SEISMIC DESIGN AND DETAILING OF EXTERIOR REINFORCED CONCRETE BEAM-COLUMN JOINTS

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SUMMARY

The role of horizontal hoop reinforcement in joint for seismic resistance is a subject of much debate. Currently there is little consensus within the design and research communities as to declare whether joint hoops serve to confine the core concrete or to carry joint shear directly. The ACI 318-02 Code provisions emphasize the importance of the confinement of the joint core, which results in congested joints and causes difficulty in construction. Moreover, the increasing use of high-strength concrete, resulting in larger amount of joint hoops, poses an even worse situation.

The main objective of this paper was to investigate the effect of joint hoops on the shear strength of exterior reinforced concrete beam-to-column connections subjected to earthquake loading. An attempt was made to relieve the congestion of steel in joints. A newly developed softened strut-and-tie model postulates that the function of joint hoop is to carry shear as a tension tie, to constrain the crack width, and not to confine the concrete core. The softened strut-and-tie model suggests that transverse steel is more important for resisting shear other than for confining concrete, therefore the required amount and spacing limits of the joint hoops can be alleviated. Consequently, the other objective was to evaluate the performance of exterior joints which conform to the design philosophy per the softened strut-and-tie model.

Six exterior beam-to-column subassemblages were tested under reverse cyclic loading. All test specimens were designed to have adequate shear strength of joints according to the softened strut-and-tie model. The parameters investigated include the amount and the detailing of joint hoops. The test results indicate that a lesser amount of hoop reinforcement with wider spacing could be used without significantly affecting the performance of joints if the connections are provided with adequate shear strength according to the softened strut-and-tie model

INTRODUCTION

The role of horizontal hoop reinforcement in joint for seismic resistance is a subject of much debate. It has been argued that hoops carry a substantial portion of the joint shear directly with the remainder being carried by the concrete core in the form of a diagonal compression strut [1]. An alternative

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argument is that hoops contribute to the shear resistance of joints indirectly by confining the concrete core, thus enhancing its diagonal compressive strength [2]. These conflicting views about the function of transverse reinforcement lead to different demands for hoop as well as the disparity in detailing rules.

Currently, the ACI 318-02 Code provisions [2] emphasize the importance of the confinement of the joint core. In consequence, the closely spaced transverse reinforcement in the end regions of laterally loaded columns must be detailed within joints unless a suitable confinement is provided by the surrounding beams [2]. The use of crosstie is inevitable since the maximum spacing between legs of hoops is limited to 350 mm on center [2]. These ACI requirements for adequate concrete confinement result in congested joints which are very difficult to construct. Moreover, the increasing use of high-strength concrete, resulting in larger amount of joint hoops [2], poses an even worse situation for construction. It seems necessary to declare whether joint hoops serve to confine or to carry shear in a more concise manner.

A softened strut-and-tie (SST) model, satisfying equilibrium, compatibility, and constitutive laws of cracked reinforced concrete, has been developed for determining the shear strength of beam-column joints [3, 4]. Joint hoops play two roles in the shear-resisting mechanisms as postulated by the SST model. One is to form tension tie and provide additional shear-transferring path beside the main diagonal strut. The other is to control the crack widths and retard the softening process of the cracked concrete. The SST model suggests that transverse reinforcement is more important for resisting shear than for confinement, therefore the required amount and spacing limits of the joint hoops can be alleviated.

The main objective of this study was to investigate the effect of joint hoops on the shear strength of exterior reinforced concrete beam-to-column connections subjected to earthquake-type loading. Other objective was to evaluate the performance of exterior joints which conform to the SST design philosophy. To achieve these objectives, six exterior beam-to-column subassemblages were tested under reverse cyclic loading.

RESEARCH SIGNIFICANCE

The study reported herein is intended to clarify the effect of joint hoops on the shear-resisting behavior of exterior beam-column connections under large load reversals. An attempt was made to relieve the congestion of steel in joints. The test results indicate that a lesser amount of hoop reinforcement with wider spacing could be used without significantly affecting the performance of joints if the connections are provided with adequate shear strength according to the SST model.

