2019

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The 2019 World Congress on
Advances in Structural Engineering and Mechanics (ASEM19)
Jeju Island, Korea, September 17 - 21, 2019

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ABSTRACT

The staggering numbers of eccentric reinforced concrete beam-column joints without seismic design details were used in existing RC frame building due to geometrical constraints, which implied high susceptibility of the building structures to anticipated seismic risk. Three exterior RC beam-column joints were fabricated and tested, which were applied reversed cyclic loads to simulate seismic action. In this study, the effects of stirrup ratio in joints and the eccentricity which is defined as the distance between the axis of the beam and column on seismic performance are investigated. The test results provide a further understanding of the failure mode and shear strength of exterior beam-column joints. It is shown that the eccentricity will significantly reduce the seismic performance and shear strength of the joints, which will cause the brittle failure of frame buildings, while the stirrups in the joint core can improve the seismic performance. To verify the availability of current codes in predicting the shear strength of eccentric beam-column joints with non-seismic detailed, the experimental results are compared with the predicted shear force of two non-seismic codes (HK code and Eurocode 2) and three seismic codes (Eurocode 8, NZS 3101 and ACI 318-14). The comparison results indicate that the existing non-seismic and seismic design codes of practice do not predict the shear strength of the exterior non-seismically designed joints precisely.

1. INTRODUCTION

The beam-column joint is one of the key components in typical reinforced concrete (RC) moment-resisting frame structures as the beam-column joint plays an important role in transferring the internal forces between the adjacent beams and columns. In post-earthquake reconnaissance (Moehle 1991, Sezen 2003, and EERI 2001), shear failure of joints was observed which destroyed the mechanism and led to the collapse of many RC buildings. However, the staggering numbers of the existing

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RC building structures built in the low or moderate seismic risk regions were traditionally designed without any seismic resistance details, which were mainly designed to resist the service loads. Indeed, neglecting the seismic design of beam-column joints imply high sensitivity to potential earthquake risk.

In the regions of low or moderate seismicity, such as in mid-America, the UK and Hong Kong, the seismic risk cannot be negligible although there is a geological advantage as they are far away from the boundary of the plate. Many typical earthquakes, such as the Newcastle in 1991 (EERI 1991), Turkey in 1999 (Sezen 2003) and Wenchuan in 2008, have repeatedly demonstrated that the RC beam-column joints without considering seismic resistance details are more vulnerable.

When the RC frame buildings are subjected to earthquake load, the possible brittleness will be concentrated in the beam-column joints. This is dependent upon not only the flexural capacity ratio of the beam to column, but also the detailing of transverse links in the joint core, which affect significantly the shear strength of the beam-column connection (Scott 1992 and Hegger 2003). It has been shown that severe damage and/or collapse of many RC framed buildings in recent earthquakes is the result of poor reinforcement detailing of the beam-column joints. It is necessary to maintain the integrity of the beam-column joint to avoid the sudden degradation of the brittle failure of the frame structure.

Eccentric RC beam-column joints, which largely required by architectural considerations in practice, were extensively used in existing RC frame structures. The eccentricity, which is formed by the difference in the axis between the beam and the column, generates torsional moment and affects the ductility, shear strength and other seismic behaviours of the eccentric joints. Lawrance (1991), Joh (1991), and Raffaelle (1995) reported that early degeneration of ductility and shear strength was observed in the eccentric beam-column joints with square columns. Teng (2003) indicated that the stiffness and strength degradation was observed when the eccentric joints were subject to cyclic loading. Lee (2007) reported the experimental results which show that eccentricity had negative effects on the seismic performance. Nonetheless, only limited results of non-seismic detailed eccentric exterior joints have been reported in the literature.

In this study, three 2/3-scale RC exterior beam-column joints were designed according to the Hong Kong Code of Practice (HKSUC 2013), fabricated, and tested under reversed cyclic-load. The primary intention of this project is to study the effects of the eccentricity and the stirrup ratio in joints on the seismic behaviour of non-seismic detailed RC beam-column joints subjected to simulated seismic loading. Then, by comparing the experimental results with the predicted values of three seismic and two pre-seismic design codes, which are widely used and include Eurocode 2, HK Code, Eurocode 8, NZS 3101 and ACI 318-14, the effectiveness of the current codes for predicting the shear strength of beam-column joints with non-seismic detailed is evaluated.

