Effects of Loading Conditions and Hoop Details on Residual Axial Load Capacity of R/C Columns Failing in Shear

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Abstract

In order to avoid pancake-type collapse of existing old R/C buildings during severe earthquakes, it is necessary to evaluate the residual axial load capacities of the existing R/C columns. These "residual axial load capacity" is defined as the axial load carrying capacity of a column after the column suffers serious damage; it corresponds to the safety limit. The standard popularly used in Japan for the evaluation of seismic performances of existing R/C buildings includes evaluation methods for residual axial load capacities, which have dramatic effects on seismic performance indexes. The objectives of this study are to examine the residual axial load carrying capacities of R/C columns after shear failure. We have focused on the loading methods and the confining effects of hoop reinforcement depending on the reinforcing details of the columns.

Keywords: column; residual axial load capacity; reinforcing detail; shear failure

1. Introduction

The revised standard for the seismic evaluation of existing reinforced concrete (R/C) buildings published by the Japan Building Disaster Prevention Association (JBDPA) in 2001 includes evaluation methods for the axial load capacity and residual axial load capacity of column members. Here, the axial load capacity means the axial load bearing capacity before the column fails in shear. The residual axial load capacity refers to the axial load bearing capacity after shear failure. The axial load capacity and the residual load capacity have considerable effects on seismic performance indexes. However, the evaluation method for residual axial load capacity has not been sufficiently examined through experiments.

Kato carried out experiments on the axial load capacity of R/C columns failing in shear with varying reinforcing details (Kato 2009). The primary objective of these experiments was to study the relationship between the results of uniaxial compressive loading tests (i.e., axial force-axial deformation) and lateral loading tests (at a drift angle where the axial load capacity is lost). For this purpose, both the axial loading test and the lateral loading test were conducted using specimens having the same physical properties. In this study, the effects of loading conditions and hoop reinforcing details on the residual axial load capacity of R/C columns were examined using the test results reported by Kato (2007, 2008).

2. Summary of Experiment on Residual Axial Loading Capacity

2.1 Test specimens and loading equipment

A total of nine sets of specimens were tested in two years. Four sets tested in 2005 are collectively called Series 2005, and five sets tested in 2006 are collectively called Series 2006. Table 1. shows the specifications of the specimens, and Tables 2. (a) and (b) show the test results for different loading methods. Fig.1. shows the cross section and reinforcing details of the test specimens. The size of the test specimens was 180×180×1200 mm, and a test portion at the centre measuring 360 mm was used. The central portion was chosen because both ends of the test specimen were covered by foundation pieces as shown in the figure. The size of the specimens used in this study was small. The effects of size on specimens having a square cross-section of 370 × 370 mm were examined for axial load capacities (Kato 2011). Thus, the results of this study can be applied to larger specimens with a minor modification.

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specimens were designed to fail in shear instead of flexure. Axial deformation was obtained as an average of four deformations measured using displacement transducers. Its length was at the central portion of the column as 310mm. The loading setup is shown in

| Table 1. Specification of Test Specimens |
|-----------------------------------------|
| specimen | section (mm) | height (mm) | main bar (yield stress (N/mm²)) | hoop (hook detail) | hoop yield stress (N/mm²) | hoop spacing (mm) | concrete strength (N/mm²) |
|-----------|--------------|-------------|-------------------------------|-------------------|-------------------------|-------------------|--------------------------|
| series 2005 | SH series | 180 x 180 | 360 | 4 – D10 (371) | 2-D6 (90° hook(4d)) | 316 | 70 | 32.2 |
|           | SL series | 180 x 180 | 360 | 2-D6 (welded hook) | 19.1 |
|           | WH series | 180 x 180 | 360 | 2-D6 | 32.2 |
|           | WL series | 180 x 180 | 360 | 2-D6 | 19.1 |
| series 2006 | H52L series | 180 x 180 | 360 | 4-D10 (345) | 2-D6 (135° hook(6d)) | 52 | 90 | 16.8 |
|           | H90L series | 180 x 180 | 360 | 2-D6 (90° hook(4d)) | 52 | 15.6 |
|           | H52L series | 180 x 180 | 360 | 2-D6 (90° hook(4d)) | 420 |
|           | S52L series | 180 x 180 | 360 | 3-D6 (90° hook(4d)) | 8-D6 (333) |
|           | H52L series | 180 x 180 | 360 | 3-D6 (90° hook(4d)) | 404 |

