Evaluating Method of Deformation at Losing Point of Axial Load Carrying Capacity of RC Columns

Daisuke Kato*, Yudai Miyajima and Yukiko Nakamura

1 Professor, Department of Architecture, Faculty of Engineering, Niigata University, Japan
2 Graduate Student, Department of Architecture, Faculty of Engineering, Niigata University, Japan
3 Lecturer, Department of Architecture, Faculty of Engineering, Niigata University, Japan

Abstract

RC buildings often suffer severe damage, including pancake-type total collapse, during strong earthquakes. The objective of this study is to find a way to prevent pancake-type collapse in old RC buildings during strong earthquakes. In 2006, the authors conducted static loading tests on RC column specimens failing in shear and proposed an equation for evaluating the lateral deflection angle at the losing point of axial load carrying capacity. In this study, first, the equation was reexamined using data for specimens with a wider range of parameters. Comparison with this new experimental data showed that the equation is effective for conservative evaluation. Second, the applicability of the equation to RC columns failing in flexure was also examined. For this, the lateral deflection angle of columns failing in flexure was obtained by adding the flexural component to the shear component proposed already. The proposed method was found to be effective. Finally, a trial evaluation of the axial deformation at the losing point of the axial load carrying capacity was performed, and the equation was found to be effective, though with some exceptions.

Keywords: reinforced concrete structure; column; axial load carrying capacity; reinforcing detail; shear failure

1. Introduction

Many RC buildings have suffered considerable damage, including pancake-type total collapse, during strong earthquakes. The objective of this study is to find a way to prevent pancake-type collapse in old RC buildings during strong earthquakes. For this purpose, some studies have been performed on the axial load carrying capacities of RC columns (Pujol et al. (2000), Moehle et al. (1999), Nakamura et al. (2002)). The authors also conducted static loading tests on RC columns failing in shear and proposed an equation for evaluating the lateral deflection angle at the losing point of the axial load carrying capacity (Kato et al. (2006)). The "losing point of the axial load carrying capacity" is defined as "the point where a column specimen cannot sustain the scheduled constant axial load during the loading test," and it is sometimes abbreviated as the axial capacity point in this report.

The equation proposed in 2006 is reexamined herein using data for specimens with a wider range of parameters. Further, the applicability of the equation to RC columns failing in flexure was examined. Trials to evaluate the axial deformation at axial capacity point were also carried out.

2. Summary of Evaluation Equation Proposed by Kato et al. (2006)

In this section, the authors provide a summary of the equation for evaluating the lateral deflection angle at the axial capacity point for RC columns failing in shear, which was proposed by Kato et al. in 2006, and shown here.

The equation is as follows:

\[ R_{\text{axis}} = \frac{0.027}{\eta} \left( \frac{\eta}{P_{f,\text{col}}} \right) \]

where

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

\[ P_{f,\text{col}} = P_{f,0} \cdot (1 - 0.5 \cdot \frac{S}{D}) \cdot R_{d} \]

\[ P_{f,0} = b \cdot D \cdot p_{w} \cdot \sigma_{w} \frac{\sin \theta \cdot \cos \theta + \mu \cdot \sin \theta}{\sin \theta \cdot \cos \theta - \mu \cdot \cos \theta} + A_{c} \cdot \sigma_{c} \]

where \( N \) is the axial load; \( Q \) is the shear force at the losing point of the axial load capacity and can be
replaced by the shear strength $Q$, shown later; $\mu$ is the coefficient of friction on a slip surface, which is 0.77; $\theta$ is the slip angle, which is $60^\circ$; $b$ is the width; $D$ is the depth of the cross section; $p_w$, $\sigma_{yw}$, and $S$ are the shear reinforcement ratio, yield strength, and spacing respectively; $A_s$ and $\sigma_y$ are the gross cross-sectional area and the yield strength of the main reinforcement respectively; and $R_d$ is the effectiveness factor of the reinforcing details. $R_d = 1$ for a welded tie hoop and $R_d = 0.8$ for a $90^\circ$ hook (extra length = 4$d$). Equation (1) is derived from the test data within the $p_w$ range of 0.4%–0.68%, and 0.7 < $\eta$ < 2.8.

