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An Experimental Study on The Performance of Reinforced Concrete Members Subjected to Repeated Huge Earthquake Damage and Repair

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ABSTRACT

Recently, some repaired reinforced concrete (RC) structures were damaged by the aftershocks like the Great East Japan Earthquake 2011, and by the earthquake like Tokachi-Oki Earthquake 2003 after Kushiro-Oki Earthquake 1995. There were RC structures repeated damage and repair due to huge earthquakes. So, we should study not only repaired RC member's performance but also re-repaired RC member's performance. Based on experimental investigations, we clarified the following: the re-repaired RC member's performance is not directly affected by the repetition of damage and repair, but affected, as repaired RC member's performance, by the damage degree of longitudinal reinforcements before re-repairing, by repair methods, and by repairing materials.

Keywords.re-repaired reinforced concrete members, degree of damage to longitudinal reinforcements, repair method, repair material.

1. Introduction

Civil structures often remain in service for extended periods, and a significant number today have been used for 100 years or more. In seismically active Japan, such structures may well be subjected to earthquake-related damage more than once during their design lifetime. Indeed, some RC structures have been repeatedly damaged and repaired, such as the JR Nemuro main line bridge over the Toshibetsu River, which was damaged by the 1993 Off Kushiro Earthquake and the 2003 Off Tokachi Earthquake18). As large-scale earthquakes are often followed by large aftershocks, structures repaired after the main shock have a significant likelihood of being damaged again by such post-quake seismic activity. By way of example, elevated bridge columns repaired after the main Off Pacific Coast of Tohoku Earthquake of March 11, 2011, were damaged again by an aftershock on April 7. Accordingly, studies on structural repair-ability must include consideration for the performance of members subjected to repeated damage and repair. Against such a background, this study involved reverse cyclic load testing of repeatedly damaged and repaired RC members assuming that the structures were damaged by multiple earthquakes. The test results were analyzed to determine how the degree of damage and the repair method affect member proof strength and deformation capacity, and to examine how repeated damage and repair influences member performance.

2. Outlines of Experiment

2.1 Specimens

Initial specimens were created to represent the columns of RC rigid-frame elevated railway bridges with bending fracture morphology. The specimens were subjected to damage in a reverse cyclic loading test using the maximum displacement as an indicator, and were then treated to create repaired specimens. These were then subjected to damage again in a reverse cyclic loading test and treated to create re-repaired specimens. The specimens were used to study how repeated repair influences member performance and generates pre-/post repair differences. Table 1 gives an overview of the test. Three initial specimens with the same specifications (No.1, No.2 and No.3) were used initially. As basic specimen (BS) for comparison was also the same specification. BS was subjected to reverse cyclic loading with the same displacement once for the three times for the latter. Figure 1 shows the load-displacement conditions for BS. The repaired specimens were made by damaging initial specimens and repairing them, and the re-repaired specimens were made by damaging repaired specimens and repairing them again. The repaired specimens were R3M, R6M and R6R, and the re-repaired specimens were R5(R3M)M, R6(R6M)M and R6(R6R)R. The number (R3, R5 or R6) means the maximum displacement which was experienced. And M and R mean the repair and re-repair method: M indicates patch repair using mortar, and R indicates patch repair using resin mortar. Figure 2 shows the details of the initial specimens, which had the same specifications. The cross-section shape was a square measuring 900 x 900 mm, and the shear span was 3,300 mm (with a shear span ratio of 4.02). The longitudinal bar type was D32, the tensile reinforcement ratio was 1.07%, and the tie hoops were the D16 type. In the range of 1,800 mm from the column base, middle tie hoops were placed every 200 mm, and the tie hoop ratio was 0.66%. In the range higher than this, the tie hoop ratio was 0.44%.