2. EXPERIMENTAL PROGRAMME

2.1 Specimens

The geometric dimensions of the three beam-column joints are the same, with the cross-section dimension of the beam is 150 mm × 450 mm and the column is 300 mm × 300 mm. The longitudinal reinforcement of the column is 4T20, and the beam is reinforced with longitudinal reinforcement 2T20 at the top and bottom, respectively. The diameter of the stirrup is 10 mm, and the details are shown in Fig. 1.

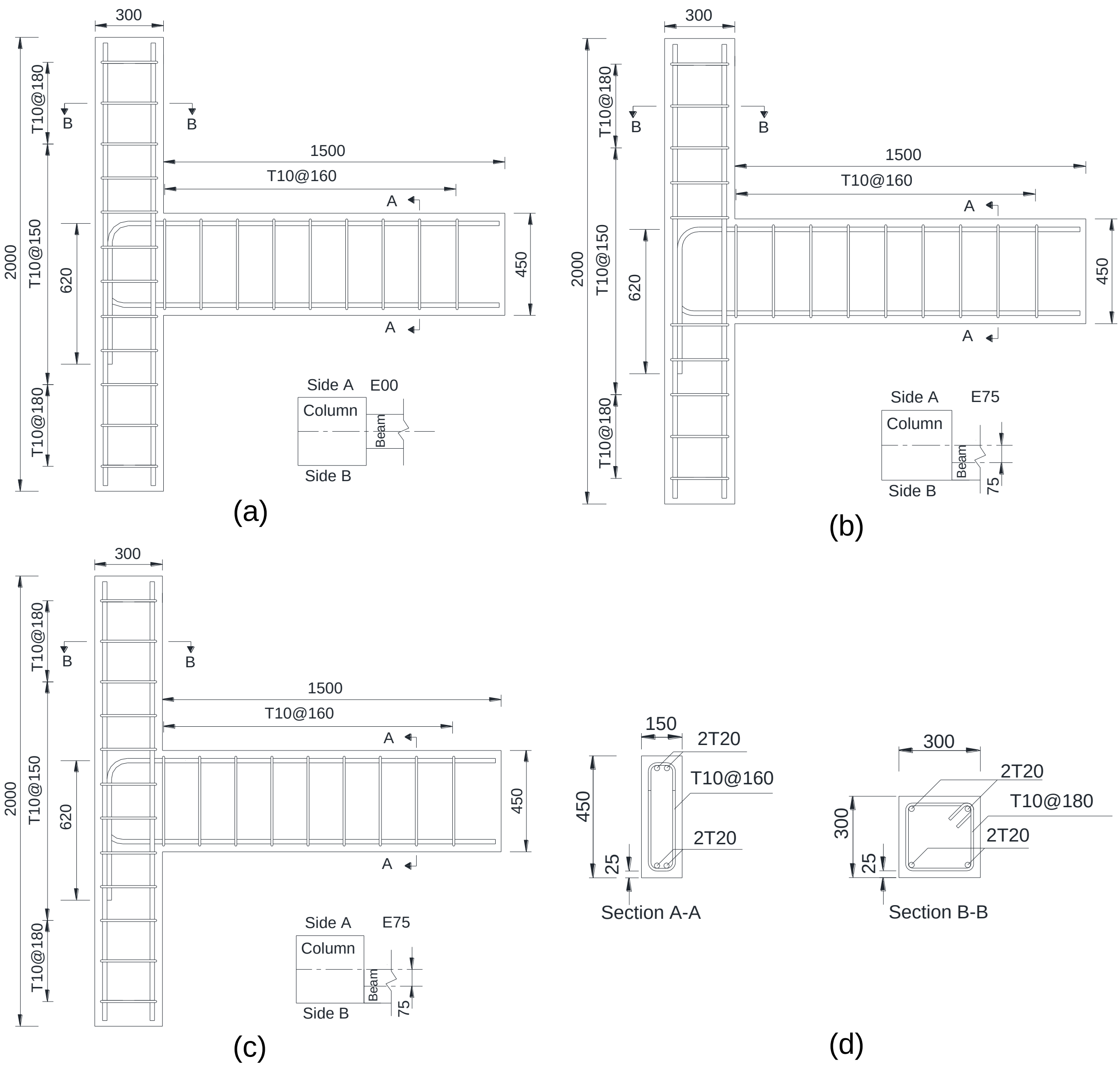


Fig. 1 Details of specimens (dimensions in mm) (a) specimen JB-2T-E00, (b) JB-0T-E75, (c) JB-2T-E75, (d) reinforcement details of beams and columns

(a) As shown in Fig. 1(a), the eccentricity (*e*) of the specimen named JB-2T-E00 is 0 mm, which refers to the distance between the centerlines of the beam and column, and there is no stirrup in the core of the joint.