The concept of the equation is based on the idea that the deflection at the losing point of the axial load capacity does not depend on the commonly used axial load ratio using the subjected axial load ($N$) and the axial load strength of the section ($bD\sigma_y$) but depends on the equivalent axial load ratio using the equivalent axial load ($\text{e}_N$) and the axial load resisted by friction at the starting point of the sliding of the column ($P_{\text{fr,cal}}$). The equivalent axial load ($\text{e}_N$) is the normal component of the sliding force along the inclined surface caused by a shear crack. Fig.1 shows this condition. In contrast, Fig.2 shows the concept of the axial load resisted by friction at the starting point of the sliding of the column. In this figure, point $E$ represents the starting point of the condition where the axial force is resisted by friction only along the inclined crack surface. Moreover, the figure shows how to determine point $E$ using experimental data. The axial load $P_{\text{fr,cal}}$ for calculation was empirically obtained using experimental data.

3. Specimens Examined for Axial Load Carrying Capacity

3.1 Tests to derive Equation (1)

Table 1.(a) shows the properties of the test series that were used for proposing Eq. (1). Table 2.(a) shows the subjected axial load and the test results of each specimen. The objective of these tests was to examine the effects of various reinforcing details on the axial load carrying capacities of RC columns failing in shear. The details of tests were reported by Kato et al. (2006), and the test data for the $P$ and $H$ series were reported by Kato et al. (2004) in English. The test results include the lateral deflection and axial deformation at the axial capacity point, which were defined as maximum values observed during the loading tests. The lateral deflection angle was obtained as the lateral deflection divided by the column height ($H$). However, it must be noted that the axial strain was obtained as the axial deformation divided by the depth of the column section ($D$). This is because plastic axial deformation occurs within the range of the column section, not all along the column height.

3.2 Tests conducted after 2006

After proposing Eq. (1), the authors conducted additional tests for the columns that failed in shear in order to verify the validity of Eq. (1) for a wide range of variables. Table 1.(b) shows the properties of the test series, and Table 2.(b) shows the subjected axial load.
load and the test results of each specimen. One of the parameters of these tests was the size of the section, which should be examined in order to improve the feasibility of the equation.

Although details of tests were reported by Miyajima et al. (2007 and 2008), the outline of the testing method is given in this section. Fig.3 shows the examples of cross section and reinforcing details. The loading equipment is shown in Fig.4. Although the size of the test specimens was 180 × 180 × 1200 mm in these examples, the test section was a central section of 360 mm because both ends of the test specimens were covered by foundation pieces as shown in Fig.4. The parameters of the test were the section size, subjected axial load ratio, hoop lateral tie diameter (shear reinforcement ratio), and detail of hoop lateral tie