| Table 2. Loading Method and Test Results |
|-----------------------------------------|
| (a) series 2005 |

| series | specimen name | main loading method | load test loading (kN) | pre loading | post loading | maximum axial strength (kN) | residual axial strength ratio * |
|--------|----------------|---------------------|------------------------|-------------|-------------|----------------------------|-----------------------------|
| SH     | SH-0 | uni axial | 1018 | 100 |
|       | SH-1 | lateral | 300 | 0.02 | 0 | confine | 300 | 0.29 |
|       | SH-2 | lateral | 500 | 0.015 | 0 | confine | 500 | 0.49 |
|       | SH-3 | residual | 300 | 0.015 | 0 | confine | 884 | 0.87 |
|       | SH-4 | residual | 300 | 0.015 | 0.015 | free | 450 | 0.44 |
|       | SH-5 | residual | 300 | 0.015 | -0.015 | confine | 404 | 0.40 |
| SL     | SL-0 | uni axial | 618 | 100 |
|       | SL-1 | lateral | 150 | 0.025 | 0 | confine | 150 | 0.24 |
|       | SL-2 | lateral | 300 | 0.02 | 0 | confine | 300 | 0.49 |
|       | SL-3 | residual | 150 | 0.02 | 0 | confine | 569 | 0.92 |
| WH     | WH-0 | uni axial | 1001 | 100 |
|       | WH-1 | lateral | 300 | 0.02 | 0 | confine | 503 | 0.30 |
|       | WH-2 | lateral | 500 | 0.015 | 0.015 | confine | 560 | 0.50 |
|       | WH-3 | residual | 300 | 0.015 | 0 | confine | 967 | 0.97 |
| WL     | WL-0 | uni axial | 607 | 100 |
|       | WL-1 | lateral | 150 | 0.04 | 0 | confine | 210 | 0.25 |
|       | WL-2 | lateral | 300 | 0.02 | 0 | confine | 314 | 0.49 |
|       | WL-3 | residual | 150 | 0.02 | 0 | confine | 497 | 0.82 |
|       | WL-4 | residual | 150 | 0.02 | 0 | confine | 575 | 0.95 |
|       | WL-5 | residual | 150 | 0.02 | -0.02 | free | 315 | 0.52 |

| series 2006 |

| series | specimen name | main loading method | load test loading (kN) | pre loading | post loading | maximum axial strength (kN) | residual axial strength ratio * |
|--------|----------------|---------------------|------------------------|-------------|-------------|----------------------------|-----------------------------|
| HL     | H52L-0 | centric axial loading | 589 | 100 |
|       | H52L-1 | lateral | 300 | 0.015 | 0 | confine | 309 | 0.51 |
|       | H52L-2 | lateral | 150 | 0.03 | 0 | confine | 161 | 0.25 |
|       | H52L-3 | residual | 300 | 0.01 | 0 | confine | 605 | 1.03 |
|       | H52L-4 | residual | 300 | 0.01 | 0.01 | free | 479 | 0.81 |
|       | H52L-5 | residual | 150 | 0.015 | 0.015 | free | 380 | 0.65 |
| HO     | H90L-0 | centric axial loading | 572 | 100 |
|       | H90L-1 | lateral | 300 | 0.015 | 0 | confine | 434 | 0.52 |
|       | H90L-2 | lateral | 150 | 0.03 | 0 | confine | 150 | 0.26 |
|       | H90L-3 | residual | 150 | 0.015 | 0.015 | free | 398 | 0.70 |
| HS     | H52L-0 | centric axial loading | 615 | 100 |
|       | H52L-1 | residual | 50 | 0.015 | 0.015 | free | 413 | 0.67 |
|       | H52L-2 | residual | 250 | 0.015 | 0.015 | free | 264 | 0.43 |
|       | S52L-0 | centric axial loading | 646 | 100 |
|       | S52L-1 | lateral | 150 | 0.03 | 0 | confine | 150 | 0.23 |
|       | S52L-2 | residual | 150 | 0.02 | 0.02 | confine | 513 | 0.79 |
| H52L-0 | centric axial loading | 569 | 100 |
|       | S52L-1 | lateral | 300 | 0.025 | 0 | confine | 337 | 0.53 |
|       | S52L-2 | residual | 450 | 0.011 | 0 | confine | 450 | 0.79 |
|       | S52L-3 | residual | 300 | 0.011 | 0.011 | free | 517 | 0.91 |

