16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1614

Registration Code: S-1464711395

CYCLIC BEHAVIOUR OF REINFORCED CONCRETE BEAM-COLUMN KNEE JOINTS

N. Zhang[1], J.S. Kuang[2], S. Mogili[3]

[1] *PhD Student, The Hong Kong University of Science and Technology, Hong Kong, (nzhangab@ust.hk)*
[2] *Professor, The Hong Kong University of Science and Technology, Hong Kong, (cejkuang@ust.hk)*
[3] *PhD Student, The Hong Kong University of Science and Technology, Hong Kong, (smogili@connect.ust.hk)*

Abstract

Over the last few decades, few studies have been conducted on the seismic behaviour of reinforced concrete beam-column knee joints, which are normally at the roof level of a moment-resisting frame building. In practice, design and detailing recommendations on inter-storey beam-column joints are generally adopted for knee joints albeit the differences in their seismic performance, as only few special design provisions are presented for knee joints in most of the design codes in the world. To investigate the seismic performance of beam-column knee joints, large-scale reinforced concrete beam-column knee joints, which were fabricated to simulate those in as-built RC frame buildings designed to ACI 318-14 and ACI-ASCE 352R-02, were tested under reversed cyclic loading. Particular emphasis is given to the effects of horizontal and vertical reinforcement on the shear strength and ductility capacity of the joints. It is shown from the experiments that reinforcement placed in the core of beam-column joints can effectively confine the joint core and improve the seismic performance, and also prevent effectively spalling of the concrete. Test results are compared with those predicted by four seismic design codes, including ACI 318-14, EC8, NZS3101 and GB50010. In general, these design codes of practice do not accurately predict the shear strength of seismically designed knee joints.

Keywords: RC beam-column connections; knee joints; reinforced concrete; cyclic loading; large-scale tests

1. Introduction

The discipline of earthquake engineering has witnessed tremendous improvements and innovations in the seismic design of reinforced concrete (RC) frame structures over the last three decades. Notable advances have been achieved in the seismic behaviour and design of RC beam-column connections, in particular conventional interior and exterior beam-column joints.

Beam-column joints generally fail to reach their nominal adjoining member strength either due their inability to withstand the high induced joint shear stresses, or due to bond and anchorage failure. In the case of beam-column knee joints which are normally seen at the roof level of frame buildings and pier bents of an RC bridge, this is clearly evident when the joint is subjected to an opening moment as it tends to divide the joint into two triangular halves across the re-entrant corner [1]. Once the diagonal crack is initiated during opening cycles, further concrete cover loss and continuous deterioration of the joint strength is inevitable. The discontinuity of connecting beam and column makes knee joints more vulnerable to the spalling of the concrete cover as compared with conventional interior joints. Knee joints are more critical as they do not possess the advantage of axial compression, which is generally believed to enhance the confinement and improve ductility.

Reinforced concrete beam-column knee connections are much more vulnerable to the opening action rather than the closing action owing to geometrical asymmetry, as observed in almost all the experiments of knee joints in published literatures [2-5]. Experimental results aforementioned showed that the average opening shear capacity of knee joints is only around half of the closing shear capacity. Though only few investigations have been conducted on the seismic performance of knee connections, the experimental results reflect a general trend of the poor opening behaviour of knee joints under reversed cyclic loading. Unfortunately, till now, none of the codes of practice has envisaged this severe vulnerability of knee joints to the opening movement. When the moment-resisting frame is subjected to the seismic loads, the opening tendency of knee joints is ineluctable. In this regard, the potential vulnerability of beam-column knee connections as lateral load-resisting structural members is often ignored by the design codes due to the lack of understanding of the structural performance of knee joints under seismic action.

Indeed, due to very few experimental and computational investigations on RC knee joints, no provisions of the beam-column knee joints design were systematically included in the representative seismic design codes of practice around the world, including ACI 318-14, Eurocode 2 and Eurocode 8, etc. As a consequence, engineers may only use the design methods of conventional beam-column joints for knee joints. However, due to the discontinuity of connecting beam and column, knee joints are more vulnerable to spalling of the concrete cover as compared with conventional interior joints. Even worse is that knee joints do not possess the advantage of an axial compression, which is generally believed to be capable of enhancing the confinement and improving ductility. Hence, there is an urgent need to conduct research studies on the seismic performance of beam-column knee joints to propose a method of simple analysis and design procedures for practical purpose.