(b) The eccentricity of the specimen named JB-0T-E75 is 75 mm, which is 1/4 of column width, and there is no stirrup in the core of the joint too.

(c) The specimen JB-2T-E75 is reinforced with the horizontal links of 2T10 in the joint core and the eccentricity is 75mm.

The reinforcement used in this study is the high strength bars, which have high-strength and strong ductility with the yield strength, f_y, of 500 N/mm^2. The compressive strengths of concrete are summarized in Table 1.

Table 1 Material properties

Specimen	JB-2T-E00	JB-0T-E75	JB-2T-E75
Concrete compressive strength, f_{cu} (f'_c): MPa	40.1(32.1)	44.38(35.5)	42.3(33.8)

2.2 Experimental set-up and load

The experimental set-up used in this investigation is illustrated in Fig. 2. Rotate the specimen 90°, that is, the column is in the horizontal position and the beam is in the vertical position for convenience testing.

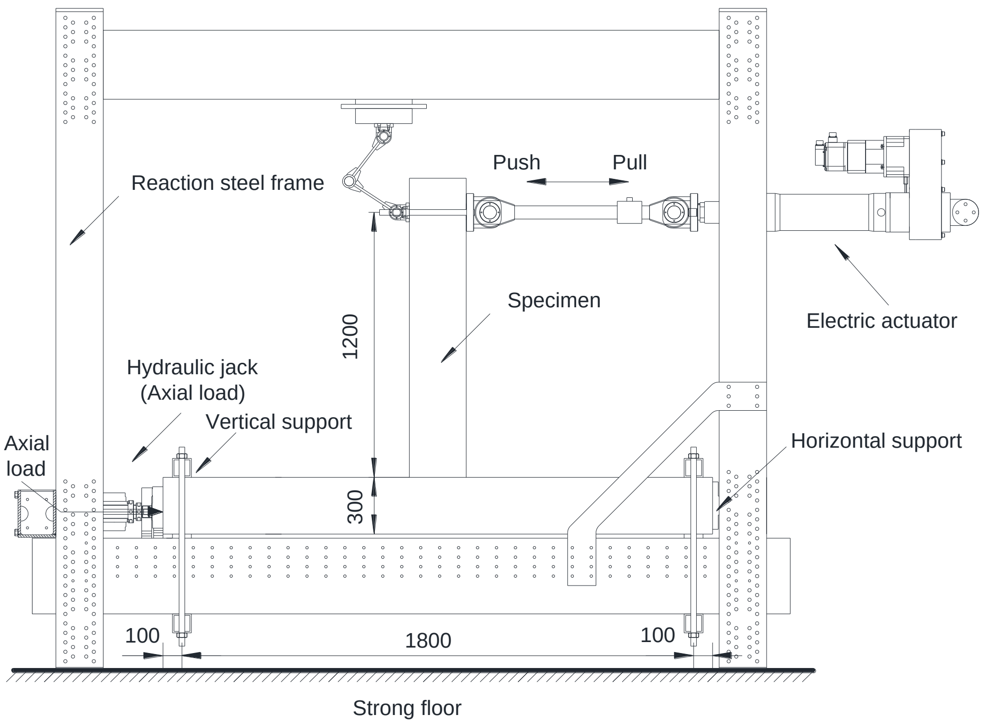


Fig. 2 Test set-up

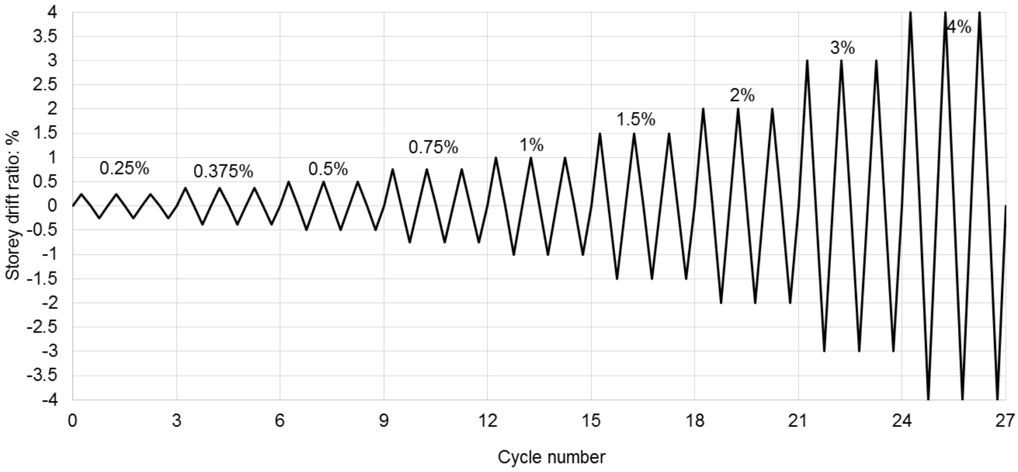


Fig. 3 Loading history