2.2 Initial loading

For all specimens, 25 mm was set as the yield displacement (δ_y). The maximum displacement for the No.1 was set to 75 mm ($3\delta_y$) (a level at which the longitudinal bars would not buckle), and that for the No.2 and No.3 was set to 150 mm ($6\delta_y$) (a level at which the longitudinal bars would buckle). Different loading methods were used for the specimens and others listed in this report’s bibliography described how loading history influences the member performance of initial specimens. The axial compression stress intensity was set to

Table 1. Test overview

Order	Basic specimen	No.1	No.2	No.3
1	Initial loading			
	Displacement	$3\delta_y$: 75 mm	$6\delta_y$: 150 mm	$6\delta_y$: 150 mm
	Damage status	Cracking and flaking	Longitudinal bar buckling	Longitudinal bar buckling
2	Repair			
	Repaired	R3M	R6M	R6R
	Work method	Plastering	Mold filling	Mold filling
	Materials for repair	Grouting : cement grout Repair material : mortar (Ratio is 6.9%)	Grouting : none Repair material :mortar (Ratio is 42.4%)	Grouting : epoxy resin Repair material : resin mortar (Ratio is 34.5%)
3	Loading after repair			
	Displacement	$5\delta_y$: 125 mm	$6\delta_y$: 150 mm	$6\delta_y$: 150 mm
	Damage status	Longitudinal bar buckling	Longitudinal bar buckling	Longitudinal bar buckling
4	Re-repair			
	Re-repaired	R5(R3M)M	R6(R6M)M	R6(R6R)R
	Work method	Mold filling	Mold filling	Mold filling
	Materials for repair	Grouting : cement grout Repair material : mortar (Ratio is 20.8%)	Grouting : cement grout Repair material : mortar (Ratio is 55.7%)	Grouting : epoxy resin Repair material : resin mortar*1 (Ratio is 100%)
5	Loading after re-repair			
	Displacement	$8\delta_y$: 200 mm	$8\delta_y$: 200 mm	$8\delta_y$: 200 mm

*1: The whole concrete part of the column base was replaced with resin mortar.
*2: Displacement means maximum displacement
*3: Ratio means amount of repair material used (excluding the volume of repair material for the portion expanded during repair) / Volume in the range 900 mm from the base (900 x 900 x 900 mm)

3.87 N/mm^2 (an axial force of 3,138 kN) assuming that the maximum value is generated by variations in the axial force acting on RC rigid-frame viaduct's columns during earthquakes.

2.3 Repair

The repaired specimens were made by resetting the horizontal displacement and horizontal load to zero during repair to avoid the influence of residual displacement on the load-displacement relationship. When buckling caused longitudinal bars to move outside their concrete cover positions, or when the filling state of repair material needed to be ensured for the sake of work quality, the cross-section was widened. In the range up to 80 mm in height from the column base, however, the pre-damage section dimensions were maintained to avoid any increase in bending strength due to section enlargement. No bend stretching of longitudinal bars or replacement of loose tie hoops was conducted.

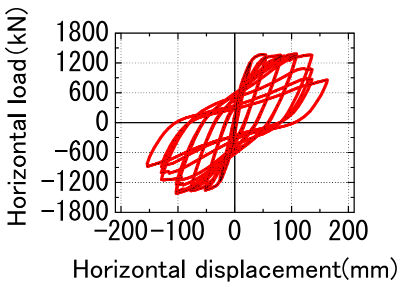


Figure 1. Load-displacement of Basic specimen

Table 2. Loading program

Specimen	Loading Program
No.1	3,2,1,3,2,1,3,2,1δ_y
No.2	6,5,4,3,2,1,6,5,4,3,2,1 ,6,5,4,3,2,1δ_y
No.3	1,2,3,1,2,3,1,2,3,4,4,4 ,5,6δ_y
BS	Same displacement cycle x 1 (1δ_y step-up)