In this paper, reversed cyclic-load tests of large-scale RC beam–column knee joints, simulating the behaviour of those in as-built RC framed buildings designed to ACI 318-14 and 352R-02 are presented. The primary objective of this experimental study is to investigate the effect of horizontal and vertical shear reinforcement ratios on the joint shear strength and hysteretic behaviour of seismically detailed beam–column knee joints subjected to earthquake-type loading. To evaluate the validity of code-prescribed methods for predicting the shear strength of knee joints, the experimental results are compared with ACI 318-14, NZS 3101, Eurocode 8 and Chinese seismic design code GB50010-2010.

2. Experimental Programme

2.1 Specimens

Four RC beam–column knee joints, designed to ACI 318-14 and ACI 352R-02 were fabricated and tested, with a square cross-section of 300 × 300 mm for both beam and column. Longitudinal reinforcement in beams of all specimens was 3T20 at both top and bottom, respectively, considering moment reversals. Since the strong-column weak-beam philosophy is not strictly applicable to roof level beam-column connections, the column reinforcement identical to the adjoining beam was adopted. The joint shear reinforcement was taken as recommended in ACI 352R-02, where the horizontal reinforcement is in the format of closed stirrup with 135° hooks and vertical reinforcement is in the format of invert U-shape tie for construction convenience.

Except for one specimen with no shear reinforcement as a reference specimen to investigate the inherent shear strength and ductility, the differences among the rest of 3 specimens were the areas of the horizontal and vertical reinforcement. This variation in area of reinforcement was provided by changing the diameter of the reinforcement but keeping the number of stirrups constant in both horizontal and vertical directions. As the number of stirrups in the joints is the same in horizontal and vertical directions, the confinement in all specimens was assumed identical. The gross shear reinforcement ratio is calculated as the area of the shear reinforcement divided by the gross corresponding area of the joint core.

Geometry and reinforcement layout of specimens are shown in Fig. 1. Material properties and reinforcement ratio are summarised in Table 1. The cube strengths of concrete ranges from 40.2 N/mm^2 to 48.0 N/mm^2, and the yield strengths of steel are 520 N/mm^2 and 500 N/mm^2 for T20 and T10, respectively.

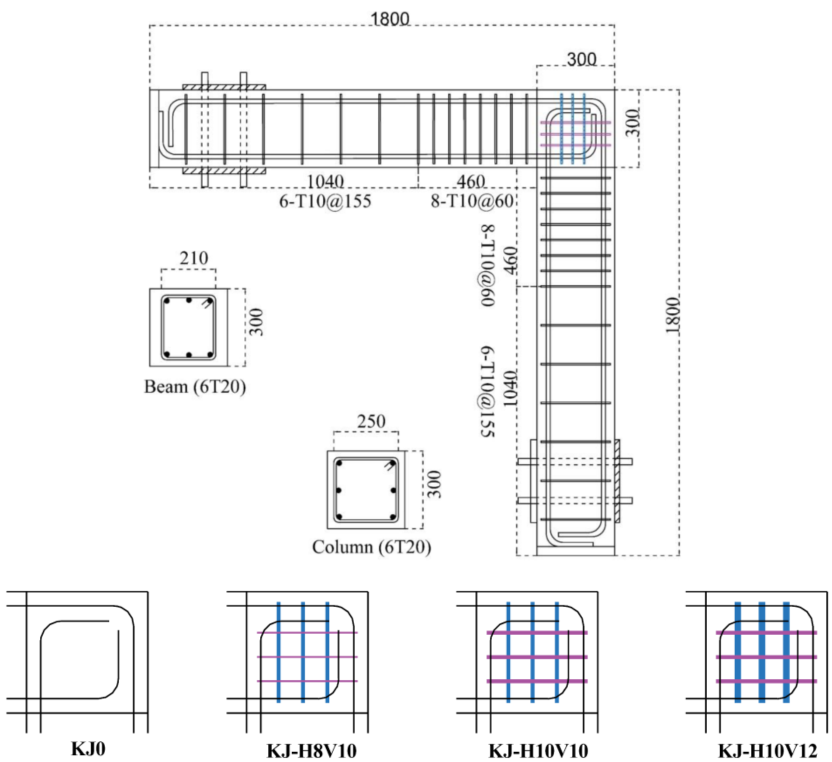

Fig. 1 – Geometry and reinforcement layout of specimens

Table 1 – Material properties and reinforcement details

Specimen	**Beam steel ratio (%)**	**Shear reinforcement ratio (%)**		**Concrete strength (MPa)**			
		Horizontal	Vertical	f_{cu}	f_c'	f_{ck}	$f_d(f_c)$
KJ0	1.2	0	0	48	38.40	32.16	21.55
KJ-H8V10	1.2	0.34	0.53	44.3	35.44	29.68	19.89
KJ-H10V10	1.2	0.53	0.53	45.56	36.45	30.53	20.45
KJ-H10V12	1.2	0.53	0.75	40.23	32.18	26.95	18.06

