

Cyclic Testing of Exterior Beam-Column Joints with Headed Reinforcement in Varying Joint Aspect Ratio

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ABSTRACT: To examine the effects of joint aspect ratio (beam depth to column depth ratio) on shear strength and required amount of transverse reinforcement in exterior beam-column joints, 6 joint specimens were tested under reversed cyclic loading. The main experimental parameters were the joint aspect ratio, the amount of transverse reinforcement, and the anchorage types of beam bars (hooked and headed bars). The test results indicate that, for a joint aspect ratio equal to or greater than 1.0, all joints showed typical flexural behavior. Even transverse reinforcement was reduced to One-thirds of the transverse reinforcement required by ACI 352R-02; the hysteretic behavior and strengths of the joints were similar to those of the joints designed in accordance with ACI 352R-02. For a joint aspect ratio equal to or less than 2.0, nominal strength of joints could not be developed and joint shear failure occurred where the requirements of ACI 352R-02 were satisfied. From the analysis of measured shear strengths of the joints, it is suggested that the shear strength factor of ACI 352R-02 is reduced as the joint aspect ratio increases, if the joint aspect ratio is higher than 1.65. The test results also indicate that there was no significant difference between anchorage types of hooked or headed bars.

KEYWORDS: Beam Column Joints, Joint Aspect Ratio, Joint Shear Strength.

I. INTRODUCTION

Recently, as reinforced concrete structures with long spans become popular, such as halls, theaters, manufacturing facilities, and multi-function buildings, deeper beam depth is needed to control deflection of the beam. As the span increases, the joint aspect ratio (that is, beam depth to column depth ratio) may become higher from b_1 to b_2 , as shown in Fig. 1. The joint aspect ratio can be over 1.5, and may sometimes reach 2.5 in low-rise buildings with very long spans. Wong and Kuang¹ showed that the joint aspect ratio had a significant effect on the shear strength and ductility of beam column joints from cyclic tests of non-seismically designed joints. Hwang and Lee^{2,3} suggested a model for predicting shear strengths of discontinuity regions, including exterior beam-column joints based on the strut-and-tie model, constitute law, and strain compatibility. The model consisted of three resisting mechanisms and showed that the ratios of force distribution among the three mechanisms were determined by the angle θ of diagonal strut. In the case of $\tan \theta \geq 2.0$, the entire joint shear force is resisted by only horizontal mechanism. Tsonos⁴ conducted cyclic tests of exterior beam-column joints of which the joint aspect ratio was 1.5, and proposed a theoretical model for predicting shear strengths. In the proposed model, joint shear strengths are in inverse proportion to joint aspect ratios. The Tsonos model, also via a ratio g_{cal}/g_{ult} , which must be lower than 0.50,

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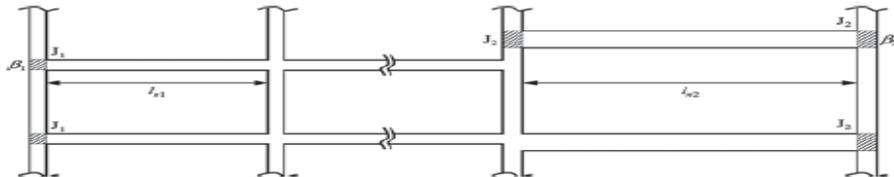


Fig. 1 Joint aspect ratios with different lengths of span.

where g_{cal} and g_{ult} are design and ultimate shear strength factors, respectively, secured the formation of plastic hinge in the beams for flexural strength ratios higher than 1.20 in accordance with ACI 352R-02 and the concentration of the damage only in the beams, while the joint regions remained intact. Recently, Park and Mosalam⁵ published an analytical model for predicting shear strengths of unreinforced exterior beam-column joints based on a mechanism consisting of two struts. The proposed model accounts for the joint's aspect ratio but it deals with only unreinforced joints. These models showed very good predictions of joint shear strengths for tests^{1,4,6-13} on exterior beam-column joints. However, no tests showed joint aspect ratios greater than 1.5. Therefore, shear strengths of exterior beam-column joints with joint aspect ratios greater than 1.5 need to be verified experimentally. In addition, joints with very low aspect ratios, such as equal to or less than 1.0, have also been rarely investigated. ACI 318-11,¹⁴ ACI 352R-02,¹⁵ and Euro code 816 do not consider joint aspect ratio in determining joint shear strength and required transverse reinforcement, and they do not provide any restrictions on joint aspect ratios. Tests on exterior beam-column joints with varying joint aspect ratios are needed to address the effects of joint aspect ratios on shear strength and the required amount of transverse reinforcement. An experimental study was carried out with 14 exterior beam-column joints with varying joint aspect ratios from 0.67 to 2.5. For joint aspect ratios of 0.67 and 1.0, joints having two-thirds of the transverse reinforcement A_{sh} , 352 required by ACI 352 were also tested to examine the effects of the transverse reinforcement amount on joint shear strength in a low joint aspect ratio. In addition, anchorage types of beam bars were included in the variables because design provisions on headed bars have recently been incorporated in ACI 318-08.17.