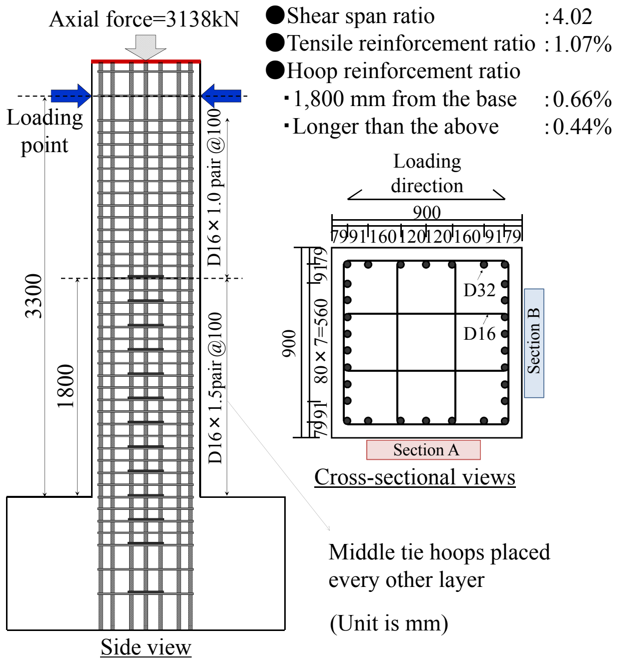


Figure 2. Initial specimen and Basic specimen

a) R3M specimen repair

Only concrete that had loosened and flaked was removed, and patch repair was conducted on defective parts using mortar. Cement grout was also applied to parts with surface cracks measuring 0.2mm or more in width. Patch repair was based on the plastering method because the defective range was approximately at the concrete cover position.

b) R6M specimen repair

Only concrete that had loosened and flaked was removed, then molds were placed and patch repair was conducted on defective parts using mortar. No grouting was conducted.

c) R6R specimen repair

Only concrete that had loosened and flaked was removed, then molds were placed and patch repair was conducted on defective parts using resin mortar. Grouting with epoxy resin was then conducted on parts with surface cracks measuring 0.1mm or more in width except on the patch repair parts.

2.4 Loading after repair

The reverse cyclic incremental loading method was used with one cycle each for integral multiplications of 1δ_y, (25 mm). The maximum displacement of the R3M specimen was set to 5δ_y, and those for the R6M and R6R were set to 6δ_y. Upon completion of the second loading, longitudinal bar buckling was observed in the R3M.

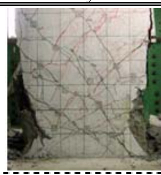
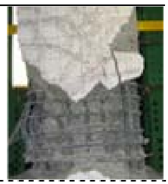
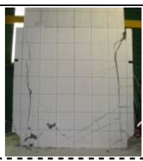
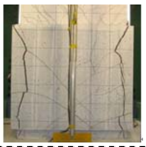
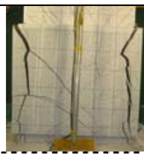
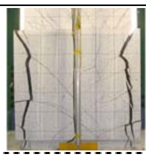
2.5 Re-repair

The same process as that for the repaired specimens described earlier was applied.

a) R5(R3M)M specimen repair

Only concrete and repair material that had loosened and flaked was removed, then molds were placed and patch repair was conducted on defective parts using mortar. Cement grout was also applied to parts with surface cracks measuring 0.2mm or more in width.

Table 3. Damage processes (observed from Section A in Figure 2)

	$3\delta_y$	$4\delta_y$	$5\delta_y$	$6\delta_y$	$8\delta_y$
R3M				No loading	No loading
Load			Maximum		
R5(R3M)M					
Load		Maximum			
R6M					No loading
Load	Maximum				
R6(R6M)M					
Load	Maximum				
R6R					No loading
Load		Maximum			
R6(R6R)R					
Load			Maximum		

b) R6(R6M)M specimen repair

Only concrete and repair material that had loosened and flaked was removed. Enclosed arc welding was conducted on one ruptured longitudinal bar. Unlike the repair procedure for the other specimens, grouting was conducted first, followed by patch repair. Specifically, cement grout was applied to parts with surface cracks measuring 0.2mm or more in width. Molds were then placed and patch repair was conducted on defective parts using mortar.

c) R6(R6R)R specimen repair

Parts of concrete that had peeled were chipped off, and patch repair on defective parts was conducted using resin mortar. Grouting with epoxy resin was also conducted on parts with surface cracks measuring 0.1mm or more in width.

