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Effect of Horizontal Joint Reinforcement on Shear Behaviour of RC Knee Connections

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***Abstract*—**To investigate seismic performance of beam-column knee joints, four full-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. In the experimental programme, particular emphasis was given to the effect of horizontal reinforcement (in format of inverted U-shape bars) on the shear strength and ductility capacity of knee joints. Test results are compared with those predicted by four seismic design codes, including ACI 318-14, EC8, NZS3101 and GB50010. It is seen that the current design codes of practice cannot accurately predict the shear strength of seismically designed knee joints.

***Keywords*—**Large-scale tests, RC beam-column knee joints, seismic performance, shear strength.

I. Introduction

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 during the past. However, by now only a small number of experimental and computational investigations have been conducted on RC knee joints which are normally seen at the roof level of frame buildings and pier bents of an RC bridge, the provisions of the beam-column knee joints design have not been systematically included in the representative seismic design codes of practice around the world, such as American code ACI 318-14, European codes EC2 and EC8, New Zealand code NZS 3101, and Chinese code GB 50010, etc. As a consequence, engineers can only apply the current design methods of conventional beam-column joints into knee joints design.

So far it is still in dispute on the dominating function of joint reinforcement. The New Zealand standards and Europe codes insist on both the confinement and the direct shear-transfer ability of joint transverse reinforcement, while the US standards only trust the confinement function of joint transverse reinforcement.

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 transverse reinforcement on the joint shear strength and hysteretic behaviour of seismically detailed beam–column knee joints subjected to earthquake-type loading.

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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.

II. Experimental Programme

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 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 [1], 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 one specimen with no shear reinforcement as a reference specimen to investigate the inherent shear strength and ductility, the difference among the other three specimens was the amount of horizontal joint reinforcement. This variation was provided by changing the diameter of the reinforcement but keeping the number of stirrups constant in both the horizontal and vertical directions. As the number of stirrups in the joints is the same in the 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 I. The cube strengths of concrete ranges from 36.86 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.

TABLE I
MATERIAL PROPERTIES AND REINFORCEMENT DETAILS

Specimen	Gross shear reinforcement ratio (%)		Concrete strength N/mm^2	
	Horizontal	Vertical	f_{cu}	f_c'
KJ0	0	0	48	38.40
KJ-H8V10	0.34	0.53	44.3	35.44
KJ-H10V10	0.53	0.53	45.56	36.45
KJ-H12V10	0.75	0.53	36.68	32.18