2.2 Test Apparatus and Loading Sequence

The test set-up and loading system are shown in Fig. 2. For convenience of applying loading and testing, the whole beam-column knee connection sub-assembly is laid down and therefore is in the same elevation. An actuator is connected to the beam and column tip to apply the opening and closing loads to the connection. Proper boundary conditions to simulate the actual working situation of the beam–column knee joint are applied as if it were part of a moment-resisting frame structure, where both the beam end and column end is considered as the point of contra-flexure so as to simulate inflection points in the structure. The axial load applied to both the beam and column is taken into consideration within the specimen design and analysis.

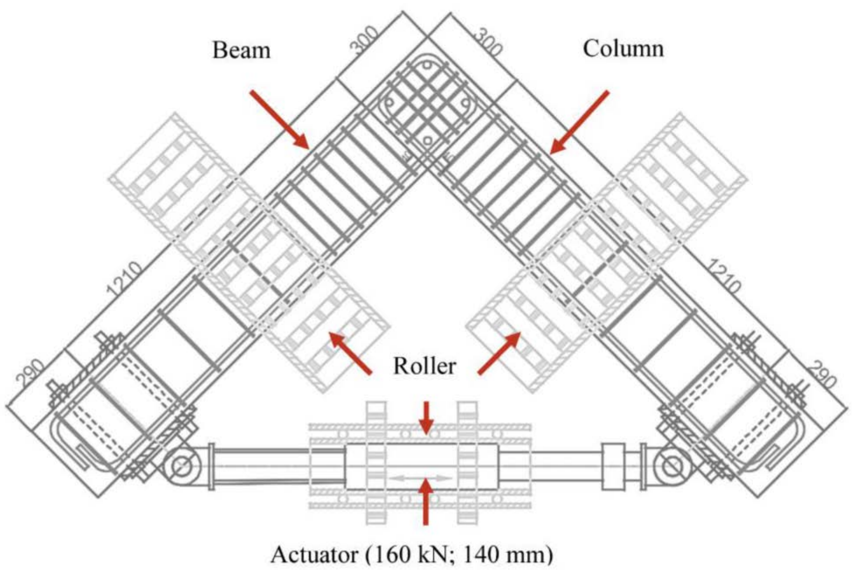

Fig. 2 – Test setup

The loading sequence consisting of reversed cyclic opening and closing displacement histories is shown in Fig. 3. The displacement amplitude of the initial cycle is 1.5 mm peak to peak with subsequent cycles increasing successively until the failure was observed.

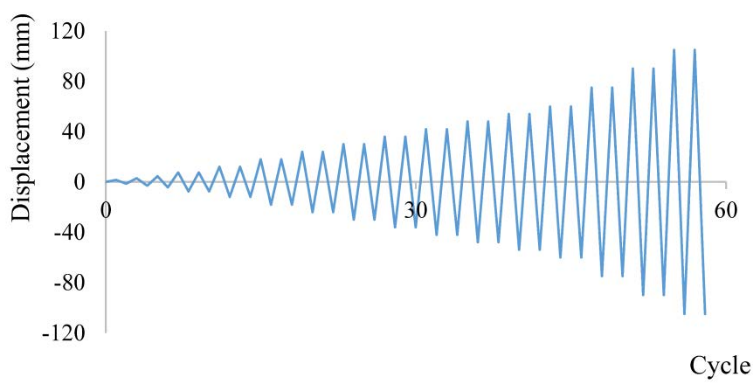

Fig. 3 – Loading system

3. Test results

Failure of all joints occurred by joint shear failure. Table 2 summarises the maximum test loads of specimens and calculated shear stresses in joints under both opening and closing action. The shear stresses are derived by considering the joint as a part of the column subjected to shear from the connecting beam. The input shear to the knee joint is calculated by

$$V_{jh}(\text{closing}) = T_{s,b} \quad \text{and} \quad V_{jh}(\text{opening}) = T'_{s,b} - V_c \tag{1}$$