SOFTENED STRUT-AND-TIE MODEL

The simplified version of the SST model [5] for the design of joints is briefly introduced in this section. Fig. 1 shows the earthquake-induced forces acting on an exterior joint. The horizontal joint shear force V_{jh} is estimated as

$$V_{jh} = T - V_{col} \tag{1}$$

where T is the tensile force resulting from the steel of the beam; and V_{col} is the horizontal column shear above the joint. The diagonal compression C_d to be resisted according to the strut-and-tie model is found to be (Fig. 1)

$$C_d = V_{jh} / \cos\theta \tag{2}$$

where θ is the angle of inclination of the diagonal compression with respect to the horizontal axis. For estimating the design value of horizontal joint shear force $V_{jh,u}$, an overstrength factor of 1.25 for the beam steel should be included [2].
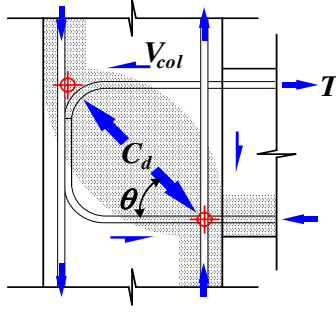
Fig. 1 Forces at exterior joint

Based on the SST model [5], the nominal diagonal compression strength $C_{d,SST}$ can be defined as

$$C_{d,SST} = (K_h + K_v - 1)\,\zeta\,f_c'A_{str} \tag{3}$$

where K_h and K_v are the indexes of horizontal and vertical ties, respectively; ζ is the softening coefficient and can be approximated as $\zeta \approx 3.35/\sqrt{f_c'} \leq 0.52$; f_c' is the compressive strength of a standard concrete cylinder in unit of MPa; and A_{str} is the effective area of the diagonal strut.

The horizontal tie index K_h is expressed as

$$K_h = 1 + (\overline{K}_h - 1) \times A_{th}f_{yh}\,/\,\overline{F}_h \leq \overline{K}_h \tag{4}$$

where A_{th} is the area of horizontal tie; f_{yh} is the yield strength of joint hoop reinforcement; $\overline{K}_h$ is the horizontal tie index with sufficient horizontal reinforcement and can be estimated as

$$\overline{K}_h \approx 1\,/\,[1 - 0.2\,(\gamma_h + \gamma_h^2)] \tag{5}$$

where γ_h is the fraction of diagonal compression carried by the horizontal tie in the absence of the vertical tie and is defined as [6]

$$\gamma_h = (2\tan\theta - 1)/3 \quad \text{for} \quad 0 \leq \gamma_h \leq 1 \tag{6}$$

$\overline{F}_h$ is the balanced amount of the horizontal tie force and can be calculated as

$$\overline{F}_h = \gamma_h \times (\overline{K}_h\zeta\,f_c'A_{str}) \times \cos\theta \tag{7}$$

The related equations to the vertical tie are the same as Eqs. (4) to (7), except that all the subscript h are replaced by v and $\cos\theta$ and $\sin\theta$ are interchanged.

TEST PROGRAM

Six exterior reinforced concrete beam-column connections using concrete with design compressive strength of 70 and 28 MPa and Grade 60 steel were constructed and tested [7,8]. A typical beam-column subassemblage tested in this study is shown in Fig. 2. Sufficient shear reinforcement was provided in the beam and columns outside of the joint to prevent shear failure in the beam or the column. All test specimens were designed to have adequate shear strength of joints according to the SST model. The parameters investigated include the amount and the detailing of joint hoops. Figure 3 presents the dimensions and the reinforcement details of joints.

Fig. 2 Specimen configuration and test setup

Fig. 3 Beam-column joint details
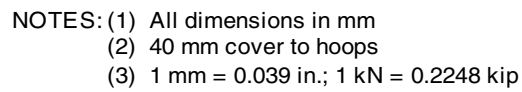
All specimens were cast flat rather than vertical as in actual construction. The test day compressive strength for the concrete cylinders and the average yield stress for the reinforcing steel are presented in Table 1. The design values for the test parameters as well as the actual values for each specimen are listed in Table 2.

