An Experimental Study on The Effect of Repairing RC Piers by The Injection of Epoxy Resin

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Abstract: A cyclic loading test of an RC pier specimens repaired by epoxy resin injection was conducted for the purpose of establishing a rational repair method for RC piers damaged by earthquakes. Specimens were full-scale RC pier models, which were damaged in advance to reproduce conditions as close as possible to those of actual repair work. As a result of the experiment, it was found that repaired specimens showed plastic deformability equivalent to or higher than unrepaired specimens although rigidity lowered at the time of yield displacement.
Keywords: epoxy resin injection, RC pier, repair, toughness, full-size specimen

1. INTRODUCTION

Because many RC piers suffered severely damage in the Hyogo-ken Nanbu Earthquake in 1995, a full-scale design method using the new criteria has been introduced with focus on plastic deformation performance following the yield of members, and seismic performance of RC piers has improved dramatically.

It is, however, necessary to carry out repairs to put a damaged pier back into service, since this design method allows damage in the plastic zone.

For the purpose of establishing rational repair methods for damaged RC piers, the authors performed repairs by epoxy resin injection for small-scale RC pier specimens damaged by horizontal cyclic loading, and after completion of repairs, confirmed the effect of the repairs by conducting cyclic loading.

The experiment revealed that seismic performance equivalent to or higher than that prior to repairs was ensured although initial rigidity decreased for one specimen, which was repaired to the extent that cover concrete would not begin to swell, and that sufficient repair effects could not be obtained for a specimen on which repairs were carried out after cover concrete began to swell.[1)]

It is also considered important to reproduce the cracking condition of the structure subject to repair in order to evaluate the repair effect in actual repair work since the efficiency of epoxy resin injection into cracks depends on the open width and depth of cracks.

In this study, therefore, a cyclic loading test using full-scale RC pier specimens was performed to evaluate and examine the crack repair effect for the purpose of approximating the body size, ratio of reinforcement, loading conditions and other details as much as possible to an actual structure.

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2. EXPERIMENTAL OVERVIEW

2.1 Experiment method

Figure 1 shows a view of the experimental equipment. To reproduce loading conditions that were as close as possible to those of an actual structure in the horizontal cyclic loading test, a steel girder simulating the superstructure of a bridge was placed on the RC pier specimen. The experimental setup consisted of two steel girders 15.0 + 15.0 = 30.0 m in total length, 3.0 m in width, 0.8 m in girder height and 1,058 kN in total weight; a sue that connected the superstructure and substructure, a hydraulic jack and a reaction force abutment.

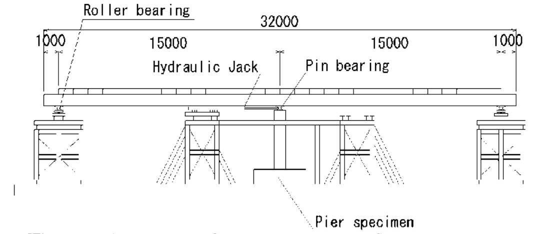


Fig. 1 A view of experimental equipment

The experiment was conducted by a cyclic loading in the horizontal direction using a hydraulic jack for both compression and tension, which was placed at the pin sue section on the RC pier specimen, under conditions where a vertical load of 747.3 kN (actual measurement value) was applied to the intermediate support section of the RC pier specimen by the girder weight.

Cyclic load was carried out by setting the yield strain of reinforcement to 1,920 μ , which was obtained by material testing, expressing the load-displacement when strain of reinforcement reached the yield strain at the base of the pier as yield-displacement δ y and the load at that time as yield load Py and increasing the displacement amplitude gradually to 2 δ y, 3 δ y and so forth. The number of cyclic loadings for each displacement amplitude was three.

Ultimate displacement was defined as that at the point when positive or negative load at the first loading for each displacement amplitude became smaller than yield load Py.

