ANALYSIS OF DAMAGE MECHANISM OF ROAD BRIDGE DAMAGED BY KUMAMOTO EARTHQUAKE

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Abstract

Many road bridges were damaged in the 2016 Kumamoto earthquake. On the main regional road Kumamoto Takamori Line, despite bridges that were seismically designed based on the 1996 road bridge specifications, there were cases in which the recovery of the function could not be performed quickly. In the 1996 Road Bridge Specification, Level 2 ground motion was specified based on the lessons learned from the Hyogoken-Nanbu Earthquake. Level 2 ground motion type II follows the current road bridge specifications specified in 1996, and it is not possible to clarify the damage factors of bridges designed based on the 1996 road bridge specifications. Therefore, it is very important in considering future seismic design methods.

In this paper, we will investigate the damage caused by the seismic action of road bridges that were seismically designed based on the 1996 road bridge specifications damaged by the Kumamoto earthquake. The purpose is to make an estimation based on the damage traces found in the previous survey.

Looking at the strong motion displacement records around the bridges covered in this paper, we can see that the displacement was north, east, and downward, and the displacement remained. When this is compared with the acceleration record, it can be seen that a large displacement occurred during the main movement.

The substructures of the bridges were moved about 1 m each, and the amount of movement was different for each substructure. The rubber bearing had a large residual displacement, and its direction was different for each fulcrum. In addition, the finger joints were engaged with each other in a state shifted in the direction perpendicular to the bridge axis. A displacement limiting structure installed on the abutment was sheared.

The damage was analyzed especially focusing on ground displacement. As a result, it was confirmed that damage estimated to be due to the effect of ground displacement was observed. The substructure will follow and move at least due to the ground displacement at the time of the earthquake. It became clear that there was a possibility that the part and the superstructure were damaged. Based on this experience, in the future construction of road bridges, it is necessary to investigate the possibility of ground displacement during an earthquake and to minimize the impact on the bridge at each stage of the route planning and structural planning. Therefore, it is considered necessary to conduct appropriate examination.

Keywords: Damage mechanism, 2016 Kumamoto earthquake, Bridge, Rubber bearing, ground displacement

1. Introduction

Many road bridges were damaged in the 2016 Kumamoto earthquake. On the main regional road Kumamoto Takamori Line, despite bridges that were seismically designed based on the 1996 road bridge specifications, there were cases in which the recovery of the function could not be performed quickly. In the 1996 Road Bridge Specification, Level 2 ground motion was specified based on the lessons learned from the Hyogoken-Nanbu Earthquake. Level 2 ground motion type II follows the current road bridge specifications specified in 1996, and it is not possible to clarify the damage factors of bridges designed based on the 1996 road bridge specifications. Therefore, it is very important in considering future seismic design methods.

In this paper, we will investigate the damage caused by the seismic action of road bridges that were seismically designed based on the 1996 road bridge specifications damaged by the Kumamoto earthquake. The purpose is to make an estimation based on the damage traces found in the previous survey.

2. Impact of earthquakes observed around the bridges

Fig. 1 shows locations of the bridge and the observation point of strong ground motion around it superimposed on the surface crack distribution map[2] around the Futagawa Fault Zone by aerial photo interpretation of GSI (Geospatial Information Authority of Japan). The Oginosaka-bridge and Nishihara-mura government office, which is the observation point for strong ground motion, are located in the surface crack zone, and the Oginosaka-bridge is relatively close to the Nishihara-mura government office, at a distance of about 6 km.

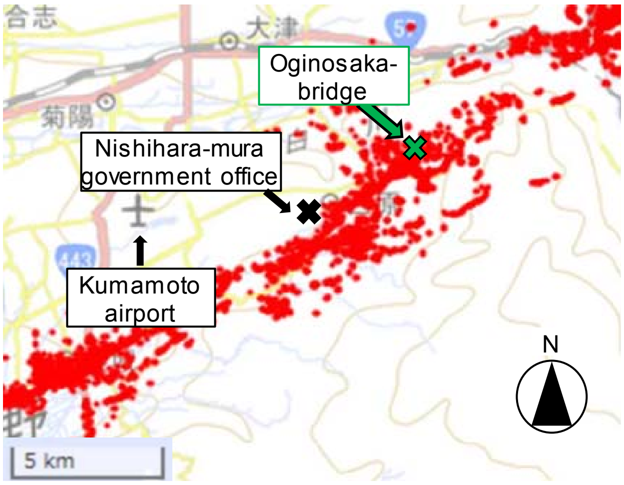

Fig. 1 – Crack distribution caused by the Kumamoto earthquake and the location of the bridge to be analyzed

Fig. 2 shows the acceleration of the seismic motion observed at 1:25 on April 16 in Komori, Nishihara-mura, and a time-series record[3] of the displacement obtained by Iwata's integration and baseline correction of this record. Looking at the displacement record, it can be seen that it displaced north, east, and down from about 1:25:16, and that the displacement amount remained almost as it was. Comparing this with the acceleration recording, it can be seen that the large displacement occurred during the main motion.