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Table 1 Material properties

Specimen	Concrete	Reinforcement						
		Beam bars #8		Column bars #10		Joint hoops		
	f'_c MPa	f_y MPa	f_u MPa	f_y MPa	f_u MPa	size	f_y MPa	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	
70-3T44[7]	76.8	430	605	421	659	#4	498	
70-3T4[8]	75.2	491	715	458	690	#4	436	
70-2T5[8]	76.6	491	715	458	690	#5	469	
70-1T55[8]	69.7	491	715	458	690	#5	469	
28-3T4[8]	35	491	715	458	690	#4	436	
28-0T0[8]	33	491	715	458	690	—	—	

Note: 1 MPa = 145 psi

Table 2 Design parameters

Specimen	M_R	Joint strength		Joint hoop			
		$\dfrac{V_{jh,u}}{V_{jh,SST}}$	$\dfrac{V_{jh,u}}{V_{jh,ACI}}$	Amount	Spacing mm	$\dfrac{\rho_h}{\rho_{h,ACI}}$	$\dfrac{A_{th}f_{yh}}{\gamma_h V_{jh,u}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
70-3T44	2.9 (3.0)	0.88 (0.90)	0.62 (0.63)	3 layers 2-#4	97	0.91 (1.00)	1.63 (1.85)
70-3T4	3.1 (3.0)	0.76 (0.89)	0.54 (0.63)	3 layers 1-#4	97	0.46 (0.45)	1.01 (0.88)
70-2T5	3.1 (3.0)	0.76 (0.88)	0.54 (0.63)	2 layers 1-#5	146	0.31 (0.33)	1.05 (0.98)
70-1T55	3.1 (3.0)	0.76 (0.92)	0.54 (0.66)	1 layers 2-#5	293	0.31 (0.36)	1.05 (0.98)
28-3T4	5.0 (4.9)	0.86	0.56	3 layers 1-#4	122	0.61 (0.75)	0.91 (0.80)
28-0T0	5.0 (4.9)	0.90	0.56	none	---	0	0

Note: 1 mm = 0.0394 in.; Numbers outside parentheses are the design values; numbers inside are the actual values.

In order to provide confinement through the joint, Specimen 70-3T44 [7] was detailed with the joint hoops as per the ACI requirements. As shown in Fig. 3, the joint of Specimen 70-3T44 was reinforced with three layers of double #4 hoops with crossties. The joint hoop reinforcement ratio ρ_h of Specimen 70-3T44 was as high as 2.44% and its spacing was 97 mm (Table 2).

The Specimens 70-3T4, 70-2T5, and 70-1T55 [8] were intended for testing the effectiveness of hoop detailing based on the concept of shear resistance. Those specimens had larger dimension than that of Specimen 70-3T44 (Fig. 3), but their joint hoop ratios were only about a third of Specimen 70-3T44 [column (7) of Table 2]. The hoop details of Specimen 70-3T4 conformed to the ACI 318-02 Code [2]. Specimen 70-3T4 was constructed using three layers of #4 hoops with crossties at the joint (Fig.

3). However, the strict detailing rules of joint hoops with the purpose of confinement were alleviated for Specimens 70-2T5 and 70-1T55. The joint of Specimen 70-2T5 was built using two layers of #5 hoops without crosstie (Fig. 3). Furthermore, two set of #5 hoops, functioning as a tension tie, were grouped into the middle of joint of Specimen 70-1T55 (Fig. 3).

It is commonly believed that the elastic ties can maintain the integrity of the members under severe cyclic loading caused by earthquakes. Therefore, the amount of joint hoops of the Specimens 70-3T4, 70-2T5, and 70-1T55 was designed to remain in elastic range for tension tie during tests according to the SST model. The required horizontal tie force can be estimated as $\gamma_h V_{jh,u}$, and these specimens were provided with barely enough joint hoops, i.e. $A_{th} f_{yh} / \gamma_h V_{jh,u} \approx 1$ (Table 2).

Specimen 28-3T4 [8] was constructed using three layers of #4 hoops without crossties at the joint (Fig. 3). The strict detailing rules of joint hoops with the purpose of confinement were alleviated, and the normal strength concrete was used for Specimen 28-3T4. This is to check the applicability of the SST design philosophy to the exterior joints using normal strength concrete.

Specimen 28-0T0 [8] is a lower bound unit, which had barely enough joint strength ($V_{jh,u} / V_{jh,SST} \approx 0.9$) and no joint hoop (Table 2). From the perspective of the SST model, the ACI 318-02 Code [2] overestimates the shear strength of exterior joints. It is noted that the design joint shear force is approximately a half of the ACI value ($V_{jh,u} / V_{jh,ACI} \approx 0.56$; Table 2).