where $T_{s,b}$ and $T'_{s,b}$ are the tensile forces in the longitudinal reinforcement of the beam under closing and opening actions, respectively; V_c is the horizontal column shear underneath the joint. The joint shear input is calculated by adopting the ACI equivalent stress block to represent concrete stresses for both opening and closing actions considering both applied moment and axial force, which is derived from the load applied by the actuator. Table 2 also presents the normalised shear stress as compared with corresponding concrete compressive strength f'_c and opening shear strength of the reference specimen KJ0. It is noted that the average of opening shear stresses from Table 2 is only 62% of the closing shear stresses, which agrees very well with the previous experimental data [2-4]. Considering the geometry symmetry of knee joints, the earthquake induced opening moment has the same magnitude as the closing moment. It is reasonable to claim that the opening shear of the knee joint dominates its structural performance under earthquake excitation and is therefore taken as the dominating shear strength of beam-column knee joints.

Table 2 – Maximum test loads and corresponding joint shear stresses

Specimen	Loading direction	Maximum test load (kN)	Experimental joint shear V_{jh}(kN)	Normalised shear stress		$V_{jh,o}/V_{jh,c}$
				$v_{jh}/\sqrt{f'_c}$	Relative value	
KJ0	closing	67.35	254.20	0.46	1.00	0.56
	opening	44.77	141.10	0.25	0.56	
KJ-H8V10	closing	82.32	318.98	0.59	1.25	0.54
	opening	53.74	170.45	0.32	0.67	
KJ-H10V10	closing	81.43	312.62	0.58	1.23	0.66
	opening	65.19	206.82	0.38	0.81	
KJ-H10V12	closing	75.53	291.06	0.57	1.15	0.70
	opening	64.39	204.91	0.40	0.81	

3.1 Hysteresis response

The hysteresis responses of specimens are shown in Fig. 4 as the relative displacement between the beam and column tip against the diagonal load measured by the load cell in the actuator (see Fig. 2), which is well accepted as an effective qualitative means of assessing the seismic performance. Failure of all four specimens are concentrated within the joint region, where the crack patterns are depicted in Fig. 4. It is observed from Fig. 4 (a) that the reference specimen KJ0 has relatively poor seismic performance with regard to the hysteretic behaviour under reversed cyclic loading. Since no shear reinforcement is placed inside the joint region, it is not surprising to see pinching, along with deterioration of the concrete and degradation of the shear transfer and a sudden drop of shear stress and stiffness after reaching its maximum stress.

Figs. 4(b) and 4(c) show the hysteretic responses of specimens with same level of confinement provided by joint reinforcement (both 3 closed stirrups and 3 invert U-shape ties) but different horizontal transverse reinforcement ratio (diameter 8 mm for KJ-H8V10 and diameter 10 mm for KJ-H10V10, respectively). The responses of the two specimens are similar. Improvements in global ductility and opening shear are clearly associated with the increase of the horizontal reinforcement ratio. It is also observed that a minor improvement in the energy dissipation and load retention capacities from the corresponding hysteresis loops is achieved by increase in the horizontal reinforcement ratio.

