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Experimental and Numerical Analysis Study of A Newly Developed Bridge Railing Using Extruded Aluminum-Alloy

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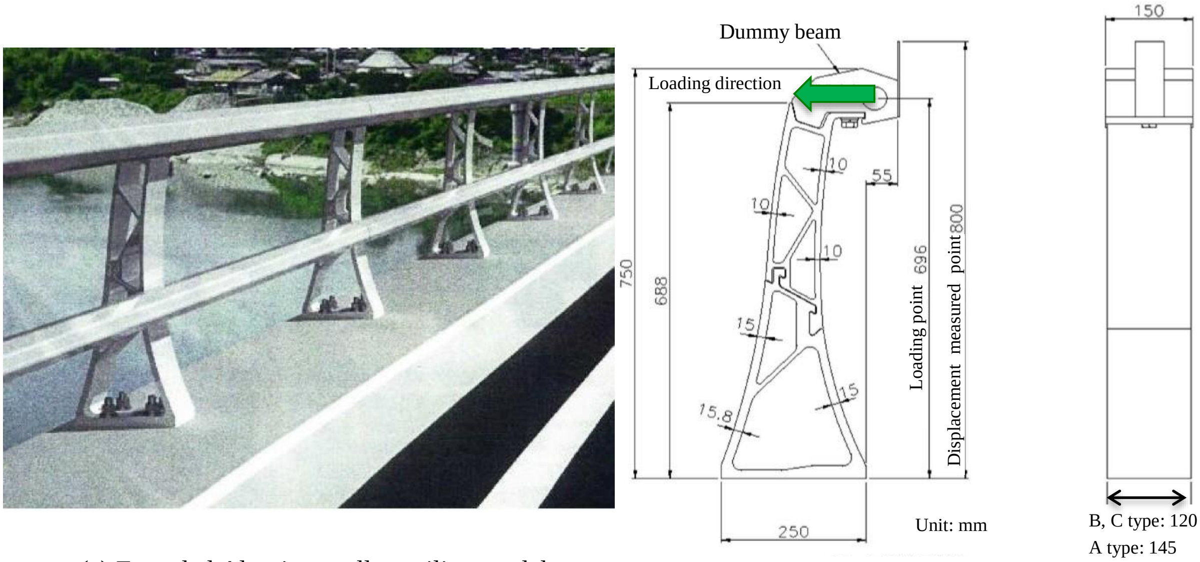
ABSTRACT
A new type of bridge railing was developed using the extruded multi-hollow-type shape of aluminum-alloy to have the improved cost performance and appearance. First, static tests and numerical simulations were performed using model posts of railing made from aluminium-alloy plate with 70 mm thick to determine the multi-hollow-type sectional dimensions. Then, extruded posts of railing with flange width of 145 mm and 120 mm were tested and analysed to prove the performance following the specifications for the design of the railing in Japan. The static tests and the dynamic tests using heavy weight of 460 kg on extruded aluminum-alloy specimens were conducted to check the ultimate strength, energy absorption capacity and dynamic behaviour. The numerical analysis results of static and dynamic behaviours were almost consistent with the test results. Finally, the collision numerical simulation between the railing and a heavy truck with weight of 25 t, speed of 45 km/h and collision angle of 15 degree was performed. From the test and numerical analysis simulation results, the new type of post was proved to be available for different strength types of bridge railing changing the flange width when cutting the extruded long member.

KEYWORDS: *Bridge railing, extruded aluminum-alloy, dynamic collision test, heavy truck impact analysis*

1. INTRODUCTION

The design of bridge railing in Japan was revised from the specification-based type to the performance-based one in 2002. And then, a necessity of consideration for landscape on highways was included in 2004[1)]. Existing bridge railings tended to be mismatch around the highway landscape, especially, the railings with low permeability tended to inhibit a view from drivers on vehicles. To this problem, railings with steel or aluminum-alloy considering landscapes have been developed[2, 3)].