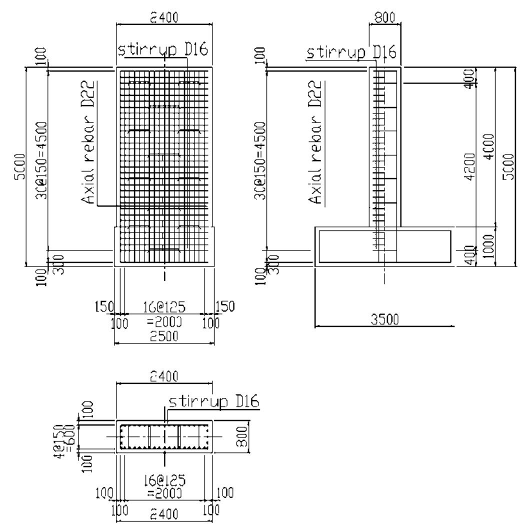


Fig. 2 A conceptual drawing of the form and bar arrangement of a specimen

Specimens were repaired after being subjected to predetermined damage by preliminary loading, and another loading test was then performed. Because measurement by the reinforcement strain gauge in the axial direction would become impossible at the stage of preliminary loading, yield displacement δ y of the standard specimen was used as standard displacement of cyclic loading on the repaired specimens.

2.2 Specimens

Specimens resembling the scale of an actual pier were used to simulate the wall-type RC pier generally used for highway bridges. Figure 2 illustrates a conceptual diagram of the form, size and reinforcement arrangement of the specimens.

The form/size of a specimen is a rectangular section (ratio of side length 1:3) 4.0 m in body height and 0.80 × 2.40 m in section size. Tensile reinforcement ratio was P_t = 0.38% and the volume ratio of the hoop reinforcement was ρ_s = 0.24%.

Table.1 List of specimens

Name of specimen	Displacement amplitude at preliminary loading	Resin injection length (mm)	Amount of resin injected (cc)
4.0-N	—	—	—
4.0-R-4	4 δ y	19,345	12,333
4.0-R-6	6 δ y	38,640	27,101

Table.2 Dynamic characteristic values of materials used

Name of specimen	Name of material	Compressive strength (MPa)	
		At the time of preliminary loading	After repair
4.0-N	Concrete	26.2	-
4.0-R-4	Concrete	31.1	32.4
	Epoxy resin	-	48.4
4.0-R-6	Concrete	27.7	31.1
	Epoxy resin	-	60.4

The horizontal load-bearing capacity of these specimens calculated in accordance with the Specification for Highway Bridges –seismic design [2)] was Pa = 469 kN, yield displacement was δ y = 17.6 mm and allowable ductility factor was μ a = 5.562.

For specimens to be repaired, preliminary load was set at two levels – 4 δ y and 6 δ y, to simulate the damage conditions from the state where crack width increased to approximately 1 mm to the state immediately before cover concrete began to swell. For repair of cracks, epoxy resin injection was conducted using the low-pressure, low-speed injection method in the state where horizontal displacement was returned to zero after completion of preliminary loading, on the assumption that repairs are carried out by recovering residual gradient after damage is suffered.

Table 1 presents the list of specimens used. In the table, the first item gives the height of the specimen, the second indicates the status of repair (N: unrepaired, R: resin injection) and the third is the displacement amplitude of preliminary loading (δ / δ y).

Concrete used for preparation of specimens was plain concrete 24 MPa, and reinforcement were SD345 type. The mean yield-point strength of reinforcement was 390 MPa. Table 2 displays the list of material testing results of concrete and epoxy resin.

Table.3 List of experimental results

Name of specimen	Displacement(mm)		Load(kN)		Ductility factor
	δ y	δ u	Py	Pa	δ y/ δ u
4.0-N	22.5	202.5	431	606	9
4.0-R-4	22.5	270	316	662	12
4.0-R-6	22.5	247.5	315	657	11

3. EXPERIMENTAL RESULTS

3.1 Load-displacement relationship

Table 3 shows the list of experimental results. In the table, δ y and Py indicate the displacement and load at the loading point, respectively, while Pa is the maximum load and δ u is the ultimate displacement. Figure 3 shows the load-displacement envelope. Yield-load Py of repaired specimens was as low as 73% of the unrepaired 4.0-N specimen.