Table 2. Results of Tests
(a) conducted from 2002 to 2006 by the authors

| specimen name | subjected axial load [kN] | maximum value until losing axial load carrying capacity | experimental result | maximum lateral strength [kN] | lateral deflection [mm] | lateral deflection angle [rad] | axial deformation [mm] | axial strain |
|---------------|--------------------------|------------------------------------------------------|---------------------|-----------------------------|------------------------|-------------------------------|----------------------|-------------|
| P-1           | 300                      | 134                                                  | 9.0                 | 0.023                       | 6.56                   | 0.036                         |                      |             |
| P-2           | 300                      | 134                                                  | 9.0                 | 0.023                       | 6.56                   | 0.036                         |                      |             |
| H-1           | 400                      | 137                                                  | 6.3                 | 0.018                       | 1.96                   | 0.011                         |                      |             |
| H-2           | 400                      | 137                                                  | 6.3                 | 0.018                       | 1.96                   | 0.011                         |                      |             |
| W-3           | 300                      | 111                                                  | 9.0                 | 0.025                       | 2.08                   | 0.012                         |                      |             |
| W-4           | 300                      | 111                                                  | 9.0                 | 0.025                       | 2.08                   | 0.012                         |                      |             |
| S-3           | 300                      | 111                                                  | 9.0                 | 0.025                       | 2.08                   | 0.012                         |                      |             |
| W52-1         | 500                      | 155                                                  | 6.3                 | 0.018                       | 3.79                   | 0.021                         |                      |             |
| W52-2         | 350                      | 137                                                  | 9.0                 | 0.025                       | 7.55                   | 0.042                         |                      |             |
| W90-1         | 350                      | 120                                                  | 4.5                 | 0.013                       | 1.17                   | 0.007                         |                      |             |
| W90-2         | 350                      | 120                                                  | 4.5                 | 0.013                       | 1.17                   | 0.007                         |                      |             |
| D13W-1        | 300                      | 122                                                  | 10.8                | 0.030                       | 8.27                   | 0.046                         |                      |             |
| D13W-2        | 500                      | 130                                                  | 5.4                 | 0.013                       | 2.65                   | 0.015                         |                      |             |
| D13W-3        | 500                      | 130                                                  | 5.4                 | 0.013                       | 2.65                   | 0.015                         |                      |             |
| D13S-1        | 300                      | 110                                                  | 7.2                 | 0.020                       | 3.52                   | 0.020                         |                      |             |
| D13S-2        | 500                      | 126                                                  | 4.6                 | 0.013                       | 1.81                   | 0.010                         |                      |             |
| φ4W-1         | 300                      | 111                                                  | 10.8                | 0.030                       | 4.87                   | 0.027                         |                      |             |
| φ4W-2         | 500                      | 108                                                  | 3.6                 | 0.010                       | 1.95                   | 0.011                         |                      |             |
| Wi-1          | 300                      | 120                                                  | 7.2                 | 0.020                       | 0.84                   | 0.005                         |                      |             |
| Wi-2          | 500                      | 134                                                  | 5.4                 | 0.013                       | 0.81                   | 0.004                         |                      |             |
| SiH-1         | 300                      | 127                                                  | 7.2                 | 0.020                       | 1.16                   | 0.006                         |                      |             |
| SiH-2         | 500                      | 139                                                  | 5.4                 | 0.015                       | 1.22                   | 0.007                         |                      |             |
| Wi-1          | 150                      | 84.5                                                 | 14.4                | 0.040                       | 9.44                   | 0.052                         |                      |             |
| Wi-2          | 300                      | 86.7                                                 | 7.2                 | 0.020                       | 6.27                   | 0.035                         |                      |             |
| SiL-1         | 150                      | 82.7                                                 | 9.0                 | 0.025                       | 4.39                   | 0.024                         |                      |             |
| SiL-2         | 300                      | 87.2                                                 | 7.2                 | 0.020                       | 4.10                   | 0.023                         |                      |             |