There are mainly two types of aluminum-alloy bridge railings. One is the casting type and another is the extruding type. The casting type is made one by one normally, and each mold must be prepared for different shapes of railing posts. Therefore, the manufacturing efficiency and the degree of freedom for design is not so high. On the other hand, a newly developed extruding type of railing post as shown in Fig. 1.1 was proposed for solving these problems. Therefore, aluminum-alloy railing posts are manufactured by extruding to the width direction of post. That is, a lot of posts can be obtained by cutting from one long extruded member for the higher manufacturing efficiency. And also, multi-hollow-type sectional shape is adopted for improving the appearance and permeability. It is difficult to manufacture multi-hollow-type section of railing posts by casting, however, they can easily obtained by extruding with one type of die.



(a) Extruded Aluminum-alloy railing model (b) Cross-sectional shape

Figure 1.1 Newly developed bridge railing with extruded aluminum-alloy

In this study, performances of a newly developed bridge railing using the extruded multi-hollow-type section of aluminum-alloy with improved cost performance and appearance were evaluated. First, static and dynamic impact tests and numerical simulation were performed using model posts of railing made from aluminium-alloy plate with 70 mm thick to determine the multi-hollow-type sectional dimensions. Then, extruded posts of railing with flange width of 145 mm and 120 mm were tested and analyzed to prove the performance following the specifications for the design of the railing in Japan[1]. The static loading tests and the dynamic tests using heavy weight of 460 kg on extruded aluminum-alloy specimens were conducted to check the ultimate strength, energy absorption capacity and dynamic behaviour. Finally, the collision numerical simulation between the railing and a heavy truck with weight of 25 t, speed of 45 km/h and collision angle of 15 degree was performed. From the test and numerical analysis simulation results, it was investigated whether the newly developed bridge railing be suitable for different strength levels by changing the flange width when cutting the extruded long member.

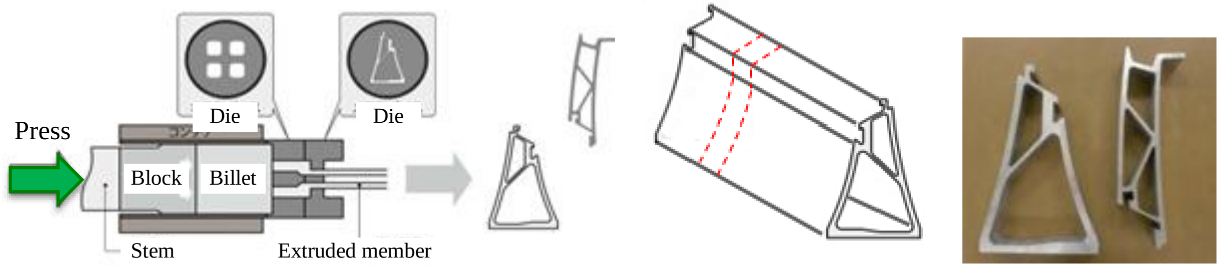
2. MECHANICAL BEHAVIOUR OF POST WITH ALUMINUM-ALLOY

2.1. Test Specimen

At first, specimens were cut out from aluminium-alloy plate with 70 mm thick (so called, plate specimen). The cross sectional shape of specimen. After confirming the performance of specimen cut out from the aluminium-alloy plate with 70 mm thick, a die for extruding post specimens was made. The specimens were extruded (so called, extruded specimen). These specimens were made by cutting the member in the extruding direction. The flange widths of specimens were 145 mm and 120 mm respectively. They corresponded to A type and B type posts of the specifications for the design of the railing in Japan[1].