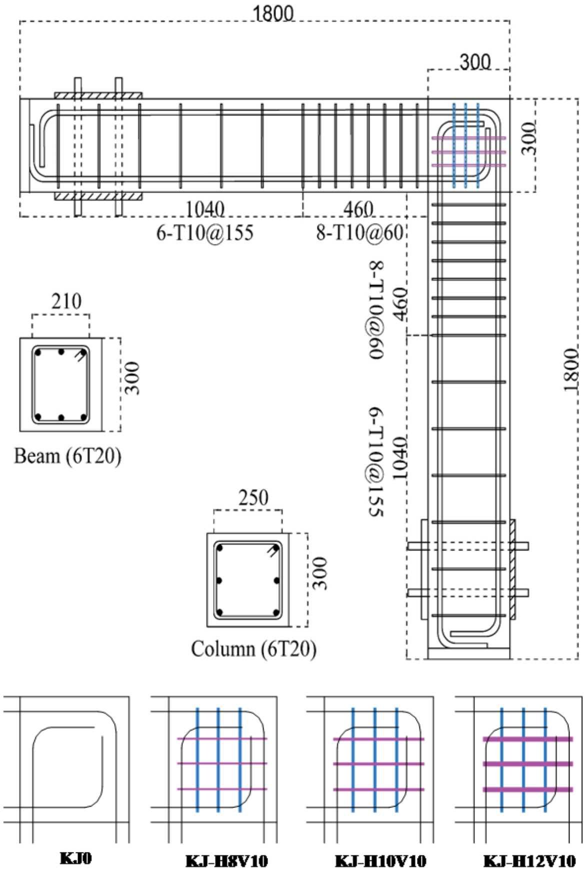

Fig. 1 Geometry and reinforcement layout of specimens

III. 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.

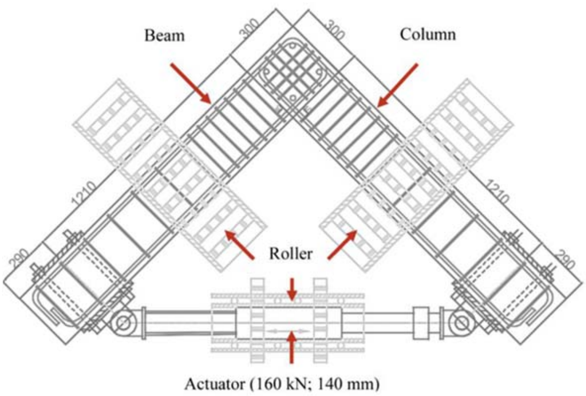

Fig. 2 Test setup

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.

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.

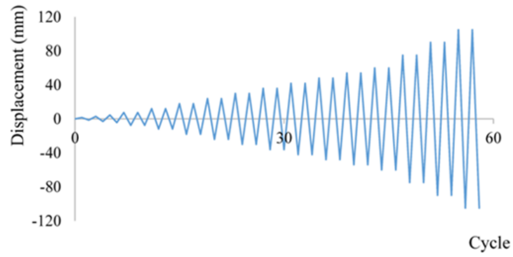

Fig. 3 Loading system

IV. Test Results

A. Shear Strength

Failure of all joints occurred by joint shear failure. Table II 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:

$$V_{jh,closing} = T_{s,b} \tag{1}$$

where $T_{s,b}$ is the tensile forces in the longitudinal reinforcement of the beam under closing action. 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 II
Maximum Test Loads and Corresponding Joint Shear

Specimen	Max. test load (kN)	Shear Strength V_{jh} (kN)	Normalised shear stress $v_{jh}/\sqrt{f_c'}$
KJ0	67.35	254.20	0.46
KJ-H8V10	82.32	316.99	0.58
KJ-H10V10	81.43	312.62	0.57
KJ-H12V10	60.07	229.04	0.47

B. Hysteresis Behaviour

The hysteresis responses of the tested specimens are illustrated 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 has well been accepted as an effective qualitative means of assessing the seismic performance. The failure of all the four specimens is concentrated within the joint region, where the crack patterns are depicted in Fig. 5.

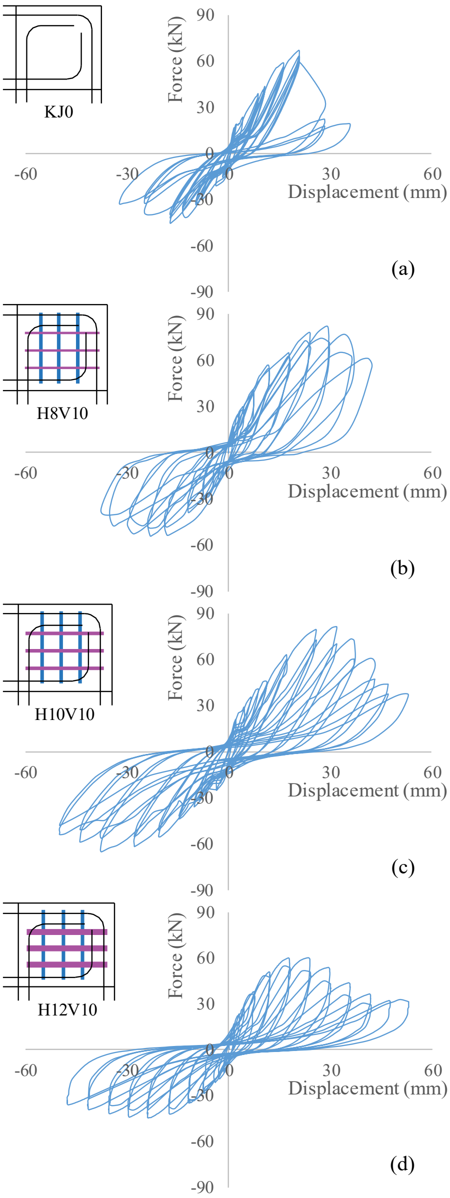

Fig. 4 Load–displacement hysteretic loops of tested specimens (a) KJ0; (b) KJ-H8V10; (c) KJ-H10V10; and (d) KJ-H10V12

It is observed from Fig. 4 (a) that the reference specimen KJ0 has relatively poor seismic performance with regards to the hysteretic behaviour under reversed cyclic loading. Since no shear reinforcement is placed inside the joint region, it is not surprising to see an amount of pinching, along with deterioration of the concrete and degradation of the shear transfer, as well as the sudden drop of shear stress and stiffness, after reaching its maximum stress.

