EFFECT OF THE TORSIONAL MOMENT ON THE SHEAR STRENGTH OF REINFORCED CONCRETE COLUMNS DUE TO ECCENTRIC JOINTING OF BEAM TO COLUMN

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SUMMARY

In this paper, the effect of the torsional moment, caused by the eccentric jointing of beam to column, on the shear capacity of reinforced concrete column is discussed. Several typical reinforced concrete structures damaged in the past few earthquakes are introduced. From the inspections of these damaged structures, it has been found that some columns in each of these structures were planned to joint beams to columns eccentrically. The concrete cracks, caused by the earthquakes, appeared spirally upwards round the surface of the columns, or developed obliquely along the whole length of the columns. These cracking patterns show that the column failure is a kind of the torsional failure caused by the combination of torsion and shear. On the basis of the existing experimental results of 110 reinforced concrete specimens under the action of the torsion, a simplified formula is obtained, which has been taken account of the effect of the torsional span ratio, and could be used to predict the torsional capacity of rectangular reinforced concrete members in pure torsion. Furthermore another formula is also proposed, by which the reduction of shear capacity of reinforced concrete columns loaded by torsion and shear simultaneously could be determined. The calculated results by these formulas have been compared with experimental ones available in the literatures, and a good agreement has been noted. As a result, a particular consideration should be given to the influence of the eccentricity of beam - column joints on the shear capacity of columns, both in seismic evaluation of existing structures and in seismic design of new reinforced concrete structures.

INTRODUCTION

Analysis of building damages in earthquakes has proven that the torsional moment due to eccentric beam-column joints has greatly reduced the shear capacity of the column [AIJ, 1998; Hirosawa and Zhou, 1998; Zhou, Hirosawa and Shimizu, 1998]. The torsional moment becomes significantly large when a narrow wall girder is eccentrically jointed to the long side of a flat column. In the Kagoshima-ken Hokuseibu Earthquake both in March and May 1997, only reinforced concrete school buildings were severely damaged. Inspections and analysis of the seismic damage have proven that some damages can be attributed to excessive torsional moment due to eccentric beam-column joint [Zhou, Hirosawa and Shimizu, 1998]. Experimental results in the literatures supported this conclusion by showing that the torsional moment due to eccentric beam-column joints may reduce the shear capacity of the column from *30* to *40* percent [Morita, 1972; Hattori et al., 1970]. An inspection of existing reinforced concrete school buildings also showed that the building with eccentric beam-column joints reached into *80* percent and increased as the date of completion became younger. The design without eccentric beam-column joint is less than *20* percent in the recent medium height reinforced concrete buildings.

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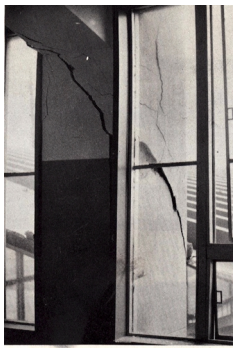


Photo. 1: Building damaged by the 1968 Tokachi-oki earthquake

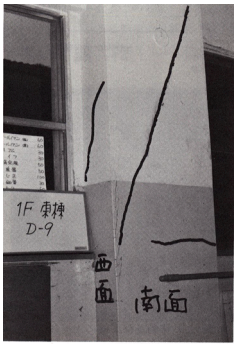


Photo. 2: Building damaged by the 1978 Izu-Oshima earthquake

Photo. 3: Building damaged by the 1995 Hyogo-ken Nanbu earthquake

Photo. 4: Building damaged by 1997 Kagoshima-ken Hokuseibu earthquake

Photo. 5: Building damaged by 1997 Kagoshima-ken Hokuseibu earthquake

This study aims to discuss the evaluation of torsional moment and its effect on the shear capacity of columns with eccentric beam-column joints by inspecting the damaged buildings in the past earthquakes and by referring the past experimental studies.

