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Interaction of internal forces of interior beam-column joints of reinforced concrete frames under seismic action

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Abstract. This paper presents detailed analysis of the internal forces of interior beam-column joints of reinforced concrete (RC) frames under seismic action, identifies critical joint sections, proposes consistent definitions of average joint shear stress and average joint shear strain, derives formulas for calculating average joint shear and joint torque, and reports simplified analysis of the effects of joint shear and torque on the flexural strengths of critical joint sections. Numerical results of internal joint forces and flexural strengths of critical joint sections are presented for a pair of concentric and eccentric interior connections extracted from a seismically designed RC frame. The results indicate that effects of joint shear and torque may reduce the column-to-beam flexural strength ratios to below unity and lead to "joint-yielding mechanism" for seismically designed interior connections. The information presented in this paper aims to provide some new insight into the seismic behavior of interior beam-column joints and form a preliminary basis for analyzing the complicated interaction of internal joint forces.

Keywords: axial strength; beam columns; flexural strength; interaction; joints; reinforced concrete; seismic behavior; shear; torsion

1. Introduction

Structural members of reinforced concrete (RC) frames can be classified into beams, columns, and beam-column joints. A beam-column joint in an RC frame is a portion of the column within the maximum depth of the framing beams; however, seismic behavior of the joint is substantially different from and much more complicated than that of the upper and lower columns (Fig. 1). In spite of the intensive research efforts devoted to RC beam-column joints since the 1960s (Hanson and Connor 1967, Jirsa 1991, Lee and Yu 2009, Li *et al.* 2009, Lu *et al.* 2012, Shiohara 2012, Unal and Burcu 2012, Shrestha *et al.* 2013, and many others), seismic joint behavior has not been understood conclusively, and significant gaps exist in the seismic joint design provisions in different codes (ACI 318 2008 and its companion document ACI-ASCE 352 2002, MCC 2001a, NZS 1995). The recent strong earthquakes in the world, such as the 2008 China Wenchuan earthquake, have again demonstrated the vulnerability of beam-column joints of RC frames to seismic damage (Fig. 2) and highlighted the necessity for improving seismic design of joints.

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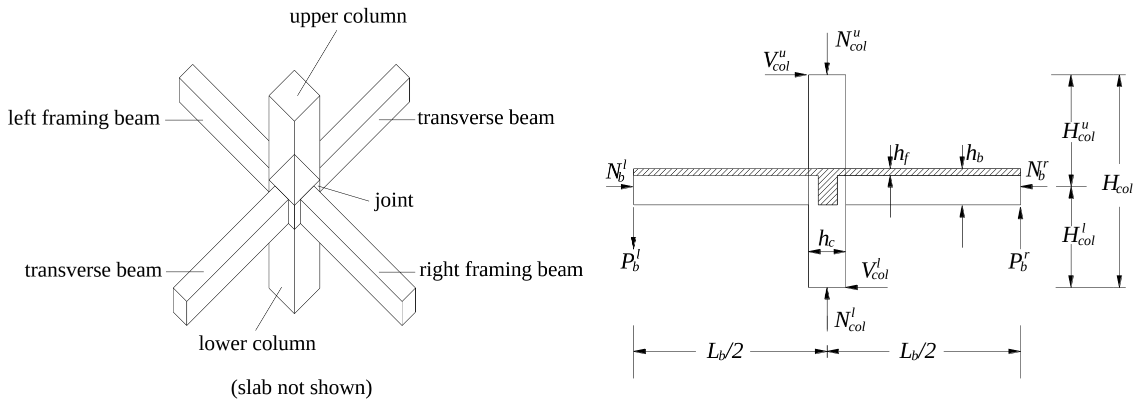


(a) (b)

Fig. 1 Illustration of an interior beam-column connection: (a) three dimensional geometry; (b) under forward lateral loading

(a) (b)

Fig. 2 Beam-column joints damaged during the China Wenchuan earthquake of May 12 2008

Fig. 1(b) shows an interior beam-column connection isolated at the inflexural points from an RC frame under seismic action. From the forces and stresses applied by the framing beams on the joint, it can be seen that shear in the joint is much larger than shear in the upper and lower columns. Zhou (2009) reported that maximum shear in an interior joint at the beam yielding at the column faces is on average 5.9 times the column shear. Laboratory tests and field investigations demonstrate that cyclically reversed joint shear induced by a strong earthquake causes extensive diagonal cracking in the joints of RC frames. It has been well recognized that tensile cracking in concrete reduces the concrete compressive strength in the direction parallel to the cracking (Vecchio and Collins 1986). Reduction of concrete strength in a joint lowers the axial compressive strength and the flexural strength of the critical joint sections. If the sum of the reduced flexural strengths of the critical joint sections becomes less than the sum of the flexural strengths of the framing beams, the critical joint sections may experience reinforcement yielding or concrete crushing, leading to “joint-yielding mechanism”; if the axial compressive strength of a critical joint section is reduced to below the joint axial force, the joint may fail by crushing. When an eccentric beam-column joint is subjected to seismic action, torque is induced in the joint (Teng and Zhou 2003), reducing further the axial and flexural strengths of the critical joint sections. The discussion above suggests that interaction of internal joint forces may play a critical role in evaluating seismic behavior of beam-column joints.

To get conclusive understanding of seismic joint behavior, joint performance indices and joint performance requirements have to be defined clearly. Zhou (2009) and Zhou and Zhang (2012) proposed four performance indices and suggested four performance requirements for RC joints subjected to a strong earthquake. The four joint performance indices proposed are: (1) column-to-beam flexural strength ratio; (2) joint shear deformation; (3) joint axial compressive strength; and (4) beam reinforcement slip out of joint. The four joint performance requirements suggested are: (1) column-to-beam flexural strength ratio evaluated at the critical joint sections is kept above unity; (2) joint shear deformation remains elastic during the elastic seismic response of RC frames, and the percentage of joint shear deformation in the lateral story drift ratio of RC frames does not increase during the inelastic seismic response of the frames; (3) joint axial compressive strength is maintained above the joint axial force; and (4) percentage of beam rotation at the column faces due to the beam reinforcement slip out of joints in the lateral story drift ratio of RC frames does not exceed a limit value. Given the joint performance indices and joint performance requirements as described above, evaluation of seismic joint behavior and formulation of joint design requirements can be made by analyzing the effects of joint design parameters (such as joint shear stress, joint transverse reinforcement and anchorage length of beam reinforcement in the joint) on the joint performance indices.