With the placement of the transverse reinforcement, improvements in global ductility and shear strength are clearly observed, as seen from the hysteretic responses of specimen KJH8V10 in Fig. 4 (b). However, with the continuing increase of the horizontal reinforcement from 0.34% (KJ-H8V10) to 0.53% (KJ-H10V10), the global performance is not improved obviously, as shown in Fig. 4 (c). The softening behaviour of KJH10V10 after reaching the ultimate displacement is rather obvious. Moreover, the maximum tested shear input is almost same for KJ-H8V10 and KJ-H10V10. The effect of horizontal reinforcement on improving the seismic performance seems to have reached a plateau for knee joints.

When the horizontal reinforcement ratio is further increased to 0.75% (KJ-H12V10), the hysteresis loops of specimen KJ-H12V10 shows a thinner and pinched shape, as seen in Fig. 4 (d). Even the degradation of both stiffness and strength of specimen KJ-H12V10 in opening action is observed as rather gradual and steady, and the maximum texted load of specimen KJ-H12V10 is only 73% of specimen KJ-H8V10. This implies a worse performance of knee joints under cyclic loading when the horizontal transverse reinforcement ratio is larger than a certain value.

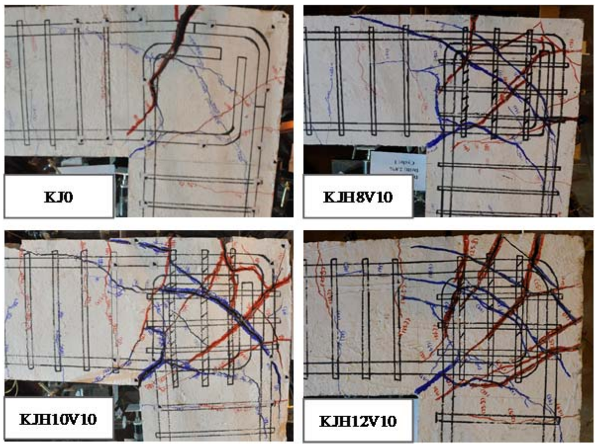

Fig. 5 Cracking patterns of specimens

Although detailing transverse and vertical reinforcement in joint core can effectively enhance the joint shear and seismic performance of the beam–column knee joints, it is hard to admit that any of these specimens have possessed the desirable seismic behaviour, especially under opening action. The average normalised opening shear of these four specimens is only 62% of that of closing shear. Moreover, the hysteresis loops of all specimens also indicate a relatively low energy dissipation capability and a potential undesirable inductile failure when the direction of loads reverses under seismic excitation.

C. Effect of Horizontal Joint Reinforcement

It is convinced that the horizontal 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 [2], where the joint shear reinforcement can directly participate in resisting the shear transferred from the adjoining members.

To investigate the effectiveness of horizontal shear reinforcement in joint cores on the seismic performance and enhancement of shear-resistance, specimens KJ0, KJ-H8V10, KJ-H10V10 and KJ-H12V10 with different horizontal reinforcement ratio, are considered and compared.

Since specimen KJ-H8V10, KJ-H10V10 and KJ-H12V10, are equipped with three closed stirrups (in horizontal direction) and three invert U-shape ties (in vertical direction). Since the number of the transverse reinforcement and their location are the same for these three specimens, the confinement provided by the transverse reinforcement is assumed to be identical.

