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Shear behavior of RC interior joints with beams of different depths under cyclic loading

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Abstract. Extensive reinforced concrete interior beam-column joints with beams of different depths have been used in large industrial buildings and tall building structures under the demand of craft or function. The seismic behavior of the joint, particularly the relationship between deformation and strength in the core region of these eccentric reinforced concrete beam-column joints, has rarely been investigated. This paper performed a theoretical study on the effects of geometric features on the shear strength of the reinforced concrete interior beam-column joints with beams of different depths, which was critical factor in seismic behavior. A new model was developed to analyze the relationship between the shear strength and deformation based on the Equivalent Strut Mechanism (ESM), which combined the truss model and the diagonal strut model. Additionally, this paper developed a simplified calculation method to estimate the shear strength of these type eccentric joints. The accuracy of the model was verified as the modifying analysis data fitted to the test results, which was a loading test of 6 eccentric joints conducted previously.

Keywords: shear strength; deformation; joint; eccentricity; earthquake resistance

1. Introduction

The reinforced concrete (RC) beam-column joint is the key component in a structure since it is the connection within the reinforced concrete frame to coordinate deformations and to transfer the internal forces including bending moments, compression forces and shear forces (Parate and Kumar 2016, Parra-Montesinos and Wight 2002). Moreover, in reinforced concrete structural systems, the beam-column joint is recognized as a complex and critical component, which may be damaged during earthquakes (Kang and Tan 2018). When a RC beam-column joint is under seismic loading, the tension and compression forces from beams produce large shear forces in the joint. Thus, the concept "strong connection, weak member" is applied in earthquake resistance design (Yan *et al.* 2017), and it is essential to confirm the joints shear forces to ensure the performance of the joint, which affects the safety of the entire reinforced concrete frame structure. Since the 1960s, numerous experiments and analyses on the earthquake resistance of reinforced concrete beam-column joints have been conducted (Kim and LaFave 2007, Lu *et al.* 2012). The studies mainly focused on the requirements to develop the seismic design of RC joints, such as the shear strength of a joint, the column-beam flexural strength ratio, required transverse reinforcement (Chun 2014) the anchorage length of the beam (Zhou 2009).

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The eccentric RC joint, which is emerging rapidly in recent years, has more complex internal forces. In the literature, there have been few studies on eccentric RC beam-column connections. Some of these works were interested in interior joints (Teng and Zhou 2003), while others focused on exterior joints (Lee and Ko 2007, Zhou and Zhang 2012). The majority of previous studies found that the eccentric joints had relatively lower shear strengths and weak deformation capacity, and the preference was to use effective joint sizes in designing eccentric joints (LaFave and Shin 2009). Moreover, the geometric features of the eccentric joint had a significant effect on its seismic performance, even up to the overall frame because the eccentricity between the axes of the beams or columns in the eccentric joint can influence the behavior of the joint, particularly in the shear strengths and deformation capacity. To date, although there have been amount of studies performed to verify the mechanism of the shear strength of eccentric joints, the eccentric reinforced concrete beam-column joint with different beam depths (Fig. 1), which is widely used in industrial and tall buildings to meet the functional and structural requirements, has not been studied enough from the past works (Joh *et al.* 1991) compared with the studies for regular RC joints or other eccentric joints. To the author's best knowledge, there have been minimal investigations by Joh (1991), Xing (2013) regarding eccentric joints with different beam depths. However, there is no consistent opinion on how to reasonably analyze and accurately calculate the shear strength and deformation in the RC beam-column joint with different beam depths.

This paper confirmed a new model to predict the relationship between shear strength and deformation with sufficient accuracy in RC beam-column joints with different

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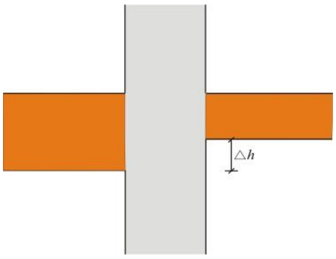


Fig. 1 Eccentric reinforced concrete beam-column joint with different beam depths

depths beams. To estimate the critical parameters and to verify the analysis results with model, the previous test results of 6 eccentric joints under cyclic loading were used to confirm the model. To avoid the heavy calculation, a simplified calculation of shear strength in eccentric joints with beam of different depths and the results of the simplified one fitted the analysis results. Details about the analysis of the joint with different beam depths are shown in the following sections.

2. Experimental program

To investigate the seismic behavior of the eccentric joints, six one-third scale interior RC joint specimens with different beam depths were designed based on the guidelines of current Chinese design code (GB50010 2010) and tested under cyclic loading (Xing *et al.* 2013). All the design parameters are shown in Table 1 and include the specimen number, the cross section and the reinforcement. The main variable parameters are the sizes of the shallow beams, reinforcements, and the eccentricities of the joint specimens.

The designed concrete strength should be 40 MPa, and the actual value of the concrete strength of specimens is tested and shown in Table 2. Other essential material properties of the joint specimens are also included in the following table.

The set-up of the tests is shown in Fig. 2.

3. Test results

The test was conducted, and the experimental data and features of the specimen failures were obtained. Detailed results of the cyclic loading test will be discussed in this section.