This paper presents detailed analysis of the internal forces of RC interior beam-column joints induced by seismic action, identifies critical joint sections, proposes consistent definitions of average joint shear stress and average joint shear strain, derives formulas for calculating average joint shear and joint torque, and reports simplified analysis of the effects of joint shear and torque on the column-to-beam flexural strength ratio. A companion paper (Zhou and Zhang 2012) has reported parallel information on exterior beam-column joints. Complexity of seismic joint behavior arises from the complicated interaction of internal joint forces; the information presented in this paper and the companion paper is intended to form a preliminary basis for analyzing the interaction of internal joint forces.

2. Internal forces of interior beam-column joints under seismic action

2.1 Designations of five horizontal joint sections

This research focuses on five horizontal joint sections as shown in Fig. 3. These joint sections, designated as S1 through S5, are located at the levels of beam bottom, beam bottom reinforcement, mid-height of joint core, beam top reinforcement, and beam top, respectively. In the following analysis, the symbols V_j, M_j, T_j, and N_j are used to denote shear, bending moment, torque, and axial force, respectively, of any horizontal joint section, whereas a superscript is used in these symbols to represent the internal forces of S1 through S5 (for instance, M_j^1 represents the bending moment of S1).

2.2 Shear of horizontal joint sections

For an interior beam-column connection under forward lateral loading (Fig. 1(b)), joint shear V_j can be analyzed for three scenarios: (1) when the framing beams crack at the column faces; (2) when the framing beams attain initial yielding at the column faces; (3) when the framing beams reach ultimate yielding at the column faces.

Joint shear at beam cracking at column faces. Beam axial forces N_b^l and N_b^r are taken as zero, the strains and stresses of the beam sections at the column faces can be determined from the sectional analysis as shown in Fig. 4 for the left beam. The concrete flexural cracking stress f_{cr} is taken as $0.62\sqrt{f_c}$ (f_c = concrete compressive strength) as per ACI 318 (2008), and the concrete cracking strain ε_{cr} is assumed to be 0.0001. For the sake of simplicity, slab participation in beam flexure is not considered. Using the stress-strain relationship as per MCC (2002) (Fig. 5) to relate the extreme concrete compressive stress σ_c to the corresponding strain ε_c, the strains and stresses of the section can be determined iteratively from the sectional equilibrium equation. Subsequently, joint shear V_j can be determined using the following steps: (1) calculate the beam-end forces P_b^l and P_b^r from the moment equilibrium equations of the left and right beams, respectively; (2) determine column shear V_{col} ($V_{col}^u = V_{col}^l$) from the moment equilibrium equation of the connection; and (3) obtain V_j from the equilibrium equation of the horizontal forces of the joint.

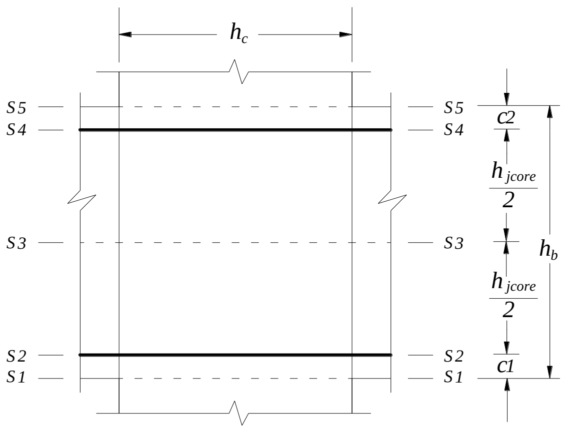


Fig. 3 Illustration of five horizontal joint sections

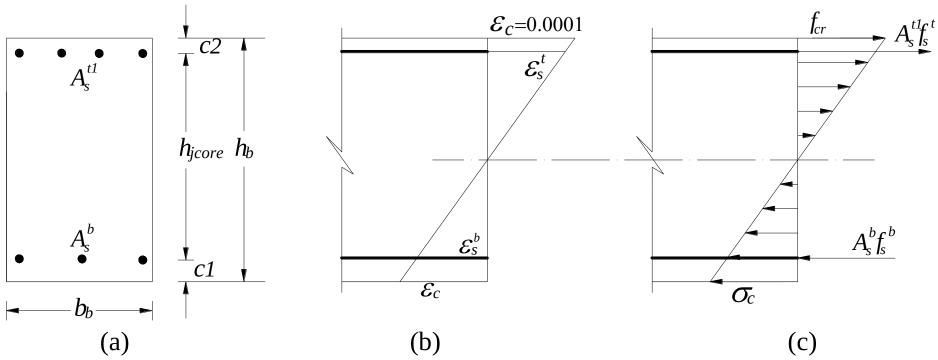


Fig. 4 Sectional analysis of left beam at cracking: (a) geometry; (b) strains; (c) stresses/forces