Horizontal load was applied with an actuator using displacement control as shown in Fig. 2. Figure 4 presents the loading history of this test program.
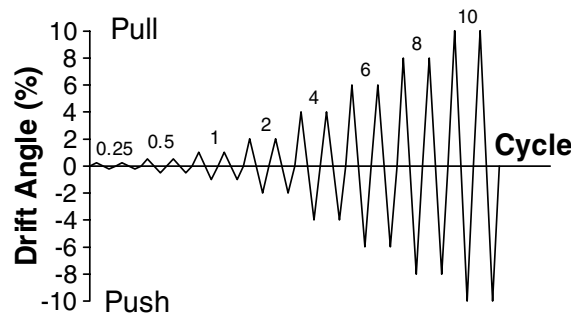
Fig. 4 Loading history

A complete description of the test program can be found in the Reference 9.

DISCUSSION OF TEST RESULTS

Plots of the applied load versus the drift ratio for all specimens are shown in Fig. 5, where the drift ratio is defined as the deflection of the load point divided by the distance between the load point and the column center line. The curves of the joint force V_{jh} versus the joint shear deformation γ_j are also plotted in Fig. 5, where V_{jh} was calculated using Eq. (1) and γ_j was measured by gauges.
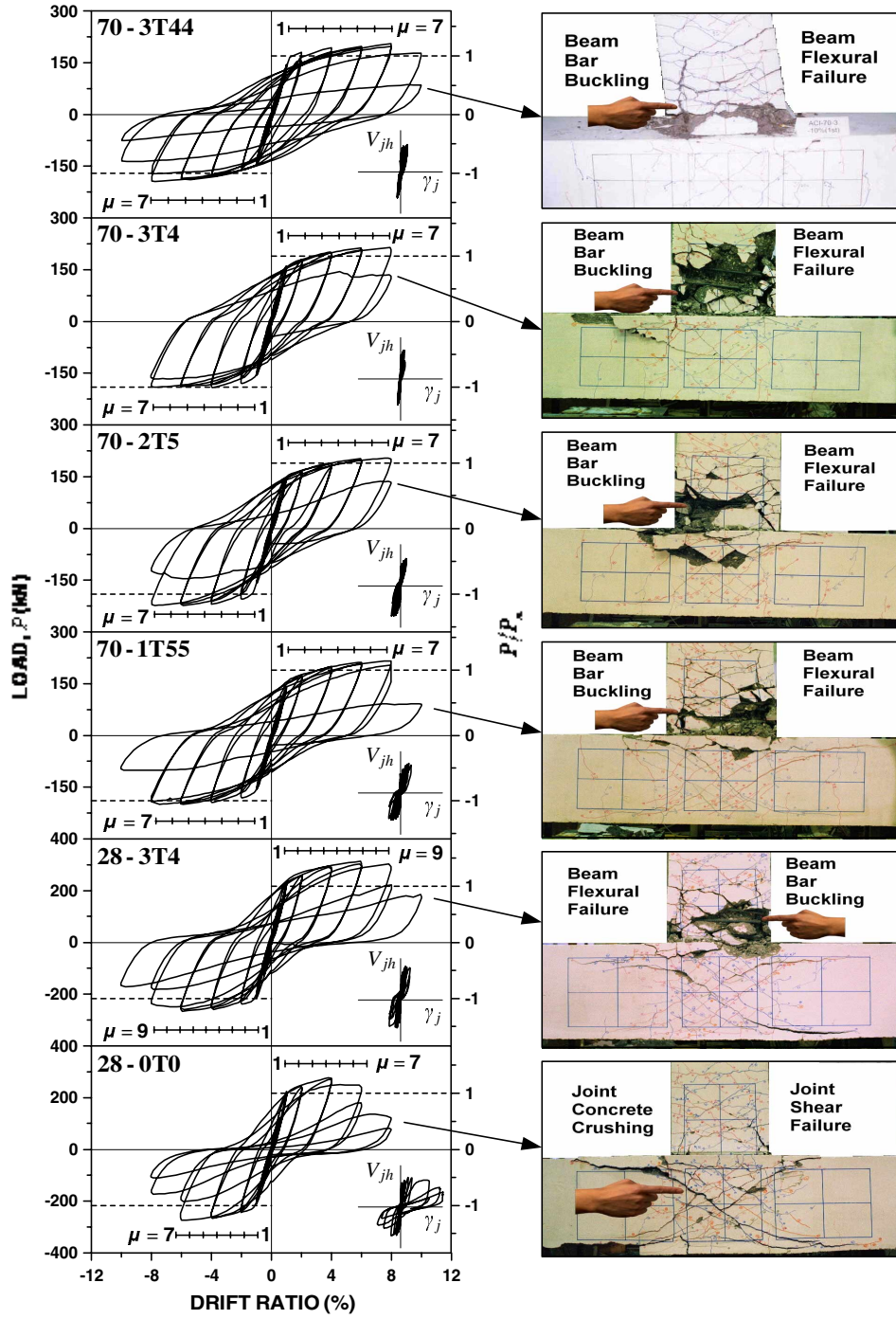
Fig. 5 Load versus deflection response of specimens