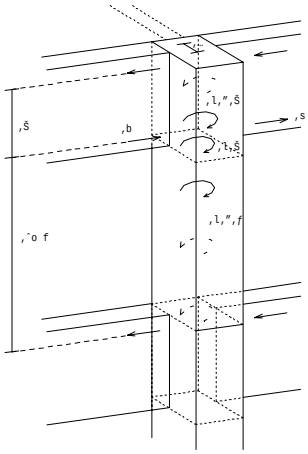


Figure 1: Torsional moment due to eccentric beam-column joint

2. DEVELOPMENT OF THE TORSIONAL MOMENT DUE TO THE ECCENTRIC JOINT AND THE EARTHQUAKE DAMAGES IN THE PAST

2.1 Development of torsional moment

In a column to which beams connected eccentrically, two couples of forces, as results of bending moments in the beams due to horizontal load, act at the portion apart a distance *e* from the column center (see also in Figure 1). In a condition without the torsional deformation of the column at the floor slab level, an eccentric moment $Mj=(T+C)e$ works at the bottom bar level of the beam and can be shared as the torsional moments of the joint zone and the column as well as the out-of-plane bending moment of orthogonal girders at the top of the column. Setting the torsional moments at the top of the column and the joint zone as Mtc and Mtj respectively, we have $Mtc/Mtj=j/ho'$ neglecting the confining effect of the orthogonal beams on the safe side.

The torsional moment works in the column can be approximately given by

$$Mtc \cong Qc \cdot e \tag{1}$$

where Qc is the shear force working on the column and e is the eccentric distance between the beam and the column.

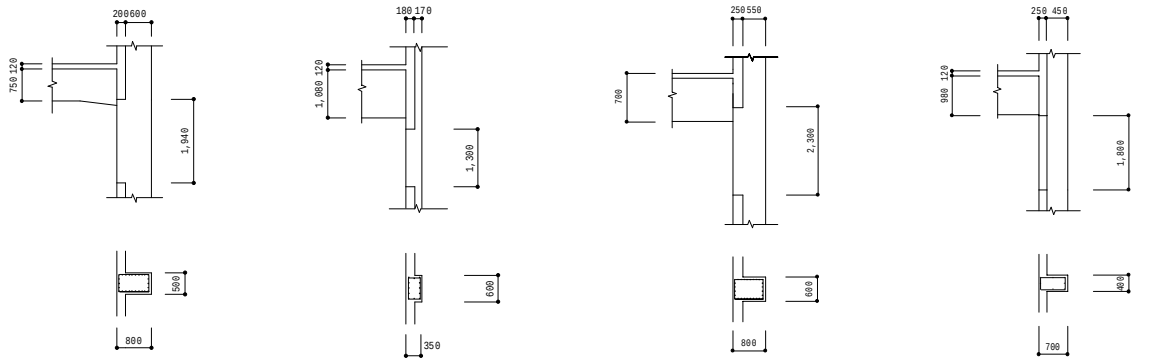
2.2 Earthquake damages in the past

2.2.1 Hakodate University

The main building of Hakodate University was damaged by the 1968 Tokachi-oki Earthquake [AIJ, 1968] as shown in Photo.1, and the dimensions of the column and the beam are shown in Figure 2 (a). Cracks of this type were found in the first and the second floor. The diagonal cracks extended from one side to the adjacent side to form a helical shape. This type of failure may be attributed to pure torsion [AIJ, 1991].

2.2.2 Inatori Junior High School

Columns of Inatori Junior High School damaged by the 1978 Izu-Oshima Earthquake are shown in Photo. 2



(a) Building of Hakodate University **(b) Building of Inatori Junior High School** **(c) Building of Amagasaki High School** **(d) Building of Miyanojo Agricultural High School**

Figure 2: Dimension of the column and beam with eccentric joint damaged by past earthquake

[AIJ, 1980], and the dimensions of the column and the beam are shown in Figure 2 (b). The helical cracks extended over the adjacent sides implying the effect of torsion.

2.2.3 Amagasaki High School

Building of Amagasaki High School was damaged by the 1995 Hyogo-ken Nanbu Earthquake [Ishibashi et al., 1995] as shown in Photo.3, and the dimensions of column and beam are shown in Figure 2 (c). The diagonal cracks extended over the internal height of the column implying the shear type torsional failure [AIJ, 1991].