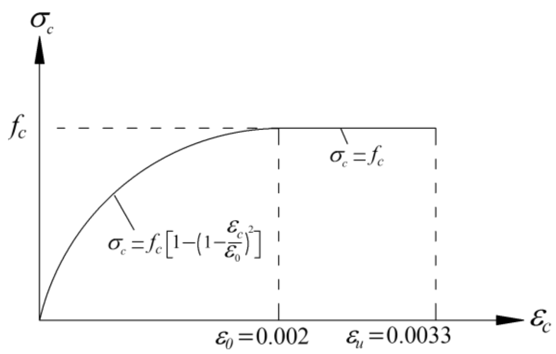


Fig. 5 Concrete stress-strain relationship

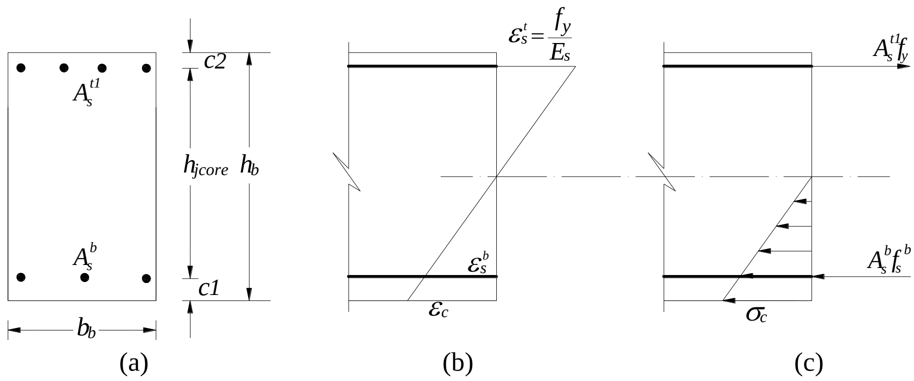
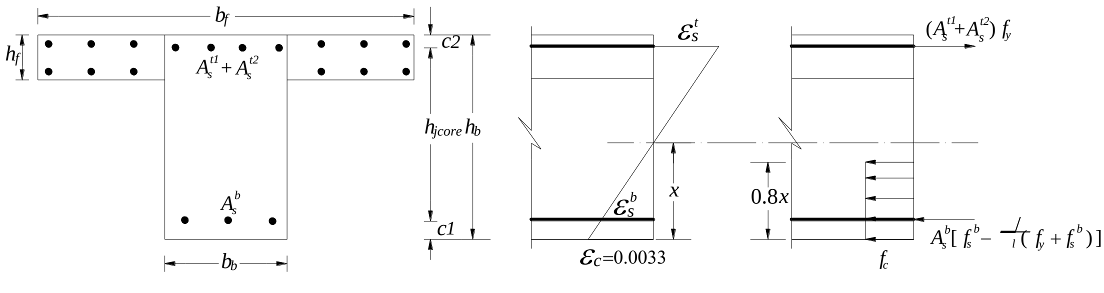


Fig. 6 Sectional analysis of left beam at initial yielding: (a) geometry; (b) strains; (c) stresses/forces

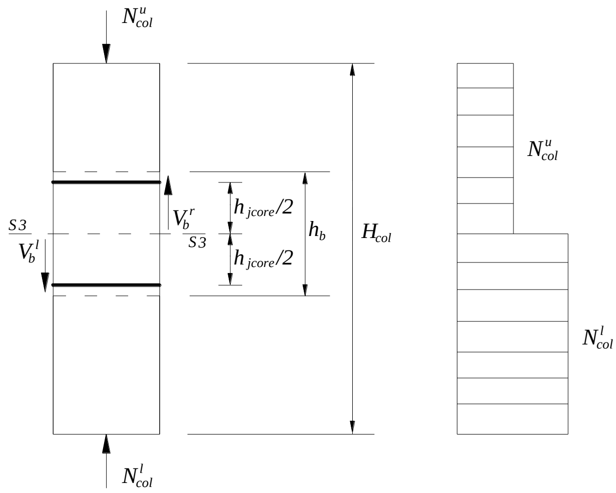
Joint shear at initial beam yielding at column faces. Beam axial forces N_b^l and N_b^r are taken as zero, the strains and stresses of the beam sections at the column faces are assumed to be as shown in Fig. 6 for the left beam, and the concrete stress-strain relationship in Fig. 5 is adopted to relate the concrete compressive stress σ_c to the strain ε_c. Using equilibrium equation to determine the strains and stresses of each beam section, joint shear V_j can then be determined following the same steps as described in the previous paragraph.

Joint shear at ultimate beam yielding at column faces. The strains and stresses of the beam sections at the column faces are assumed to be as shown in Fig. 7 for the left beam, the beam flange width b_f is determined as per ACI 318 (2008) so as to account for the effect of slab participation in beam flexure, and the extreme concrete compressive strain is taken as 0.0033 as per MCC (2002). Since yielding of under-reinforced framing beams under seismic action leads to beam elongation, restraint of the beam elongation by the columns induces axial compressive force in the beams (Zerbe and Durrani 1989). Hence, at the ultimate beam yielding at the column faces, the effect of beam axial compressive forces N_b^l and N_b^r on joint shear V_j should be taken into account. The information presented by Zhou and Zhang (2012) suggested that the upper limit of N_b^l and N_b^r might be taken as $0.1f_c b_b h_b$. On the other hand, bond deterioration in interior joints following the beam yielding at the column faces reduces the compressive stresses of the beam compression reinforcement at the column faces, and even makes the beam compression reinforcement in tension. To consider the effect of bond deterioration on joint shear, the stresses of



(a) (b) (c)

Fig. 7 Sectional analysis of left beam at ultimate yielding: (a) geometry; (b) strains; (c) stresses/forces



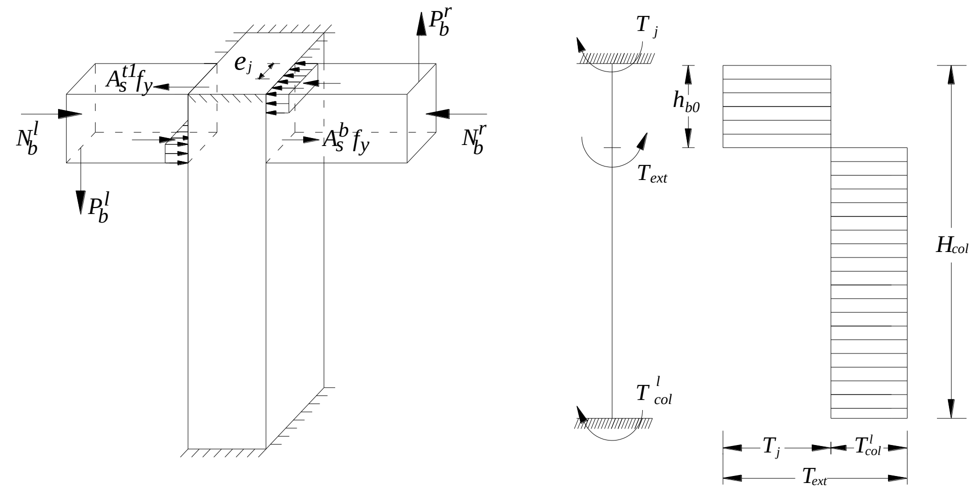
(a) (b)

Fig. 8 (a) vertical forces acting on column; (b)variation of column axial force

beam compression reinforcement at the left and right column faces are expressed as $[f_s^b - \phi_l(f_y + f_s^b)]$ (Fig. 7(c)) and $[f_s^t - \phi_r(f_y + f_s^t)]$, respectively, in which f_s^b and f_s^t are the stresses of beam compression reinforcement assuming perfect bond in the joint, ϕ_l and ϕ_r are bond deterioration factors ranging from zero (corresponding to perfect bond in the joint) to unity (when bond in the joint is completely lost). For given values of N_b^l, N_b^r, ϕ_l and ϕ_r, the strains and stresses of the beam sections at the column faces can be determined from the sectional equilibrium equations, and joint shear V_j can be obtained as described above.