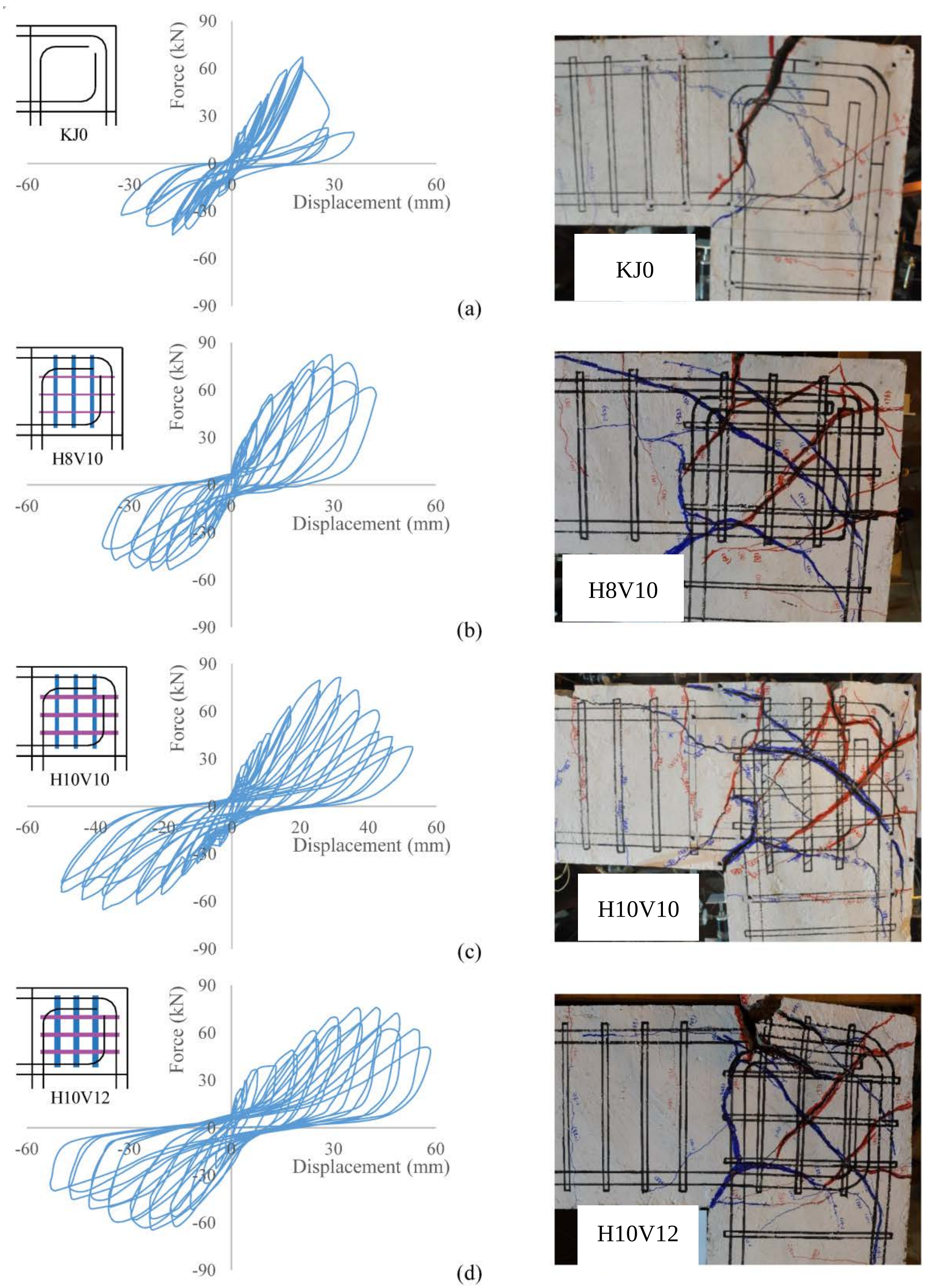

Fig. 4 – Load–displacement hysteretic loops and joint failure modes

Providing vertical reinforcement in a joint region is generally believed to result in relatively high ductile behaviour [6]. Although the hysteresis loops of specimen KJ-H10V10 show a thinner and pinched shape as shown in Fig. 4(c), the softening behaviour after reaching the ultimate displacement is rather obvious. In Fig.

4(d), it is observed that the hysteretic loops of specimen KJ-H10V12, where the diameter of vertical U links is larger, showing a much thicker and wider shape. Moreover, the degradation of both stiffness and strength of specimen KJ-H10V12 is also observed to be rather gradual and steady. Since a larger enclosed area of the hysteresis loop indicates higher energy dissipation and load-retention capacities, it can be implied that better seismic performance is associated with KJ-H10V12 as compared with other three specimens.

Although the horizontal and vertical reinforcement in joint core enhanced the joint shear and seismic performance of the beam–column knee joints, it seems that these specimens did not possess the desirable seismic behaviour, especially under opening action. The average normalised opening shear of these 4 specimens is only 62% of that of closing shear. Moreover, the hysteresis loops of specimens also indicate a relatively low energy dissipation capability and a potential undesirable non-ductile failure when the direction of loads reverses under seismic excitation.

3.2 Effect of shear reinforcement

To investigate the effectiveness of horizontal and vertical shear reinforcement in joint core on the seismic behaviour and enhancement of shear resistance, specimens KJ0, KJ-H8V10, KJ-H10V10 and KJ-H10V12 with different combination of horizontal and vertical reinforcement ratio are considered and compared. Variation of the observed normalised shear stress to the horizontal shear reinforcement ratio of joint is depicted in Fig. 5(a). Increase in shear resistance with the increase of the joint horizontal reinforcement ratio is observed. More specifically, it is seen that there is a dramatic increase in opening shear of the joints as the horizontal reinforcement ratio increases from 0 (KJ0), 0.34% (KJ-H8V10) to 0.53% (KJ-H10V10), with a potential trend of continuous increase when the horizontal reinforcement ratio is over 0.53%. Similar increase in the closing shear of knee joints specimens with increase of the horizontal reinforcement ratio from 0 to 0.34%. However, it seems no further beneficial effect of horizontal reinforcement on the shear resistance of beam–column joints can be attained when the horizontal reinforcement ratio is larger than 0.34%. This limitation agrees well with suggestions by Kitayama et al [7] and Kuang and Wong [8,9], where a maximum stirrup ratio of 0.4% is proposed for the case of conventional inter-storey beam-column joints.

