of displacement is 91 mm. This peak is over twice value than post displacement in case of impact angle with 15 degree. The lateral deformation of this railing is shown in Fig. 8. It can be seen that both first cases of impact angle as 15 and 20 degree, largest displacements are recorded at post number 7. In the other, largest displacement is occurred at post number 8. Those are cause from differences of truck position between impact angle cases. For the curved railing with radius 150 m, the great displacement occurs in case of larger impact angle as 20 degree. Displacement peaks are 82 mm and 53 mm for 20 and 15 degree of impact angles, respectively. Affected area of deformations occurs at six spans from post 5 to post 11. Figs. 6, 7 and 8 show that post displacements increases with increasing of impact angle.

The kinetic energy of truck is depended on its weight and velocity. A portion of the truck energy is shifted to railing during impact collision. With the same truck conditions, the kinetic energy of truck is unvarying. Table 6 shows the energy distribution of railings in relating to the impact angles. It shows that in the same truck energy level, curved railing subjected to larger impact angle absorbs much kinetic energy than other curved railings. Absorbed energy of railing is small portion in comparing to the initial energy of truck.

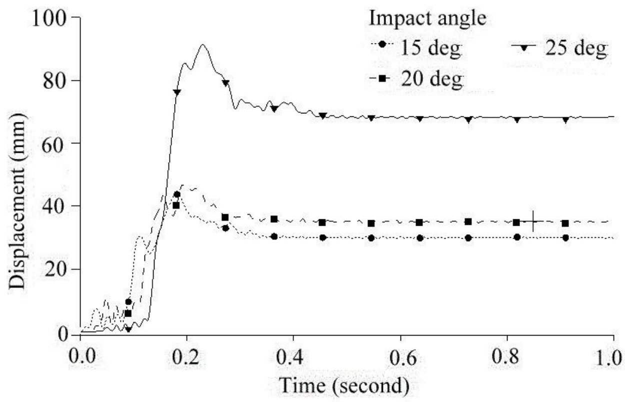

Fig. 6 Displacement – time history of railing post (curved railing with 100 m of radius)

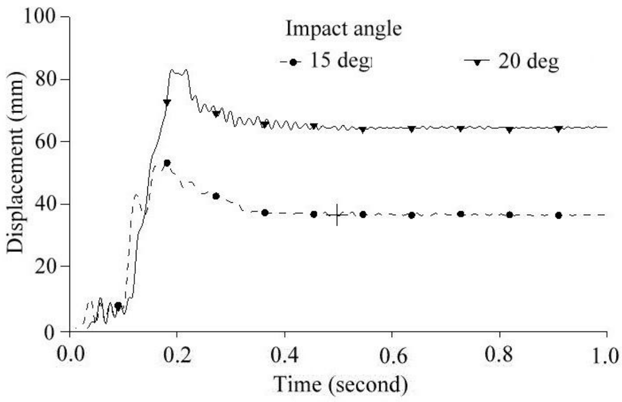

Fig. 7 Displacement – time history of railing post (curved railing with 150 m of radius)

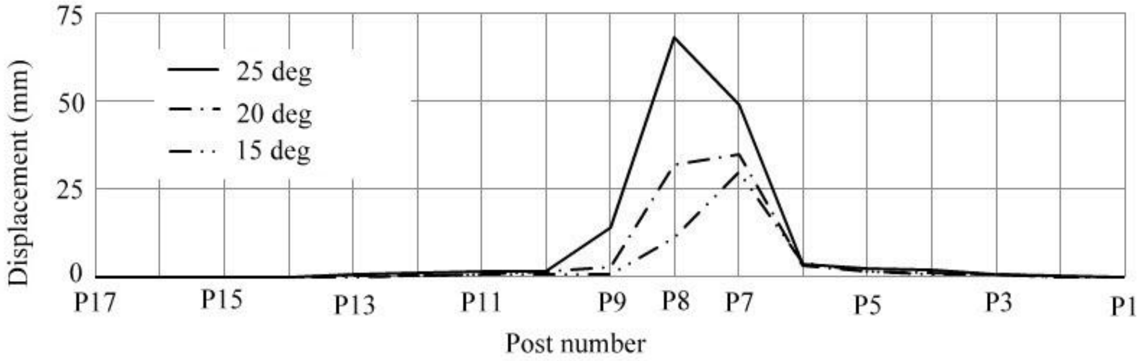

Fig. 8 Lateral deformation of railing (curved railing with 100 m of radius)