2.3 Bending moment of horizontal joint sections

To simplify the calculation of joint bending moment M_j, vertical shears applied by framing beams on the joint V_b^l (= P_b^l) and V_b^r (= P_b^r) are assumed to act at S3 of the joint (Fig. 8(a)). From the stresses/forces acting on the column/joint, M_j can be determined from the moment equilibrium equation of the joint. It should be noted that at S3, M_j has two values, denoted by M_j^{31} and M_j^{32}, respectively.



(a) (b)

Fig. 9 (a) forces applied by eccentric beams on column; (b) torques in joint and column

2.4 Axial forces of horizontal joint sections

Since V_b^l and V_b^r are assumed to act at S3 (Fig. 8(a)), variation of axial force over the column depth is as shown in Fig. 8(b). It can be seen that the axial forces of S1 and S2 are equal to that of the lower column $N^l{}_{col}$, and the axial forces of S4 and S5 are the same as that of the upper column $N^u{}_{col}$.

Axial force of a column in an RC frame building subjected to a strong earthquake consists of three components. The first component is caused by gravity loading of the building and has two characteristics: (1) its magnitude is indeterminate, since actual distribution of floor live load in the building is unknown when an earthquake takes place; (2) its magnitude does not change throughout the earthquake. The second component is caused by horizontal seismic action and varies with the lateral story drift of the building. For an RC frame building with regular beam spans and uniform distribution of gravity loading, this component of axial force is insignificant in interior columns but significant in exterior columns (Ghannoum and Moehle 2012). The third component is induced by vertical seismic motion and alternates between compressive and tensile axial forces. Hence, axial force of a column in a frame building during a strong earthquake is indeterminate and may vary in a wide range.

2.5 Torque of eccentric interior joints

Beam-column connections can be classified into concentric and eccentric connections. The beam centerlines of eccentric connections are offset from the column centerlines. When an eccentric connection is subjected to seismic action, torque is induced in the joint (Teng and Zhou 2003). To evaluate the seismic behavior of eccentric joints, joint torque has to be estimated.

Fig. 9(a) shows a column in an RC frame building and the stresses/forces applied by eccentric framing beams on the column at the beam yielding at the column faces. The external torque applied by the eccentric beams on the column T_{ext} can be estimated by

$$T_{ext} = [(A_s^{t1} f_y + N_b^l) + A_s^b f_y] e_j \tag{1}$$

where A_s^{t1} and A_s^{b} = areas of beam top reinforcement (not including slab reinforcement) and beam bottom reinforcement, respectively; e_j= joint eccentricity. Assuming that T_{ext} acts at S2, variation of internal torque over the column height can be simplified as shown in Fig. 9(b).

Under the action of T_{ext}, the column rotates about the column centerline. However, the column rotations at the levels of the column top and bottom are restrained by the floor slabs of the building. Hence, torsional compatibility equation of the column can be expressed as

$$\frac{T_j h_{b0}}{(GC)_j} - \frac{(T_{ext} - T_j)(H_{col} - h_{b0})}{(GC)_{col}} = 0 \tag{2}$$

where T_j = joint torque; H_{col} = column height; h_{b0} = effective beam depth; $(GC)_j$ and $(GC)_{col}$ = elastic or secant torsional rigidities of the joint and the column, respectively, depending on whether the joint and the column have cracked or not under seismic action (Tavio and Teng 2004). The torsional rigidity $(GC)_j$ differs from $(GC)_{col}$ due to the effects of two factors. One factor is the participation of floor slab and transverse beams in resisting the joint torsion that enhances $(GC)_j$; the other factor is the joint damage induced by cyclic joint shear and torque that reduces $(GC)_j$. The torsional rigidities $(GC)_j$ and $(GC)_{col}$ can be conveniently related to each other by

$$(GC)_j = k(GC)_{col} \tag{3}$$

where k is a coefficient. It can be expected that k reduces from larger than unity prior to joint cracking to smaller than unity after severe joint cracking during a strong earthquake. For a given value of k , solving T_j from Eqs. (2) and (3) gives

$$T_j = \frac{k(\xi - 1)}{1 + k(\xi - 1)} T_{ext} \tag{4}$$

where $\xi = H_{col} / h_{b0}$.

3. Average joint shear stress and average joint shear strain

Average shear of joint core V_{jave} (referred to as "average joint shear" hereafter) can be defined as

$$V_{jave} = \frac{\int_0^{h_{jcore}} V_j dy}{h_{jcore}} \tag{5}$$

where h_{jcore}= height of joint core. It can be derived that V_{jave} can be calculated from the column shears V^u_{col} and V^l_{col} by

$$V_{jave} = -V_{col}^u \left(\frac{H_{col}^u}{h_{jcore}}\right)\beta_1 - V_{col}^l \left(\frac{H_{col}^l}{h_{jcore}}\right)\beta_2 \tag{6}$$

whereH^{u}_{col} and H^{l}_{col}= distances from beam centerline to column top and bottom, respectively; $\beta_1 = 1 + h_c / L_b - h_b / (2H^u_{col})$; $\beta_2 = 1 + h_c / L_b - h_b / (2H^l_{col})$. Derivation of Eq. (6) is similar to the derivation of V_{jave} for exterior joints presented in the companion paper (Zhou and Zhang 2012). If $N_b^l = N_b^r$, then, $V^u_{col} = V^l_{col}$ (= V_{col}), and Eq. (6) can be simplified into

$$V_{jave} = -V_{col}\left(\frac{H_{col}}{h_{jcore}}\right)\beta \tag{7}$$

where β=1+h_c/L_b−h_b/H_{col}.