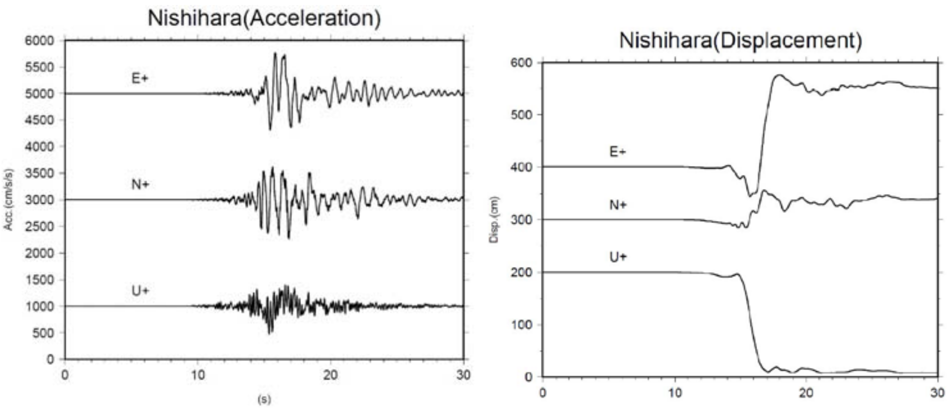

Fig. 2 – Earthquake motion observed at Komori, Nishihara Village

In addition, the ground displacement[4)] observed by this earthquake is spread over as shown in Fig. 3, and large values are observed in some places. From these facts, it is presumed that a large ground displacement occurred during the shaking of the seismic motion even at the bridge targeted in this paper.

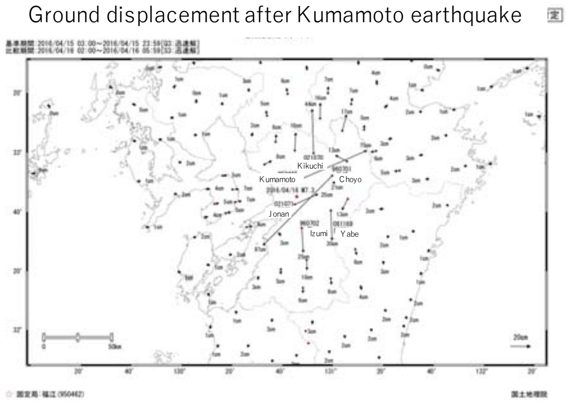

Fig. 3 – Ground deformation due to Kumamoto earthquake

3. Damage of Oginosaka-bridge and estimation of its factors

3.1 Outline of Oginosaka-bridge

Oginosaka-bridge is a non-composite steel girder bridge with a length of 128m and a length of 128m, located in Nishihara-mura, Aso-gun. The bearing type is laminated rubber bearing, the substructure type is an inverted T-type abutment / extended pier, the foundation type is an A1 abutment with a direct foundation, and the others are deep foundations. A lateral displacement restraint structure was installed above. The design was based on the 1996 Road Bridge Specification and was completed in 2000. Fig. 4 shows a general view of the bridge.