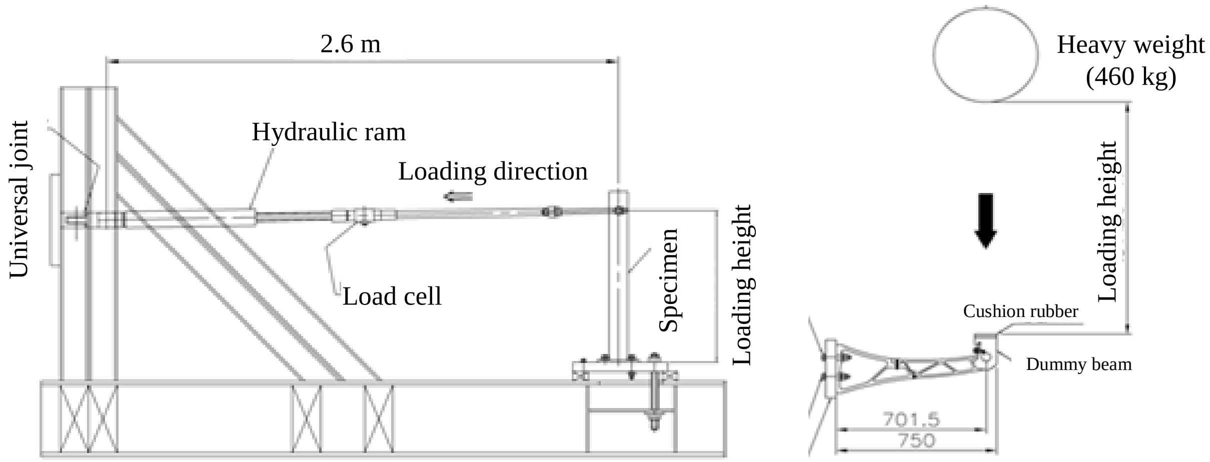
The height of normal bridge railing is between 900 mm and 1000 mm from the ground surface to the top of main beam in Japan. And also, the height of guard is generally 250 mm. Therefore, it is required that the height of railing post is from 650 to 750 mm. The size limitation of general extruding press machines with 10 to 25 MN classes in Japan is a circumscribed circle with the radius of 160 mm. Even though the strength of press machine is 40 MN, the radius is up to 300 mm. Although the radius is 530 mm in the case of the strongest press machine in Japan with 95 MN class, the railing post cannot be extruded from one die. Therefore, the railing post in this study was made by two parts of the upper and the lower sides extruded separately as shown in Fig. 2.1. These two parts were connected by fitting together and stainless bolts after the extruding.

Static loading tests proposed in the specifications for the design of the railing in Japan[1] were carried out on the newly developed bridge railing post with multi-hollow-type section. After that, dynamic tests with heavy weight collision and numerical analyses were also performed for investigating the dynamic performance of post.



(a) Extruding aluminum-alloy member (b) Cut of long extruded member (c) The upper and lower part of post