Average shear stress of joint core τ_{jave} (referred to as "average joint shear stress" hereafter) can be defined by

$$\tau_{jave} = \frac{V_{jave}}{A_j} \tag{8}$$

where A_j=effective joint area to be determined as per ACI 318 (2008). Using Eq. (6) or (7), τ_{jave} can be calculated from the column shears.

Average shear deformation of joint core γ_{jave} (referred to as "average joint shear strain" hereafter) can be defined by (Fig. 10(a))

$$\gamma_{jave} = \frac{\int_0^{h_{jcore}} \gamma_j dy}{h_{jcore}} \tag{9}$$

where γ_j=shear deformation of an infinitesimal portion of joint core.

When a beam-column joint is modeled as a two dimensional member in structural analysis, the average joint shear stress τ_{jave} and average joint shear strain γ_{jave} defined consistently in this research can be used to establish joint shear constitutive relationship under seismic action (Fig. 10(b)). Average joint shear strain is a critical joint performance index; determination of average joint shear strain from the applied average joint shear stress under seismic action provides critical information for evaluating local joint behavior and its effect on global frame behavior. Detailed discussion of this point is available in the companion paper (Zhou and Zhang 2012).

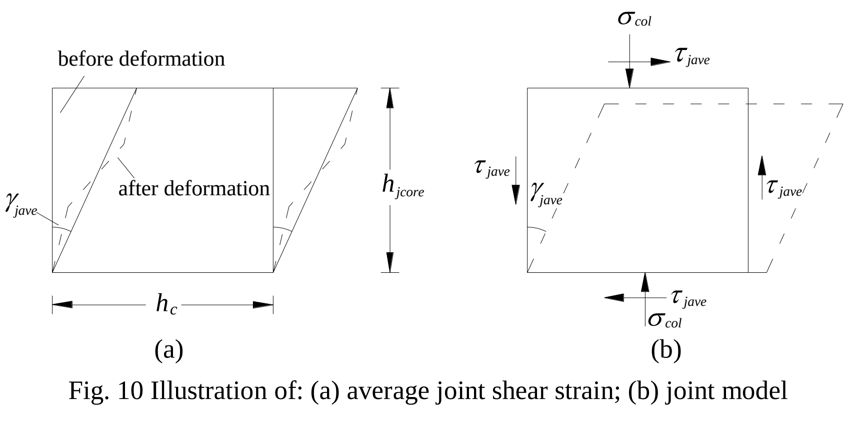
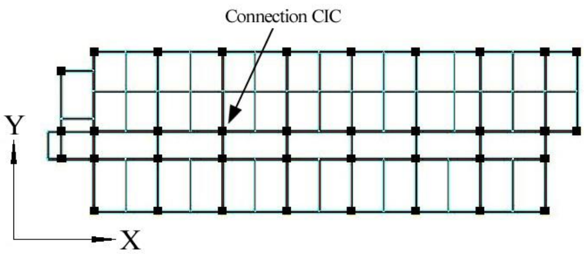


Fig. 10 Illustration of: (a) average joint shear strain; (b) joint model

(a)



(b)

Fig. 11 Prototype building and Connection CIC: (a) photograph; (b) second floor plan

Table 1 Geometrical and material data of Connections CIC and EIC

Beam	L_b	b_b	b_f	h_b	h_f	$c1$	$c2$	A_s^{t1}	A_s^{t2}	A_s^b	f_y	f_c
	7200	300	1800	700	110	37.5	37.5	1900	589	1000	440/360	20.1/14.3
Column	H_{col}	H_{col}^u	H_{col}^l	b_c	h_c	c3	A_s^u	A_s^l	f_y	f_c	$N/(Af_c)$	
											upper	lower
	4250	1950	2300	600	600	42.5	4000	7000	440/360	23.4/16.7	0.47	0.58

Notes: 1. Units: mm for dimension, mm^2 for area, and N/mm^2 for strength;
2. b_f = width of beam flange determined according to Clause 8.12.2 of ACI 318 (2008);
3. A_s^{t2}= equivalent area of slab reinforcement within b_f, including 100% of the top layer and 50% of the bottom layer of slab reinforcement within b_f;
4. c3 = concrete cover + half diameter of column longitudinal rebars;
5. A_s^u and A_s^l= areas of longitudinal rebars of upper and lower columns, respectively;
6. HRB400 rebars are used for beam and column longitudinal rebars. Both the nominal yield strength (taken as 1.1 times the strength grade) and the design yield strength (determined as per MCC (2002)) are shown for HRB400 rebars;
7. C30 and C35 concretes are used for beams and columns, respectively. Both the nominal and design compressive strengths determined as per MCC (2002) are shown for C30 and C35, respectively;
8. $N/(Af_c)$ = column axial force ratio (N = column design axial force, A = column sectional area,f_c=design concrete strength of column). The values shown are determined by PKPM.

4. Numerical results of internal forces of two interior joints under seismic action

4.1 Description of Connections CIC and EIC

A six-story office building in the campus of Hainan University (Fig. 11(a)) is selected as prototype building for this research. An RC frame is designed for this building for a seismic intensity represented by a peak ground acceleration of 0.2g (g = gravity acceleration) in accordance with the Chinese codes (MCC 2001a, MCC 2001b, MCC 2002) and typical design practice in China. Description and main design information of the frame are available in the companion paper (Zhou and Zhang, 2012). A concentric interior connection designated as “CIC” is extracted from the second floor of the frame (Fig. 11(b)) for the analysis in this research. The geometrical and

Table 2 Column-to-beam flexural strength ratios of Connections CIC and EIC

Strength type	Left beam	Right beam	Upper column		Lower column		$\frac{\sum M^R_{col}}{\sum M^R_b}$
	M^R_b	M^R_b	N^u_{col}	M^R_{col}	N^l_{col}	M^R_{col}	
Nominal	673.5	297.1	2142.7	784.9	2599.8	1103.9	1.95
Design	546.6	241.2	2573.3	660.4	3122.6	883.7	1.96

Notes: 1. Units: kN for axial force, and kN.m for flexural strength;
2. Nominal column axial force is the combined effect of non-factored loads, and design column axial force is the combined effect of factored loads, determined from PKPM results as per MCC (2001a);
3. Nominal flexural strength is calculated using nominal material strengths and nominal axial force, and design flexural strength is calculated using design material strengths and design axial force.