The test results on strength and ductility are revealed in Table 3. The measured joint strength $V_{jh,test}$ was determined from the peak applied load P_{max} using Eq. (1). The displacement ductility μ is defined as Δ_{max} / Δ_y, where Δ_{max} is the horizontal displacement at the free end of the beam corresponding to P_{max}. The yield displacements Δ_y for all test units were calculated by extrapolating the measured horizontal displacement at $0.75 \, M_n$, linearly to M_n, where M_n is the nominal flexural strength of the beam.

Table 3 Test results

Specimen	Test results							Comparisons		
	Strength		Ductility			Dissipated energy to 8% drift	Failure mode	Hoop	Shear Strength	
	P_{max}	$V_{jh,test}$	$P_{n,calc}$	Δ_y	μ			$\dfrac{A_{th}f_{yh}}{\gamma_h V_{jh,test}}$	$\dfrac{V_{jh,test}}{V_{jh,SST}}$	$\dfrac{V_{jh,test}}{V_{jh,ACI}}$
	kN	kN	kN	mm		kJ				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
70-3T44	205	1065	169	24	8.7	267	BF	1.69	0.99	0.69
70-3T4	214	1110	190	24	7.1	269	BF	0.88	0.90	0.63
70-2T5	224	1162	190	24	7.1	255	BF	0.94	0.92	0.66
70-1T55	217	1126	189	23	7.3	261	BF	0.97	0.93	0.67
28-3T4	313	1290	217	18	9.2	320	BF	0.66	1.01	0.72
28-0T0	276	1138	217	19	6.6	213	BF-JS	0	0.98	0.66

Note: 1 kN = 0.2248 kip; 1 mm = 0.0394 in.; Failure mode BF means the flexural failure of beam hinging, and BF-JS means the joint shear failure after beam hinging.

The failure modes of the test specimens were classified into BF and BF-JS (Table 3). The term of BF designates the beam flexural failures due to the buckling of the beam compression bars. The classification of BF-JS means the joint shear failure after the development of the beam flexural hinge. The occurrence of the beam bar buckling and the distortion of the joint shear deformation are shown in Fig. 5. Photographs of these two different modes of damaged specimens at the conclusion of the tests are presented in Fig. 5.

Importance of Shear Strength
Specimen 28-0T0 was detailed without any horizontal reinforcement in the joint (Fig. 3). However, sufficient shear strength was provided for the joint of Specimen 28-0T0 according to the SST model. Although failed in joint, satisfactory hysteretic response was obtained for the Specimen 28-0T0 (Fig. 5), and the displacement ductility μ can reach a value of 6.6 (Table 3). This observation indicates that designing the joint with sufficient shear strength will ensure a certain level of performance even without joint reinforcement. However, it should be noted that the axial compressive load on the columns during the tests was very small (Fig. 2). With a high axial load present, buckling of the longitudinal column bars would have been more likely.

As shown in Table 3, the strength ratios $V_{jh,test}/V_{jh,SST}$ are close to one, and the failure mode contained the type of BF-JS. This correlation gives evidence that the joint shear strength is crucial for seismic behavior of beam-column joint and that the joint strength can be accurately predicted by the SST model for the joints using normal or high strength concrete. On the other hand, the strength ratios $V_{jh,test}/V_{jh,ACI}$ are always less than one despite the occurrence of joint failure (Table 3). This indicates that the ACI 318-02 Code [2] overestimates the shear strength of the exterior beam-column joints.