II. RESEARCH SIGNIFICANCE

While joint shear strength can be affected by joint aspect ratio, current design codes do not consider the effects of joint aspect ratio in calculating joint shear strength and required transverse reinforcement. Given the paucity of experimental research on the behavior of exterior joints with a joint aspect ratio over 1.5 or under 1.0, a total of 14 full-scale, exterior joints were tested under reversed cyclic loading. The test results provide valuable information on the behavior of exterior joints with varying aspect ratios such as recommendations for a shear strength factor and transverse reinforcement, and the effects of anchorage types of beam bars.

III. DESIGN CODES ON SHEAR STRENGTH AND TRANSVERSE REINFORCEMENT IN EXTERIOR JOINT

ACI 352R-02

Joint ACI-ASCE 352 design recommendations for monolithic beam-column joints (ACI 352R-0215) provide comprehensive design recommendations for a variety of reinforced beam-column joint configurations. Requirements for horizontal transverse reinforcement and joint shear strength of Type 2 connections with rectangular hoop and cross-tie are specified as follows

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$$A_{sh,352} = 0.3 \frac{s_h b_c'' f_c'}{f_{yh}} \left(\frac{A_g}{A_c} - 1 \right)$$

$$\phi V_{n,352} = \phi 0.083 \gamma_{352} \sqrt{f_c'} b_j h_c \quad (\text{MPa})$$

where $A_{sh,352}$ should not be less than $0.09 s_h b_c'' f_c' / f_{yh}$; f is 0.85; s_h is center-to-center spacing of hoops or hoops plus cross-ties; b_c'' is the core dimension of the tied column, outside to outside edge of transverse reinforcement bars, perpendicular to the transverse reinforcement area being designed; A_c and A_g are the area of the column core measured from outside edge to outside edge of the hoop reinforcement and the gross area of the column section, respectively; and the factor γ_{352} depends on the joint configuration and is 12 for corner exterior joints with a continuous column. The required transverse reinforcement of Eq. (1) is the same as Eq. (21-4) of ACI 318^{11, 14} which applied for members subjected to bending and axial load rather than for joints. This equation was developed with the intent that spalling of shell concrete would not result in a loss of axial load strength of the column. Equation (1) is not directly related to joint shear strength and it includes only the plane configuration to confine core concrete. Shear force, which should be resisted by a joint, is computed on a horizontal plane and the joint shear strength of Eq. (2) depends on only a horizontal configuration, such as the effective area of the joint and connection classification. Joint aspect ratio is not included in Eq. (1) and (2).

Eurocode 8

In Eurocode 8,¹⁶ the joint shear strength and required transverse reinforcement for exterior joints are determined as follows

$$V_{n,EC8} = 0.8 \eta f_{cd} \sqrt{1 - \frac{v_d}{\eta}} b_{j,EC8} h_{jc}$$

$$A_{sh,EC8} = \left\{ \frac{\left(\frac{V_{jhd}}{b_{j,EC8} h_{jc}} \right)^2}{f_{ctd} + v_d f_{cd}} - f_{ctd} \right\} \frac{b_{j,EC8} h_{jb}}{f_{yh}}$$

where $h = 0.6(1 - f_{ck}/250)$; h_{jc} and h_{jb} are the distances between extreme layers of longitudinal reinforcement in the column and beam, respectively; and f_{cd} , f_{ck} , v_d , $b_{j,EC8}$, V_{jhd} , and f_{ctd} are defined in 5.5.3 of Eurocode 8. Similarly to Eq. (2), the joint shear strength of Eq. (3) is dependent on only the horizontal joint area but Eq. (4) includes column