Load after loading of 3 δ y, however, exceeded the load of the unrepaired specimen, while the maximum load was 8 to 9% larger. While the ultimate displacement was 202.5 mm (9 δ y) for the 4.0-N specimen, it was 270.0 mm (12 δ y) for the 4.0-R-4 specimen and 247.5 mm (11 δ y) for the 4.0-R-6 specimen and exceeded the value of the unrepaired 4.0-N specimen, which was the standard specimen.

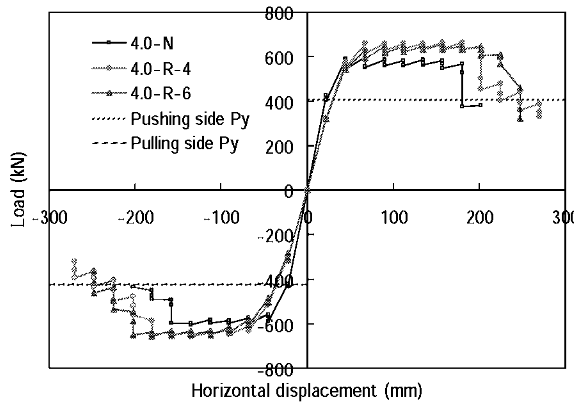


Fig.3 Load-displacement envelope

Figure 4 shows the load-displacement relationship from the beginning of loading to the first pushing load of 1 δ y. While the figure depicts a clear difference in rigidity of the 4.0-N specimen between the horizontal displacement of 0 to 6 mm before occurrence of cracking and 6 to 22.5 mm after that, no clear changes in rigidity were observed from the beginning of loading to 1 δ y for the 4.0-R-4 and 4.0-R-6 specimens. It can therefore be seen that the rigidity was identical to the rigidity at the horizontal displacement of 6 to 22.5 mm after the occurrence of cracking on the 4.0-N specimen.

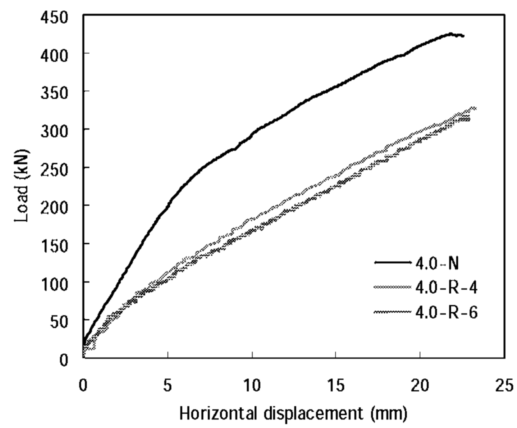


Fig.4 Load-displacement envelope (beginning of loading ～ 1 δ y)

This suggests that the initial flexural rigidity in the case of epoxy resin injection lowered to the same level as the rigidity after occurrence of cracks on the standard specimen because fine cracks (crack width: 0.05 mm or less) remain which cannot be injected with epoxy resin.

3.2 Damage conditions of specimens

Photo 1 shows the destruction properties of specimens after completion of the experiment.

In the unrepaired 4.0-N specimen, which was the standard specimen, horizontal cracks occurred at intervals of 200 to 300 mm in the height direction from the bottom at the time of loading of 1 δ y. Horizontal cracks subsequently increased and progressed to loading of 4 δ y and then changed into diagonal cracks until loading of 5 δ y.

Exfoliation of small pieces of cover concrete became apparent at the base of the compressive side at the time of loading of 6 δ y, and cover concrete began to swell over a wide area at the time of loading of 7 δ y. Cover concrete exfoliated over a wide area and the load decreased dramatically at the time of loading of 8 δ y. The load then fell below Py and reached the ultimate state with loading of 9 δ y. The area of exfoliation of cover concrete was approximately 800 mm from the base.

In the case of the 4.0-R-4 specimen, preliminary loading was carried out up to 4 δ y, where horizontal cracks would become predominant and the crack width would increase to 1 mm.