2.2.4 Miyanojo Agricultural High School and Sendai High School

Building of Miyanojo Agricultural High School and Sendai High School were damaged by the 1997 Kagoshima-ken Hokuseibu Earthquake [Tokuhiro et al., 1998] as shown in Photo.4 and 5, and the dimensions of column and beam are shown in Figure 2 (d). These cracks are also helical implying the presence of torsion.

Buildings with noticeable damages are mentioned and the dimensions of columns and beams and their eccentric joints are shown in Figure 2. Structural conditions common to these columns under torsional and shear-failure are as follows.

a) Beams were eccentrically jointed to columns.
b) Spacing of the column hoop was so wide since the design was based on the former structural standard.
c) Clear span ratio of the columns was intermediate ($ho/D \cong 4$).
d) The columns were rigidly framed in two directions.

These torsional failure examples were the result of restricted inspection therefore significant number of examples might have been present.

3. CAPACITY OF RC MEMBERS SUBJECTED TO TORSION AND VERIFICATION OF THE EXPERIMENTAL DATA IN THE PAST STUDIES

3.1 Verification of experimental data of members subjected to pure torsion

Many studies used beams preferably to investigate the structural performance of reinforced concrete members subjected to torsional stress, and in experiments, simple rectangular cross section has been often employed. Experiments on the pure torsion of columns are very few. However, a column and beam with a rectangular cross section can be regarded to show similar behavior if the effect of axial load can be neglected. In this study, behavior of column under torsional stress is inferred by that of beams, which has been documented in 8 literatures with 110 specimens [Kanou and Nakayama, 1965; Kanou and Ishiguri, 1982; Kanou and Takemura, 1983; Nakayama and Kanou, 1975; Tomii et al., 1965; Wada and Kanou, 1969; Wang and Kang, 1988; Yamada and Tamura, 1968]. Conditions of the beam specimens are shown in Table 1.

Table 1: Conditions of the specimens subjected to pure torsional load

B (cm)	D (cm)	a/D	σ_B (kgf/cm^2)	p_w (%)	p_t (%)	Number of the specimens
10 ~ 30	10 ~ 30	1 ~ 6	104 ~ 400	0 ~ 3.56	0.23 ~ 8.96	110

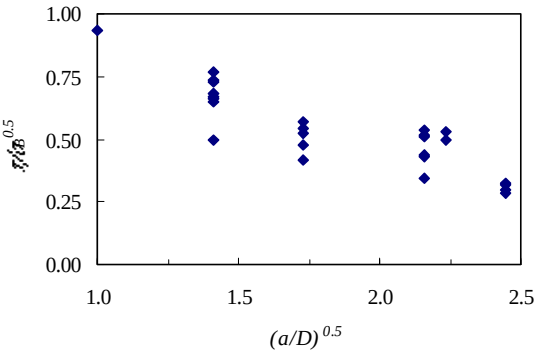


Figure 3: Effect of the torsional span ratio

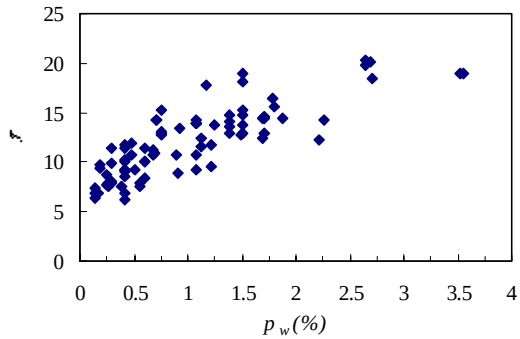


Figure 4: Relationship between the torsional stress and the torsional reinforcement ratio

A large number of formulas have been proposed to estimate the pure torsional capacity of the reinforced concrete member, *Mto*, which is a sum of the concrete strength term and torsional reinforcement term as shown in the following equation [AIJ, 1991].

$$Mto = \left(\alpha_1 \cdot \sigma_B{}^{\beta_1} + \gamma_1 \cdot p_{wt} \cdot \sigma_{wy}\right) B^2 \cdot D \qquad (2)$$

where σ_B is the compressive strength of concrete in kgf/cm^2, p_{wt} and σ_{wy} are the torsional reinforcement ratio and its yield point strength, B and D are the short and long dimension of the rectangular cross section of a column in *cm*, and α_1, β_1, γ_1 are constants to be determined in experiment.