3.1 Lateral load-drift response

The test results of the lateral load-drift response are shown in Table 3.

3.2 Failure characteristic of joints with different beam depths

The RC beam-column joints were designed as two types by adjusting the sizes of the beam and column sections along with the amount of longitudinal reinforcements. For the first type joints, which were WJ-1, WJ-3, WJ-4 and WJ-5, shear failure occurred in the joints before the tensile bars yielded in the beams and columns because the resistances of the beams and columns were designed to be relatively stronger. For the second type joints, which were J-7 and J-8, the mechanical properties of the joints degraded after the tensile bars yielded in the beams and columns because the

Table 1 Design parameters

		Specimen	WJ-1	WJ-3	WJ-4	WJ-5	J-7	J-8
Beam	Deeper beam	Cross section (mm^2)			180×500		180×400	
		Reinforcing bars			2×3Φ16		2×3Φ18	
		Actual yield strength (MPa)			369.0		436.0	
		Moment capacity (*k*N.m)			100.1		120.4	
	Shallow beam	Cross section (mm^2)	180×400	180×350	180×300	180×250	180×300	180×250
		Reinforcing bars		2×3Φ16		2×2Φ16	2×3Φ18	2×2Φ18
		Actual yield strength (MPa)			369.0		436.0	
		Moment capacity (*k*N.m)	77.9	66.8	55.6	44.0	87.2	47.0
Column		Cross section (mm^2)				260×260		
		Reinforcing bars			2×3Φ20		2×3Φ20	
		Actual yield strength (MPa)			393.0		459.0	
		Axial load (*k*N)	330	440	330	440	525	
		Moment capacity with axial load (*k*N.m)	260.4	233.0	260.4	233.0	265.6	
Joint		Vertical eccentricity (mm)	50	75	100	125	50	75
		Ration of column depth to beam bar diameter			16.25		14.4	
		Transverse reinforcement			ϕ6@120		ϕ6@65	
		Actual yield strength (MPa)			391.0		356.0	
		Volumetric steel percentage of loop reinforcement			0.39%		1.16%	
Ratio of column moment capacity with axial load to beam moment capacity			1.46	1.40	1.67	1.62	1.06	1.14

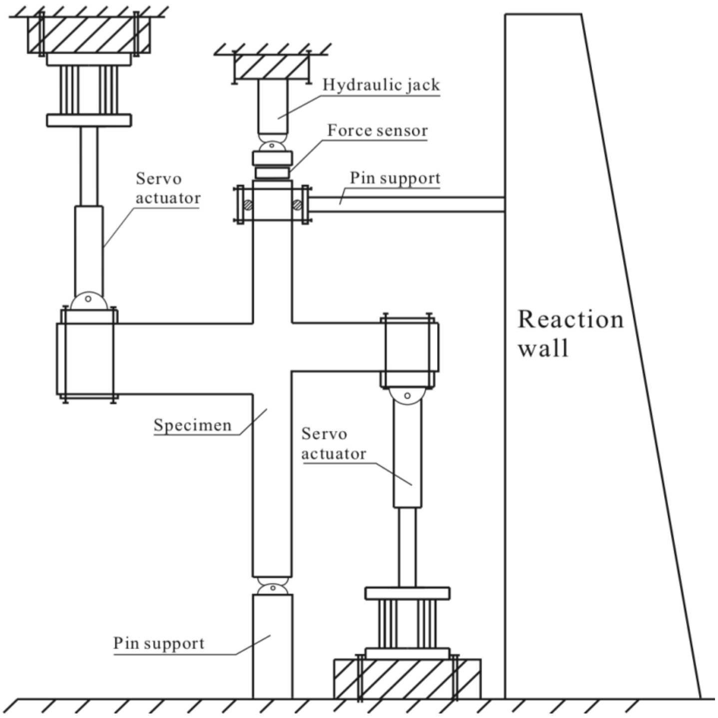


Fig. 2 Test set-up

Table 2 Material properties

Type of steel	ϕ		ϕ		Ф	
Bar diameter (mm)	6	8	16	20	16	20
Yield strength (MPa)	391	356	369	393	436	459
Yield strain (με)	1911	1720	2170	2296	2247	2507
Ultimate strength (MPa)	551	520	528	557	588	602
Concrete strength* (MPa)	36.6(31.8)					

*Concrete strength: The concrete strength of WJ-1, WJ-3, WJ-4 and WJ-5 is 36.6 MPa. The concrete strength of J-7 and J-8 is 31.8 MPa.