An axial load, which is equal to 10% of the column capacity, is applied to the column to simulate the gravity load from upper floors. The reversed cyclic loading, as shown in Fig. 3, is applied to the beam end in a quasi-static mode controlled by the displacement mode, and each target lateral displacement consisting of three cycles at monotonically increasing drift levels (0.25%, 0.375%,0.5%, 0.75%, 1.0%, 1.5%, 2.0%, 3.0% and 4.0%). The reversed cyclic loading is defined by the storey drift ratios, where the storey drift ratio, Δ, is defined in Eq. (1). The specimens are considered to be failed when the strength of specimens is reduced to 80% of the peak load.

$$\Delta = \frac{\delta}{L_b + 0.5h_c} \times 100\% \tag{1}$$

where δ is the displacement at the level of cyclic loading; L_b and h_c are the beam length and the depth of the column, respectively.

3. TEST RESULTS

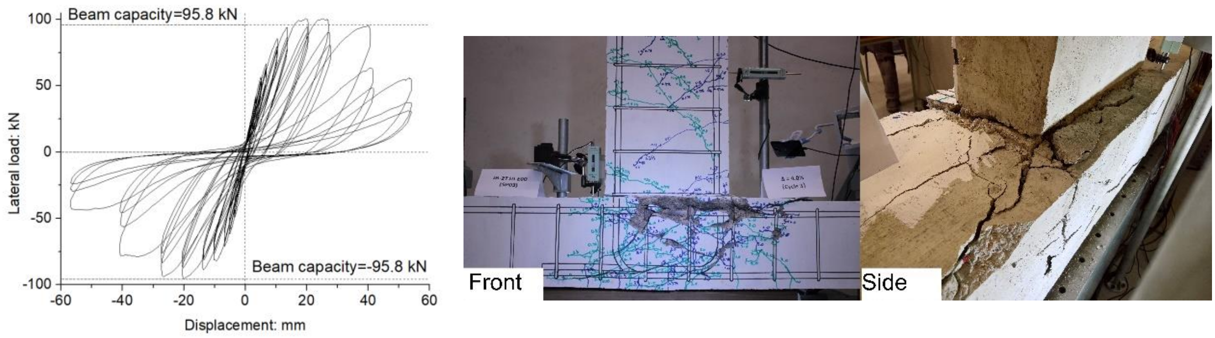
3.1 Damage characteristic and hysteretic behavior

Table 2 shows the maximum experimental load applied at the end of the beam, and the hysteretic behaviours and the cracks patterns at the failure of the specimens presented in Fig. 4.