(b) conducted after 2006 by the authors

| specimen name | subjected axial load [kN] | maximum value until losing axial load carrying capacity | experimental result | maximum lateral strength [kN] | lateral deflection [mm] | lateral deflection angle [rad] | axial deformation [mm] | axial strain |
|---------------|--------------------------|------------------------------------------------------|---------------------|-----------------------------|------------------------|-------------------------------|----------------------|-------------|
| H52LL-1       | 300                      | 82.1                                                  | 5.4                 | 0.013                       | 6.47                   | 0.036                         |                      |             |
| H52LL-2       | 150                      | 76.4                                                  | 10.8                | 0.030                       | 6.00                   | 0.033                         |                      |             |
| H90LL-1       | 300                      | 70.3                                                  | 5.1                 | 0.014                       | 1.02                   | 0.006                         |                      |             |
| H90LL-2       | 150                      | 73.9                                                  | 10.8                | 0.030                       | 4.47                   | 0.025                         |                      |             |
| S52LL-1       | 150                      | 79.5                                                  | 10.8                | 0.030                       | 3.87                   | 0.022                         |                      |             |
| I52LL-1       | 300                      | 101                                                  | 9.0                 | 0.025                       | 4.92                   | 0.027                         |                      |             |
| I52LL-2       | 450                      | 73.8                                                  | 3.6                 | 0.010                       | 7.42                   | 0.041                         |                      |             |
| V78LL-1       | 675                      | 176                                                  | 5.8                 | 0.016                       | 5.45                   | 0.020                         |                      |             |
| V135LL-1      | 675                      | 166                                                  | 3.6                 | 0.010                       | 3.24                   | 0.012                         |                      |             |
| V135LL-2      | 337.5                    | 153                                                  | 4.7                 | 0.013                       | 7.42                   | 0.027                         |                      |             |
| L52LL-1       | 300                      | 71.5                                                  | 5.9                 | 0.016                       | 6.11                   | 0.034                         |                      |             |
| L90LL-1       | 300                      | 74.0                                                  | 5.2                 | 0.014                       | 2.65                   | 0.015                         |                      |             |
| L90LL-2       | 150                      | 62.2                                                  | 6.6                 | 0.018                       | 4.55                   | 0.025                         |                      |             |

(135° hook, 90° hook, presence of tie). All specimens were designed to fail in shear. The axial deformation was measured at two points on both sides of the test specimens in the central 310-mm length.

Lateral loading tests were conducted using two vertical jacks to make the deformation at the top and the bottom of test specimens symmetrical. Specimens were subjected to lateral load reversals using one horizontal jack under a scheduled constant axial load shown in Table 2.(b). The lateral load was reversed twice for each drift angle of 1/100, 1.5/100, 2/100, and 2.5/100 rad. The loading tests were conducted until the specimen lost its axial load carrying capacity.

3.3 Tests conducted by other researchers

In order to study the feasibility of Eq. (1), the data of RC column specimen tests conducted by other researchers in which the specimens were loaded until they lost their axial load carrying capacities were examined. Specimens were divided into two groups: shear failing columns and flexural yielding columns, which were determined by the calculated strength. Table 3.(a) shows the section, the subjected axial load, and the test results of specimens failing in shear. Table 3.(b) shows the section, the subjected axial load, and
the test results of specimens failing in flexure. Details of these tests were reported by Kato et al. (2001) and Sasaki et al. (2002).

4. Feasibility of Equation (1)

Fig. 5(a) shows the relationship between the observed deflection angle at the axial capacity point of specimens and the equivalent axial load ratio calculated using Eqs. (2) and (3). The solid line in the figure represents Eq. (1), which was empirically obtained using the experimental data shown in Table 2(a). Hollow square marks represent specimens in Tables 2.(a) and (b), and solid marks represent specimens in Table 3. Specimens in Table 3 were divided into two groups: specimens with constant axial load and specimens with a varying axial load.

As described in Section 2, Eq. (1) shows good estimation for specimens listed in Table 2 with hollow square marks. In contrast, the solid line obtained by Eq. (1) is located around the lower limit of the data in Table 3 with solid marks. Although the figure shows a scattering, Eq. (1) is found to be effective for specimens in Table 3, including specimens with a...
varying axial load.

Fig.5.(b) compares the observed deflection angle at the axial capacity point of specimens with the value evaluated by using Eq. (1) directly. The evaluation method using Eq. (1) is found to be effective as a conservative equation for evaluating the deflection angle at the axial capacity point of RC columns failing in shear including specimens with a varying axial load.

5. Application of Equation (1) to columns failing in flexure

The method for evaluating the deflection angle at the losing point of the axial load capacity for RC columns failing in flexure was proposed by Kato et al. (2001) and Sasaki et al. (2002). Fig.6.(a) shows the relationship between the observed deflection angle at the losing point of the axial load capacity of the specimens failing in flexure shown in Table 3.(b) and the calculated deflection angle proposed by Kato et al. (2001) and Sasaki et al. (2002). The accuracy is not bad. However, the method was based on flexural analysis using plane remained plane after bending, which was assumed to be different from the real behavior. Therefore, in this section, the applicability of the equation to RC columns failing in flexure is discussed.