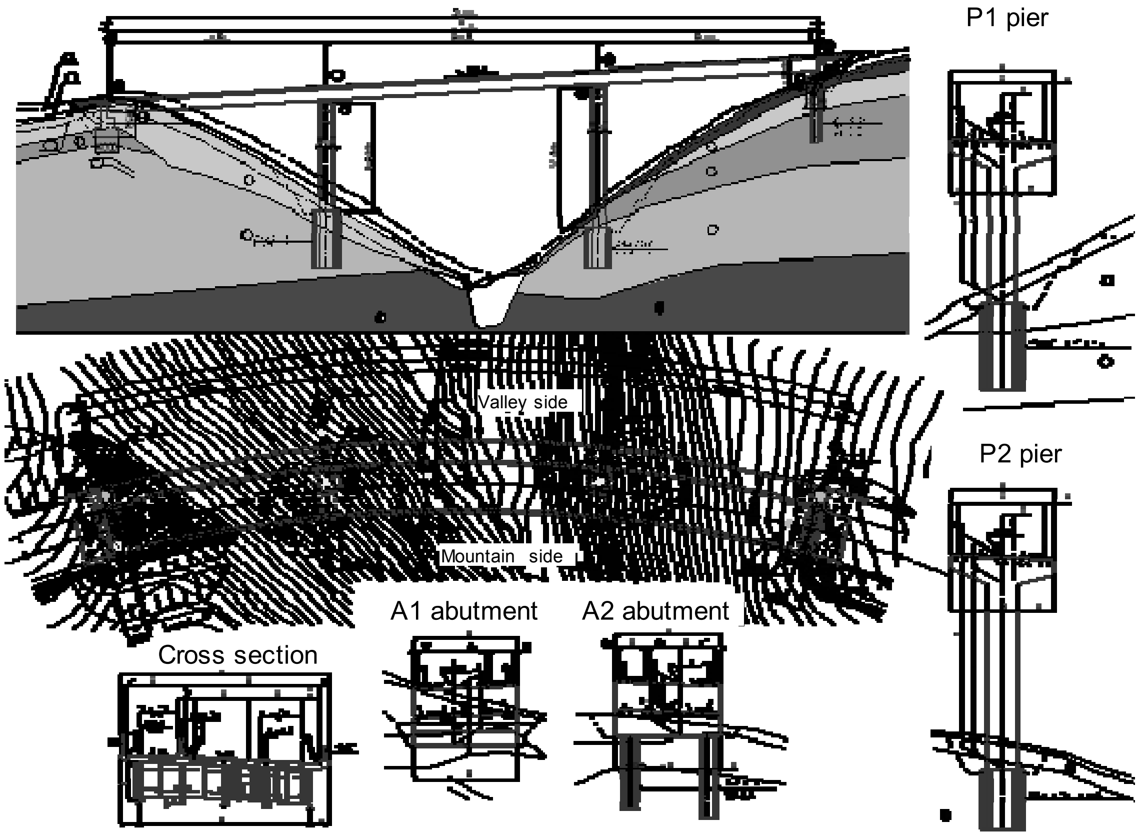

Fig. 4 – General drawing of Oginosaka-bridge

3.2 Damage status of Oginosaka-bridge

As shown in Photo 1, the parts of finger-joint device of A1 abutment engaged each other over the girder had shifted 240 to 270 mm to the valley side in the direction perpendicular to the bridge axis, and the joint gap extended 30 to 165 mm in the bridge axis direction compared to the standard width. The girder side of the joint device settled, and a step of 20 to 50 mm was generated from the abutment side, but no damage was found.

At the support point on the A1 side of the main girder, deformation of the web, stiffener, and flange was observed as shown in Photo 2. There was no other major damage to the superstructure between A1-P1.

All the bearings on the A1 abutment had a residual deformation of about 20 cm on the valley side, and the mounting bolts on the side blocks on both sides of the bearing designed as joint protectors were damaged. However, as shown in Photo 3, some bolts remained on the side blocks on the valley side of G1, G2, and G5 without breaking and those side blocks had not fallen down. In the center of each upper shoe plate, there were scratches on both sides with the side blocks. Photo 4 shows the scratches on the upper shoe plate of A1G1 bearing. As shown in Photo 5, one of the two lateral displacement restraint structures had shear fracture.

Photo 1 – Finger-joint device of A1 abutment


Photo 2 – Deformation of A1 support point of main girder


Photo 3 – A1 abutment

Photo 4(a) – Scratches on the upper shoe plate of A1G1 bearing (Valley side)

Photo 4(b) – Scratches on the upper shoe plate of A1G1 bearing (Mountain side)

Photo 5 – Damage of the lateral displacement restraint structure on A1 abutment

The A1 abutment had a horizontal displacement as described in 3.3, but no tilt was apparently caused by the earthquake. The foundation of A1 Abutment is a direct foundation, and it is estimated that there was no damage to the foundation. At the base of the parapet on the A1 abutment, a crack with a width of 6 mm was formed from the front (length: 1950 mm) to the side (length: 1150 mm), but did not penetrate the back. There was a 200mm x 300mm defect near the expansion joint device attachment of the parapet.

The bearing on the P1 pier had a residual deformation of about 5 cm on the mountain side. As shown in Fig. 5, the pier had some cracks at the top and the middle of the column, but no crack at the base. The rebar was not considered to have yielded. The P1 foundation was confirmed with a borehole camera and found no damage.