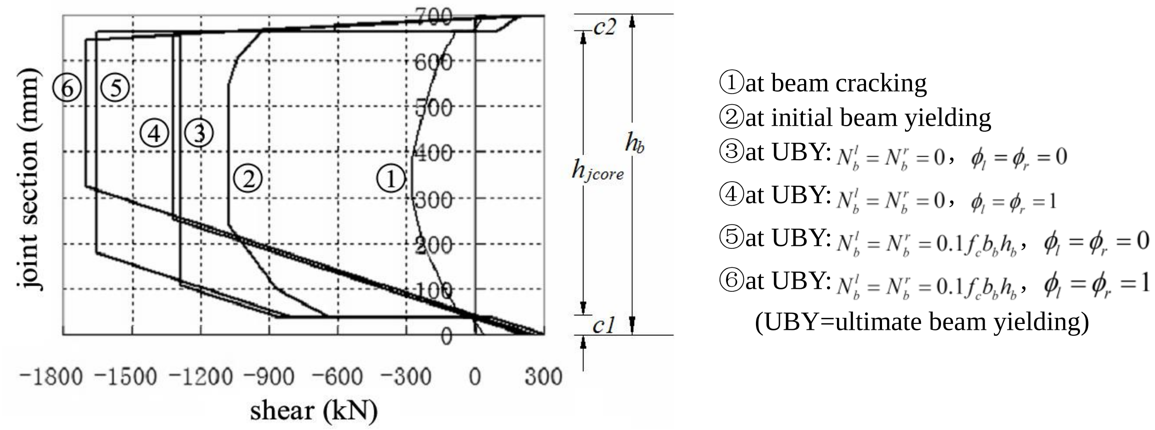


Fig. 12 Nominal joint shears of Connections CIC and EIC

material data of Connection CIC are shown in Table 1. Connection EIC is a one-sided eccentric companion connection of CIC with an eccentricity of 150 mm between the column and beam centerlines. The column-to-beam flexural strength ratios calculated as per MCC (2002) for seismic loading in the +X direction are presented in Table 2. It can be seen that the "strong column-weak beam" requirement is well satisfied for Connections CIC and EIC.

4.2 Internal forces of Connections CIC and EIC under seismic action

Table 3 and Fig. 12 show the numerical results of nominal column and joint shears of Connections CIC and EIC under seismic loading in the $+X$ direction. Several observations can be made from Table 3 and Fig. 12: (1) joint shear V_j within the joint core is much larger than outside the joint core, hence, seismic joint damage mainly occurs within the joint core; (2) since V_j is not constant in magnitude within the joint core, the average joint shear V_{jave} may differ from the maximum joint shear V_{jmax} significantly. Hence, it is the average joint shear stress τ_{jave} instead of the maximum joint shear stress τ_{jmax} ($=V_{jmax}/A_j$) that can be related to the average joint shear strain γ_{jave} by joint shear constitutive relationship; (3) bond deterioration in the joint increases V_{jmax} and τ_{jmax} slightly, but reduces V_{jave} and τ_{jave} significantly, suggesting that bond deterioration in interior joints may alleviate seismic joint damage;(4) at the ultimate beam yielding at the column faces, beam axial forces N_b^l and N_b^r induced by the beam elongation increase V_{jave} significantly and therefore aggravate seismic joint damage.

Table 4 and Fig. 13 present the numerical results of nominal joint bending moments of Connections CIC and EIC at the ultimate beam yielding at the column faces under seismic loading in the +*X* direction. It can be seen that: (1) the maximum joint bending moment is M_j^2 rather than

Table 3 Nominal column and joint shears of Connections CIC and EIC

Item	At beam cracking	At initial beam yielding	At ultimate beam yielding					
			$N_b^l=N_b^r=0$		$N_b^l=N_b^r=0.05f_cb_bh_b$		$N_b^l=N_b^r=0.1f_cb_bh_b$	
			$\phi_l=\phi_r=0$	$\phi_l=\phi_r=1$	$\phi_l=\phi_r=0$	$\phi_l=\phi_r=1$	$\phi_l=\phi_r=0$	$\phi_l=\phi_r=1$
V_{col}	40.8	196.7	249.1	217.3	278.8	238	306.2	256.6
$V_{j\max}$	-278.8	-1077.7	-1286	-1317.8	-1467.5	-1508.2	-1651	-1700.7
V_{jave}	-205	-1011.4	-1261	-1089.8	-1413.1	-1198.3	-1555	-1295.1

Notes: 1. Unit: kN for shear;
2. Column and joint shears are calculated using nominal material strengths;
3. $V_{col} = V^u_{col} = V^l_{col}$

Table 4 Nominal joint bending moments of Connections CIC and EIC at ultimate beam yielding

N_b^l and N_b^r	ϕ_l and ϕ_r	M_j^1	M_j^2	ΔM_j^3	M_j^4	M_j^5
$N_b^l=N_b^r=0$	$\phi_l=\phi_r=0$	485.8	490.9	-88.3	-385.9	-398.6
	$\phi_l=\phi_r=1$	423.8	427.7	-76.9	-330.4	-347.7
$N_b^l=N_b^r=0.05f_cb_bh_b$	$\phi_l=\phi_r=0$	543.6	549.8	-98.7	-432.1	-446
	$\phi_l=\phi_r=1$	464.2	468.9	-84.3	-364.4	-380.9
$N_b^l=N_b^r=0.1f_cb_bh_b$	$\phi_l=\phi_r=0$	597.1	604.3	-108.4	-476	-489.9
	$\phi_l=\phi_r=1$	500.3	505.7	-90.9	-394.7	-410.5

Notes: 1. Unit: kN.m for bending moment;
2. Joint bending moment is calculated using nominal material strengths;
3. $\Delta M_j^3 = M_j^{32} - M_j^{31}$