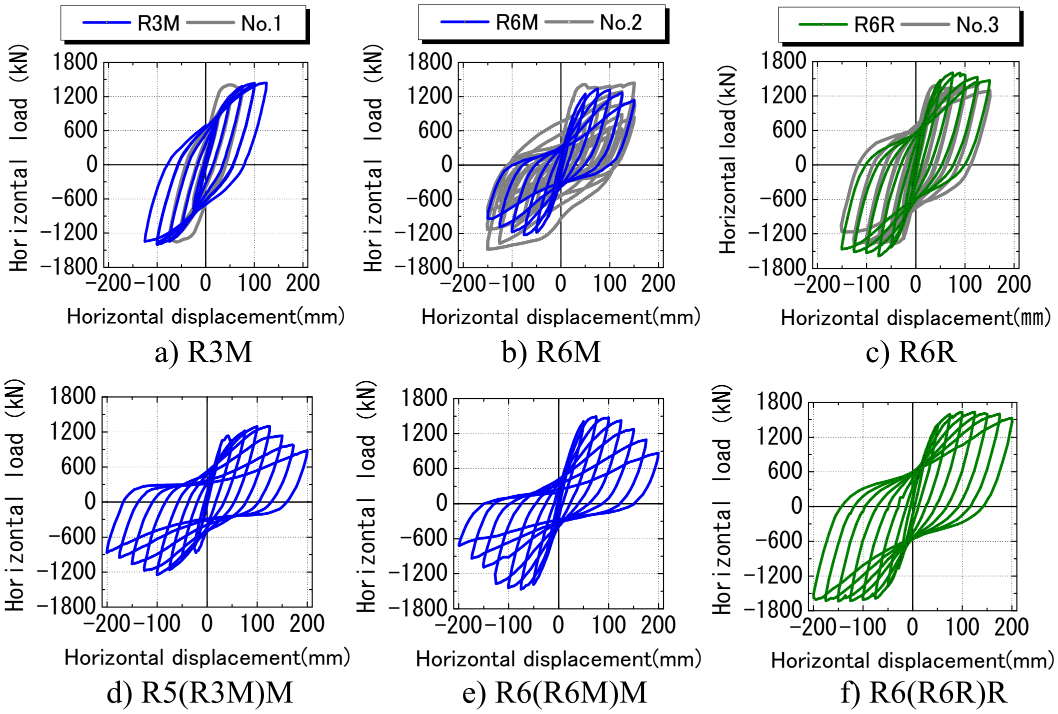


Figure 3. Load-displacement

Table 4. Maximum loading and the displacement with maximum loading

Specimen	R3M	R6M	R5(R3M)M	R6(R6M)M	R6R	R6(R6R)R
Maximum Load(kN)	1437 ($5\delta_y$)	1298 ($4\delta_y$)	1336 ($3\delta_y$)	1494 ($3\delta_y$)	1606 ($4\delta_y$)	1633 ($5\delta_y$)

2.6 Loading after re-repair

The reverse cyclic incremental loading method was used with one cycle each for integral multiplications of $1\delta_y$ (25mm). Loading up to 8δy was applied to the R5(R3M)M, R6(R6M)M and R6(R6R)R.

