SEISMIC DAMAGE AND REPARABILITY EVALUATION OF RC COLUMNS IN TERMS OF CRACK VOLUME

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ABSTRACT

According to the current seismic design method, the importance in the definition of seismic performance of civil structures is to consider the reparability of damaged structures after the earthquakes. This paper focuses on the quantitative evaluation of seismic damage level, especially in shear, and recovered performance of the structure after repairing. The series of lateral cyclic loading tests of RC column specimens, which were designed to fail in shear, were conducted. The first series of test were for the measurement of diagonal crack width in each loading cycle, and the second series were for the evaluation of repair work using resin injection to the cracks. It was clarified that the total crack volume in the column increased with the experienced deformation level, and the rate of increase in the volume depends on the ratio of designed shear to flexural capacities of the column. Furthermore, slight difference in the effect of resin injection repairing was found among the specimens subjected to the different deformation levels during preloading.

KEYWORDS: seismic damage, reparability, lateral cyclic loading test, total crack volume, resin injection, ratio of shear to flexural capacities

1. INTRODUCTION

The experiences in the recent severe earthquakes and the seismic damage in the civil engineering structures in Japan have led the great improvement in the seismic design method of reinforced concrete (RC) structures based on performance-based design. In the modified design method, seismic performance in terms of safety, reparability and serviceability are defined according to the importance of the structures and the earthquake intensity levels, as shown in **Table 1** (JSCE, 2007). Here, verification of reparability is a key item for an appropriate seismic design of the structures having Seismic Performance 1 and 2. In the design specification for Railway structures in Japan (RTRI, 2004), the damage level of RC structures or members are qualitatively incorporated to the required repair works. The damage of RC members is categorized into 4 levels, of which limit states are yielding of re-bars (Damage Level (DL) I), maximum lateral capacity that is incorporated to the initiation of re-bar buckling (DL II), the maximum deformation level at which the lateral force is not lower than the yielding capacity (DL III), and further (DL IV). For DL I, no repair work is needed because it may be the limit state for “Seismic Performance 1”. For DL II, only the cross section repair and resin injection

Table 1. Seismic Performance and Design Earthquake Ground Motion (JSCE, 2007)

Level 1 Design Earthquake	Earthquake ground motion that is likely to occur a few times within the lifetime of a structure.
Level 2 Design Earthquake	Very strong earthquake ground motion that has only a rare probability of occurrence within the lifetime of a structure.
Seismic Performance 1	Function of the structure during an earthquake is maintained, and the structure is functional and usable without any repair after the earthquake.
Seismic Performance 2	Function of the structure can be restored within a short period after an earthquake and no strengthening is required.
Seismic Performance 3	There is no overall collapse of the structural system due to an earthquake even though the structure does not remain functional at the end of the earthquake.
The structure satisfies “Seismic Performance 1” against “Level 1 Design Earthquake”, and the structure satisfies “Seismic Performance 2” or “Seismic Performance 3” against “Level 2 Design Earthquake”	

to cracks are sufficient repair works, whereas for DL III, correction of lateral ties is needed in addition to the above-mentioned works. For DL IV, the replacement of the member or reconstruction of the structure can be one of engineering choices.

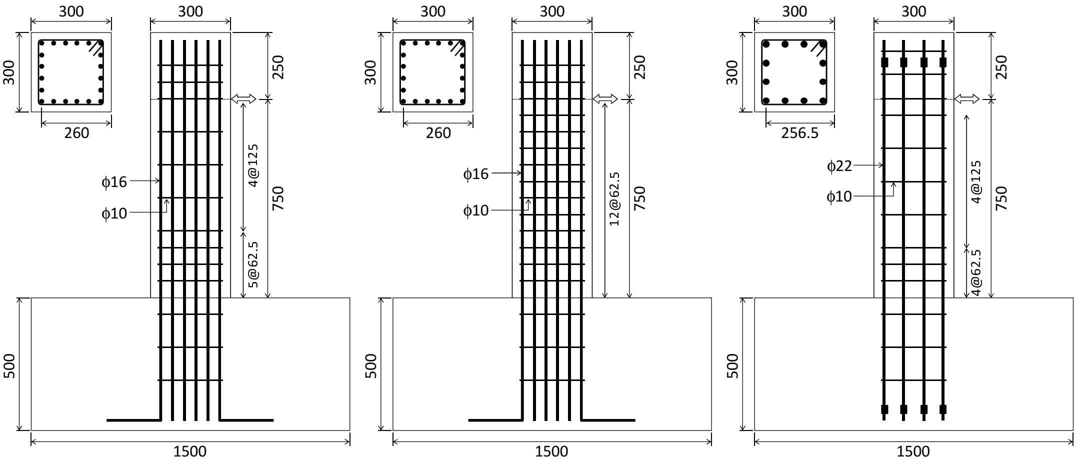
Even though the RC member is designed to fail in flexure at its ultimate state, several diagonal cracks may occur in the damage level II. The residual diagonal cracks after the earthquake may be so small that resin cannot be injected in the repair work. The energy dissipation of such RC member will more or less be lost, resulting that the member may no longer have a similar performance to that before the earthquake. Therefore, quantitative evaluation of seismic damage, including the damage in shear, has much importance in the seismic performance verification, as well as the evaluation of repair works and the recovery in the performance after repair (JSCE, 2008).