Figure 2.1 Manufacturing procedure of extruded aluminum-alloy post



(a) Static loading test (d) Dynamic loading test

Figure 2.2 Static and dynamic loading test apparatus

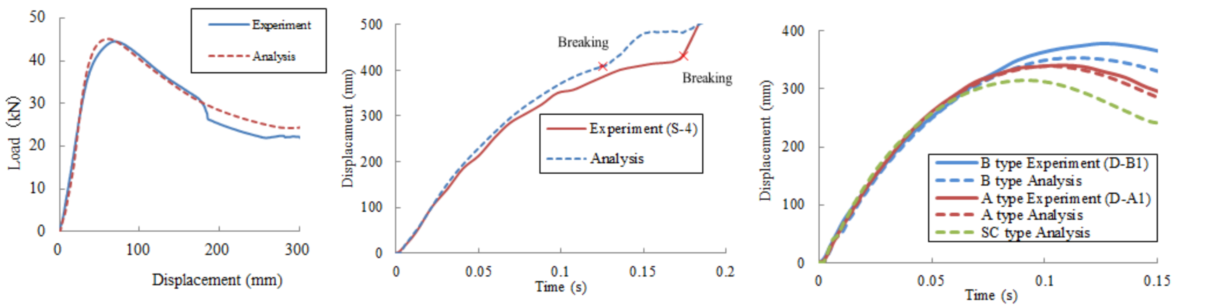
2.2. Static Loading Test

Two post specimens were cut out from aluminium-alloy plates with 70 mm thick. It means that the flange width of specimens was 70 mm. Relationships between load and displacement were obtained by applying 300 mm of displacement with the testing apparatus shown in Fig. 2.2 (a). From the obtained load-displacement diagram shown in Fig. 2.3 (a), the ultimate load *Pw* was decided as follows. That is, the load-displacement curve up to 300 mm of displacement is approximated by bi-linear shape so that the areas enveloped by the lines become the same, which means the absorbed energy. The obtained ultimate loads were 32.7 kN and 33.2 kN from two specimens.

On the other hand, two types of extruded specimens simulating for actual railing posts were made. The widths of specimens were 145 mm (A type) and 120 mm (B type) respectively. The number of each specimen type were three. The same static loading tests as the case for the plate specimens were carried out on the extruded specimens. The load-displacement curves of three A type extruded specimens were almost the same. The average of ultimate load was 32.1 kN. That of B type extruded specimens was 26.9 kN.

2.3. Dynamic Loading Test

Fig. 2.2 (b) shows the appearance of dynamic loading tests. The specimen was rotated, set horizontally and fixed. A heavy steel weight (460 kg) was dropped and collided to the specimen from the specified height. The collision position was the height of main beam at which the distance from the base was around 700 mm. The drop height of heavy weight was decided so that the potential of heavy weight became the same as the absorbed energy obtained by the load-displacement curves of static loading test. Furthermore, the drop height was changed several times so that the displacement of post became over 300 mm.



(a) Static test (b) Dynamic test on plate specimen (c) Dynamic test on extruded specimens

Figure 2.3 Comparison of loading tests and numerical simulations

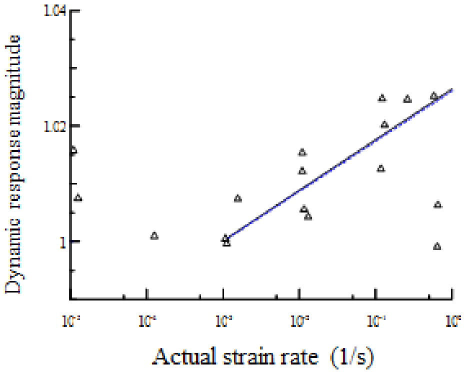


Figure 3.1 Effect of strain rate of aluminum-alloy

Firstly, four post specimens of which the width was 70 mm were cut out from aluminium-alloy plates. A heavy weigh was dropped on one of them from the height of 1104 mm so that the displacement of over 400 mm was applied for investigating its fracture behaviour. Fig. 2.3 (b) shows the time history of displacement of this specimen. The maximum displacement of this specimen was 420 mm. The tension flange in the lower part of the post was broken.

Secondary, two types of the extruded specimens simulating for actual railing posts were made. The numbers of A type and B type specimens were three and two respectively. The heavy weight drop tests were carried out on them. The drop height of weight was decided as well as the cases of plate specimens. Fig. 2.3 (c) shows the examples of time histories of displacement.

3. NUMERICAL SIMULATION OF STATIC AND DYNAMIC LOADING TESTS

Numerical simulations of the static and dynamic loading tests were carried out. Commercial FE programs of ABAQUS and LS-DYNA were used for the static tests and the dynamic tests respectively in the numerical simulations based on FEM. The mechanical properties of aluminum-alloy used in the analyses were the true stress and true strain relationships obtained by modifying the nominal stress and nominal strain relationships of material tensile tests[4]. The effect of strain rate was considered by using the dynamic response magnitude as shown in Fig. 3.1 proposed by the author[4], which was based on the material experiments. The stainless bolts (SUS304) used in the connection between the upper and the lower parts of post were modeled as a perfect elastic-plastic body. The yield stress was decided as 205 MPa referred by JIS. The bolts used between the dummy beam and the post were the stainless (A2-70 SUS). The anchor bolts used for fixing the post to the ground were SCM435. They were also modeled as perfect elastic-plastic bodies, of which the yield stressed were 450 MPa and 785 MPa respectively.