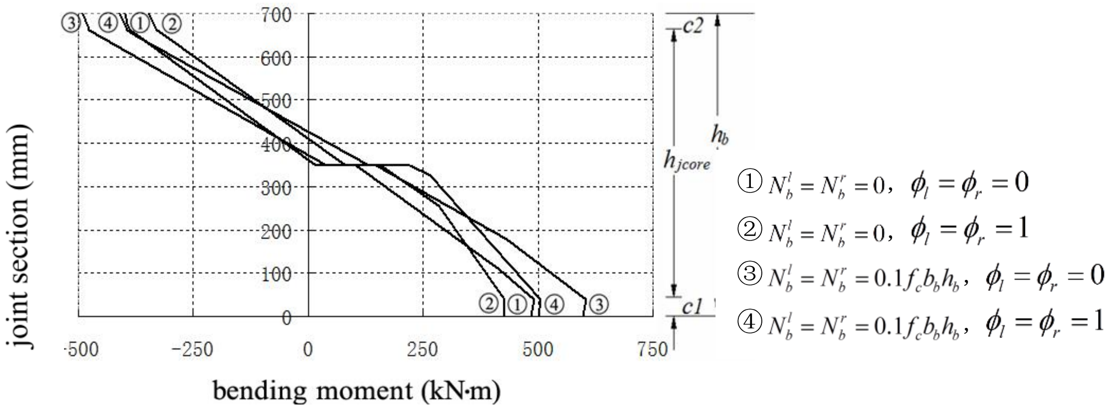


Fig. 13 Nominal joint bending moments of Connections CIC and EIC at ultimate beam yielding

Table 5 Nominal joint and column torques of Connection EIC at ultimate beam yielding

N_b^l and N_b^r	T_{ext}	k =1.5		k =1.0		k = 0.5	
		T_{col}	T_{j}	T_{col}	T_{j}	T_{col}	T_{j}
$N_b^l = N_b^r = 0$	191.4	19.3	172.1	27.6	163.8	48.2	143.1
$N_b^l = N_b^r = 0.05 f_c b_b h_b$	223	22.5	200.5	32.1	190.9	56.2	166.8
$N_b^l = N_b^r = 0.1 f_c b_b h_b$	254.7	25.7	229	36.7	218	64.1	190.6

Notes: 1. Unit: kN.m for torque;
2. Torque is calculated using nominal material strengths.

M_j^1 or M_j^5; (2) bond deterioration in the joint reduces joint bending moment; (3) beam compressive axial forces N_b^l and N_b^r increase joint bending moment.

Table 5 shows the numerical results of nominal torques in the joint and lower column of Connection EIC at the beam yielding at the column faces under seismic loading in the +X direction. It can be seen that: (1) the joint torque T_j is much larger than the column torque T_{col}, indicating that the external torque T_{ext} is mainly resisted by the joint; (2) when the joint-to-column torsional rigidity ratio k reduces during a strong earthquake, T_j reduces, but T_{col} increases; (2) the beam compressive axial forces N_b^l and N_b^r increase both T_j and T_{col}.

The numerical results of the axial forces of the upper and lower columns of Connections CIC and EIC N^u_{col} and N^l_{col}, determined from the PKPM results as per MCC (2001a) without considering the effect of vertical seismic motion, are shown in Table 2 for seismic loading in the +X direction. As discussed previously, the joint axial forces N_j^1 and N_j^2 are equal to N^l_{col}, and N_j^4 and N_j^5 are of the same magnitude as N^u_{col}.

4.3 Identification of critical joint sections

From the numerical results presented above, the internal forces of S1 and S2 of Connections CIC and EIC can be compared as follows: V_j^2 is much larger than V_j^1; M_j^2 is slightly larger than M_j^1; N_j^2 is equal to N_j^1; and T_j^2 is larger than T_j^1. Similar comparison can be made between S4 and S5. It is clear that S2 and S4 of Connections CIC and EIC have higher capacity demands than S1 and S5. However, S2 and S4 have lower capacities than S1 and S5, because seismic damage within the joint core is more severe than outside the joint core. It can thus be concluded that S2 and S4 are the critical joint sections of Connections CIC and EIC.

5. Effects of joint shear and torque on column-to-beam flexural strength ratio of interior connections under seismic action

5.1 Effect of joint shear on flexural strengths of critical joint sections under seismic action

The effect of cyclic joint shear on the flexural strength of a critical joint section (S2 or S4) of Connection CIC under seismic loading in the +X direction is evaluated as follows: (1) determining the axial force of the section (equal to N^l_{col} or N^u_{col}, as discussed previously), and assuming it to remain constant after the beam yielding at the column faces; (2) expressing the joint concrete

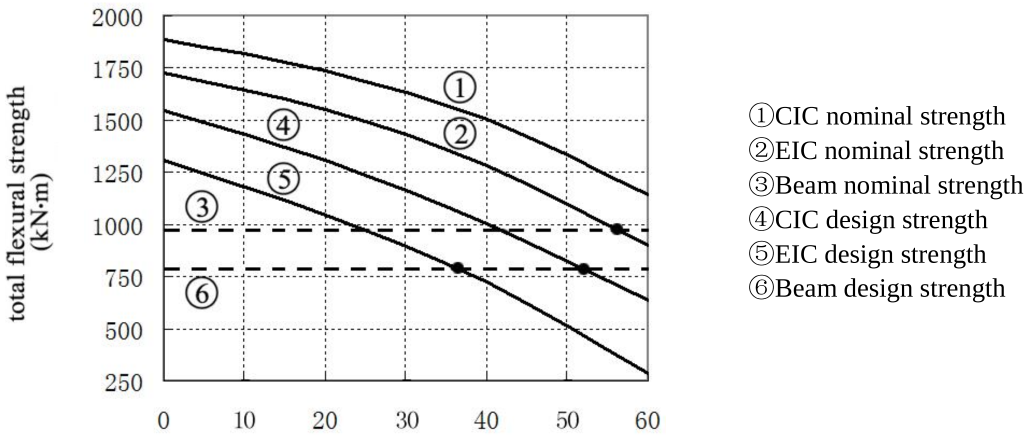


Fig. 14 Total flexural strengths of critical joint sections of Connections CIC and EIC