Variation of normalised maximum tested shear stress to the horizontal transverse reinforcement ratio is depicted in Fig. 6. 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 maximum shear input of the joints as the horizontal reinforcement ratio increases from 0% (KJ0), 0.34% (KJ-H8V10) to 0.53% (KJ-H10V10). 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.* [3] and Kuang and Wong [4], [5], where a maximum stirrup ratio of 0.4% is proposed for the case of conventional inter-storey beam-column joints. Moreover, the test result from specimen KJ-H12V10 also shows a potential decrease of the maximum shear stress when the horizontal reinforcement ratio is further increased.

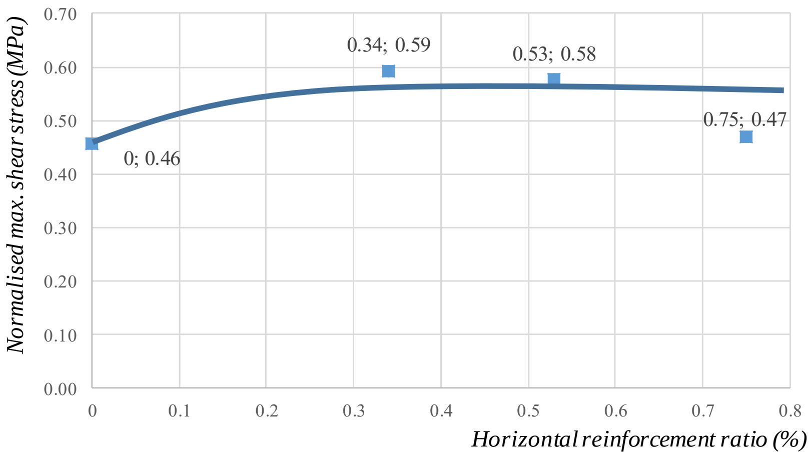

Fig. 6 Variation of joint observed shear to the gross horizontal joint reinforcement ratio

V. Comparisons with 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 prevalent seismic design codes ACI 318–14, EC8 (2004), NZS 3101:2006 and GB 50010-2010.

A. ACI 318-14

The ACI 318-14 requirements for shear is that the nominal joint capability should exceed the factored shear force applied to the joint. This is given by:

$$ØV_n \geq V_u \quad (2)$$

where V_n represents the nominal joint capacity and V_u is the factored shear force. The factor Ø is a strength reduction factor as the standard follows strength based design methodology in lieu of the limit state design method. This factor is given as 0.85 for the seismic design of joints. The nominal joint shear strength V_n is:

$$V_n = \gamma_c \sqrt{f_c'}\, A_j \text{ (psi)} \quad (3)$$

$$V_n = 0.083\, \gamma_c \sqrt{f_c'}\, A_j \text{ (Mpa)} \quad (4)$$

where A_j represents the effective cross-sectional area of the joint and is given by the product of the joint depth and the effective joint width. The constant γ_c is a measure of the degree of confinement provided by members framing into the joint. The test specimens in this study are classified in ACI code as corner joints with a discontinuous column, and the coefficient is then taken as 8.

B. Eurocode 8

In Eurocode 8: Design of Structures for Earthquake Resistance – Part 1, the prior concern on the shear resistance of a beam-column joint is that the diagonal compression induced in the joint core by the diagonal strut mechanism shall not be greater than the compressive strength of concrete. The shear strength of interior beam–column joints can be determined by:

$$V_{jhd} = \eta f_{cd} \sqrt{(1 - \frac{v_d}{\eta})} b_j h_{jc} \quad (5)$$

where $\eta = 0.6\left(1 - \frac{f_{ck}}{250}\right)$; f_{cd} is the design value of concrete compressive strength (MPa), v_d is the normalised axial force in the column above the joint, and b_j is he effective joint width. For exterior beam-column joints, the shear strength is 80% of the value given by (5). In this test program, no axial force above the joint is applied to the joints. Therefore, the shear strength of a beam-column knee joints is expressed as:

$$V_{jhd,knee} = 0.48\left(1 - \frac{f_{ck}}{250}\right) f_{cd} b_j h_{jc} \tag{6}$$

C. NZS 3101: 2006

In the New Zealand standard for concrete structures part 1- the design of concrete structures (NZS 3101-1:2006) provides quantitative rules for the assessment and design of beam-column joints. The joint shear shall be assumed to be resisted by a concrete mechanism and a truss mechanism, comprising horizontal and vertical stirrups or bars and diagonal concrete struts. It is specified that, to avoid the diagonal compression failure, the maximum horizontal design shear force across a joint, V_{jh}^*, shall satisfy:

$$V_{jh}^* \leq min\{0.2 f_c' b_j h_c\,; 10 b_j h_c\} \tag{7}$$

where h_c is the overall depth of the column in the direction of the horizontal shear to be considered and the effective joint width, b_j.