The anchor bolts were modeled by beam elements for considering the axial force and bending behaviours. Pre-tension forces on the bolts corresponding to the axial forces on bolts were applied by setting a calculation step for it before the steps for applying the displacement on the post. The magnitudes of pre-tension forces were 34.8 kN and 33.6 kN on the front and rear anchor bolts respectively, which were the same value as those actually measured by the experiments.

A super computer CX400 (FUJITSU, 460 TFLOPS) set in Information Technology Center of Nagoya University was used for the numerical simulations.

Fig. 2.3 (a) shows the comparison of time histories of displacements by the experiment of plate specimen (S-4) and the numerical simulation results. Although the occurrence of breaking was relatively faster in the analysis, the behaviour obtained by the experiment could be mostly simulated by the analysis.

Fig. 2.3 (b) shows the comparison of time histories of displacements by the experiments of A and B types of excluded specimens and the numerical simulation results. They were almost agreed with each other. By the way, the numerical simulation result of SC type (the flange width of post was 160 mm) was also shown in the figure for reference.

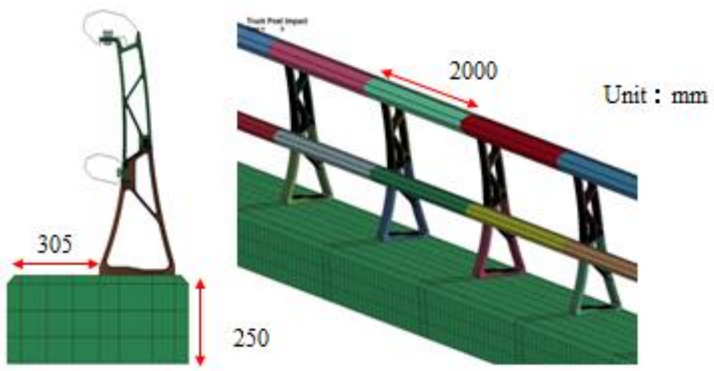
4. TRUCK COLLISION SIMULATION OF BEAM TYPE RAILING BY EXTRUDED ALUMINUM-ALLOY

Many cases of truck collision simulations of beam type bridge railings by steel and aluminum-alloy were performed[5-11)]. Here, a truck collision simulation was carried out on the railing with the newly developed aluminum-alloy posts, of which the static and the dynamic responses were confirmed in this study. The objective of these simulations was to check whether this railing satisfy the performances in the specifications for the design of the railing in Japan[1)]. The subject was A type post of extruded aluminum-alloy.

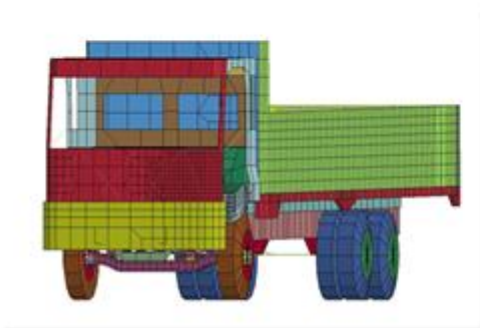
4.1. Numerical Simulation Model

Fig. 4.1 (a) shows the numerical simulation model for the railing. The beam was the same aluminum-alloy (A6061S-T6) with a hollow-section of which the mechanical properties were modeled by a multi-linear elastic plastic material. The equivalent stress and strain relationship followed the von-Mises yield criterion. The element type of beam was Belytschko-Tsay shell element. The support of railing was the concrete base as shown in Fig. 4.1 (a) modeled with referring the manual of experiment of truck collision on railing in Japan[12)]. The material properties of concrete was modeled by using soil and crushable form in LS-DYNA, which were considered fracture of material. They followed the Drucker-Prager yield criterion under the compressive loads and they did not transfer tensile stress under the tensile loads when the stress reached the tensile strength for modeling the element fracture. The parameters of each material properties were decided by the compressive strength obtained by the experiment. The strain rate effect of concrete was not considered because it did not affect the numerical simulation results when the deformation of base concrete was in the elastic region[13)]. The concrete was modeled by solid element with one integration point. The bottom surface of concrete base was perfectly fixed as a boundary condition. The numbers of nodes and elements were 34,697 and 27,568 per one span of railing.