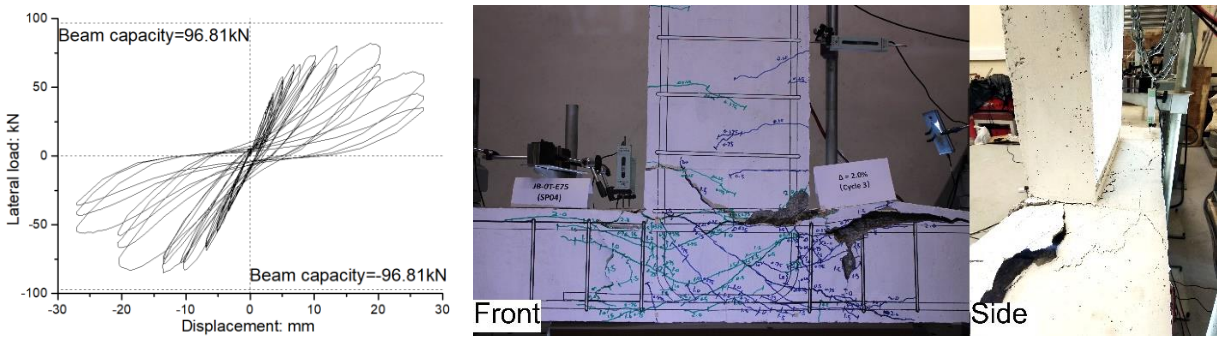
Visible crossing cracks were discovered in the joint cores of the three specimens, and the concrete is obviously crushed and flaked. For specimen JB-2T-E00, it can be seen from the side view that the failure condition on both side A and side B is similar, where a large number of cracks can be observed. It is worth noting, however, that for the other two eccentric joints, the damage on the side B is significantly more obvious than that on the side A. This shows that the eccentricity leads to the non-uniform stress of the beam-column joints under the earthquake, which is unfavorable to the seismic performance of the RC joints.

Table 2 Maximum experimental loads and shear strength

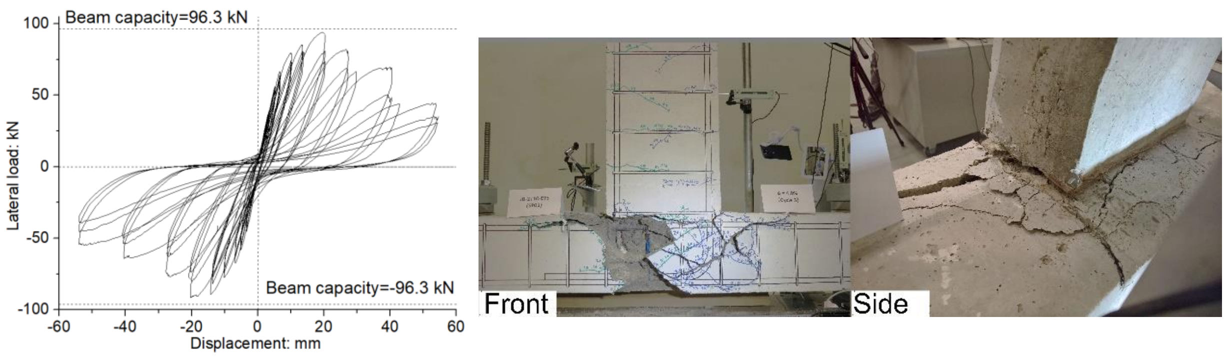
Specimen	Maximum test load P_{max}: kN	Beam capacity P_n	P_{max}/ P_n	Joint shear strength: kN	Normalised shear stress	
					$v_j/\sqrt{f_c'}$	Relative value
JB-2T-E00	100.64	95.83	1.05	255.85	0.50	1.00
JB-0T-E75	84.77	96.81	0.88	215.50	0.40	0.80
JB-2T-E75	94.13	96.36	0.98	239.30	0.46	0.92



(a) Specimen JB-2T-E00



(b) Specimen JB-0T-E75



(c) Specimen JB-2T-E75

Fig. 4 Hysteretic cuvers and the cracks patterns

The maximum experimental load is 105% of the beam capacity, for specimen JB-2T-E00 as shown in Fig. 4 and Table 2, and the specimen failed in a ductile mode. The other eccentric specimens with the maximum experimental load are 88% and 98% of the beam capacity, respectively, failed before yielding of longitudinal beam steel bars, and this brittle failure is unacceptable.

3.2 Joint shear strength

The shear strength is an important factor to evaluate the seismic performance of specimens, which can be calculated by considering the joint subjected to the shear force transferred from the adjacent beam. The shear force, V_j, can be expressed by Eq. (2) (Paulay 1992).

$$V_j = T_b - V_{col} = \frac{PL_b}{0.9d_b} - \frac{P(L_b+0.5h_c)}{L_c} \quad (2)$$

where T_b and V_{col} are the tensile force in steel of the beam and the shear force of the column, respectively; P is the applied lateral load at the end of beam; L_b, L_c and d_b are the length of beam and column and the effective depth of the beam, respectively, and h_c is the depth of column.