* : maximum axial strength (subjected axial load at preloading in case of lateral loading specimen) divided by maximum axial strength of accompanying axial loading specimen
** : maximum member deflection angle 0.02 of specimen WL-4 was given by one loading cycle
2.2 Loading method (pre-loading and post-loading)

Eight residual axial loading tests were carried out for each of the specimens in Series 2005 and Series 2006. Loading methods are shown in the first half of Table 2. The loading was divided into two parts: pre-loading and post-loading. Pre-loading represented lateral loading, i.e., the lateral load was repeated under a constant axial load. Pre-loading was followed by post-loading, i.e., the axial load was applied at a specific drift angle. The main loading methods of the specimens were uniaxial loading, lateral loading, or residual axial loading (Table 2.).

Table 2. shows the constant axial load and maximum drift angle after pre-loading; it also shows the drift angle and its confining condition after post-loading. The maximum drift angles of residual loading test specimens for pre-loading were determined by referring to the corresponding tests of Kato (2009).

The lateral displacements for the lateral loading test in the case of pre-loading were 1/100, 1.5/100, 2/100, 2.5/100 rad. Each test was performed twice. However, in order to consider the effects of the damage level by pre-loading on the residual axial capacity, the cycle repeated once for the specimen WL-4, which had the same loading method except for the repeated cycle as in specimen WL-3.

For post-loading, three confining conditions were considered:

1) Centrically loaded-confined: When the specimen reached the scheduled maximum drift angle by pre-loading, the lateral displacement was made zero by maintaining certain axial forces of pre-loading (i.e., the usual unloading method). Axial load was applied while confining the lateral displacement to zero. This process will be described hereafter as centric-confined.

2) Eccentrically loaded-confined: When the specimen reached the scheduled maximum drift angle by pre-loading, axial load was applied by confining the drift angle. This process will be called eccentric-confined.

3) Eccentrically loaded-free: When the specimen reached the scheduled maximum drift angle by pre-loading, axial load was applied without confining the drift angle. We call this eccentric-free.

These three confining conditions were supposed to be presented of the three conditions of buildings and columns after an earthquake. The first condition is when a building survives an earthquake, its residual deformation is almost zero, and only the objective column has the possibility of losing its axial capacity (centric-confined). The second condition is when a building is significantly deformed and has undergone residual deformation, but it maintains its lateral capacity as a whole building (eccentric-confined). The third condition is when almost all columns are damaged to the same degree (eccentric-free).

3. Summary of Test Results

The results of the lateral loading test for Series 2005 are shown in Fig.3. The full lines represent the relationships between lateral deformation and the lateral force of specimens at a low axial load. The dotted lines represent the relationships at a high axial load. For each set of specimens, the constant axial load for pre-loading of the residual loading specimen was equal to the lower axial load of accompanying lateral loading specimens. The maximum drift for pre-loading of the residual loading specimen was equal to that of the accompanying lateral loading specimen under the higher axial force. This behavior is not shown in the figure because it is almost the same as that for the test specimens shown by full lines. Note that the termination points of pre-loading are marked by ○. All the specimens failed in shear during pre-loading, as expected.

After the termination of pre-loading, an axial compression load was applied to some test specimens at different drift angles. For other specimens an axial compression load was applied after returning their displacement to zero. The maximum axial force due to post-loading is shown in the latter half of Table 2. Note that the maximum axial force for lateral loading specimens means constant axial load applied to the specimen because no more axial load could be applied to the specimen that had lost the axial load capacity. (There were some exceptions because the confining condition for post loading was different (see Table 2.).) These points are further elucidated in Chapter 4.

In Fig.4., the relationship between the axial force and axial deformation from Series 2005’s residual axial load test is compared with the results of uniaxial compression tests. The axial load starting point for post-loading is ○. The results of the residual axial loading tests are summarized as follows.