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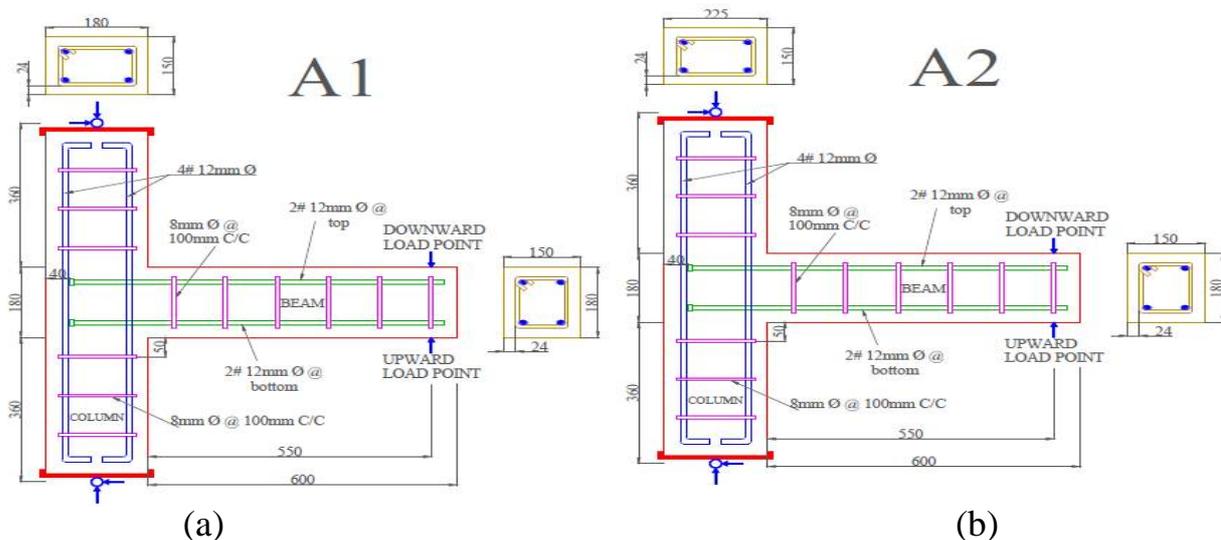
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depth as well as beam depth. Eurocode 8 adopted a simple plane stress model for the verification of the shear strength of beam-column joints.¹⁸ The model assumes homogeneous stresses in the body of the joints, consisting of shear stress, vertical normal stress, and horizontal normal stress. Column depth and beam depth in Eq. (4) are used only to calculate the principal stresses in vertical and horizontal directions, respectively. Joint aspect ratio h_j/b_j does not affect the joint shear strength and the amount of transverse reinforcement. In Tsonos's study,⁴ it was demonstrated that the design assumptions of Euro code 8 did not avoid premature joint shear failures and did not ensure the development of the optimal failure mechanism with plastic hinges occurring in the beams, while columns remained elastic according to the requisite strong column-weak beam.

IV. EXPERIMENTAL PROGRAM

The main variable is a joint aspect ratio from 0.67 to 2.5. For joint aspect ratios of 0.67 and 1.0, the joints that had two-thirds of Ash,352 were also tested. Two anchorages of beam bars that is, hooked bars and headed bars—were used as shown in Fig. 2. For the test specimens, H denotes standard hook anchorage and M denotes mechanical or headed anchorage. A total of 14 specimens with a story height of 3.57 m, were tested under reversed cyclic loading, as shown in Fig. 3. The beam lengths from the column face were varied to ensure flexural behaviors of beams; these are summarized in Table 1. The specimens were designed in accordance with ACI 352R-02, except joint shear strength. The nominal shear strength V_n ,³⁵² of each specimen was almost equal to the joint shear force V_u but, for the specimens with joint aspect ratios equal to or less than 1.5, the nominal joint shear strength the main variable is a joint aspect ratio from 0.67 to 2.5. For joint aspect ratios of 0.67 and 1.0, the joints that had two-thirds of Ash,352 were also tested. Two anchorages of beam bars—that is, hooked bars and headed bars—were used as shown in Fig. 2. For the test specimens, H denotes standard hook anchorage and M denotes mechanical or headed anchorage. A total of 14 specimens with a story height of 3.57 m. were tested under reversed cyclic loading, as shown in Fig. 3. The beam lengths from the column face were varied to ensure flexural behaviors of beams; these are summarized in Table 1. The specimens were designed in accordance with ACI 352R-02, except joint shear strength. The nominal shear strength V_n ,³⁵² of each specimen was almost equal to the joint shear force V_u but, for the specimens with joint aspect ratios equal to or less than 1.5, the nominal joint shear strengths.