Based on the aforementioned background, the objective of this paper is to quantify the seismic damage level of RC columns in terms of crack volume. The reason why the crack is focused on is that, only the external cracks on the surface of the member may give us the information of damage in the member after the earthquake, and the repair works may be planned according to the measurement of such external cracks. The repair by resin injection to existing cracks was also investigated in this paper.

2. LATERAL CYCLIC LOADING TEST OF RC COLUMNS

Two series of RC column specimens were prepared. Three specimens in A-series were for quantitative damage evaluation in terms of crack volume, and the other three specimens in B-series were for evaluation of resin injection to cracks. The details of test specimens are shown in **Fig.1**, and all the test cases and parameters as well as the material mechanical strength are tabulated in **Table 2**. The calculated design flexural and shear capacities are also shown in the table. The three specimens in A-series were designed to have 1.0, 1.5 and 0.5 times of shear capacities as much as those flexural capacities. The three specimens in B-series had the completely same configuration to A-1 specimen that may fail in shear after flexural yielding.

All the specimens were subjected to lateral cyclic displacements through the loading jack under constant vertical load of 90kN (equivalent to 1.0 N/mm^2 axial stress). Lateral displacement was increased by 7mm in amplitude (3.5mm for A-3),



(a) A-1, B-1, B-2 and B-3 (b) A-2 (c) A-3

Fig.1 Details of Test Specimens (unit: *mm*)

Table 2. Test Cases and Parameters

Case		Concrete	Longitudinal Reinforcing Bar		Lateral Reinforcing Bar		Flexural Capacity	Shear Capacity	Capacity Ratio
		f'_c (N/mm^2)	No.- Diam.	f_{sy} (N/mm^2)	Diam.@ Spacing	f_{wy} (N/mm^2)	P_u (kN)	P_s (kN)	P_s / P_u
A	A-1	52.1	20-ϕ16	394.5	ϕ10@125	397.6	248.6	255.7	1.03
	A-2	52.7	20-ϕ16	394.5	ϕ10@62.5	397.6	248.9	358.3	1.44
	A-3	54.7	12-ϕ22*	1177	ϕ10@125	397.6	481.5	242.0	0.50
B	B-1	46.8	20-ϕ16	380.2	ϕ10@125	384.5	235.6	260.0	1.10
	B-2	47.5	20-ϕ16	380.2	ϕ10@125	384.5	236.0	260.7	1.10
	B-3	49.7	20-ϕ16	380.2	ϕ10@125	384.5	237.3	263.1	1.11

* High strength deformed bars were used.

and each amplitude cycle was repeated three times. For A-series specimens, crack width and length was carefully measured in each loading cycle by using digital micro scope, and the lateral displacements were applied up to failure. For B-series specimens, loading was interrupted at a certain displacement level and resin was injected to the existing cracks, followed by the reloading up to failure.