Table 3 Test results

Specimen		First-crack		Critical-crack*		Ultimate		Failure	
		Shear (*k*N)	Joint shear angle (10^{-3} rad)	Shear (*k*N)	Joint shear angle (10^{-3} rad)	Shear (*k*N)	Joint shear angle (10^{-3} rad)	Shear (*k*N)	Joint shear angle (10^{-3} rad)
WJ-1	Positive	207	0.2	301	1.1	349	3.4	279	10.5
	Negative	-165	-0.3	-318	-1.7	-345	-3.9	-274	-14.7
WJ-3	Positive	255	0.6	359	2.0	387	4.6	324	14.5
	Negative	-258	-0.6	-378	-1.6	-396	-1.9	-312	-16.2
WJ-4	Positive	200	0.4	316	1.5	419	12	380	24.6
	Negative	-232	-0.1	-336	-1.1	-432	-4.7	-386	-21.6
WJ-5	Positive	266	0.6	416	2.2	446	5.6	367	uncollected
	Negative	-266	-0.2	-380	-1.3	-400	-4.5	-323	uncollected
J-7	Positive	239.6	0.27	375.7	4.1	494.1	10.26	393.4	25.32
	Negative	-253.8	-0.39	-444.8	-2.7	-495.1	-6.91	-408.4	-13.31
J-8	Positive	248.7	0.24	437.2	2.3	566.3	6.59	472.2	19.74
	Negative	-310	-0.82	-484.7	-1.2	-506.2	-5.12	-461.7	-17.96

∗Two criteria to define critical-crack level: 1) the shear crack was formed through the diagonal direction in the whole core area of the joint; 2) the width of the shear crack reached 0.3 mm in core area of the joint.

resistances of the beams and columns were designed with regard to the required shear and bending strength only.

In the loading test, the critical crack occurred first and the peeling concrete emerged in the center of the core of the joint. Then, as the cyclic loading increased, the range of the peeling concrete extended to the majority of the core region of the joint. During the test, as the maximum stress of the specimen was equal to the ultimate stress, the concrete was crushed in the center of joint core, and the stirrups failed to confine the concrete. The concrete then crushed and was gradually dropped off. Finally, in the joint region, much of the concrete was lost and the reinforcement could be observed directly, indicating that the joint was completely damaged. The final features of the joint specimens are shown in Fig. 3, and the red lines represent the regions of Equivalent Diagonal Strut of eccentric RC interior joints.

With detailed observation of the specimens, the failure modes of these RC beam-column joints with different beam depths were compared to the failure modes of regular joints. As a result, there were three features of eccentric beam failure modes; (1) the distribution of cracks were asymmetrical and this phenomenon was more obvious in joints with larger eccentricities; (2) the failure developed gradually from the center to the overall joint region; (3) The strength of critical-crack level was found to be 80% strength of the ultimate level. It is suggested that the shear strength of critical-crack level can be used to control the design of eccentric joints because the strengths of both critical-crack level and ultimate level are close.

The behavior of the joint specimen subjected to cyclic

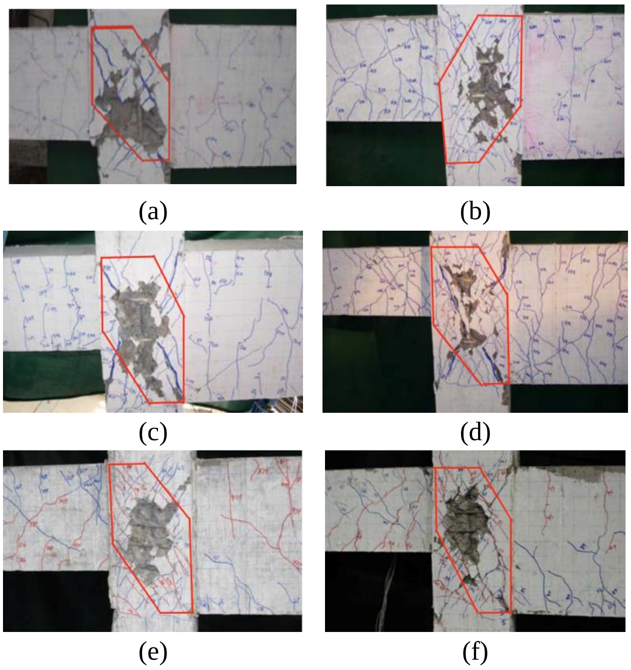


Fig. 3 Failure mode of joint (a) WJ-1, (b) WJ-3, (c) WJ-4, (d) WJ-5, (e) J-7, and (f) J-8

loading was significantly affected by the different beam depths of the joint. The eccentricity of the joint was capable of weakening the flexural capacity of the main beam and reducing the confinement in the joint region. Since the beam flexural capacity was decreased, the shear stress of the eccentric joint with different beam depths also decreased compared to the regular joint. Hence, the lower shear stress in the eccentric beam-column joint improved the overall performance of the joint. To the contrary, the joint was weakly confined due to the large eccentricity, which can be considered as an exterior joint connected with a larger span beam stub. Thus, the eccentricity had a negative impact on the confinement of the joint (Xing *et al*. 2013). Moreover, the shear strength would increase if the increasing eccentricity of the joint positively affects the joint and vice versa.