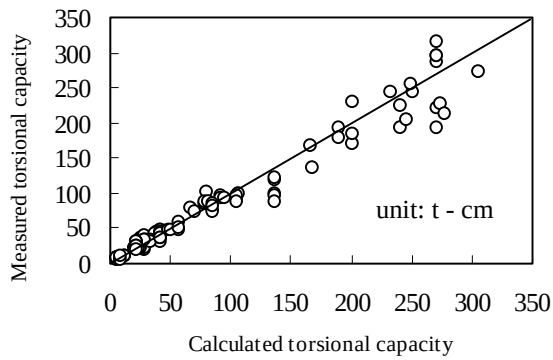


Figure 5: Comparison of calculated values with experimental results

On the other hand, the past experiments [Nakayama and Kanou, 1975; Kanou and Ishiguri, 1982; Kanou and Nakayama, 1965; Yamada and Tamura, 1968] have shown that effect of the torsional span ratio upon the pure torsional capacity is significant. It is shown in Figure 3. The relationship between the torsional stress and the torsional reinforcement ratio is shown in Figure 4. It can be seen that the torsional reinforcement can increase the torsional capacity within a restricted range ($p_{wt} \leq 0.02$) but no further improvement is expected outside of the range. Therefore, we propose the following formula (3) that can give a practical torsional capacity taking into account of the torsional span ratio.

$$Mto = \left(0.8\sqrt{\sigma_B} + 0.45\, p_{wt} \cdot \sigma_{wy}\right) B^2 \cdot D \Big/ \sqrt{a/D} \qquad (3)$$

where p_{wt} is less than *0.02* and a is the net length of a member subjected to torsion.

The proposed equation (3) was applied to the experimental results of members subjected to pure torsion and the calculated values showed good agreement with the experimental results as shown in Figure 5. Average ratio of calculated and experimental value was *1.07* and the coefficient of variation was *0.168*.

3.2 Verification of experimental data of members subjected to torsional and axial load

It was experimentally confirmed that the axial load has great influence on the pure torsional capacity of reinforced concrete members. The relationship between the torsional capacity-axial load ratio and the measured torsional capacity of concrete members [Bishara and Pier, 1968; Pandit and Mawal, 1973; Yamada and Tamura, 1968] is shown in Figure 6. The conditions of the specimens are shown in Table 2. As the axial load of members increases, the torsional capacity increases, but the experimental results show that the increase of axial load ratio

Table 2: Conditions of the specimens subjected to torsional and axial load

B (cm)	D (cm)	a/D	σ_B (kgf/cm^2)	p_w (%)	p_t (%)	$\sigma o/\sigma_B$	Number of the specimens
14 ~ 16	16 ~ 30	2.5 ~ 5.1	224 ~ 463	0 ~ 3.14	0 ~ 1.79	0 ~ 0.79	44

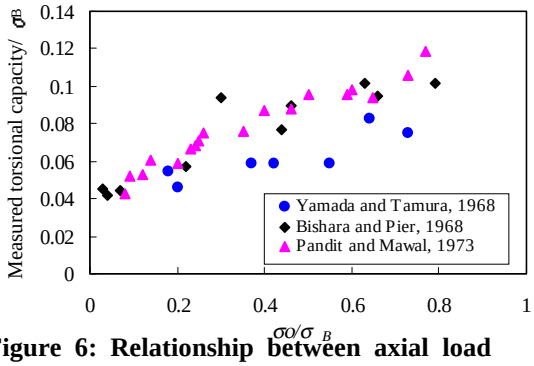


Figure 6: Relationship between axial load ratio and measured torsional capacity

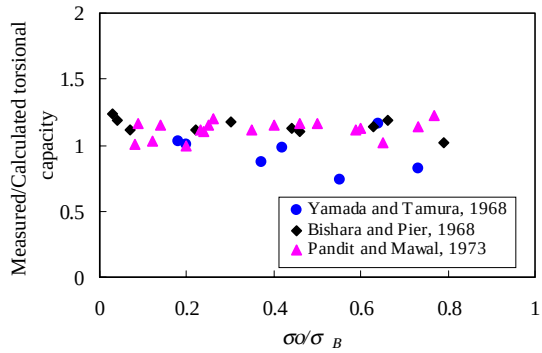


Figure 7: Relationship between axial load ratio and measured-calculated ratio of torsional capacity

may also reduce the deformation capacity resulting in a brittle failure.
A formula of calculating the pure torsional capacity taking into account of the axial compressive load has been presented [Pandit and Mawal, 1973] as follows.