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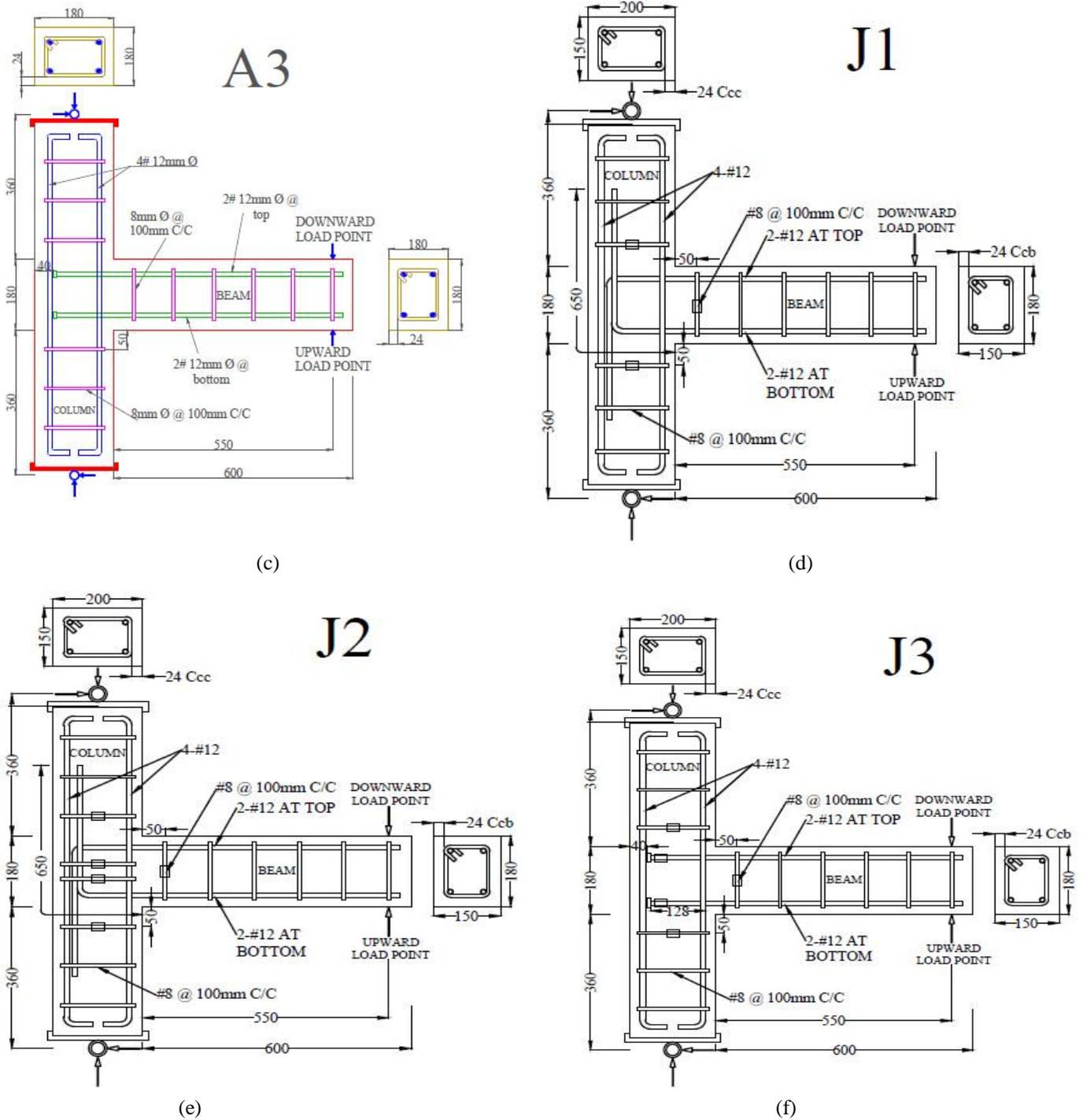