With regard to the damage to the specimen at the completion of preliminary loading, horizontal cracks similar to those in the 4.0-N specimen were predominant, the maximum crack width was 1.5 mm at around 500 mm from the base, and was 0.05 mm in the area higher up.

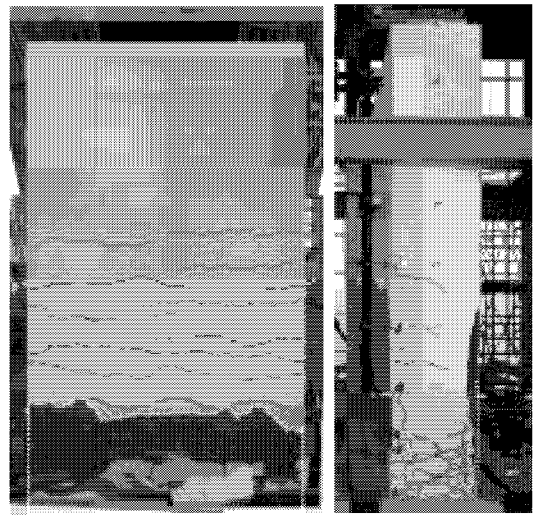
At the time of loading after epoxy resin injection into cracks in the section 500 mm from the base, horizontal cracks occurred and progressed with loading of 1 to 3 δ y, as if avoiding the section where epoxy resin was injected.

At the time of loading of 4 to 7 δ y, bending cracks that had occurred in the side of the wall changed into shear cracks. Cover concrete began to swell over a wide area with loading of 8 δ y. It exfoliated over an area up to 1,000 mm from the base and the capacity decreased dramatically at the time of loading of 9 δ y. Load decreased gradually by subsequent loading, became lower than Py and reached the ultimate state with loading of 12 δ y.

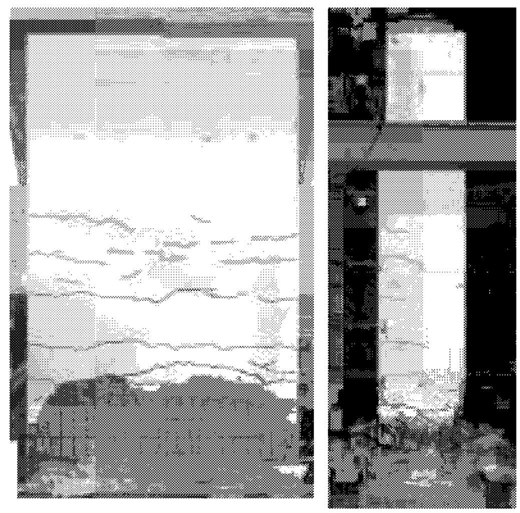
In the case of the 4.0-R-6 specimen, preliminary loading was performed until 6 δ y, which was the state just before cover concrete would begin to swell.

Regarding damage to specimens at the completion of preliminary loading, swelling of cover concrete was not observed although exfoliation of small pieces similar to those in the 4.0-N specimen were seen. The maximum crack width was approximately 2.0 mm at 600 mm from the base and was 0.05mm in the area higher up.

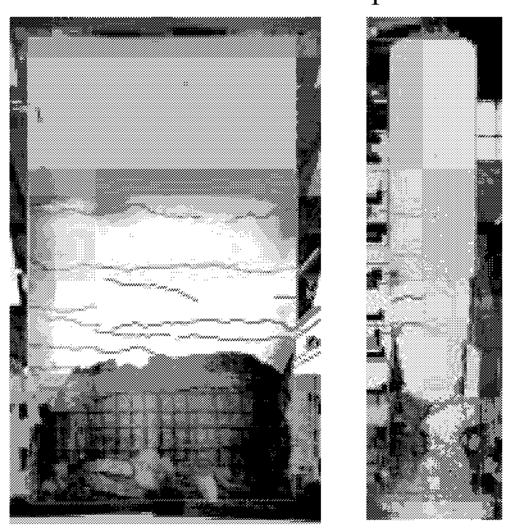
At the time of loading after epoxy resin injection into cracks in the section 600 mm



Ultimate state of 4.0-N specimen



Ultimate state of 4.0-R-4 specimen



Ultimate state of 4.0-R-6 specimen

Photo 1 Conditions of damage to specimens from the base, cracks occurred and progressed with loading of 1 to 3 δ y, as if avoiding the section where epoxy resin was injected.