1) When post-loading was conducted by returning the lateral deformation to zero and confining the deformation (i.e., centric-confined), the specimens
Fig. 3. Results of Lateral Loading Specimens and Terminated Step of Pre-loading for Accompanying Residual Loading Specimen (Series 2005)

Fig. 4. Comparison of Axial Load – Axial Deformation Relationship between Uni Axial Loading Specimens and Residual Loading Specimens (Series 2005)
Fig. 5. Relationship between Applied Maximum Drift Angle during Pre-loading and Residual Axial Load Capacity or Residual Loading Specimens: Comparison between Uni Axial Loading Specimens and Lateral Loading Specimens
showed maximum axial capacities of 82% - 97% of that of the accompanying uniaxial loaded specimens. (See test specimen SH-3 in Fig.4. (a), SL-3 in Fig.4. (b), WH-3 in Fig.4. (c), and WL-3 in Fig.4. (d).)

2) When post-loading was conducted without returning the lateral deformation to zero and without confining the deformation of pre-loading termination (i.e., eccentric-free), the maximum axial capacities declined considerably. (See test specimen SH-4 in Fig.4. (a), and WL-5 in Fig.4. (d).)

3) When the post-loading was conducted without returning the lateral deformation to zero and by confining the deformation of pre-loading termination (i.e., eccentric-confined), the maximum axial capacities were almost the same as those of the specimens without confining the deformation (i.e., eccentric-free). (See SH-4 and SH-5 in Fig.4. (a).)

4) The damage by pre-loading affected the residual axial capacity. The specimen that was loaded in only one cycle (e.g., WL-4 in Fig.4. (d)) retained larger residual axial capacity than those that were loaded several times repeatedly (i.e., WL-3 in Fig.4. (d)).

5) In the post-loading of lateral loading specimens, the axial capacity increased above the applied constant axial load of pre-loading in the case of specimens with welded hoop ties (i.e., test specimens WH-1, 2 and WL-1, 2 in Table 2.). However, in the case of a 90° hook, the capacity did not increase (e.g., test specimens SH-1, 2 and SL-1, 2 in Table 2.).

6) In terms of the reinforcing details, the axial load capacities or residual axial load capacities of test the specimens with welded hoop tie were not always higher than those with 90° hooks (such as SL-0 and WL-0 or SL-3 and WL-3).

4. Evaluation of Residual Axial Capacity of Columns Failing in Shear

4.1 Discussion on test results

The results are quantitatively examined. In the right end column of Table 2., the results of residual axial strength ratio are shown. This ratio was obtained by dividing the maximum axial strength during post-loading by the maximum axial strength of accompanying uniaxial loaded specimens. Note that for specimens whose main loading method was lateral loading, the maximum axial strength was replaced by the constant axial load applied during pre-loading.

The empty squares, triangles, and circles in Figs.5.(a)-(i) show the relationships between the applied maximum drift angle during pre-loading and the residual axial load capacity ratios of residual loading specimens. Here, test specimens for centric-confined residual loading, eccentric-free loading, and eccentric-confined loading are presented by ◊, □, and △, respectively. For comparison, the results of lateral loading test specimens are also shown with solid circles (●). Further, points on the horizontal axis and 1 on the vertical axis, which represent uniaxial compression test specimens, are shown using solid diamonds (● ●).

A comparison of the loading conditions of residual loading test specimens shows that eccentrically loaded specimens (△ and □) are located far below the centrically loaded test specimens (○) (see Fig.5. (a) and (d)). The most important result is that the eccentrically loaded test specimens (△ and □) and laterally loaded test specimens (●) with the same maximum drift angle are located at almost the same position (See Fig.5. (a), (d), (e), (f), (i), and (i)). In other words, after a column is loaded up to a certain drift angle, the residual axial capacity of the eccentrically loaded column is roughly equal to the constant axial load applied to a lateral loading column, which loses its axial loading capacity at the same drift angle. From this viewpoint, the residual axial capacity of eccentrically loaded columns can be estimated from the behavior of lateral loading columns.

This behavior can be explained using the model shown in Fig.6., which represents the equilibrium condition of concrete with diagonal shear cracks confined by hoop reinforcement. Here, σt is the stress confined by hoop reinforcement, and σl and τt are the normal and shear stresses of concrete. The figure shows that for both cases of eccentrically axial loaded specimens and laterally loaded specimens, the axial load (N) depends on the friction of the diagonal shear-crack surface in the same way. The stress conditions at the point of losing the axial load capacity were approximately the same. The difference was that the axial force changed in the case of axial loading, whereas the lateral force changed in the case of lateral loading. This is why the residual axial capacity of eccentrically loaded columns can be estimated from the behavior of lateral loading columns.