Fig.2 Change of shear reinforcement in reinforcement cage

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The design yield strength of the reinforcing bars was 415 MPa and measured yield and tensile strengths are summarized in Table 2. The compressive Strengths of the concrete of the column and beam were designed to be 42 and 30 MPa respectively, and the measured compressive strengths at the tests are shown in Table 1 Details of typical specimens are shown in Fig. 2. Tied columns with a square cross section of 180X150 mm were used. Beam width was fixed at 150 mm for all specimens. Beam depths h_b were varied in accordance with the designed joint aspect ratios and are shown in Table 1. As column reinforcing bars, 4-D12 and 4-D12 were placed to satisfy the requirement for the ratio of column-flexural strength to beam-flexural strength of ACI 352R-02. For beam reinforcing bars, 4-D12 and 4-D19 were used as top and bottom bars, respectively.

Table 1—Dimensions and material properties of test specimens

Specimen ID*	h_b , mm (in.)	$\beta = h_b/h_c$	$\Sigma M_{n,c}/M_{n,b}^\dagger$	$V_{n,352}/V_u^\dagger$	L_b , mm (ft)	Joint transverse reinforcement	f'_c , MPa (psi)	
							Beam	Column
H0.7S	200 (7.87)	0.67	7.79	0.91	1200 (3.94)	(2D13 + D10) at 75 ([2 No. 4 + No. 3] at 3 in.)	25.6 (3710)	34.8 (5050)
H1.0S	300 (11.8)	1.0	3.96	0.94				
H1.5S	450 (17.7)	1.5	2.28	0.98				
H2.0S	600 (23.6)	2.0	1.60	1.03	2400 (7.87)		26.4 (3830)	48.2 (6990)
H2.5S	750 (29.5)	2.5	1.23	1.08				
H0.7U	200 (7.87)	0.67	7.79	—	1200 (3.94)	3D10 at 75 (3 No. 3 at 3 in.)	25.6 (3710)	34.8 (5050)
H1.0U	300 (11.8)	1.0	3.96	—				
M0.7S	200 (7.87)	0.67	7.79	0.91	1200 (3.94)	(2D13 + D10) at 75 ([2 No. 4 + No. 3] at 3 in.)	25.6 (3710)	34.8 (5050)
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M1.0U	300 (11.8)	1.0	3.96	—				

all other respects, the specimens satisfied the ACI 352R-02 recommendations. The development lengths of beam reinforcing bars were constant for all specimens. The provided lengths exceeded the ACI 352 required values of l_{db} and l_{dt} , which were calculated based on the design material properties. The head was attached to the bar using a parallel-threaded connection. The net head area was four times the bar area in accordance with Clause 12.6 of ACI 318-11 and the headed bars complied with Clause 3.5.9 of ACI 318-11 and ASTM A970/A970M.¹⁹ All requirements of Clause 12.6 of ACI 318-11, except for clear spacing of 4_{db} , were satisfied. The clear spacing between headed bars was only 1.3_{db} . No column axial load was applied, as tests have shown that including axial load tends to improve joint behavior.²⁰ the beam end was then loaded under displacement control with three reversed cycles at each specified drift ratio in accordance with ACI 374.1-05.21 Test measurements included applied actuator load and beam deflection at loading point. To obtain joint shear distortion, two displacement transducers were diagonally installed in the joint, as shown in Fig. 3. Strains on beam reinforcing bars at the column face, column reinforcing bars, and horizontal transverse reinforcement were measured.

Test Results

Overall behavior at the early stage of the loading schedule, all specimens showed similar behaviors. The first flexural cracks appeared in the beams at the column faces at drift ratios of 0.2%. However, diagonal shear cracks started to develop within the joint at different drifts for the specimens; diagonal cracks appeared at 0.75% drift ratio for H0.7S and H1.0S and the cracks appeared at 0.3% drift for H1.5S and H2.0S. For H0.7S and H1.0S, beam yielding with

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limited joint damage was observed, whereas for specimens with joint aspect ratios equal or greater than 1.5, flexural yielding was accompanied by extensive diagonal cracking within the joint that produced substantial spalling of the joint cover concrete toward the end of testing, as shown in Fig. 4. As the joint aspect ratio increased, the joints became severely distorted and beam damage was reduced.