3. TEST RESULTS AND DISCUSSIONS

3.1 Test Results of A-series

Fig.2 shows the lateral load and displacement relationship of each specimen. A-1 and A-2 failed in shear after flexural yielding at 28mm and 35mm amplitude cycles, respectively, whereas A-3 failed purely in shear at 17.5mm amplitude cycle. At maximum displacement and zero loads in each loading cycle crack width and length were measured using digital micro scope. The average width of each crack was calculated and the total crack area on the surface was given as a multiplication of average crack width and length. Assuming that the crack width was kept constant through the thickness of member, the total crack volume was obtained as the crack area multiplied by the member thickness (300mm). **Fig.3** shows the relationship between the calculated total crack volume normalized by the volume of specimen (300x300x750mm) and the displacement. Here, the displacement was normalized by the flexural yield displacement of the specimen (A-1 and A-2: 7mm, A-3: 15mm) in **Fig.3(a)**, and by the ultimate displacement in **Fig.3(b)**. The normalized total crack volume depends on the ratio of shear to flexural capacities; however, there can be seen a unique relationship between the total crack volume and the displacement amplitude normalized by the ultimate displacement, as shown in **Fig.3(b)**. Therefore, it is suggested that the total crack volume can be a better damage index of RC columns which fail in shear. **Fig.3(c)** shows the relationship between the values of normalized crack volume at which the maximum displacement (loading) and zero loads (unloading) are reached. The total residual crack volume seems to be about 60% of the maximum experienced crack volume. This unique relationship may be utilized for the maximum response estimation of the actually-damaged RC columns based on the residual damage state after an earthquake and may give useful information for the subsequent repair works. The measured results here do not include the volume of spalling cover concrete; however, it affects on the state of severely-damaged RC

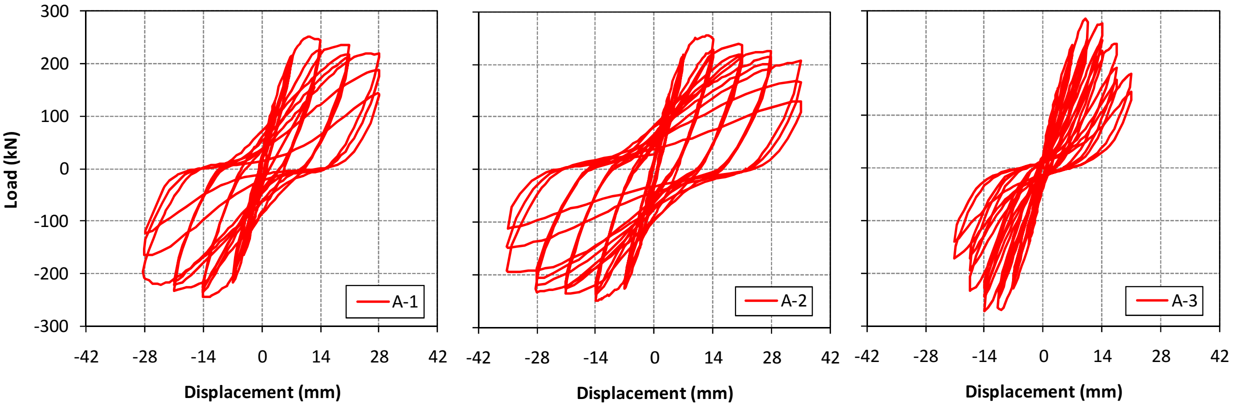
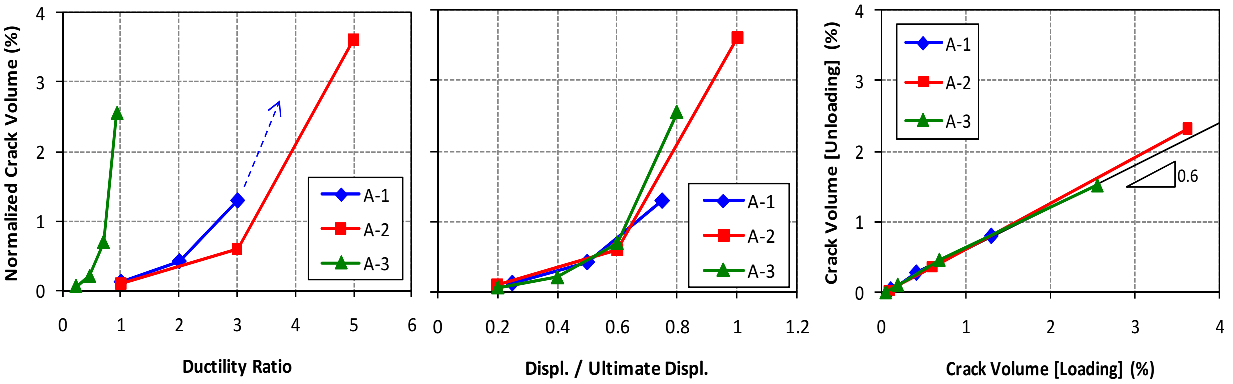