4. Modified model based on shear strut mechanism

4.1 State of plane strains in beam-column joints:

The state of plane strains in beam-column connections can be defined by the equations as follows in Fig. 4

$$\varepsilon_c = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos(2\theta) + \frac{\gamma}{2}\sin(2\theta) \quad (1)$$

$$\varepsilon_t = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos\left[2(\theta + 90^o)\right] + \frac{\gamma}{2}\sin\left[2(\theta + 90^o)\right] \quad (2)$$

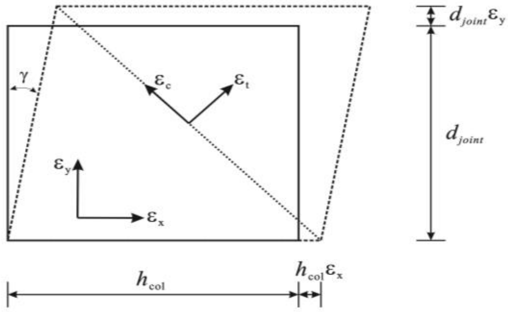


Fig. 4 State of plane strains

$$\gamma = \tan(2\theta)(\varepsilon_x - \varepsilon_y) \quad (3)$$

where ε_c is the generalized principal compression strain in the core region of joints, ε_t is the generalized principal tensile strain in the core region of joints, ε_x is the average compression strain along the *X* axis, ε_y is the average compression strain along the *Y* axis, γ is the joint shear angle (deformation), and θ is the compression angle, which is the measure between the principal compression strain and the compression reinforcement. If the compression angle is assumed, a new relationship is essential to define the state of the plane strains in the beam-column connection since there are four unknowns in three equations. Thus, k_{tc} is introduced here to establish the relationship between the generalized principal compression strain, ε_c, and the generalized principal tensile strain, ε_t, with the following expression

$$k_{tc} = -\frac{\varepsilon_t}{\varepsilon_c} \quad (4)$$

However, it should be noted that the generalized principal tensile strains not only are the concrete tensile strains but also include the cracks in the concrete. In other cases, the Poisson ratio, υ_{12}, can be assumed to be as follows according the study by Lawrance *et al*. (1991)

$$\nu_{12} = 0.2 + 850\varepsilon_{sx}, \qquad \varepsilon_{sx} \le \varepsilon_{sy} \quad (5a)$$

$$\nu_{12} = 1.9, \qquad \varepsilon_{sx} > \varepsilon_{sy} \quad (5b)$$

where υ_{12} is the Poisson ratio, ε_{sx} is the tensile strain of the reinforcement and ε_{sy} is the yield strain of the reinforcement. In the joint analysis, it can be assumed that $\varepsilon_{sx}=\varepsilon_x=\varepsilon_c(k_{tc}\tan^2\theta)/(1+\tan^2\theta)$. Before the joint stirrups yield, the value of k_{tc} ranges from 0.2 to 0.8. The specific value, 0.5, is recommended for k_{tc} as υ_{12}, the Poisson ratio, is suggested to be 0.2 for this work. Parra-Montesinos and Wight (2002) suggest that k_{tc}= 2+k_s×γ, and k_{tc} is similar to Poisson ratio, which represents the relationship between compression and tension. Then we established following equations. Consequently, k_{tc} can be obtained by the following equations with various load modes,

Monotonic loading

$$k_{tc} = 0.2 + 850\varepsilon_c\left(1 + 0.5\tan^2\theta\right)\Big/\left(1 + \tan^2\theta\right) + k_s\gamma \quad (6a)$$

$$\text{Cyclic loading:} \quad k_{tc} = 1.9 + k_s\gamma \tag{6b}$$

It is can be seen that θ_{strut} and θ adopt the mutual complementary angle. Raffaelle and Wight (1995) estimated the reasonable range of k_s from 200 to 1200 according to the theoretical analysis and a large number of tests, and suggested the following equation for evaluating k_s

$$k_s = 500 + 2000\frac{e}{b_c} \tag{7}$$

where e is the eccentricity between the beam and the column, and b_c is the width of the column.

4.2 Strength mechanisms in reinforced concrete beam-column connections

The truss mechanism and the strut mechanism are two critical mechanisms to provide the shear strength of the reinforced concrete beam-column joints. The truss mechanism is established on the forces, which are transferred through the concrete and the bond between the beam and column reinforcements inside the beam-column joints. The contribution from the strut mechanism is activated by bearing on the concrete from the compression regions of the connected beams and columns. Thus, as soon as the bond in the truss mechanism is entirely gone, only the action of diagonal compression on the strut can provide joint strength. However, it is difficult to estimate the contribution from the truss mechanism since only partial bond losses should occur in several recommendations of the ACI-ASCE Committee 352 (2002).

Considering that the shear force eventually passes through the concrete, regardless of whether it is by the truss mechanism or the strut mechanism, it is suggested in this work that the equivalent diagonal strut mechanisms can be assumed to be the same value as the shear strength of the reinforced concrete beam-column joints. The compressive strength of the concrete plays a dominant role among all the factors that affect the performance of the joints. Thus, the bond between the concrete and the bars inside the beam-column connection could be inefficient under cyclic loading. The process of bond failure will occur more rapidly because of the ‘strong-column and weak-beam’ criterion. It has been generally accepted that the bond loss accelerates after the tensile reinforcement yielding. Correspondingly, the bond stress is high and the compression bars rarely yield because the compression region of a joint is load-bearing with the surrounding concrete and adjoining the bars together. Thus, the general consensus is that the shear forces are always transmitted into the joint region through the bond. Additionally, it can be assumed that the shear strength is linearly distributed along the depths of both the column section and the joint since the diagonal compression strut and truss mechanism are combined in the beam-column connection, as shown in Fig. 5.