Table 2 summarises the shear strength of the specimen, and the shear strength is normalized to eliminate the effect of concrete strength. For the convenience of comparison, taking specimen JB-2T-E00 as the reference specimen, we can see that the shear stress of the two eccentric joints is about 80%-90% of that of specimen JB-2T-E00 which show that eccentricity had negative effects on the seismic performance agrees well the conclusion study by Lee (2007).

3.3 Effects of the eccentricity and horizontal links

The P_{max}/P_n is 1.05 for specimen JB-2T-E00, while the P_{max}/P_n is 0.98 for specimen JB-2T-E75. That is to say, the specimen JB-2T-E75 failed in a brittle mode before yielding of longitudinal beam steel bars, nevertheless, the ductile failure was observed in specimen JB-2T-E00. The normalised shear stress of specimen JB-2T-E75 is 92% of that of specimen JB-2T-E00, which proves that the eccentricity reduces the shear strength of the RC joints when the beam-column joints have the same reinforcement.

For specimens with the same eccentricity, as presented in Table 2, the normalised shear stress for specimen JB-0T-E75 and specimen JB-2T-E75 are 0.8 and 0.92, respectively. In other words, the shear strength of specimen JB-0T-E75 is 87% of that of specimen JB-2T-E75. The horizontal links in the joint core can improve the seismic performance of eccentric beam-column joints.

4. COMPARISION WITH DESIGN CODES

The comparison between the experimental results and the predicted values by different design codes are shown in Table 3. The design codes include two non-seismic design codes (Eurocode 2 and HK Code) and three seismic design codes (Eurocode 8, NZS 3101 and ACI 318-14).

4.1 Eurocode 2

From Eurocode 2, the shear strength is calculated by Eq. (3).

$$V_J = \left[C_{R,c}k(100\rho_1 f_c')^{1/3} + 1.5k_1\sigma_{cp}\right]b_w d + 0.9df_yA_{sw}/s \quad (3)$$

where $C_{R,c}$ is the shear strength of concrete; *k*=(1+√(200/*d*)≤2.0) with *d* in mm; ρ_1 is the tensile reinforcement ratio, and it is not greater than 0.02; the recommended value ofk_1 is 0.15; σ_{cp} is the axial stress of column due to axial loading, which is not greater than 0.2 times of concrete compressive strength; A_{sw} is cross-sectional area of the shear reinforcement and *s* is the spacing of links. In the calculation of this study, the partial factor of 1.5 for concrete is not considered (Parker 1997).

4.2 Hong Kong code

The non-seismic design code of Code of Practice for Structural Use of Concrete 2013, the shear strength can be calculated by Eq. (4) as there are no seismic provisions for the analysis of shear strength of the joints.

$$V_j = \frac{A_j f_y}{0.5 - \frac{C_j N}{0.8 A_c f_{cu}}} \quad (4)$$

where A_c and A_j are the area of column section and the area of effective horizontal joint shear reinforcement, respectively; C_j = 1 if joint has beams in one direction only; *N* is the design axial column load; and.

4.3 Eurocode 8

In Eurocode 8 Design of structures for earthquake resistance-Part 1: General rules, seismic actions and rules for buildings, the diagonal compression induced in the joint by the diagonal strut mechanism shall not exceed the compressive strength of concrete, the shear strength for exterior joints should be satisfied the Eq. (5). And for the joints providing horizontal links, the shear strength can be calculated by Eq. (6).

$$V_j = 0.8 \times \eta f_c b_j h_{jc} \sqrt{(1 - \frac{\upsilon_d}{\eta})} \quad (5)$$

$$V_j = [\left(\frac{A_{sh}f_y}{b_j h_{jw}} + f_{ctd}\right)(f_{ctd} + \upsilon_d f_c)]^{0.5} \times b_j h_{jc} \quad (6)$$

where $\eta = 0.6(1 - fc/250)$; f_c is the concrete compressive strength; b_j is the effective joint width; h_{jc} is the distance between extreme layers of column reinforcement; the υ_d is the normalised axial force in the column; A_{sh} is the total area of the horizontal links; f_{ctd} is the tensile strength of concrete; and h_{jw} and h_{jc} are the distance between the top and the bottom reinforcement of the beam and the distance between extreme layers of column reinforcement, respectively.