It must be noted that there exist two types of axial load losing mechanisms for columns failing in flexure: i) shear failure after flexural yielding and ii) pure flexural failure. In this section, the applicability of the equation to RC columns failing in flexure is discussed on the basis of Eq. (1). In other words, only the first type of mechanism mentioned above is discussed.

Fig.7. shows the basic concept. Fig.7.(a) shows lateral load–lateral deflection angle relationship of a column failing in shear, in which the lateral deflection angle at the losing point of the axial load capacity of this column can be expressed by \( R + R_s \), where \( R \) is the deflection angle at shear failure. In other words, the deflection angle \( R_{\text{axis},s} \) calculated by Eq. (1) is \( R + R_s \) in this figure. In contrast, Fig.7.(b) shows the relationship of a column failing in flexure, in which the lateral deflection angle at the losing point of the axial load capacity of this column is assumed to be expressed by \( R_y + R_p + R_u \), where \( R_y \) is the flexural yielding deflection angle and \( R_p \) is the plastic deflection angle that depends on the deformation capacity of the column. Further, the most important assumption in this idea is that the deflection increment from after the column loses its deformation capacity to until the column loses the axial load capacity is equal to \( R_u \) of the shear failing columns shown in Fig.7.(a).

However, there are two problems to be considered in this concept. The first problem is that the experimental data shown in Table 2.(a) cannot be separated into \( R \) and \( R_s \). In other words, only \( R \) cannot be evaluated. Therefore, it is necessary to examine the contribution of \( R_s \) to \( R + R_s \) in these specimens. Fig.8. shows the relationship between \( R_{\text{axis},s} - R \) and \( R_{\text{axis},s} \), where \( R \) is obtained as the intersection of the calculated load-deflection behavior and the calculated shear strength (Fig.7.(a)). The figure shows that the contribution of \( R_s \) is negligible. This is because the flexural strength of these specimens was designed to be very high for experimental purposes.

The second problem is that in the case of the flexural failing column, the failure zone is usually concentrated on the end zone of the column, whereas the failure zone of the shear failing column usually occurs in the middle zone of the column (see inclined crack line in Fig.1.). The difference in the position of the failure zone influences the effects of longitudinal reinforcing bars on the axial load ratio in general. Therefore,
the contribution of longitudinal reinforcing bars to the axial load ratio is cancelled because these bars are subjected to compression and tension due to the presence of the moment of the end zone. Note that all longitudinal reinforcing bars affect the axial load ratio as shown in Eq. (4) because the effect of the moment is negligible in the case of shear failing columns.

Consequently, the equation for evaluating the lateral deflection angle at the axial capacity point for RC columns failing in flexure can be expressed as follows:

$$R_{\text{axis,f}} = R_y + R_p + R_{\text{axis,s}}'$$

(5)

where $R_{\text{axis,s}}'$ can be obtained as $R_{\text{axis,s}}$ using Eqs. (1)–(4). However, it must be noted that the contribution of longitudinal reinforcing bars to the axial load ratio is canceled in the case of flexural yielding columns ($A\sigma_y$ should be 0 in Eq. (4)). $R_y$ and $R_p$ are the yielding deflection angle and the plastic deflection angle depending on the deformation capacity, which can be obtained using the existing evaluation methods. For example, $R_y$ can be obtained using Eq. (6), in which the secant yielding stiffness degradation ratio $\alpha_y$ was proposed by Sugano (1970).

$$R_y = \frac{Q_f}{K_e \cdot \sigma_y}$$

(6)

$$\alpha_y = (0.043 + 1.64 n \cdot p_t + 0.043 \frac{d}{D} + 0.33 p_t) \frac{d}{D}$$

where $Q_f$ is the flexural strength, $K_e$ is the elastic stiffness, $n$ is the modular ratio, $p_t$ is the tensile reinforcement ratio, $a$ is the shear span, $\eta_o$ is the axial stress divided by the concrete compressive strength, and $d$ and $D$ are the effective depth and the overall depth of the section.