D. GB 50010-10

In Chinese seismic standards GB 50010-10, the maximum resisting shear strength of the reinforced concrete beam-column joints is:

$$V_j = \frac{1}{\gamma_{RE}}(0.3\eta_j \beta_c f_c b_j h_j) \tag{8}$$

where γ_{RE} is the coefficient for seismic bearing capacity, and is a kind of a strength reduction factor which is taken as 0.85, η_j is a constant, which depends on the joint classification and is equal to 1.0 for knee joints, β_c is the coefficient for strength of concrete, f_c is the design compressive strength for concrete, b_j is the effective width of the joint core, and h_j is the effective depth of the joint core. After removing the safety factor of γ_{RE} and β_c, the shear strength of knee joint in GB 50010-10 is rewritten as:

$$V_j = 0.3 f_c b_j h_j \tag{9}$$

E. Comparisons

Experimental shear strengths of specimens and corresponding comparisons with those predicted by different codes of practice are presented in Table III. The safety factors in the codes are removed in calculation for uniformity. ACI 318 and 352 require that a 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 I that ACI standards have relative better predictions on the joint strengths, though the confinement requirement is satisfied in test specimens except KJ0.

TABLE III
EXPERIMENTAL JOINT SHEAR STRENGTHS AND COMPARISON WITH PREDICTIONS OF DESIGN CODES

Specimen	Joint shear V_{exp} (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-H12V10	229.04	0.71	0.36	0.44	0.43

Predictions of the 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 the crushing of the diagonal concrete strut in the joint core. In fact, it was observed in the experiment that shear failure of specimen KJ-H8V10, KJ-H10V10 and KJ-H12V10 has a 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 I, where a minimum difference of 36% is noticed in specimen KJ-H12V10. Similar overestimations were also observed by Zhang [6], Wong and Kuang [7].

VI. CONCLUSIONS

Large-scale tests of seismically designed, reinforced concrete beam-column knee joints with different ratios of horizontal joint reinforcement were conducted under reversed cyclic loading. The experimental results reflect the general trend of the seismic behaviour of RC knee joints.

1) Transverse reinforcement in the joint core has a significant effect on the shear strength and ductility of beam-column knee joints under reverse cyclic loading.
2) Beam-column knee joints with a high reinforcement ratio do not always show better hysteretic performance and enhanced ductility. The horizontal joint reinforcement ratio is strongly suggested to be limited to 0.4%.
3) 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, none of these codes can predict well on the shear resistance of knee joints.
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.

ACKNOWLEDGMENT

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REFERENCES

[1] ACI-ASCE Committee 352, *Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures. American Concrete Institute*, Michigan, USA, 2002.
[2] Priestley, M., & Paulay, T. (1992). Seismic design of reinforced concrete and masonry buildings. New York: John Wiley & Sons.
[3] Kitayama K, Otani S, Aoyama H, "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, 1991, 97-123.
[4] Kuang JS, Atanda AI, "Enhancing ductility of non-seismically designed reinforced concrete frame buildings". Proceedings of the Institution of Civil Engineers-Structures and Buildings; 2005, 158 (4), 253-65.
[5] Kuang JS, Wong HF, "Effects of beam bar anchorage on beam–column joint behaviour". Proceedings of the Institution of Civil Engineers-Structures and Buildings, 2006, 159 (2), 115-24.
[6] N. Zhang, J. S. Kuang and S. Mogili, "Cyclic behaviour of reinforced concrete beam-column knee connections," *Sixteenth World Conference on Earthquake Engineering*, Santiago, Chile, 2017.
[7] Wong HF, Kuang JS, "Effects of beam-column depth ratio on joint seismic behaviour". Proceedings of the Institution of Civil Engineers-Structures and Buildings, 2008, 161 (2), 91-101.