4.4 NZS 3101

The shear strength of a joint in the code of NZS 3101 (2017) is calculated by Eq. (7).

$$V_j = 0.2f_c'b_jh_c \text{ or } 10b_jh_c \quad (7)$$

where V_j is the lesser, and the effective width b_j is usually taken as the smaller of b_c or $b_w + 0.5h_c$, when $b_c \geq b_w$.

4.5 ACI 318-14

In ACI 318-14, the exterior beam-column joint shear strength for normal-weight concrete is specified as Eq. (8), of which the strength reduction factor of 0.85 is removed.

$$V_j = \sqrt{f_c'}A_j \quad (8)$$

where f_c' is the cylinder strength of concrete, A_j is the effective cross-sectional area within a joint, which is computed from joint depth times effective joint width.

4.6 Comparison

From the comparison between the experimental results and the predicted values by different design codes, the validity of mainly existing design codes in predicting the shear strength of the RC beam-column joints with non-seismically designed subjected to reversed cyclic loading is evaluated.

Table 3 Test results and comparisons with design codes

Specimen	Experimental shear strength V_{exp}: kN	Seismic design codes			Non-seismic design codes	
		V_{exp}/V_{ACI}	V_{exp}/V_{Nzs}	V_{exp}/V_{EC8}	V_{exp}/V_{HK}	V_{exp}/V_{EC2}
JB-2T-E00	255.85	0.50	0.44	0.96	0.67	1.03
JB-0T-E75	215.50	0.40	0.38	0.25	-	1.66
JB-2T-E75	239.30	0.46	0.39	0.88	0.63	0.96

For the two non-seismic design codes, the V_{exp}/V_{EC2} is about 1.0 and the V_{exp}/V_{HK} are in a range of 0.63 to 0.67, which indicates that the Hong Kong code significantly overestimates the shear strength of the exterior beam-column joints, while the Eurocode 2 is relatively effective in predicting the shear strength. Nevertheless, for the specimens with the same eccentricity, there is also an obvious difference in the value of V_{exp}/V_{EC2}, which is 0.96 and 1.66 respectively. The Eurocode 2 is not recommended to predict the seismic behaviour of the beam-column joints with non-seismic design details.

It can be seen from Table 3 that the V_{exp}/V_{ACI} is about 0.45, the average V_{exp}/V_{Nzs} is 0.4 and the value V_{exp}/V_{EC8} ranges from 0.25 to 0.96. Although the prediction of shear strength of the joints with horizontal links placed in joint core is better in Eurocode 8, the seismic performance of non-seismic detailed beam-column joints is overestimated in all the three seismic design codes. None of them can effectively predict the shear strength of the beam-column joints with non-seismic design details, whether eccentric or non-eccentric exterior joints.

5.CONCLUSION

In this study, three non-seismic details RC exterior beam-column joints with different eccentricity and stirrup ratio in joint cores are tested under reversed cyclic loading. The following conclusions are drawn by analyzing the test results and comparing them with the predicted values of different design codes.

(a) The eccentricity between the centerline of the beam and column has a significant effect on the shear strength and seismic performance of the RC exterior beam-column joints with non-seismic design details. When the eccentricity increases to 1/4 b_c, the shear strength decreases and the failure mode of ductility damage changes to brittle joint failure.

(b) The concrete on the eccentric side is observed obviously crushing, while concrete on the other side maintained its relative integrity. This further shows that the eccentricity leads to asymmetrical stress distribution in beam-column joints, and has negative effects on the seismic performance of the joints.

(c) The horizontal links in the joint core can improve the shear strength and enhance the seismic performance. However, the stirrup ratio has a relatively small effect on the seismic behaviour of the eccentric RC beam-column joints. It can be demonstrated from the two eccentric joints that the shear strength increment is less than 10% with the incorporation of 2T10.

(d) In general, the existing design codes cannot predict the shear strength of the non-seismically designed beam-column joints which are either eccentric or non-eccentric. The three seismic design codes even overestimate the shear strength of joints to 30%-60%. Therefore, it is necessary to develop reasonable analysis methods to improve the seismic performance of the eccentric joints with non-seismic details under low or moderate earthquakes.

6. ACKNOWLEDGEMENT

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (UGC/FDS25/E08/17).

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