$$Mto' = \alpha \cdot Mto \tag{4}$$

where α is the additional rate of pure torsional capacity due to axial load $\alpha = \sqrt{1 + 10\,\sigma_o/\sigma_B}$
σ_o is the axial stress

The relationship between axial load ratio and measured-calculated ratio of torsional capacity is shown in Figure 7 where the proposed formula (4) taking into account of the axial load can well be applied to the experimental results.

3.3 Verification of experimental data of members subjected to combined bending-shear and torsion

When combined bending-shear and torsion are applied to a reinforced concrete member, the shear unit stresses due to torsion and due to bending shear are offset each other on one side while they are added on the opposite side of the member. This means that the diagonal tensile stress in the opposite side becomes greater than that under single stress resulting in an early diagonal cracking, and reducing the shear capacity and deformation. It has been confirmed in a large number of experimental studies that reinforced concrete members under torsional stress degrade flexural and shear capacity, however, no formula available for the structural design has ever been given. A failure criteria equation (5) under combined bending-shear and torsion has been proposed as functions of each stress-strength ratios and tested in experiments.

$$\left(\frac{Mt}{Mto}\right)^{\alpha_2} + \left(\frac{Qc}{Qcu}\right)^{\beta_2} = \gamma_2 \tag{5}$$

where Mt is the applied torsional moment, Mto is the pure torsional capacity, Qc is the applied shear force, Qcu is the shear capacity at $Mt=0$ and α_2, β_2, γ_2 are the constants to be determined in experiment.

When $\alpha_2 = \beta_2 = 2$, and $\gamma_2 = 1$ in equation (5), we have a well-known equation (6) proposed by Ersoy and co-workers [Ersoy and Ferguson, 1967]. Kanou and co-workers [Kanou and Nakayama, 1968] proposed a practical equation with $\alpha_2 = \beta_2 = 2$ and $\gamma_2 = 1.4$.

$$\left(\frac{Mt}{Mto}\right)^{2} + \left(\frac{Qc}{Qcu}\right)^{2} = 1 \tag{6}$$

We used the shear capacity Qcu formula given by Arakawa for the reinforced concrete member without torsional

Table 3: Conditions of the specimens subjected to torsional and bending-shear load

B (cm)	D (cm)	a/D	σ_B (kgf/cm^2)	e_1	p_w (%)	p_t (%)	Number of the specimens
10 ~ 30	20 ~ 60	2 ~ 6	183 ~ 800	0 ~ 4.58	0 ~ 3.56	0.23 ~ 8.96	110

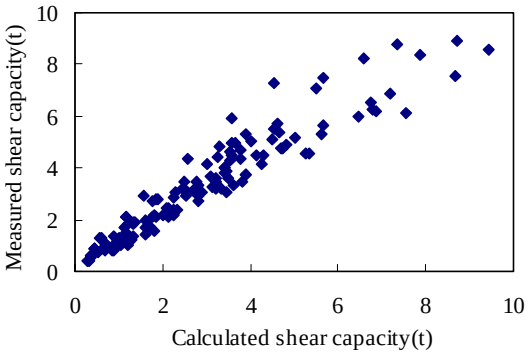


Figure 8: Comparison of measured torsional-shear capacity and calculated shear capacity