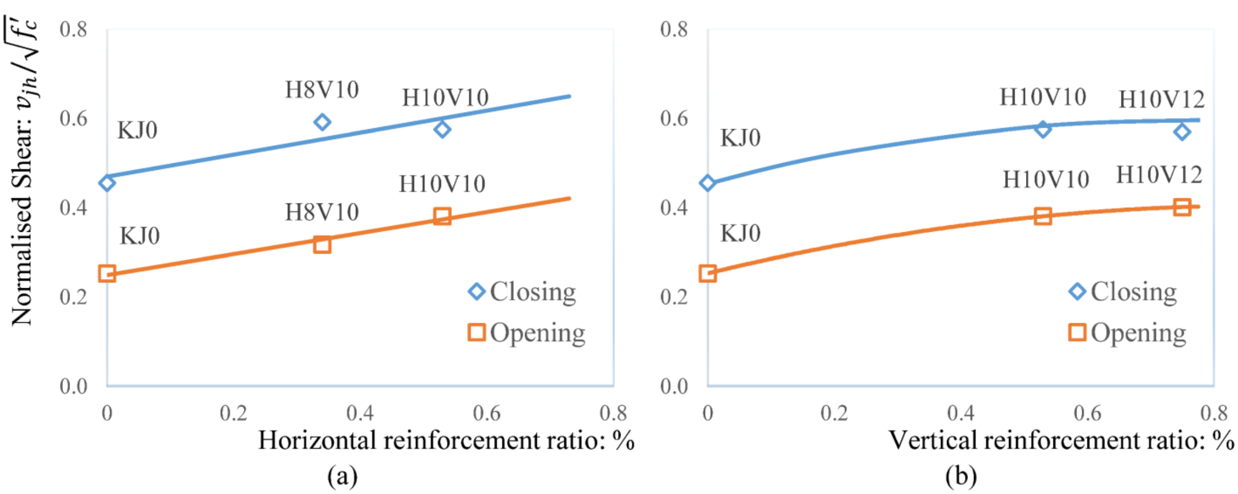

Fig. 5 – Variation of normalised joint shear stress. (a) Horizontal reinforcement; (b) vertical reinforcement

Variation of the observed normalised shear stress to the vertical shear reinforcement ratio of joint is shown in Fig. 5(b). Similar trend of increase in opening and closing shear-resistance is noticed as the increase of the vertical reinforcement ratio and seems to reach a plateau when the vertical reinforcement ratio reaches around 0.53%. It is indicated that the vertical reinforcement ratio has a significant effect on the shear-resistance for the joints with a vertical reinforcement ratio of less than 0.53%, but little effect for those with the ratio of higher than 0.53%.

4. Discussions on the function of joint reinforcement

It is convinced that the horizontal and vertical reinforcement in joint core is capable of well confining the concrete in the joint region, thus effectively enhancing the shear resistance of RC beam-column joints. However, it is still in dispute on the efficiency of so-called the "truss mechanism" proposed by Paulay and Priestly [11] and whether joint shear reinforcement can directly participate in resisting the shear transferred from the adjoining members.

To investigate the effectiveness of the "truss mechanism" of the shear reinforcement on the shear-resistance of beam-column knee joints, the tested 4 specimens, except KJ0, are all reinforced with 3 layer's transverse closed stirrups and invert U-shape ties to ascertain the identical confinement of concrete in the joint core. Test results from Fig. 5 have already shown that the confinement of the concrete is directly affected by the format of the shear reinforcement. In terms of the horizontal shear reinforcement in format of closed stirrup, the increase of shear reinforcement ratio can dramatically increase the dominating opening shear capacity of the knee joint, which therefore indicates the significant role of closed shear reinforcement in resisting the shear force in addition to the confinement to the concrete. While for vertical shear reinforcement, though invert U-shaped ties cannot confine the concrete as sufficiently as closed stirrups, the opening shear-resistance of knee joint is also slightly improved with the increase in the vertical reinforcement ratio.