Effect of Confinement
The Specimens 70-3T4, 70-2T5, and 70-1T55 shared the same properties except for the joint hoops. The detailing of the joint hoops for Specimen 70-3T4 followed the ACI strict requirements. However in Specimen 70-1T55, the crosstie was removed and the vertical hoop spacing was increased to 300 mm for the joint (Fig. 3). In disregard of the breakdown on confinement effect, these specimens possessed similar seismic behavior. This can be examined through their hysteretic curves in Fig. 5 and other indexes, such as strength, ductility, energy dissipation and failure mode, shown in Table 3.

The similarities in seismic behavior among these units imply that the joint hoop plays no role in confining concrete core.

The beneficial effect of confinement by transverse reinforcement on the seismic behavior of beam-column joint was not found in this study. The increase in strength and ductility of concrete confined by reinforcement is observed for the axially-loaded columns or the beams under flexure, where the concrete deforms under the plane-remaining-plane restriction. However, the beam-column joint is a region of high shear, thus the joint deformation is govern by the Mohr's compatibility in stead of the Bernoulli's compatibility. In consequence, the concrete strength within the joint should be described by the softening phenomenon [10, 11]. The joint hoop should be viewed as crack-controlled steel and not as concrete-confining reinforcement. Therefore the adding of joint hoop is to retard the deterioration of concrete strength and not to enhance the concrete strength. The crack-controlled reinforcement requires less amount of steel and wider spacing for detailing.

It is worthwhile to point out that Specimen 70-3T4 had the same failure mode of beam hinging as Specimen 70-3T44 (Fig. 5). However, the amount of joint hoop of Specimen 70-3T4 is only a half of that within Specimen 70-3T44. The joint hoop ratios $\rho_h / \rho_{h,ACI}$ of Specimens 70-3T4 and 70-3T44 are 0.46 and 0.91, respectively (Table 2). This reveals that the ACI requirement on the amount of joint hoop is unnecessary.

Effect of Tension Tie
Although varied in joint hoops, the Specimens 70-3T4, 70-2T5, and 70-1T55 possessed similar hysteretic behavior as presented in Fig. 5. Among those changes in joint hoops, the effects of tension tie were carefully maintained in the perspective of SST model, shown as $A_{th} f_{yh} / \gamma_h V_{jh,u}$ in Table 2. Altering the joint hoops and not disturbing the effect of tension tie can preserve the seismic behavior of beam-column joints, which means the effect of tension tie is the key role of joint hoop in seismic resistance.

Figure 6 presents the measured strains in the joint hoops for Specimens 70-3T44, in which gages 1 and 2 measured the strains including effects of tension tie and gages 3 and 4 measured only the effect of crack control. In general, the strain readings of gages 1 and 2 are larger than those of gages 3 and 4. As shown in Fig. 6, the readings of gages 1 and 2 increase rapidly and in proportion with the growth of joint shear V_{jh} for drift angle less than 1%. Afterwards gages 1 and 2 gained strains slowly due to joint deformation and mild increase in V_{jh} due to strain hardening of beam bars. The readings of gages 3 and 4 increased gradually with the expansion of joint [Fig. 6(b)].
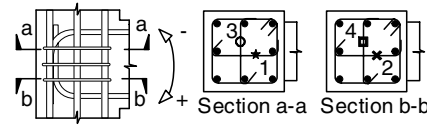
(a) Location of gages
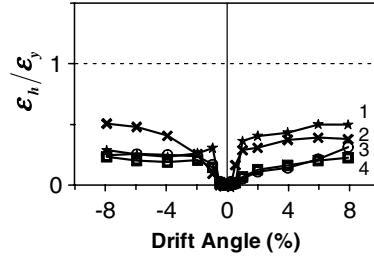
(b) Specimen 70-3T44