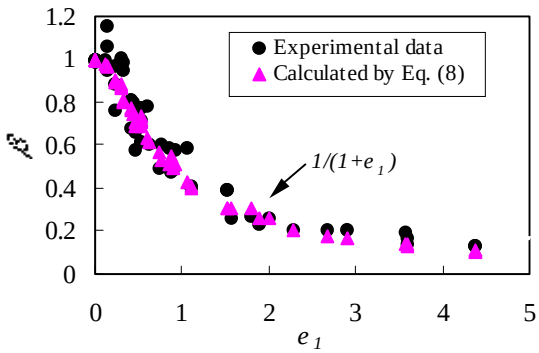


Figure 9:Relationship between shear capacity reduction and eccentric ratio

stress and applied to experimental results dealing with *152* specimens subjected to torsional-bending shear forces given in literatures [Ewida and McMullen, 1982; Funakoshi and Okamoto, 1981; Funakoshi et al., 1982; Huang et al., 1995; Kojima et al., 1985; Kanou and Nakayama, 1968; Kanou et al., 1984; Matsui and Okamura, 1981; Rahal and Collins, 1995; Tsuji, 1982; Wang and Kang, 1988]. As a result, the experimental results were well accounted for a sufficient accuracy when the failure criteria equation (6) and pure torsional capacity equation (3) are used. Comparison between measured torsional-shear capacity and calculated shear capacity Qc by equation (6) is shown in Figure 8. Conditions of the specimens are shown in Table 3. With eccentric distance e, relationship between the eccentric ratio $e_1=e/B$ and the torsional stress $\tau=Mt/(B^2D)$ is investigated and it is found that the torsional stress decreases with an increase of the eccentric ratio.

4. PROPOSAL OF A METHOD ESTIMATING SHEAR CAPACITY REDUCTION DUE TO ECCENTRIC BEAM-COLUMN JOINTS

Substituting equation (6) with (1), we have equation (7) taking into account of axial stresses. The shear capacity reduction rate of column due to torsional moment can be approximately given by the equation (8).

$$\left(\frac{Qc \cdot e}{Mto'}\right)^2 + \left(\frac{Qc}{Qcu}\right)^2 = 1 \tag{7}$$

$$f\grave{A} = \frac{Qc}{Qcu} = \left\{1 + \left(\frac{e \cdot Qcu}{Mto'}\right)^2\right\}^{-0.5} = \left\{1 + \left(\frac{e_1 \cdot Kcu}{f_{¿} \cdot Kto}\right)^2\right\}^{-0.5} \tag{8}$$

where $Kcu=Qcu/(BD)$, $Kto=Mto/(B^2D)$ and $e_1=e/B$. β is the shear capacity reduction rate of column. Another β based on the failure criteria equation proposed by Nakayama is given by the equation (9).

$$f\grave{A} = 1.4 \Big/ \left(1 + \frac{e_1 \cdot Kcu}{f_{¿} \cdot Kto}\right) \tag{9}$$

Among past studies on the members subjected to bending-shear and torsion, those available for evaluation of the shear capacity reduction [Kojima et al., 1985; Rahal and Collins, 1995; Wang and Kang, 1988] were used and the relationship between shear capacity reduction rate and eccentric ratio is shown in Figure 9. Calculated shear capacity reduction rate agrees well with the experimental results.

The eccentric beam-column joints are frequently found in low or mid-rise buildings where the axial compressive load can contribute considerably to the increase in torsional capacity of the column when the axial stress in the column of the grand floor σ_o is between $0.1\sigma_B$ and $0.2\sigma_B$. However in the school buildings where shear or