While bending cracks that had occurred in the side of the wall changed into shear cracks and progressed at the time of loading of 4 to 8 δ y, swelling of cover concrete was not observed. Cover concrete began to swell over a wide area after that with loading of 9 δ y, centering around the upper end of the repaired section. It exfoliated over an area up to 1,200 mm from the base with loading of 10 δ y. Load decreased dramatically due to fracture of the axial reinforcement, became lower than Py and reached the ultimate state with loading of 11 δ y.

Comparing the damage of each specimen, displacement amplitude at the time of exfoliation of cover concrete in 4.0-R-4 and 4.0-R-6 was greater than 4.0-N and the exfoliated area was increasing. It was therefore presumed that epoxy resin injection improved adhesion performance between the axial reinforcement/hoop reinforcement and concrete and that the injected epoxy resin displayed a resistance effect against exfoliation, resulting in a larger ultimate displacement value compared with 4.0-N.

While buckling of the axial reinforcement occurred at around 30 cm in height in the 4.0-N specimen, it occurred at around 50 cm in 4.0-R-4 and 60 cm in 4.0-R-6.

3.3 Horizontal displacement distribution

Figure 5 illustrates the horizontal displacement distribution in the height direction with load just before each specimen reached the ultimate state (4.0-N: 8 δ y, 4.0-R-4: 11 δ y, 4.0-R-6: 10 δ y).

Since the figure indicates that the horizontal displacement distribution is almost linear from the base to the loading point of the 4.0-N specimen, it was presumed that the angle of rotation between the base and 500-mm section was predominant and that plastic hinging occurred in this section.

In contrast, in the 4.0-R-4 and 4.0-R-6 specimens, discontinuous horizontal displacement distribution was observed between the base and the section around the height of 1,500 mm, indicating that damage progressed and considerable deformation occurred in the area higher than 1,500 mm in addition to the damage around the base. This corresponded with the trend for the exfoliated area of cover concrete and the buckling point of the axial reinforcement to move upward in the ultimate state.

This was presumed to be due to the upward expansion of the damaged area as a result of progress of deterioration that could not be controlled by the rigidity of the unrepaired section, although rigidity near the base was recovered to a certain extent by epoxy resin injection.

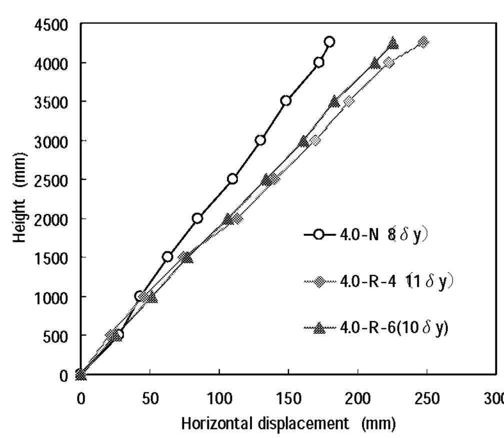


Fig. 5 Distribution of horizontal displacement in the height direction

3.4 Hysteresis absorbed energy

Figure 6 shows the relationship between the accumulated hysteresis absorbed energy and horizontal displacement until each specimen reached ultimate displacement. Hysteresis absorbed energy was calculated from the load-displacement relationship at each displacement amplitude (δ / δ y). It can be seen from the figure that, while the values of repaired specimens were slightly lower than that of the 4.0-N specimen in the initial stage of loading, the values of 4.0-R-4 and 4.0-R-6 exceeded that of 4.0-N with loading of 7 and 8 δ y, respectively. While the accumulated energy absorption at the time of loading of 9 δ y where the 4.0-N specimen reached the ultimate state was 1,889.57 kNm for the 4.0-N specimen, it was 2,227.25 kNm for 4.0-R-4 and 2,046.58 kNm for 4.0-R-6, i.e. 1.08 to 1.10 times as large as the value of 4.0-N.