3. Influence of Repeated Damage and Repair on Member Performance

3.1 Damage process and Load-displacement

Table 3 shows the damage processes of the specimens. The R3M flaked at $3\delta_y$ and peeled at $5\delta_y$ with longitudinal bar buckling, the R5(R3M)M flaked and peeled at $2\delta_y$, the R6M and R6(R6M)M flaked at $2\delta_y$ and peeled at $4\delta_y$, and the R6R and R6(R6R)R flaked at $4\delta_y$. Figure 3 shows the load-displacement relationships of the specimens after correction for additional bending moment caused by axial forces. Table 4 shows maximum loading and the displacement with maximum loading of the specimens.

3.2 Maximum load

Figure 4 shows the relationships between the maximum loads and ratios. The ratios represent the degree of damage to the concrete and repair material of the column base, which can be calculated using the method shown in Table 1. The R3M repaired for damage with no longitudinal bar buckling shows a replacement ratio below 10% because patch repair was conducted only on the concrete cover. The maximum load was approximately equal to that of the Basic Specimen (BS). Based on these results, it can be considered that the maximum load of the specimens not damaged to the point of longitudinal bar buckling was approximately equal to that observed when the specimens were undamaged.

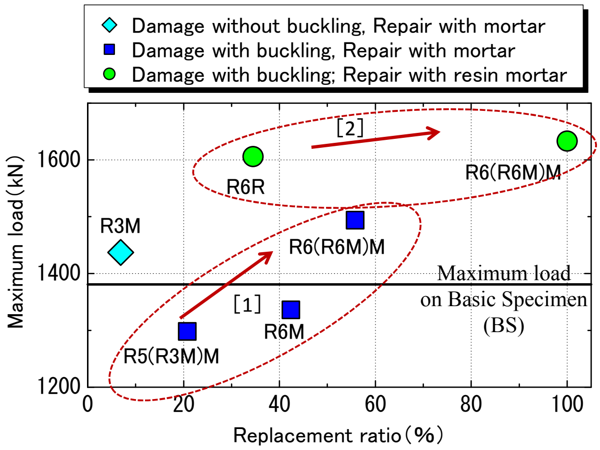


Figure 4. Relationships between maximum loads and replacement ratios

Next, specimens repaired for damage with longitudinal bar buckling were examined. When patch repair using mortar ([1] in the figure) was conducted, the R5(R3M)M and R6M had lower maximum loads than the BS. This is considered to have stemmed mainly from the larger range of flaking and peeling at the maximum load than on the BS and pre-existing damage to the core concrete before loading. The maximum load increase in proportion to higher replacement ratios is considered to result from adequate filling with repair material up to the reverse side of the longitudinal bars. In other words, as shown by the damage status of the R6(R6M)M in Tables 3, it is deemed to have stemmed from the lower likelihood of cracking on the concrete cover as compared to the R5(R3M)M, and the reduced ratio for the pre-damaged core concrete near the column base meant that the repair material was able to bear more compression force. When patch repair was conducted with resin mortar ([2] in the figure), both the R6R and R6(R6R)R had higher maximum loads than the BS. This is considered to be mainly because the resin mortar used in the test had lower compressive strength than mortar (but approximately double the tensile strength) so that cracking and flaking did not readily occur, and because the resin material exhibited stress-strain relationships different to those of cement and other materials.

The specimens damaged to the point of longitudinal bar buckling, as shown in Table 3, were subjected to their maximum loads approximately when longitudinal cracking developed into peeling, unlike the Initial specimen and the Basic specimen. The maximum load is therefore assumed to have occurred at the time of interface delamination between the repair material and the concrete or bond failure between the longitudinal bars and the repair material.