Fig.2 Load-Displacement Relationships in A-series Specimens



(a) vs. Ductility Ratio (b) vs. Normalized Displ. (c) Loading vs. Unloading

Fig.3 Variations of Normalized Total Crack Volume columns. Furthermore, the total crack volume was obtained with the assumption of equality in the internal crack width with the external one. Therefore, further investigations are needed to verify the aforementioned relationships to the columns failing in flexure or having different size.

3.2 Test Results of B-series

The specimens for B-series were designed as same as A-1 specimen. B-1 and B-2 were loaded up to 14mm and 21mm, respectively, before resin injection. Then all the three specimens were loaded again up to failure. In the reloading process for B-1 and B-2, each amplitude displacement was applied only one cycle. The epoxy resin was used in repairing, which had the density of 1.15(g/cm^3), the viscosity of 0.3-0.7(Pa*sec) and tensile strength of 10(N/mm^2) or higher, all under 20oC condition. **Fig.4** shows the load-displacement hysteresis curves of all the specimens, and **Fig.5** shows their envelope curves. The initial stiffness could not be recovered by resin injection in B-1 specimen, which was subjected to moderate damage prior to repairing, because the crack width might be so small that the resin could not be injected. However, the maximum capacity was kept even after preliminary damage. On the contrary, the initial stiffness was completely recovered by resin injection in B-2 specimen in which the relatively large preliminary deformation was applied. Moreover, the maximum capacity was slightly improved compared with the capacity in the original specimen B-3. This might be due to the replacement of damaged concrete by epoxy resin, in addition to the resin injection not only to cracks but also to the interface between concrete and reinforcing bars, which recovered the bond between them. Comparing B-1 and B-2, the ductility of the specimen was improved in B-2 rather than in B-1, even though B-2 specimen was subjected to relatively severe damage previously. The estimated reason of this fact was that, according to the crack diagrams in Fig. 6, the new cracks occurred in between the existing cracks due to the high tensile strength of epoxy resin. That is, there might be some difficulty in the occurrence of new cracks in B-2 because the specimen had already contained considerable amount of resin inside, which resulted in the recovery in stiffness as well as the improvement in capacity.

During the repairing work of B-1 and B-2, the total amount of injected resin was measured, as well as the total crack volume after the preliminary loading by using the same measuring method as done in A-series. From the engineering point of view, the amount of resin necessary for repairing