There was no major damage to the superstructure between P1 and P2.

The bearing on the P2 pier had a residual deformation of about 4 cm on the valley side. As shown in Fig. 6, the pier had some cracks in the upper and lower parts of the beam and column, but the rebar is not considered to have yielded. As a result of confirming the P2 foundation with a borehole camera, there was no damage.

There was no major damage to the superstructure between P2 and A2.

At the A2 expansion joint device, the girder had moved 25 cm to the mountain side in the direction perpendicular to the bridge axis. The deformation of the web, stiffener, and flange was observed at the support point on the A2 side of the main girder. All bearings on the A2 abutment had a residual deformation of about 20 cm on the mountain side, and the mounting bolts of the side blocks were broken only on the mountain side. In the center of each upper shoe plate, there were scratches on both sides with the side blocks.

The two lateral displacement restraint structures and the A2 abutment frame were not damaged. No damage was found on the A2 foundation with a borehole camera.

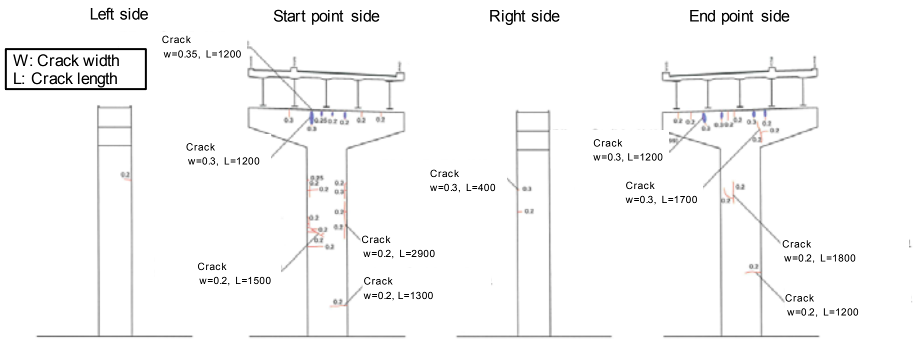

Fig. 5 – Crack diagrama of P1 pier

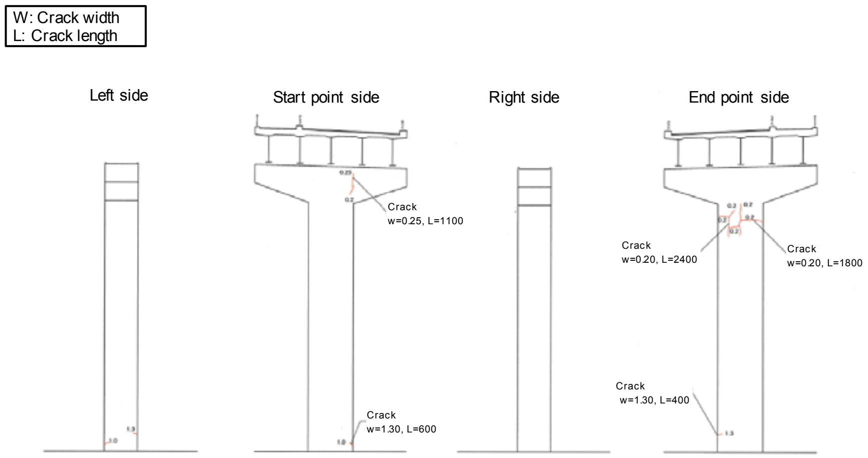

Fig. 6 – Crack diagram of P2 pier

3.3 Survey results for Oginosaka-bridge

Fig. 7 shows a comparison of the completed drawing of Oginosaka-bridge with the survey results. The A1 abutment moved 670 mm to the end point in the bridge axis direction and 820 mm to the mountain side perpendicular to the bridge axis at the ground surface position, and there was no inclination of the substructure, and it was the same at the top position of the substructure. The P1 pier moved 820 mm toward the end point in the bridge axis direction and 750 mm toward the mountain side perpendicular to the bridge axis at the ground surface position, and the substructure was inclined. It had moved 780mm toward the mountain perpendicular to the bridge axis. The P2 pier moved 1130 mm to the end point in the bridge axis direction and 1280 mm to the mountain side in the direction perpendicular to the bridge axis at the ground surface position, and the lower structure was tilted. It had moved 1230mm to the mountain perpendicular to the bridge axis. The A2 abutment moved 1310 mm to the end point in the bridge axis direction and 1120 mm to the mountain side perpendicular to the bridge axis at the ground surface position. The substructure did not tilt, and the amount of displacement at the top position of the substructure was the same to that at the ground surface.