In contrast, $R_p$ can be evaluated by using the method proposed by AIJ (1999) for example. Eq. (7) represents the shear strength based on the truss and arch mechanism, in which $R_p$ is quoted. In other words, $Q_s$ represents the potential shear strength after flexural yielding. Consequently, $R_p$ can be obtained as a suitable $R_p$ to match the shear strength $Q_s$ with the flexural strength $Q_f$ in this method. Practically, the iteration is necessary until the same value of $Q_s$ as that of $Q_f$ is obtained by varying $R_p$.

$$Q_s = \min\left(V_{a_1}, V_{a_2}, V_{a_3}\right)$$

(7)

$$V_{a_1} = \mu \cdot p_{we} \cdot \sigma_{we} \cdot b_e \cdot j_e + \left(\nu \cdot \sigma_y \cdot \frac{5p_{we} \cdot \sigma_{we}}{\lambda} \cdot b \cdot D \cdot \tan\theta\right)$$

$$V_{a_2} = \frac{\lambda \cdot \sigma_y}{3} \cdot b_e \cdot j_e$$

$$V_{a_3} = \frac{\lambda \cdot \sigma_y}{2} \cdot b_e \cdot j_e$$

$$\mu = 2 - 20R_p$$

$$\nu = (1 - 20R_p) \cdot \left(0.7 - \frac{\sigma_y}{200}\right)$$

$$\lambda = \left(1 - \frac{s}{2j_e}\right) \cdot \left(1 - \frac{b_e}{4j_e}\right)$$

where $b$ and $D$ are the width and depth of the section, $b_e$ and $j_e$ are the effective width and the depth for the
truss mechanism of the section, $s$ is the spacing of the hoop, $p_w$ is the effective hoop reinforcement ratio, $\sigma_{ry}$ is the yielding strength of the hoop, $\sigma_c$ is the concrete strength (unit: N/mm²), $\theta$ is the angle of arch action, $R_p$ is the plastic deflection angle determined by the plastic rotation of the hinge region. For more details, see Design Guidelines by AIJ (1999).

Fig. 6.(b) shows the relationship between the observed deflection angle at the losing point of the axial load capacity of specimens failing in flexure shown in Table 3.(b) and the calculated deflection angle using Eqs. (5)–(7). The scatters of the figure are found to be better than those of Fig. 6.(a), which shows the effectiveness of this method.

6. Trial to Evaluate Axial Deformation at Losing Point of Axial Load Carrying Capacity

It is also important to evaluate the axial deformation at the axial capacity point because the role of connecting beams and surrounding columns depends on the axial deformation at the axial capacity point of the failing column. In other words, in a practical building, the axial load is resisted by a combination of the columns and the connecting beams, which implies the importance of the compatibility of the axial displacement.

From this viewpoint, the trial to evaluate the axial deformation at the axial capacity point was carried out in this study although it is difficult to propose an accurate estimation for the axial deformation in general. In this study, the evaluation equation was examined by following the same approach as that used for evaluating the lateral deflection in Section 2 although it had a poor theoretical background for axial deformation.

Fig. 9.(a) shows the relationship between the observed axial strain at the axial capacity point of specimens shown in Table 2.(a) and (b) and the equivalent axial load ratio calculated using Eqs. (2) and (3). As described previously, it must be noted that these specimens failed in shear, and the axial strain was obtained by dividing the axial deformation with the depth of the column section ($D$). The figure shows that the observed axial strain gradually increases with decreasing values of the axial load ratio. The solid line in the figure is an approximation expressed by Eq. (8).

$$\varepsilon_{axial} = \frac{0.034}{\eta} \left( \frac{cN}{P_{fc, col}} \right)$$

(8)

Fig. 9.(b) compares the observed axial strain of specimens with the value calculated using Eq. (8) directly. This evaluation method (Eq. (8)) is found to be effective although the accuracy for columns with a welded hoop is bad. These specimens with a welded hoop include specimens with a large hoop spacing or high concrete strength (Table 1.), which may lead to errors. Therefore, it is important to improve the accuracy of this equation for future works.