In the figure, the position of the shear strength is $d_{joint}/3$ to the extreme compression fiber of the deeper beam and $h_c/3$ to the extreme compression fiber of the column. Thus the equivalent diagonal strut mechanism is limited in the 2/3 depth of each side of the compressive zone. The angle

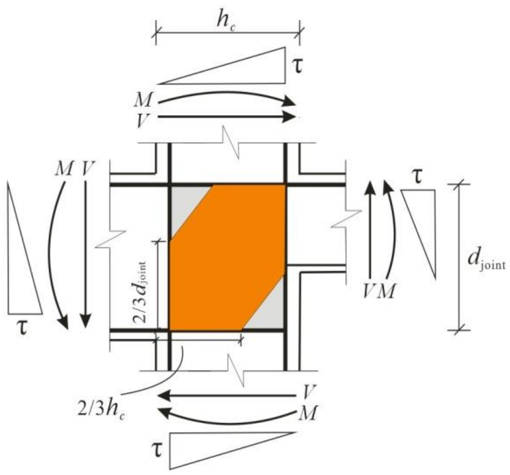


Fig. 5 Equivalent diagonal compression strut

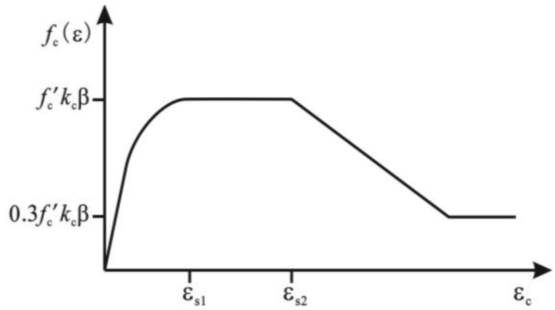


Fig. 6 Stress-strain relationship for concrete

between the equivalent diagonal compression strut and the axis of the beam, θ_{strut}, is estimated as

$$\theta_{strut} = \arctan\left(\frac{d_{joint}}{h_c}\right) \tag{8}$$

where, d_{joint} ,the equivalent joint depth is approximated as

$$d_{joint} = \frac{\rho_l}{\rho_l + \rho_r}h_{bl} + \frac{\rho_r}{\rho_l + \rho_r}h_{br} \tag{9}$$

where h_{bl} is the depth of left beam, ρ_1 is the reinforcement ratio of left beam, h_{br} is the depth of right beam, and ρ_r is the reinforcement ratio of right beam. The depth of Equivalent diagonal compression strut d_{strut} is estimated as

$$d_{strut} = (1 - \frac{2}{3}\times\frac{2}{3})\times\frac{d_{joint}h_c}{\sqrt{d_{joint}^2 + h_c}} \tag{10}$$

4.3 Shear strength of beam-column joints

The model suggested by Sheikh and Uzumeri (1982) is adopted on the stress-strain relationship for the concrete in the beam-column joints as shown in Fig. 6.

$$\text{ascending stage: } f_c = f_c'\left[2\frac{\varepsilon_c}{\varepsilon_{s1}} - \left(\frac{\varepsilon_c}{\varepsilon_{s1}}\right)^2\right]k_c\beta \tag{11a}$$

$$\text{descending stage: } f_c = f_c'\left[1 - Z\left(\varepsilon_c - \varepsilon_{s2}\right)\right]k_c\beta \tag{11b}$$

where ε_c is the concrete compression strain, $f_c^{'}$ is the concrete strength, ε_{s1} is the peak compression strain, and ε_{s2} is the compression strain at the beginning of the descending stage. k_c is a parameter that represents the increase in the compressive strength of the confined concrete, suggested to be 1.2. Z is the factor to define the curve of the descending stage, suggested to be 50 (Kent and Park 1971). β is the reduction factor for considering the deterioration of the concrete compressive strength in connections evoked by tensile strains, as defined by the following equation

$$\beta = \frac{1}{0.85 + 0.27k_{tc}} \tag{12}$$

The horizontal shear strength in the beam-column connection, V_{jh}, is estimated as

$$V_{jh} = C_{strut}\cos(\theta_{strut}) \tag{13}$$

where C_{strut} is the compressive force along the diagonal compression strut, obtained as

$$C_{strut} = f_c A_{strut} \tag{14}$$

where the equivalent area $A_{strut}=b_{strut}*d_{strut}=b_j*d_{strut}$, in which b_j is the effective width of joint core area and given by

$$b_j = \begin{cases} b_c & b_b \ge b_c/2 \\ \min(b_c, b_b + 0.5h_c) & b_b < b_c/2 \end{cases} \tag{15}$$

where b_b is the width of the beam, b_c is the width of the column, and h_c is the height of the column.