On the other hand, the variation of the observed normalised shear stress to the total shear reinforcement ratio of joint is shown in Fig. 6, where the total reinforcement ratio is the summation of the transverse and vertical reinforcement ratio. It is seen that the normalised opening shear stress is increased from 0.32 (KJ-H8V10), 0.38 (KJ-H10V10) to 0.40 (KJ-H10V12) with the increase in total joint reinforcement ratio from 0.87%, 1.06%, to 1.28%, the shear stress being increased by 19% and 26%, while the closing shear stress changes slightly when the total shear reinforcement ratio is higher than 0.87%. Additional transverse stirrups and vertical ties in joint therefore seems to have no further beneficial effect on enhancing the closing shear-resistance. Considering the remarkable improvement of weaker shear capacity of knee joints under opening movement, it is therefore deduced that the shear reinforcement in the joint region cannot only provide efficient confinement to the concrete so as to enhance the compressive strength of the concrete strut, but is also capable of transferring the shear force through the truss mechanism.

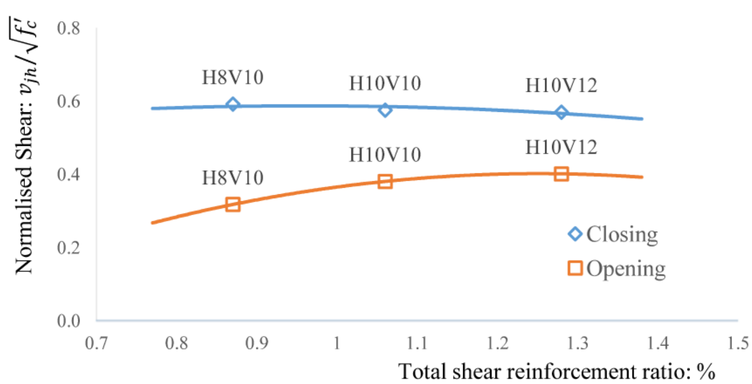

Fig. 6 – Variation of joint observed shear to the total joint shear reinforcement ratio

5. Comparison with predictions of codes of practice

To evaluate the validity of existing codes of practice around the world in predicting the shear strength of beam-column knee joints with seismic detailing under reversed cyclic loading, the test results are compared with the prescribed limiting values predicted by ACI 318-14, Eurocode 8, NZS 3101:2006 and GB 50010-2010.

Experimental shear strengths of specimens and corresponding comparisons with those predicted by different codes of practice are presented in Table 3. The safety factors in the codes are removed in calculation for uniformity. ACI 318 and 352 require that certain amount of horizontal and vertical transverse reinforcement in the type-2 beam–column connections under consideration of seismic design should be placed to enhance the confinement of the joint. It is seen from Table 3 that ACI standards have relative better predictions on the joint strengths, though the confinement requirement is satisfied in test specimens except KJ0.

Table 3 – Experimental joint shear strengths and comparison with predictions of design codes

Specimen	Experimental joint shear (kN)	Comparison			
		V_{exp}/V_{ACI}	V_{exp}/V_{EC8}	V_{exp}/V_{NZS}	V_{exp}/V_{GB}
KJ0	254.20	0.69	0.31	0.37	0.44
KJ-H8V10	316.99	0.89	0.42	0.50	0.59
KJ-H10V10	312.62	0.87	0.40	0.48	0.57
KJ-H10V12	291.06	0.86	0.42	0.50	0.60

Predictions of shear strength by EC8, NZS 3101 and GB 50010 are very close. This may be attributable to the similar assumption of the shear failure of beam-column joints, which is based on crushing of the diagonal concrete strut in joint core. In fact, it was observed in the experiment that shear failure of specimen KJ-H8V10, KJ-H10V10 and KJ-H10V12 has very strong relationship with the crushing of concrete. However, the predictions given by these three design codes severely overestimate the shear strength of beam-column knee joints, as shown in Table 3, where a minimum difference of 40% is noticed in specimen KJ-H10V10. Similar overestimations were also observed by Kuang and Wong [9].

6. Conclusions

Large-scale tests of seismically designed, reinforced concrete beam-column knee joints with different shear reinforcement ratios reversed cyclic loading were conducted. The experimental results reflect the general trend of the seismic behaviour of knee joints under reversed cyclic loading. Based on the findings from the tests and comparisons between the test results and the predictions by design codes of ACI 318-14, EC8, NZS 3101 and GB50010-10, the following conclusions can be drawn.