3.3 Maximum load retention point

The authors proposed damage level *D* and repair effect *R* as indicators for the deformation capacity of repaired members in a previous paper. The damage level *D* is an indicator that represents a damage level corresponding to the displacement (member angle) at the

maximum load retention point (*M-point*) when the specimen is undamaged. In other words, D is 1.0 if the specimen before repair or re-repair exhibits the maximum member angle equivalent to that observed at M when the specimen is undamaged, and is above 1.0 if the piece exhibits a higher maximum member angle than M. If D is above 1.0, such buckling can be considered to have occurred. Repair effect R represents the effect seen when the specimen is repaired or re-repaired in comparison with the performance observed when the piece is undamaged. If the value is below 1.0, the deformation capacity is lower than that of an initial specimen after repair. In other words, an R value of 1.0 means that the deformation capacity is equivalent to M when the specimen is undamaged, and values below 1.0 mean that the deformation capacity is smaller than M. In this study, the repair effects seen with repaired and re-repaired specimens were examined using these indicators.
Equation (1) shows damage level D, and Equation (2) shows repair effect R.

$$D = \frac{{}_E\theta_{\max} - {}_N\theta_y}{{}_N\theta_m - {}_N\theta_y} \quad (1)$$

where,
D: damage level
${}_E\theta_{max}$: maximum member angle exhibited by the specimen until re-repair(rad)
${}_N\theta_m$: member angle at M on the initial specimen (rad)
${}_N\theta_y$: yield member angle on the initial specimen (rad)

$$R = \frac{{}_R\theta_m - {}_N\theta_y}{{}_N\theta_m - {}_N\theta_y} \quad (2)$$

where,
R: repair effect
${}_R\theta_m$: member angle at M on the re-repaired specimen (rad)
(The member angle before $1\delta_y$ at which the maximum load was encountered)
${}_N\theta_m$: member angle at M on the initial specimen (rad)
(In this study, the member angle at M on the basic specimen with the same specifications under loading with the same displacement three times)
${}_N\theta_y$: yield member angle on the initial specimen (rad)

Figure 4 shows the setting method for the maximum load retention point (M) with an example in which the value is set to $2\delta_y$ ($2\theta_y$). In this test, the repaired and re-repaired specimens were loaded to be subjected to the same level of displacement once. Accordingly, unlike the Basic specimen loaded to the same level of displacement three times as shown by in Figure 1, it is considered that the generation and progress of longitudinal bar buckling does not result in reduced loading or the appearance of a definite maximum load retention point. However, it is considered possible, even with a single instance of loading, to roughly estimate whether reduced loading occurs by studying the load-displacement point at the maximum displacement load applied to the specimens in comparison with an even larger displacement than the former maximum value. In other words, when the specimens were loaded to a displacement level $1\delta_y$ greater than the displacement at the maximum load point, *a-point* (with a load corresponding to the same displacement as that at the maximum load point) in the figure should be noted as being significantly smaller. Specifically, it was

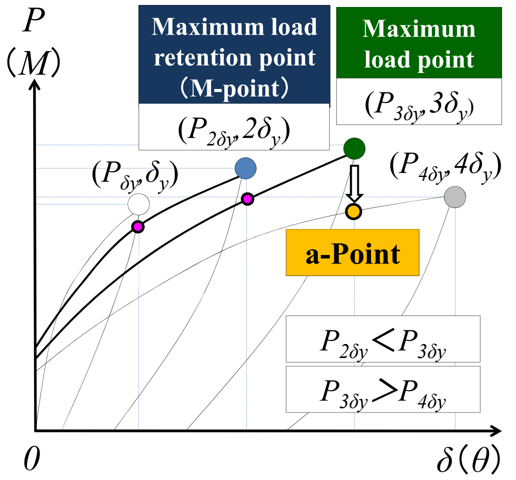


Figure 5. Setting of the maximum load retention point (M)