5. Application in eccentric joint performance analysis

The eccentric joint can be considered as an 'equivalent joint region' because of the different beam depths. As shown in Fig. 4, the width of the equivalent joint region is the average width of the upper and lower columns, and the depth of the equivalent joint region can be estimated by the following equation

$$d_j = \begin{cases} h_{eq} & 0 < \Delta h < h_c \\ h_{bl} & \Delta h \ge h_c \end{cases} \tag{16}$$

where d_j is the effective depth of the eccentric joint, Δh is the vertical distance between the left and the right beam, h_c is the height of the column section, h_{bl} is the depth of the left beam, and h_{eq} is the depth of the equivalent joint core region that can be calculated as

$$h_{eq} = \frac{\rho_{bl}}{\rho_{bl}+\rho_{br}}h_{bl} + \frac{\rho_{br}}{\rho_{bl}+\rho_{br}}h_{br} \tag{17}$$

where ρ_{bl} is the reinforcement ratio of the left beam, h_{br} is the depth of the right beam and ρ_{br} is the reinforcement ratio of the right beam.

5.1 Analyses and calculation of shear strength in eccentric joints

5.1.1 Identification of k_{tc} and k_s

The general compression and tensile strains were evaluated as the average values counted via the results that divide the distortions measured by dial indicators along the joint region in diagonal lines and the distances between the dial indicators since it was difficult to directly obtain the general compression and tensile strains under reverse cyclic loading. Then the values of initial k_s could be estimated by Eqs. (6a)-(6b). However, considering the significant difference of the k_s terms among the eccentric joint specimens, a linear relationship between the beam depth and the value of final k_s can be established as follows,

Monotonic loading

$$k_s = 1050 - 70\frac{\Delta h}{h_c} \tag{18a}$$

Cyclic loading

$$k_s = 200 - 50\frac{\Delta h}{h_c} \tag{18b}$$

The formulas above are also the equations originally recommended by this article for estimating final k_s of the eccentric RC beam-column joints. The results of k_s analyzed using Eq. (18a)-(18b) are all shown in Table 4.

5.1.2 Identification of peak strain

The peak strain is calculated by the following equation,

$$\varepsilon_{s1} = 0.001 \times 0.085 k_c f_c' \tag{19}$$

where k_c is the enhancement coefficient and is suggested to be 1.2 (Sheikh and Uzumeri 1982).

5.1.3 Calculation of shear stress

The shear stress, τ_j, can be obtained by substituting k_{tc} into Eqs. (12)-(14). It is noted that if a joint failed under cyclic loading, the concrete compressive strength in the core region of the joint will be less than 0.5 $f_c^{'}$. Thus, the limitation of the concrete compressive strength is 0.5 $f_c^{'}$ (Priestley 1997). The stress-strain relationship is represented as a red line in Fig. 7.

5.1.4 Identification of shear angle (deformation) γ

Substitute θ into Eqs. (1)-(3) to calculate the shear deformation γ, and then compare the result to the average shear deformation observed from test. If the error between them is less than 5%, the calculation is satisfied. Otherwise,

Table 4 Evaluations of k_s

Specimen	Eccentricity ($\Delta h/h_c$)	Monotonic loading (0.2+$k_s\gamma$)		Cyclic loading (1.9+$k_s\gamma$)	
		Initial k_s	Final k_s	Initial k_s	Final k_s
WJ-1	0.385	1039	1020	201	180
WJ-3	0.577	NA*	1000	296	170
WJ-4	0.769	906	990	102	160
WJ-5	0.962	709	980	87	150
J-7	0.385	1839	1020	145	180
J-8	0.577	450	1000	163	170

*The date was not collected.

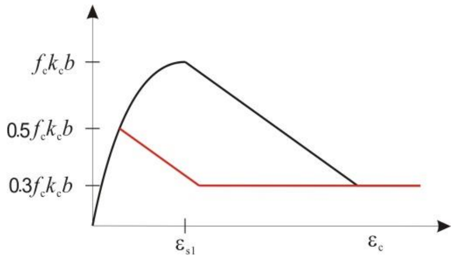


Fig. 7 Stress-strain relationship

the shear deformation will be recalculated if the error is more than 5%.

The solution procedure to predict the shear strength of the eccentric joints with different beam depths is shown in Fig. 8.

Fig. 9 shows the shear stress-shear angle relationship of the typical specimens. The curves are reliable and acceptable because the error between the theoretical and measured values of γ is less than 5%. The τ_j-γ curves of the typical eccentric joints from the different procedures including the cyclic loading test, analysis and modify