Table 6 Flexural strengths of critical joint sections of Connection CIC

η		0%	20%	40%	60%
Nominal strength	M_j^{4R}	784.9	718.4	623.2	467.1
	M_j^{2R}	1103.9	1017.1	882.6	675.9
	Total	1888.8	1735.5	1505.8	1143
Design strength	M_j^{4R}	660.4	568.1	429	258.3
	M_j^{2R}	883.7	740.2	572.5	379.8
	Total	1544.1	1308.3	1001.5	638.1

Notes: 1. Unit: kN.m for flexural strength;
2. η=reduction factor of joint concrete strength;
3. Nominal flexural strength is calculated using nominal material strengths and nominal axial force, and design flexural strength is calculated using design material strengths and design axial force.

strength reduced by cyclic joint shear in terms of $(1-\eta)f_c$ (η=reduction factor; f_c=original joint concrete strength); (3) selecting a value for η, and calculating the flexural strength of the section for the axial force and the reduced concrete strength as per MCC (2002). Table 6 and Fig. 14 show the numerical results of the flexural strengths of S2 and S4 of Connection CIC.

5.2 Effect of joint torque on flexural strengths of critical joint sections under seismic action

The effect of cyclic joint torque T_j on the flexural strength of a critical joint section of Connection EIC under seismic loading in the +X direction is estimated as follows: (1) selecting a value of k (= joint-to-column torsional rigidity ratio) and a value of N^l_b (= axial force of left beam), and estimating T_j by Eqs. (1) and (4); (2) calculating the area of longitudinal reinforcement required to resist T_j in accordance with MCC (2002) (denoting the area by A_T); (3) subtracting A_T from the total area of longitudinal reinforcement (denoting the result as A_F); (4) using A_F to calculate the flexural strength of the section as described in the previous paragraph. Table 7 and

Table 7 Flexural strengths of critical joint sections of Connection EIC

η		0%	20%	40%	60%
Nominal strength	M_j^{4R}	697.8	625.8	513.7	349.6
	M_j^{2R}	1031	922.6	771.3	550.4
	Total	1728.8	1548.4	1285	900
Design strength	M_j^{4R}	541.3	437.1	296.2	81.4
	M_j^{2R}	766.1	608.5	428.5	203.5
	Total	1307.4	1045.6	724.7	284.9

Notes: 1. Unit of flexural strength is kN.m;
2. The numerical results in the table are for T_j corresponding to k=1 and N^l_b=0;
3. Nominal flexural strength is calculated using nominal material strengths, nominal axial force, and nominal joint torque; design flexural strength is calculated using design material strengths, design axial force, and design joint torque;
4. Design joint torque is taken as 1.1 times nominal joint torque.

Table 8 Values of η at initiation of "joint-yielding mechanism" of Connections CIC and EIC

Connection	CIC		EIC	
Type of flexural strength	Nominal	Design	Nominal	Design
η	65%	52%	56%	36%

Fig. 14 present the numerical results of the flexural strengths of S2 and S4 of Connection EIC for k=1 and N^l_b=0.

5.3 Effect of joint shear and torque on column-to-beam flexural strength ratio of interior connections under seismic action

When an RC frame is subjected to a strong earthquake, flexural strengths of the critical sections of a joint reduce considerably, due to the effects of cyclic joint shear and torque; however, the flexural strengths of the framing beams at the joint increase, because of the slab participation in the beam flexure and the beam compressive axial force induced by the beam elongation. As a result, the column-to-beam flexural strength ratio at the joint decreases during a strong earthquake. When the column-to-beam flexural strength ratio reduces to unity, the bending moments of the critical joint sections reach the flexural strengths, resulting in the "joint-yielding mechanism" of seismically designed beam-column connections!

For Connections CIC and EIC, assuming that the flexural strengths of the framing beams are constant and equal to the values as shown in Table 2, the values of η (= reduction factor of joint concrete strength) at the initiation of the "joint-yielding mechanism" can be estimated from the condition that the sum of the flexural strengths of the critical joint sections equals the sum of the beam flexural strengths. The numerical results of η so determined are shown in Table 8 and Fig. 14. In spite that the column-to-beam flexural strength ratios calculated in accordance with the Chinese codes (with the effective slab width determined as per ACI 318 (2008)) are as high as about 2, reduction of joint concrete strength by 36% to 65% may trigger "joint-yielding mechanism" for Connections CIC and EIC, respectively. If the effects of column axial force fluctuation and beam axial force induced by a strong earthquake are considered, less reduction of joint concrete strength would lead to the “joint-yielding mechanism” for Connections CIC and EIC.

6. Conclusions

Detailed analysis of the internal forces of interior beam-column joints induced by seismic action is reported, numerical results of internal joint forces are presented for a pair of concentric and eccentric interior connections extracted from a seismically designed RC frame, and the two joint sections located at the levels of beam top and bottom reinforcement are identified as the critical joint sections.

Average joint shear stress and average joint shear strain are defined consistently, and formulas for calculating the average joint shear stress from the column shears are derived. The average joint shear stress and average joint shear strain can be used to establish joint shear constitutive relationship under seismic action.

A formula is proposed to estimate the torque in an interior eccentric joint induced by seismic action, and variation of the joint torque during a strong earthquake is discussed. This provides a possibility of evaluating the effect of joint torque on the seismic behavior of eccentric joints

Effects of joint shear and torque on the flexural strengths of critical joint sections are evaluated by reducing joint concrete strength, and numerical results are presented for a pair of interior concentric and eccentric beam-column connections extracted from a seismically designed prototype frame. In spite that the column-to-beam flexural strength ratios calculated as per the Chinese codes are as high as 2 for the two connections, reduction of the joint concrete strength may reduce the column-to-beam flexural strength ratios to unity and trigger the “joint-yielding mechanism” for the two connections.

Internal forces in beam-column joints induced by seismic action are complicated, and complexity of seismic joint behavior is essentially caused by the interaction of internal joint forces. The information presented in this paper and a companion paper (Zhou and Zhang 2012) provides a preliminary basis for analyzing the interaction of internal joint forces induced by seismic action.

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