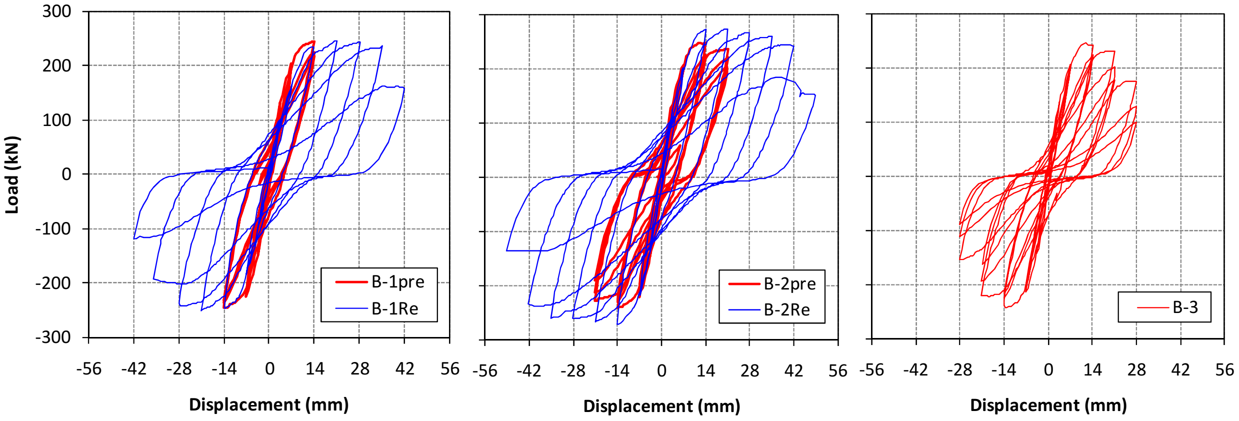


Fig.4 Load-Displacement Relationships in B-series Specimens

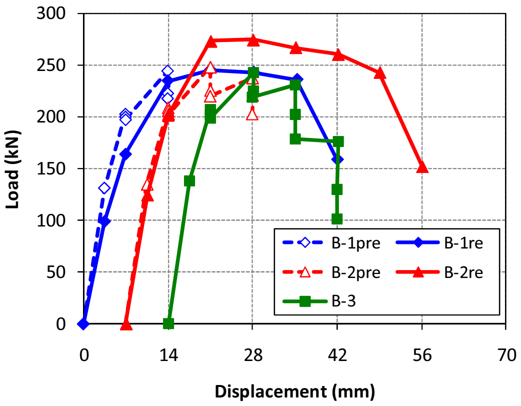
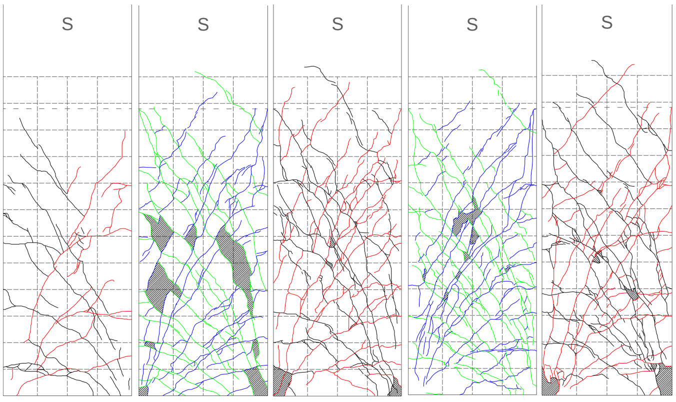


Fig.5 Load-Displacement Envelope Curve



B-1_pre B-1_re B-2_pre B-2_re B-3

Fig.6 Crack Diagrams of B-series

Table 3. Total Crack Volume and Total Amount of Injected Resin in B-1 and B-2

	B-1	B-2
Total Crack Volume (cm^3)	132.4 (0.20%)	1083.8 (1.61%)
Total Amount of Injected Resin (cm^3)	320.8 (0.48%)	1661.8 (2.46%)

may be incorporated to the total crack volume in the column. **Table 3** shows the measured results of the total crack volume and the total amount of injected resin for B-1 and B-2. The amount of resin was much larger than the total crack volume, because the resin was injected not only in cracks but in the re-bar interface. Comparing with the values plotted in **Fig.3(b)**, the total crack volume can be one of the indices to quantify the repairing work.

4. SUMMARY

This paper focuses on the quantitative seismic damage evaluation of RC columns and on the evaluation of repair work concerning the resin injection method. As a result, the possibility to utilize the total crack volume for the damage assessment of RC columns was designated. Furthermore, the effectiveness of resin injection as a repairing method, even for the severely-damaged columns, could be clarified. The total crack volume proposed in this paper may be able to be incorporated to the amount of injected resin, in order to evaluate the repair work.

When the total crack volume is utilized for the performance verification related to reparability, it shall be incorporated to the mechanical indices obtained from the numerical scheme in the design process. Here, finite element analysis may be a powerful tool for such intension. That is, the strain-based damage index given by finite element analysis will be well related to the total crack volume, in which the damage distribution over the member is considered. Therefore, both the macroscopic information based on the total crack volume and the detailed damage information obtained from the finite element analysis will be so useful that the structural performance in terms of reparability can be quantitatively verified.

REFERENCES

Standard Specifications for Concrete Structures – Design-, Japan Society for Civil Engineers (JSCE), Tokyo, Japan, 2007.

Design Standard for Railway Structures – Seismic Design-, Railway Technical Research Institute (RTRI), Tokyo, Japan, 2004. (In Japanese)

Seismic Design of Concrete Structures, Concrete Engineering Series 81, Japan Society for Civil Engineers (JSCE), Tokyo, Japan, 2008. (In Japanese)