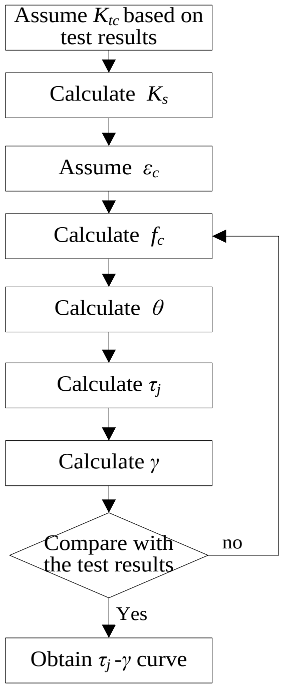
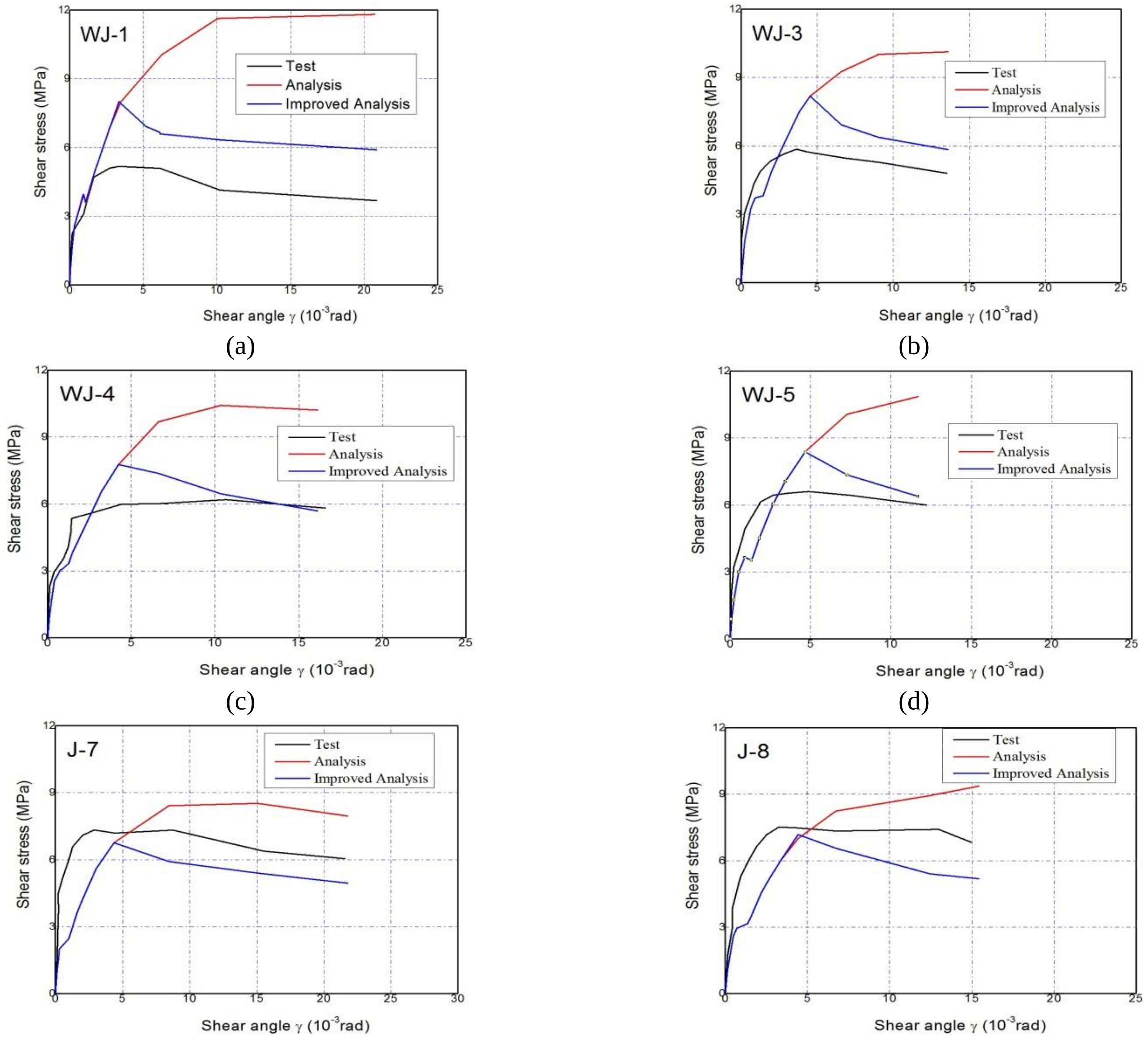


Fig. 8 Solution procedure



(a) (b) (c) (d) (e) (f)

Fig. 9 Shear stress-shear angle relationship of (a) WJ-1, (b) WJ-3, (c) WJ-4, (d) WJ-5, (e) J-7, and (f) J-8

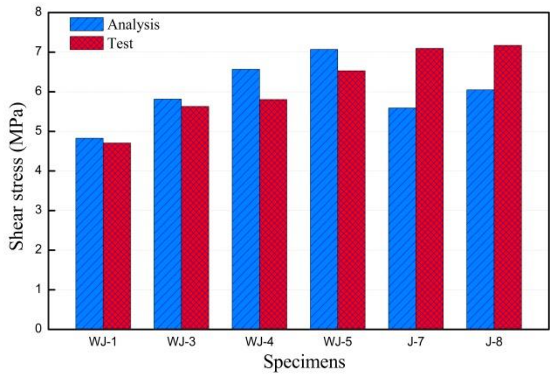


Fig. 10 Comparison between the test shear stress and the analysis shear stress

Table 5 Detailed information for Fig. 10

Specimen number	Eccentricity ($\Delta h/h_c$)	k_s	Shear stress (MPa)	
			Analysis	Test results*
WJ-1	0.385	180	4.827	4.705
WJ-3	0.577	170	5.814	5.629
WJ-4	0.769	160	6.567	5.803
WJ-5	0.962	150	7.068	6.531
J-7	0.385	180	5.591	7.095
J-8	0.577	170	6.048	7.17

*Shear stress=Shear force/($b_j d_j$)

analysis are estimated. Additionally, Fig. 10 represents the comparison between the shear stress tests and the shear stress analyses of the six joint specimens in the critical-crack level. The detailed information from Fig. 10 is shown in Table 5.