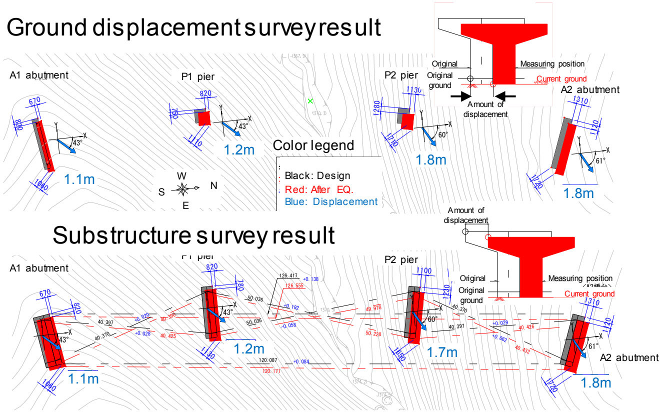

Fig. 7 – Substructure displacement of Oginosaka-bridge

Also, as shown in Fig. 8, the residual deformations of each bearing on the A1 abutment are almost 200mm toward the valley side and 50 to 170mm toward the end point, and those of each bearing on the P1 pier is almost 50mm toward the mountain side and -5 to 63mm toward the end point. On the P2 pier, the residual deformations was 30 to 45mm toward the valley side and -15 to 65mm toward the starting point, and on the A2 abutment, 200 mm or more toward the mountain side and 0 to 120mm toward the starting point.

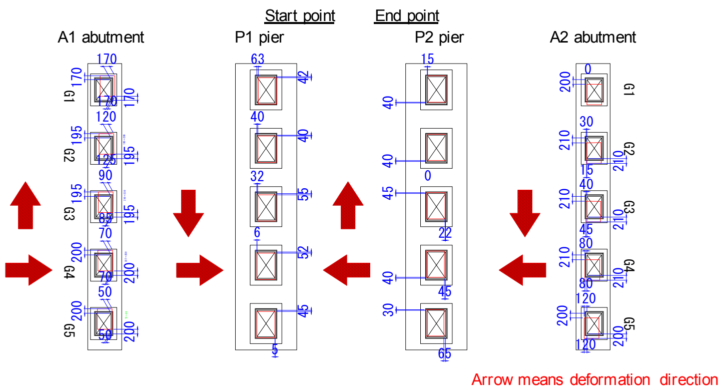

Fig. 8 – Residual deformation of bearing of Oginosaka-bridge

3.4 Damage analysis of Oginosaka-bridge

3.4.1 Relationship between residual deformation of bearing and ground displacement

The residual deformation of the bearings on each substructure is the end point direction, the end point direction, the starting point direction, and the starting point direction in the bridge axis direction, and the valley side, the mountain side, the valley side, and the mountain side in the direction perpendicular to the bridge axis in order from A1. Such residual deformation cannot occur without residual displacement of the substructure top.

Assuming that there is no residual stress in the substructure, the relative displacement in the X-axis direction (North-South direction) between the substructures is small, and the relative displacement in the Y-axis direction (East-West direction) is 385 mm westward in A1 and 336mm westward in P1, 321mm eastward in P2, 400mm eastward in A2. When the upper structure is pulled by the lower structure and rotated clockwise, because the upper structure has rigidity in the horizontal plane, the displacement of the superstructure occurs more than the displacement of the substructure at A1 and A2, and the displacement occurs in the opposite direction at P1 and P2, which coincides with the direction of the residual deformation of the bearings.

From the fact that the expansion joint device engaged each other with the superstructure displaced, it is presumed that the distance between the A1 abutment and A2 abutment opened once due to the ground displacement, and the superstructure rotated due to the ground displacement etc. while the joint device was removed, after that, the distance between A1 and A2 abutments narrowed, and the joint device engaged again.

3.4.2 Relationship between damage of lateral displacement restraint structures and ground displacement

A total of four lateral displacement restraint structures were installed, but only one on the A1 abutment had shear failure. Photo 5 shows the sheared RC block. This RC block was considered to have been destroyed by the collision with the bracket. Considering the fact that the joint device was almost no damage even after the earthquake and was taking a reaction force in the direction perpendicular to the bridge axis, in order for the RC block to be damaged, the engagement of the finger joint must had been disengaged by displacement in the vertical direction or pulling in the bridge axis direction. The height of damage position of the RC block almost matched the state where the girder was slightly lowered due to deformation of the rubber bearings after the earthquake, indicate that it was not hit while the expansion joint had gap in the vertical direction. On the other hand, it is presumed that the bracket was displaced toward the valley side when the bracket was displaced toward the end point from the horizontal damage position of the RC block.