7. Conclusions and Scope for Future Work

1) The equation (Eq. (1)) for evaluating the lateral deflection angle at the losing point of the axial load capacity for columns failing in shear, proposed by Kato in 2006, was reexamined using specimens with a wider range of variables. The
evaluation method was found to be effective as a conservative evaluation equation.

2) The equation for evaluating the lateral deflection angle at the axial capacity point for RC columns failing in flexure was proposed on the basis of the evaluation equation for columns failing in shear (Eq. (5)). The evaluation method was found to be effective.

3) The equation for evaluating the axial deformations at the axial capacity point for RC columns failing in shear was proposed (Eq. (8)). The evaluation method was found to be effective although the accuracy for columns with a welded hoop was bad. The specimens with a welded hoop include specimens with a large hoop spacing or high concrete strength, which may lead to errors. Therefore, it is important to improve the accuracy of this equation for future works.

References

1) Architectural Institute of Japan (1999). Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Inelastic Displacement Concept. (in Japanese).

2) Kato, D. and Ohnishi, K. (2001) Axial load carrying capacity of R/C columns under lateral load reversals, The third U.S.-Japan Workshop on performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures, pp.231-239.

3) Kato, D., Li Zhuzhen, Suga, K. and Nakamura, Y. (2004) Effects of Reinforcing Details on Axial Load Capacity of R/C columns, the 13-th World Conference on Earthquake Engineering, 2004, CD-ROM.

4) Kato, D., Li Zhuzhen, Nakamura, Y. and Honda, Y. (2006) Tests on Axial Load Capacity of Shear Failing R/C Columns Considering Reinforcing Details (Relationship between Axial Loading Test and Lateral Loading Test), Journal of Structural and Construction Engineering, Architectural Institute of Japan, No.610, pp.153-159. (in Japanese).

5) Moehle, J. P., Elwood, K. J. and Sezen, H. (1999) Shear failure and axial load collapse of existing reinforced concrete columns, The first U.S.-Japan Workshop on performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures, pp.233-247.

6) Miyajima, Y., Tomita, Y. Li Zhuzhen and Kato, D. (2007) Tests of axial load capacity of shear failing R/C columns to evaluate effects of reinforcing details, Proceedings of the Japan Concrete Institute, Vol.29, No.2, 2007, pp.79-84 (in Japanese).

7) Miyajima, Y., Abe, H. and Kato, D. (2008) Test of Axial Load Capacity of R/C Column Specimens with Various Size, Proceedings of the Japan Concrete Institute, Vol.30, No.2, 2008, pp.163-168 (in Japanese).

8) Nakamura T., Yoshimura M., Owa S. (2002) Axial load carrying capacity of reinforced concrete short columns with shear mode, Journal of structural and construction engineering, AJI, No.561, pp.193-100 (in Japanese).

9) Sasaki, J. and Kato, D. (2002) Evaluating Method of Crack Width, Crushing Area and Axial Load Carrying Capacity of R/C Columns, Proceedings of the Japan Concrete Institute, Vol.24, No.2, 2002, pp.253-258 (in Japanese).

10) Sugano, S. (1970) Experimental study on restoring force characteristics of reinforced concrete members, a thesis submitted to The University of Tokyo, The university of Tokyo, December 1970 (in Japanese).

11) Pujol, Santiago, Sozen, Mete and Ramirez, Julio (2000) Transverse reinforcement for columns of RC frames to resist earthquakes, Journal of Structural Engineering, April 2000, pp.461-466.