5.2 Simplified calculation of shear strength in eccentric joints

To appropriately simplify the relatively cumbersome calculation procedure discussed above is necessary and manageable. The test results indicate that the emerging of the critical diagonal crack is the sign of complete damage of the specimen based on the equivalent diagonal compression strut. As a result, the critical-crack level should be used to control the design. The relationship between the horizontal shear stress, τ_j, and the concrete strength, f_c', is represented by the following equation

$$\tau_j = \alpha_1 \alpha_2 f_c' \quad (20)$$

where α_1 and α_2 are factors to respectively indicate the relationship between k_s and f_c' and the horizontal shear stress, τ_j, estimated as follows in eccentric joint specimens

$$\alpha_1 = 0.34 - 0.001 k_s \quad (21a)$$

$$\alpha_2 = 0.0002 f_c'^2 - 0.033 f_c' + 1.7 \quad (21b)$$

The comparison between the shear stress obtained from Eqs. (18), (21a)-(21b) and the shear stress estimated by code (GB50010 2010) is shown in Fig. 11.

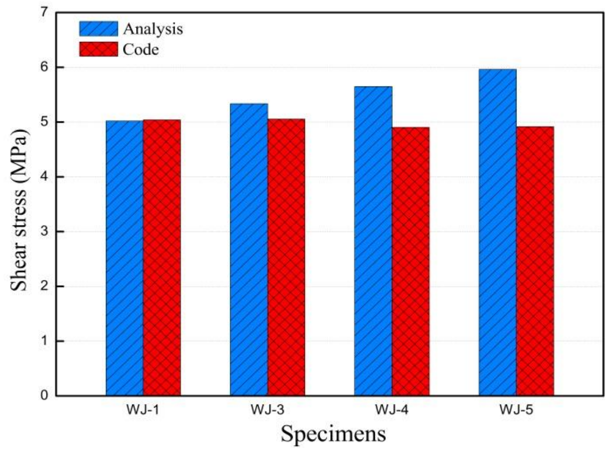


Fig. 11 Comparison between analysis and code

6. Conclusions

This paper investigated the effects of geometric features on seismic behavior, especially in regard to the shear strength of reinforced concrete interior beam-column joints with beams of different depths.

- A new model was proposed to analyze the relationship between the shear strength and the deformation based on the Equivalent Strut Mechanism (ESM), which combined the truss model and the diagonal strut model.
- Modified values of k_s and k_{tc} are suggested in this work. The following were drawn from this work: 1) The compatibility of deformation based on the state of the plane strains in the connection with 2) the k_{tc} factor related to the general compression and tensile strains to indicate the deformation in eccentric joints. The evaluation of the horizontal shear strength in the specific case considered was completely described in the context. The results of the modifying analysis fit the experimental data.
- The test of the six joint specimens conducted for this study to verify the critical parameters of the new model and investigated the relationship of the results between the tests and the analysis. The data contributed to improve the database of the eccentric joints with beam of different depths.

However, it is expected that further analysis of reinforced eccentric beam-column joints will be required if there are more specimens to verify the equations discussed in this work.

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Notations

α_1, α_2	Factors to respectively indicate the relationship between k_s and f_c'
A_{strut}	Area of Equivalent diagonal compression strut
β	Reduction factor for considering the deterioration of the concrete compressive strength in connections evoked by tensile strains
b_b	Width of the beam
b_c	Width of the column
b_j	Effective width of joint core area
C_{strut}	Compressive force along the diagonal compression strut
d_j	Effective depth of the eccentric joint
d_{joint}	Equivalent joint depth
d_{strut}	Depth of Equivalent diagonal compression strut
e	Eccentricity between the beam and the column
ε_c	Generalized principal compression strain in the core region of joints
ε_{s1}	Peak compression strain
ε_{s2}	Compression strain at the beginning of the descending stage
ε_{sx}	Tensile strain of the reinforcement
ε_{sy}	Yield strain of the reinforcement
ε_t	Generalized principal tensile strain in the core region of joints
ε_x	Average compression strain along the X axis
ε_y	Average compression strain along the Y axis
$f_{c,}$	Concrete strength
f_c'	Concrete compressive strength
γ	Joint shear angle (deformation)
h_{bl}	Depth of left beam
h_{br}	Depth of right beam
h_c	Height of the column
h_{eq}	Depth of the equivalent joint core region
k_c	Parameter that represents the increase in the compressive strength of the confined concrete, suggested to be 1.2
k_s	Linear relationship between k_{tc} and
k_{tc}	Relationship between the generalized principal compression strain and the generalized principal tensile strain
θ	Compression angle between the principal compression strain and the compression reinforcement
ρ_l	Reinforcement ratio of left beam
ρ_r	Reinforcement ratio of right beam
τ_j	Shear stress
υ_{12}	Poisson ratio
V_{jh}	Horizontal shear strength in the beam-column connection
Z	Factor to define the curve of the descending stage, suggested to be 50
Δh	Vertical distance between the left and the right beam