The collision truck simulation model was originally developed by Nagoya University with support of a truck maker. Fig. 4.1 (b) shows the FE model of a truck with 25 t (245 kN). The validity and accuracy of this truck model was verified by comparing with truck collision experimental results of steel railings[7, 8)].



(a) Bridge railing model



(b) Truck model

Figure 4.1 Bridge railing model and truck model

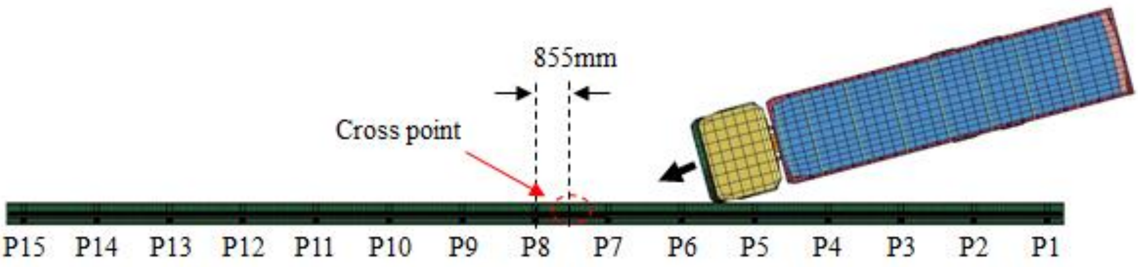


Figure 4.3 Cross point

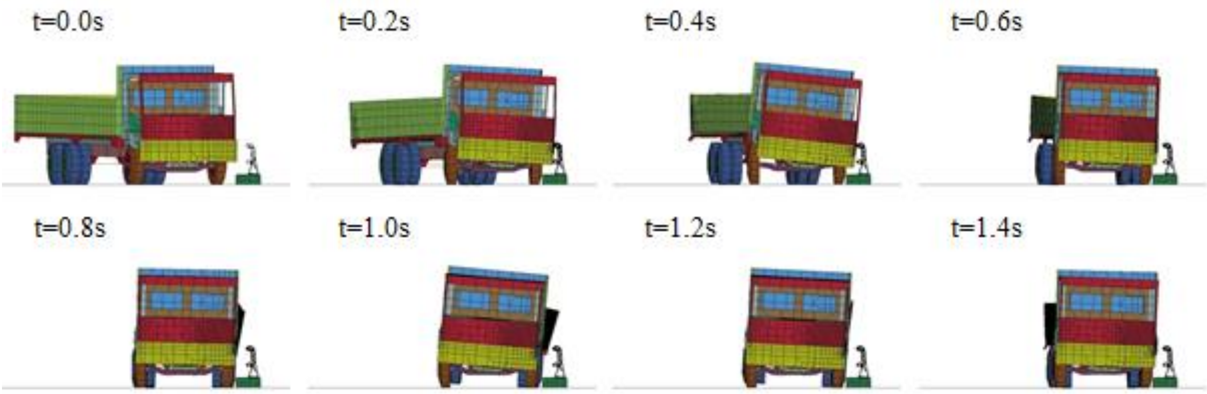


Figure 4.4 Truck behaviour

4.2. Truck Collision Conditions

The truck collision conditions in the specifications for the design of the railing in Japan[1] are 25 t of truck weight, 45 km/h of collision speed, 15 degrees of collision angle and 130 kJ of collision energy. The manual for experiment of truck collision on railing in Japan[12] defines an intersection point between the center lines of truck and railing as a cross-point. The most severe evaluation can be performed by corresponding the point with the largest deformation to the weakest position in the case of deformation type of railing. The cross-point of this simulation was set on P8 as shown in Fig. 4.2 so that the initial contact position was around the mid-span of beam at which the largest deformation might occur. This condition was decided with referring to the truck collision experiment performed in Tsukuba by PWRI in 2010[14].