Specimen A2 and A3



Specimen J1 and J2

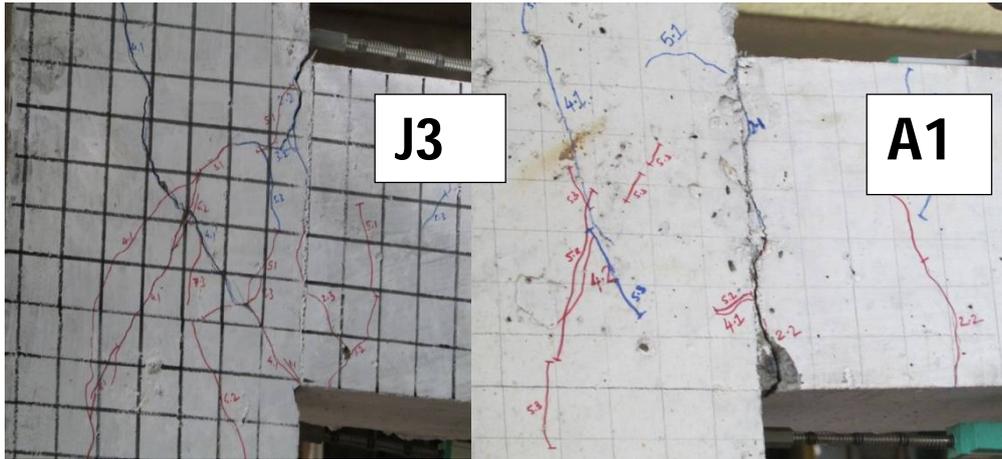


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Specimen J3 and A1

1. Observation Table

Specimen ID	Yield specimen (mm) Δy	Ultimate loading (kN) P_u		Average ultimate Load kN(P_u)	Ultimate displacement (mm) (Δu)		Average ultimate Load kN(Δu)	Average displacement ductility factor (mm) ($u = \Delta u / \Delta y$)	Average stiffness kN/mm ($K = P_u / \Delta y$)
		+ve	-ve		+ve	-ve			
A1 aspect ratio 1.2	1.5	10.3	12.81	16.705	11.61	7.18	15.2	10.13	11.13
A2 aspect ratio 0.8	9.85	11.65	14.76	19.03	23.93	24.03	41.94	4.25	1.93
A3 aspect ratio 1	3.04	16.32	14.68	23.66	23.94	23.6	35.77	11.76	7.78
J1 bent up bar without shear reinfor Cemnt	3.91	17.18	16.98	17.08	23.836	22.13	23.98	5.87	4.39
J2 bent up bar with shear reinfor cemnt	3.09	22.51	19.85	21.18	23.44	24.47	23.95	7.75	6.85

V. CONCLUSION

An experimental study to assess the effects of joint aspect ratio (beam depth to column depth ratio) on shear strength and required amount of transverse reinforcement in the exterior beam-column joint was conducted. In addition, anchorage types of beam bars (hooked and headed bars) were also evaluated. Tests were conducted on 14 essentially fullscale specimens and the main variables included joint aspect ratio, amount of transverse reinforcement, and

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anchorage types of beam bars. The test specimens were subjected to reversed cyclic lateral loading. Based on the test results, the following conclusions were drawn. 1. The specimens with an aspect ratio equal to or less than 1.0 showed typical flexural behavior of beam yielding with limited joint damage. For specimens with joint aspect ratios equal to or greater than 1.5, flexural yielding was accompanied by extensive diagonal cracking within the joint that produced substantial spalling of the joint cover concrete toward the end of testing. As the joint aspect ratio increased, the joints were severely distorted and beam damage was reduced. 2. In the case whereby the joint aspect ratio is equal to or less than 1.0, the joints having less transverse reinforcement (two-thirds of transverse reinforcement required by ACI 352) showed similar behavior to the joints designed in accordance with ACI 352R-02 in terms of failure modes, joint strength, joint distortion, and energy dissipation.

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