Considering that the clearance in the bridge axis direction of the finger joint is 105 mm, while the width of the rubber pad of the bracket is 150 mm, it is presumed that the RC block was destroyed after the displacement in the bridge axis direction of 150 mm or more between the A1 abutment and the superstructure due to the ground displacement occurred, and then the displacement in the bridge axis direction returned.

3.4.3 Relationship between scratches of upper shoe plate and behavior of superstructure

Abrasion marks between the upper shoe plate and the side block of the A1G1 bearing were located at the center of the upper shoe plate on both the valley side and the mountain side, indicating that there were many contacts. The scratch marks are located on the entire height of the upper shoe plate, and are considered to be the contact when the side blocks are upright. The gap between the upper shoe plate and the side block in the design is 5 mm, which is considered to have been caused by vibration in the direction perpendicular to the bridge axis from the beginning of the seismic motion.

The abrasion marks on the mountain side, in addition to those at the center of the upper shoe plate, are present along the lower side of the upper shoe plate from the center to the entire A1 abutment side. This suggests that the side block and the upper shoe made relative displacement while contacting at an angle.

Although the mounting bolts of the side blocks were damaged, the side blocks remained standing, and the length of one side of the upper shoe plate was 630 mm, and the length of the scratch marks was more than 500 mm. Since the clearance of the expansion joint device in the bridge axis direction is 105 mm, the device did not resist, and it can be said that only enough force was exerted to leave the side block standing. On the other hand, on the valley side, in addition to the abrasion mark on the center of the upper shoe plate, there was a collision mark on the A1 side end, and the side block fell down. These results indicate that a relative displacement of 500 mm or more occurred between the A1 abutment and the superstructure in the bridge axis extension direction, during which the superstructure was greatly displaced from the mountain side to the valley side. Since the clearance in the bridge axis direction of the expansion joint device is 105 mm, the ground displacement occurred during this period, and the spacing between A1 and A2 abutments was widened, which is consistent with the results of 3.4.1 and 3.4.2.

3.4.4 Relationship between residual deformation of P1 and P2 bearings and damage to piers and foundations

As shown in Fig. 8, the residual deformation of P1 and P2 bearings was up to 65 mm. On the other hand, the maximum displacement in the design was 124.7 mm in the bridge axis direction and 116.3 mm in the direction perpendicular to the bridge axis on P1 bearings, and 65.8 mm in the bridge axis direction and 77.2 mm in the direction perpendicular to the bridge axis on P2 bearings. The residual deformations were within the design value. By design, the allowable plasticity factor of P2 pier is 1.3, which is consistent with the fact that the pier has hardly any cracks, which is considered to be caused by earthquake, and the foundation is considered to be undamaged. In general, the stiffness of rubber bearings may increase due to environmental effects over time. However, the results of measurement of shear stiffness of A1G2 bearings after the earthquake[5)] showed that the increase was only 1.9% over the design value. The effect of the increase in the stiffness of the rubber bearing is considered to be negligible. Therefore, it is presumed that the response deformation was not significantly larger than the residual deformation, which is consistent with the fact that the P1 and P2 bearings were not damaged.

4. Conclusion

Among the road bridges damaged by the Kumamoto Earthquake, we analyzed the damage of Oginosaka-bridge on the major local road Kumamoto Takamori Line, a bridge designed based on the 1996 Specifications for Road Bridges in Japan. As a result, it was confirmed that damage was presumed due to the influence of ground displacement. It was also found that the response of the bridge generated during the earthquake can be identified to a certain extent by analyzing the damage marks. Based on the experience of this disaster, when we construct road bridges, it is necessary to carefully investigate the possibility of ground displacement during an earthquake, and conduct various steps in route planning and structural planning so that the impact on the bridge can be minimized.

5. Acknowledgements

For the writing of this paper, investigation and survey results were provided by Kumamoto River and National Highway Office and Kumamoto Reconstruction Project Office, Kyushu Regional Development Bureau. Materials on the bridge were provided by Kumamoto Prefecture. The authors also thank Kumamoto earthquake road restoration study PT for their valuable contributions.

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