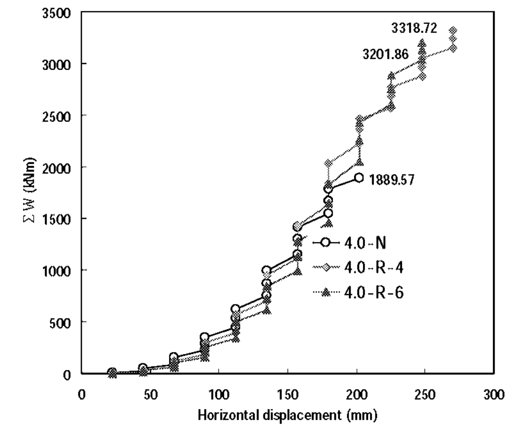


Fig. 6 Hysteresis absorbed energy

The values of accumulated hysteresis absorbed energy at the ultimate state of repaired specimens were 3,318.72 kNm for 4.0-R-4 and 3,201.86 kNm for 4.0-R-6, i.e. 1.69 to 1.76 times as large as the value of the 4.0-N specimen, indicating a very high energy absorption performance.

3.5 Equivalent viscous damping constant

Figure 7 shows the equivalent viscous damping constant, which was calculated from the hysteresis loop of each displacement amplitude.

The equivalent viscous damping constant of the 4.0-N specimen h_{eq}, which serves as the standard, increased gradually from 10.2% with loading of 1 δ y to a maximum of 26.9% with loading of 7 δ y.

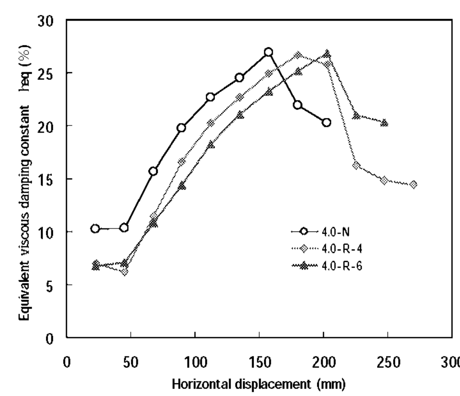


Fig. 7 Equivalent viscous damping constant

Although the values of the 4.0-R-4 and 4.0-R-6 specimens were smaller than the 4.0-N specimen until loading of 7 δ y, they exceeded the value of the 4.0-N specimen at and after 8 δ y. The maximum value was 26.6% (8 δ y) for 4.0-R-4 and 26.8% (9 δ y) for 4.0-R-6, showing values almost identical to that of the standard specimen.

5. CONCLUSION

The repair effect of epoxy resin injection was examined by the cyclic loading test using full-scale RC pier specimens for the purpose of establishing a rational repair method for damaged RC piers. The results obtained by this study can be summarized as follows:

(1) The value of ultimate displacement increases after repair by epoxy resin injection. This is presumed to be due to the ability of epoxy resin to control exfoliation of cover concrete.

(2) Rigidity at the initial stage of loading is around 73% or less than that before repair because fine cracks remain which cannot be injected with epoxy resin.

(3) While the accumulated hysteresis absorbed energy is slightly smaller than that of the standard specimen in the initial stage of loading, the value exceeds that of the standard specimen at the level of loading where the standard specimen reaches the ultimate state.

(4) Because rigidity of the section where epoxy resin is injected recovers to a certain degree, the range where cover concrete begins to swell and buckling of axial reinforcement occurs tends to move upward.

From the above results, seismic performance can be recovered to a level equivalent to or higher than that before damage is sustained. This can be achieved by injecting epoxy resin into cracks from the state where horizontal cracks are predominant to the state just before cover concrete exfoliates.

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