4.2 Estimating equation

As discussed in section 4.1, the residual axial capacity after shear failure can be estimated from the drift angle when the axial load capacity in eccentric loading is lost after shear failure. Kato (2009) estimated the equation for the drift angle when the axial load capacity is lost after shear failure. The proposed equation can be used to evaluate the average of test results as follows:

![Fig.6. Basic Concept of Stress Condition of Concrete](Image)
where $N$ is the axial load and $Q$ is the shear force at the time the axial load capacity is lost. However, the shear force at this time cannot be evaluated. Therefore, it was replaced by the shear strength in the original paper (Kato 2009). The coefficient of friction ($\mu$) on the slip surface was 0.77. The slip angle ($\theta$) was 60°. The width is represented by $b$, and $D$ is the height of the cross section. The hoop reinforcement ratio, yield strength, and space are represented by $p_{sw}$, $\sigma_{sy}$, and $S$, respectively. $A_r$ and $A_s$ are the cross section and yield strength of longitudinal reinforcement. $R_f$ is the effectiveness factor for reinforcing details, which is 1 for a welded tie hoop and 0.8 for 90° hook (the extra effectiveness factor for reinforcing details, which is 1 for welded tie hoop and 0.8 for 90° hook).

The reinforcing detail results of each test specimen were close to those of eccentrically loaded specimens. Considering that the axial load capacities of eccentrically loaded columns were located at the lower limit of all the axially loaded columns, we concluded that Equation (1) can be used as a conservative design equation for residual axial capacity.

\[
R = \frac{0.027}{\eta} \quad (\eta = \frac{N}{p_{sw}}) \quad (1)
\]

\[
\dot{N} = N + Q \frac{\sin^2 \theta \cos^2 \theta - 2 \mu \sin \theta \cos \theta}{\sin \theta \cos \theta - \mu \cos^2 \theta}
\]

\[
P_{sw} = b \cdot D \cdot p_{sw} \cdot \sigma_{sy} \frac{\sin \theta \cos \theta + \mu \sin \theta \cos \theta}{\sin \theta \cos \theta - \mu \cos^2 \theta} + A_r \cdot \sigma_y
\]

In Fig. 5, the relationships calculated using Equation (1) are shown by solid lines. The horizontal axis represents the drift angle, $R$, calculated using equation (1) by varying the axial load $N$ for each series. The vertical axis represents the axial load divided by $bDp_{sw}A_s$), where $\sigma_y$ is the concrete strength. (Note that the axial force ratio of the vertical axis is not $\eta$ in Equation (1).) As for the shear strength, $Q$ was calculated using the method proposed by AIJ (1999). Because these calculated relationships were derived from the results of laterally loaded test specimens ($\bullet$), these lines were close to those of laterally loaded test specimens. An important observation is that these lines were also close to those of eccentrically loaded specimens ($\triangle$ and $\square$). Considering that the axial load capacity of eccentrically loaded columns ($\triangle$ and $\odot$) was located at the lower limit of all axially loaded columns ($\odot$, $\triangle$, and $\square$), it can be concluded that Equation (1) can be used as a conservative design equation for residual axial capacity.

5. Closing Remarks
1) When post-loading was conducted by returning the lateral deformation to zero (i.e., for eccentrically loading), the maximum axial capacity declined significantly. This was regardless of the confined condition of lateral deformation, i.e., it was true for both eccentric-confined and eccentric-free.

2) When the residual axial load was applied without returning the lateral displacement to zero (i.e., for eccentrically loading), the maximum axial capacity declined significantly. This was regardless of the confined condition of lateral deformation, i.e., it was true for both eccentric-confined and eccentric-free.

3) After the column was loaded up to a certain drift angle, the residual axial capacity of the eccentrically loaded column was roughly equal to the constant axial load applied to a lateral loading column, which loses its axial loading capacity at the same drift angle.

4) The reinforcing detail results of each test specimen showed that the axial load capacities or residual axial load capacities of the test specimens with welded hoop ties were not always higher than those with 90° hooks.

5) Relationships obtained using Equation (1) were close to those of eccentrically loaded specimens. Considering that the axial load capacities of eccentrically loaded columns were located at the lower limit of all the axially loaded columns, we concluded that Equation (1) can be used as a conservative design equation for residual axial capacity.

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