(1) The average opening shear capacity of test specimen is only 61% of closing shear, which makes knee joints undergo a very high probability of opening shear failure when subjected to the earthquake-induced loads. Hence, it is suggested that more studies on seismic behaviour of knee joints under opening moments to be conducted in the future considering its geometric and location characteristics.

(2) Both horizontal and vertical reinforcement ratios in joint core have a significant effect on the shear strength and ductility of beam-column knee joints under reverse cyclic loading. In general, beam-column knee joints with a higher reinforcement ratio show better hysteretic performance and enhanced ductility. More specifically are

   a) The vertical transverse reinforcement, in format of invert U-shape ties, is proved be capable of enhancing the shear capacity and improving the hysteretic performance of knee joints and strongly recommended to extend to the codes of practice in the world considering its ease of placement.

   b) Both closing and opening shear-resistance of knee joints increases as the vertical transverse reinforcement ratio increases. However, it is found in this study that, when the vertical reinforcement ratio is over 0.6%, no further influence on the enhancement of shear-resistance of joints is observed.

   c) With the increase of horizontal transverse reinforcement ratio, the opening shear-resistance of knee joints increases more remarkably as compared with closing shear-resistance. In this study, the normalised opening shear is increased by 20% and 50% when the horizontal reinforcement ratio is increased from 0, 0.35% and 0.53%; however, it is observed that no beneficial effect of the horizontal reinforcement on the shear strength of beam–column joints can be attained when the horizontal reinforcement ratio is larger than 0.4%.

(3) None of codes of practice considered in this study has differentiated the opening and closing shear capacity of the beam-column knee joints. When compared with the codes of practice, no test specimen in this study attains the shear strength predicted by these design codes. The shear resistance of beam-column knee joints, especially under opening movement, has been severely over-estimated. It has been found that

a) ACI 318 in combination with 352 has relatively better predictions for the closing shear resistance in this study, where the closing shear resistances of knee joints specimens with satisfying confinement are about 90% of the predictions.

b) EC8, NZS 3101, GB50010 severely overestimate the shear capacity of knee joints. The experimental results of shear stresses in this study are only about 50% of the predicted values.

(4) There is therefore an urgent need to develop rational methods of analysis for predicting the shear strength and designing RC beam-column knee joints. This is particularly important for the seismic design of RC moment-resisting frames.

7. Acknowledgements

The support of the Hong Kong Research Grant Council under grant number 613712 is gratefully acknowledged.

8. References

[1] Angelakos B. (1998): The behavior of reinforced concrete knee joints under earthquake loads. Department of Civil Engineering, University of Toronto.

[2] Mazzoni S, Moehle JP, Thewalt CR (1991): Cyclic response of RC beam-column knee joints: test and retrofit. Pacific Earthquake Engineering Research Center, UC Berkeley, USA.

[3] Cote PA, Wallace JW (1994): A study of reinforced concrete knee-joints subjected to cyclic lateral loading. *Report No.CU/CEE 1994/04*, Department of Civil and Environmental Engineering, Clarkson University, NY, USA.

[4] Megget LM (1998): The seismic behaviour of small reinforced concrete beam-column knee Joints. *Bulletin of the New Zealand National Society for Earthquake Engineering*, **31**, 215-45.

[5] Hotta H, Nishizawa N (2012): Experimental study on influence of arrangement of main bars on stress transmission in reinforced concrete beam-column knee joints. *15th WCEE*, Lisbon, Portugal.

[6] ACI-ASCE Committee 352 (2002): *Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures*. American Concrete Institute, Michigan, USA.

[7] Kitayama K, Otani S, Aoyama H (1991): Development of design criteria for RC interior beam-column joints. *ACI SP-123 Design of Beam-Column Joints for Seismic Resistance*, American Concrete Institute, Michigan, 97-123.

[8] Kuang JS, Atanda AI (2005): Enhancing ductility of non-seismically designed reinforced concrete frame buildings. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*; **158** (4), 253-65.

[9] Kuang JS, Wong HF (2006): Effects of beam bar anchorage on beam–column joint behaviour. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **159** (2), 115-24.

[10] Wong HF, Kuang JS (2008): Effects of beam—column depth ratio on joint seismic behaviour. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **161** (2), 91-101.

[11] Paulay T, Priestley MJN (1992): *Seismic Design of Reinforced Concrete and Masonry Buildings*. Wiley.