Table 6 Energy distribution on railing

Impact angle (deg)	Truck kinetic energy (kJ)	Impact energy (kJ)	Absorbed energy of railing (kJ)	
			(radius 100 m)	(radius 150 m)
15	1260	161	26.0	35.7
20		282	49.0	67.6
25		480	66.5	

Movements of truck in impact collision with curved railing are presented in Fig. 9. The curved railing has 100 m of radius. This figure shows truck movements for 15 and 25 degree of impact angle cases. It can be seen that after impact moment, the truck runs towards end of railing, and is guided back to road by railing. According to above descriptions, performances of railings are met requirements of Japanese specifications. However, railing displacements, energy shifted to railing are increased with increasing impact angles. Both railings with 100 and 150 m of radius, result values of railing subjected to highest impact angle are twice than results in mentioned impact angle case. In addition, by reason of human problems, velocity of vehicles may higher than permissive velocity. In those cases, impact energy of collision may be large. Therefore, on safe view, higher railing grade can be adopted on curved bridges.

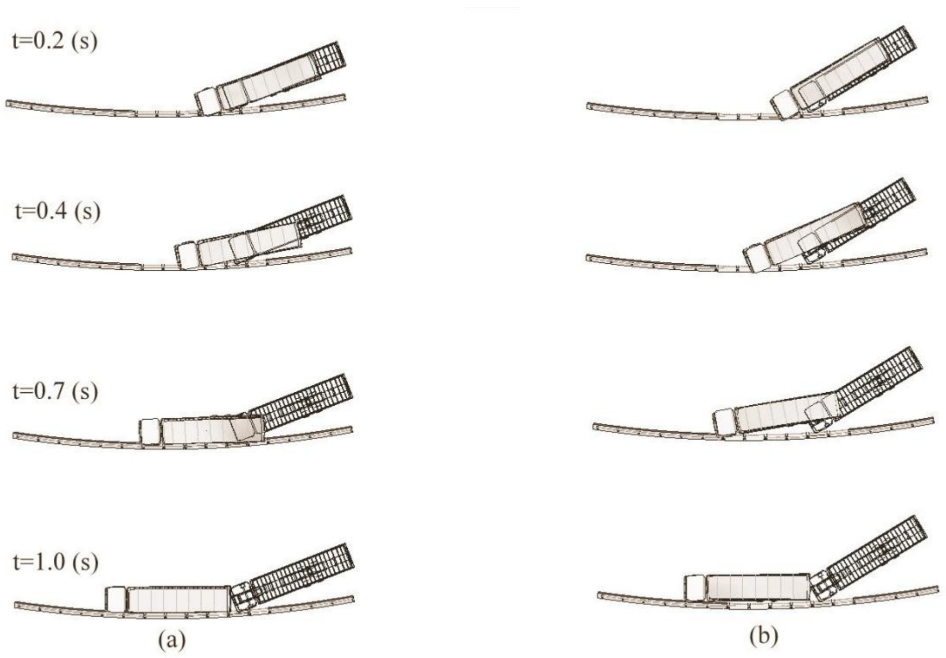

Fig. 9 Truck movement for curved railing with 100 m of radius (a) 15 degree of impact angle, and (b) 25 degree of impact angle

SUMMARY AND CONCLUSIONS

In this study, the numerical simulations are developed to study on performances of curved steel railing on the bridges. To verify performances of curved railing, the results are compared to results of straight railing with the same collision conditions. For some case, impact angle of truck and curved railing may be larger than mentioned angle by Japanese specifications. Therefore, curved railings are subjected to those angles to study on its performances. The conclusions are summarized as follows:

(1) From comparisons of curved and straight railing results, in the same truck energy level, largest displacement occurs at straight railing. This displacement is twice than curved railing with smallest radius. Post displacement and shifted energy to railing are increased with increasing radius of curved railing. The straight railing is in more dangerous state than curved railings.
(2) The curved railings using grade and features that are designed for straight railing are meet required performances of Japanese specifications. Such grade and features of straight railing can adopt for curved railing on the bridges.
(3) In some cases of curved bridges, impact angles between the truck and curved railing are larger than mentioned angle by Japanese specifications. The kinetic energy of truck shifted to railing and railing deformation are much when increasing the impact angles.

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