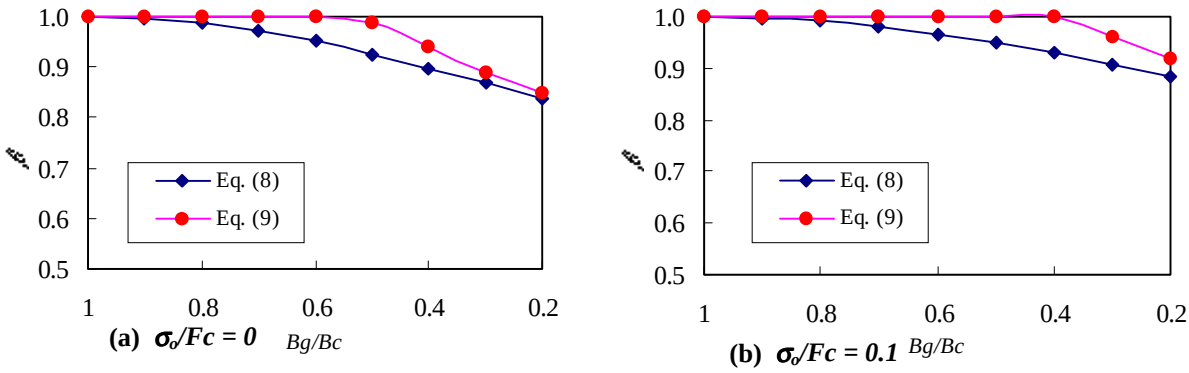


Figure 10: Column with square cross section *Dc/Bc=1.0*

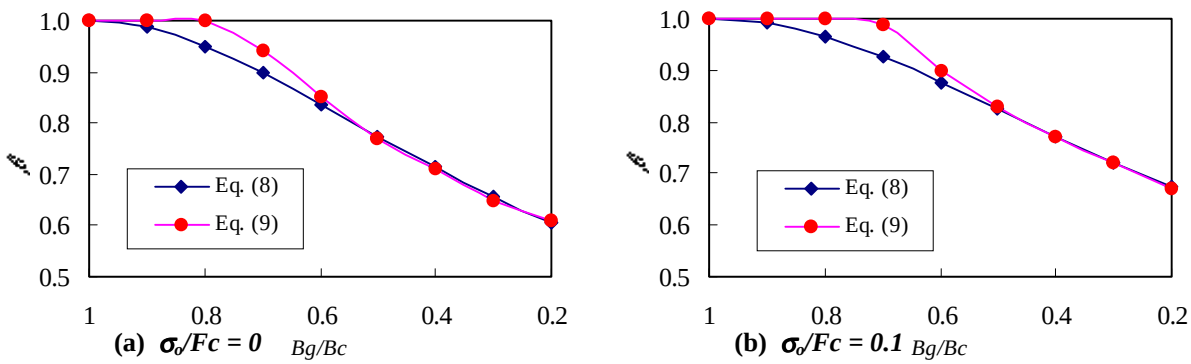


Figure 11: Column with flat section *Dc/Bc=0.4*

torsional failure are likely to occur in the ridge direction of the building, the axial tensile stress comparing with the long-term axial load may probably be applied to the span direction of the building due to seismic forces or another vertical motions. Thus the increase in torsional capacity of reinforced concrete column due to compressive axial load should be estimated restrainedly.

The shear capacity reduction rate of the column due to eccentric beam-column joints is shown in Figure 10 and Figure 11 as a function of *Bg/Bc* where *Bg* is the beam width and *Bc* is the column width to which the beam is jointed. Parameters in this calculation are *a/D=4*, *Bc/Dc=1* or *Bc/Dc=0.4* where *Dc* is another dimension of the column, $p_t=0.5\%$, $\sigma_B=180kgf/cm^2$ and $p_w\sigma_{wy}=3.0kgf/cm^2$. When the column has a square cross-section (*Bc=Dc*) and in the range of *Bg>0.5Bc*, the reduction of shear capacity is negligible while it becomes *20* to *25%* when the column has flat section of *Dc/Bc=0.4* and *Bg=0.5Bc=1.25Dc*. The positive contribution of axial compressive load to the torsional capacity of the column is relatively large when the column has a square cross section but it becomes negligible when the column section is flat. The shear capacity reduction of column is very likely to occur due to the eccentric joint with the flat column.

It is also shown in Figure 10 and Figure 11 that the calculated shear capacity reduction rate using equation (8) and (9) are very close when the eccentric ratio e_1 is more than 0.5. The calculated β using equation (9) becomes slightly larger than that using equation (8) when the eccentric ratio e_1 is less than 0.5 but equation (9) may be used for practical applications.

5. CONCLUSIONS

In summary, major findings are as follows.

(1) Seismic damage inspections showed that columns with eccentrically jointed beams are likely to reduce the shear capacity due to the torsional stress, and to occur shear and torsional failure.

(2) The torsional capacity of columns can be estimated with the proposed equation, which takes into account of torsional span ratio based on the existing experimental studies.

(3) The shear capacity reduction due to the eccentric beam-column joints can be estimated as the shear capacity reduction rate of the column.

(4) The torsional stress due to the eccentric beam-column joints should be taken into account in structural design and in seismic diagnosis.

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