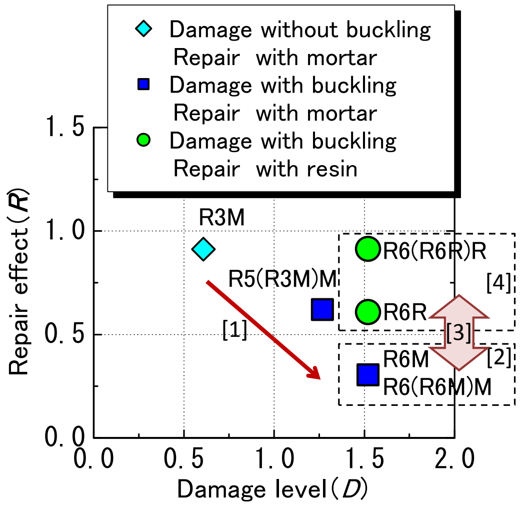


Figure 6. Relationships between damage level D and repair effect R

estimated that load reduction occurs due to repeated loading with uniform displacement at the maximum load point, and the maximum load retention point for the repaired and re-repaired specimens was set to a displacement level $1\delta_y$ lower than that at the maximum load point. Even in the loading test on the initial specimens, repeated loading with the same displacement as that seen at the maximum load point sometimes caused a load reduction, resulting in a mismatch of the maximum load point and the maximum load retention point. Accordingly, it is considered that the maximum load retention point discernible using the setting method shown in Figure 5 is the safe-side maximum displacement that ensures no generation or progress of buckling regardless of the number of cycles.

Figure 6 shows the relationship between damage level *D* and repair effect *R*. First, a study was conducted to determine how differences in *D* influence the repair effect based on the R3M, R5(R3M)M, R6M and R6(R6M)M specimens patch-repaired with mortar. As *D* increased ([1] in the figure), R fell. When the damage level remained the same ([2] in the figure), *R* also remained unchanged. From these results, *R* can be considered to depend on *D*. These outcomes are consistent with those presented in our previous papers, which maintained that the degree of pre-repair damage to longitudinal bars is an important indicator in determining post-repair member performance by examining only repair specimens, not re-repair specimens.

Next, a study was performed to determine how differences in repair methods influence the repair effect. The R6M and R6(R6M)M were compared with the R6R and R6(R6R)R, which had the same damage level *D*. Repair material was performed with mortar for the former and with resin mortar for the latter. With this treatment, the R6R and R6(R6R)R exhibited a greater repair effect R than the R6M and R6(R6M)M ([3] in the figure). This difference is considered to stem from the lower likelihood of repair material flaking mainly because resin mortar has a higher tensile strength than mortar/concrete as described in "3.2 Maximum load." The R6R and R6(R6R)R ([4] in the figure) exhibited a greater repair effect R at the same damage level *D*. This is considered to have resulted from the lower likelihood of flaking on the R6(R6R)R than on the R6R piece because resin mortar was used to replace all of the part near the column base that had been forcibly chipped off on the former, while on the latter it replaced only the part up to the back of the longitudinal bars. The difference may also have resulted from the discrepancy in the damage status of the core concrete before loading, as the R6(R6R)R did not exhibit any cracking because the whole of the column base had been replaced, while the R6R included core concrete damaged before repair because patch repair was conducted only on the damaged part.

Based on these results, the maximum load retention points of the repaired and re-repaired specimens were studied using damage level *D* (representing the level of damage caused by displacement at the maximum load retention *M-point*) and repair effect *R* (representing the repair effect). The results showed that the maximum load retention points of both the repaired and re-repaired specimens were influenced by the maximum member angles seen and by the repair method.

4. Conclusion

The findings of this study can be summarized as follows:

(1) The load carrying capacity of either repaired specimen or re-repaired specimen is influenced by both the repaired area and the material used for repair. Even if the damage of specimen came up to the buckling of longitudinal reinforcing bars, the load carrying capacity of either repaired or re-repaired specimen can be recovered as well as that of original specimen by proper repair methods.

(2) The ductility of either repaired specimen or re-repaired specimen is influenced by both the experienced maximum displacement before repair and the repair method. When the experienced maximum displacement before repair exceeded the displacement of bucking of longitudinal bars, the ductility of repaired or re-repaired specimen is certainly reduced depending upon the repaired area and the material used for repair.

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