4.3. Truck Collision Simulation Results

Fig. 4.3 shows the behaviours of truck model at the collision and after it among 1.4 seconds. The first collision occurred at the time of 0.07s. Then, the front tire and the cover, the bumper and the lower beam, and the cabin and the main beam collided respectively at almost the same time. The front tire ran along the cover without override. Although the front tire floated and the cabin inclined to the railing side, the inclination of truck body was quickly recovered by the support of main beam. The cabin separated from the main beam at the time of 0.38s. As the second collision, the rear tire collided with the cover and it floated and the carrier inclined to the railing. However, the carrier and the railing were not attached. The truck was smoothly guided at the same time when the inclination of body was recovered.

4.4. Performance Evaluation of Railing

The following performances of vehicle aberration prevention, vehicle guide and member scatter prevention in the requirements of the specifications for the design of the railing in Japan[1] were evaluated for the newly developed bridge railing model with extruded aluminium-alloy. And then, acceleration change of vehicle center was also investigated for reference.

4.4.1. Vehicle aberration prevention

This performance is evaluated by checking whether the maximum admission stroke is within the specified value or not from an estimation based on deformation of railing. It is decided that the maximum deformation of beam type bridge railing embedded in concrete is within 300 mm[1)]. Fig. 4.5 shows the time history of post with the maximum deformation and those of both sides of posts next to it. The maximum deformation was 43.6 mm which occurred at P7, which was enough smaller than 300 mm. Therefore, the vehicle aberration prevention performance was satisfied sufficiently.

4.4.2. Vehicle guide

This performance is verified by desorption speed, desorption angle and occurrence of turnover of truck. The desorption speed and angle of the center of gravity of truck were obtained from the time history of velocity. The desorption speed was 36.7 km/h, which was larger than 60 % of the collision speed of 45 km/h. The desorption angle was 2.5 degrees, which was smaller than 60 % of the collision angle. Furthermore, the turnover of truck did not occur as shown in Fig. 4.4. It can be said that the vehicle guide performance was satisfied.

4.4.3. Member scatter prevention

It was revealed that the member did not scatter only if the diagonal member of the lower part of post was broken when the post was deformed up to 300 mm by the heavy weight drop tests and their simulation. The maximum deformation of post by the collision simulation with truck of 25 t was 43.6 mm. Therefore, breaking and scatter of members might not occur because strain generated in the members was small.

4.4.4. Truck acceleration response

The synthetic acceleration of the center of gravity in the truck travel direction and the direction crossing to railing was obtained. The moving average during 10 ms of the acceleration was 5 g/ms at most. It was considerably smaller than the acceptable value of A type railing (18 g/ms) in the specifications for the design of the railing in Japan[1)].

Based on the above truck collision simulation results, it could be confirmed that the newly developed bridge railing by extruded aluminium-alloy satisfied the performances of A type railing in the specifications for the design of the railing in Japan[1)].

5. CONCLUSIONS

1) The heavy weigh drop tests on the multi-hollow sectional posts with extruded aluminium-ally were performed. It was confirmed that the posts had enough ductility without any member scatter even though 300 mm of deformation was applied. The developed railing posts of A type and B type satisfied the required performances in the specifications for the design of the railing in Japan from the viewpoints of their ductility and energy absorption capacity.
2) Numerical simulation models of the posts with extruded aluminium-alloy for the heavy weight drop tests were proposed. The simulation results by the models agreed with the experimental results well.
3) Truck collision simulations of the newly developed bridge railing with extruded aluminium-alloy were carried out. It was revealed that the railing had enough strength and deformation capacities and vehicle guide performance.

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