Fig. 6 Measured strain in the joint hoops for Specimens 70-3T44

The joint hoops of Specimens 70-3T4, 70-2T5, and 70-1T55 were designed as tension tie according to SST model and kept in elastic range for shear transferring. As shown in Fig. 7, the strains in the joint hoops of these specimens were kept fairly well in elastic range [(a)-(c)]. It should be noted that comparable strain readings were observed among specimens with different detailing for these specimens in Fig. 7. This is indicative that the major characteristic of joint hoops can be captured by viewing them as tension tie. It is also noted that the SST model can predict the requirement of tension tie reasonably well using the equation of $A_{th}f_{yh} = \gamma_h V_{jh,u}$, which corresponds one third of the ACI requirement for these Specimens (Table 2).
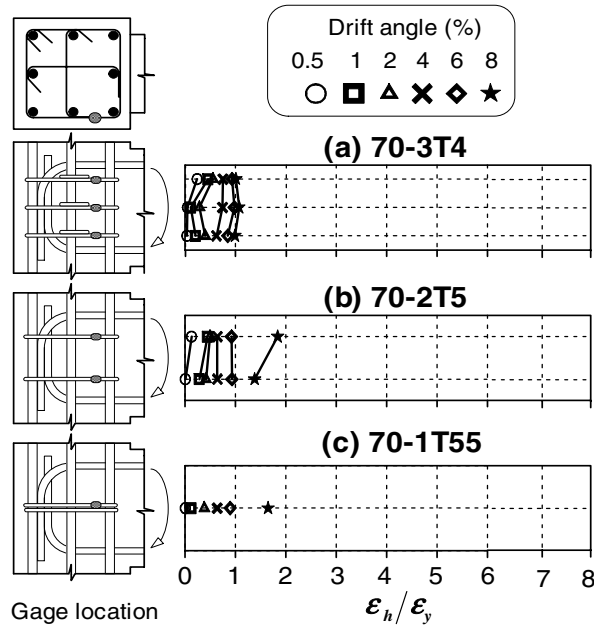

(a) 70-3T4

(b) 70-2T5

(c) 70-1T55

Gage location

Fig. 7 Measured strain in the joint hoops

Effect of Crack Control

It was observed that the Specimens 70-3T4, 70-2T5, and 70-1T55 were failed by the buckling of compression bars in beam hinges (Fig. 5), and the yielding of joint hoops of these specimens was effectively delayed by adding sufficient amount of transverse steel (Fig. 7). The factor of joint hoop yielding has a decisive influence on the failure modes of the beam-column joints. It is believed that the early yielding of joint hoop provides no reliable mechanism to restrain the deterioration of the joint

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concrete and causes the joint failure at larger displacement levels. To design the joints with the elastic joint hoops is appealing for the special moment resisting frames, because the elastic ties can maintain the integrity of the members under severe cyclic loading caused by earthquakes.

The different detailing in joint hoops for Specimens 70-3T4, 70-2T5, and 70-1T55 preserved the equivalent tie action but caused slight deviation on the effect of crack control among specimens. The crack-controlled reinforcement would be more effective with smaller spacing. Among the three specimens, Specimen 70-3T4 owned the best detailing in the aspect of crack control, followed by Specimen 70-2T5, with Specimen 70-1T55 holding the poorest detailing. By comparing the V_{jh} versus γ_j curves in Fig. 5, Specimen 70-3T4 possessed a straight linear relationship, and Specimen 70-1T55 displayed a wider-banded linearity. As shown in Figs. 7(a) to 7(c), Specimen 70-3T4 experienced the least strains in the joint hoops. Above argument can also be verified through the measurement of crack width. Figure 8 presents the measurement of crack widths in the joint regions. As can be seen, Specimen 70-3T4 yields the smallest crack width, followed by Specimen 70-2T5, with Specimen 70-1T55 giving the largest crack width.
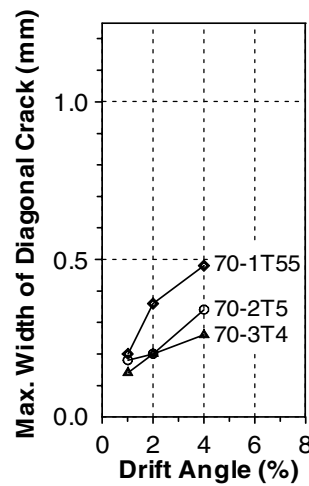
Fig. 8 Comparison of joint crack width

Although the crack-controlled ability of Specimen 70-1T55 was shown up as inferior to that of Specimen 70-3T4, but it is of interest to note that Specimen 70-1T55 is superior to Specimen 28-0T0 (Fig. 5). This indicates that the amount of joint hoop is more important than the joint hoop spacing if the vertical spacing is limited within 300 mm. Moreover as for seismic concern, Specimen 70-1T55 should be judged as effective as Specimen 70-3T4 through comparison of their strength, ductility, energy dissipation, and failure modes (Table 3). In the light of the test results, it is thus concluded that the vertical spacing of joint hoop up to 300 mm is an acceptable range.

CONCLUSIONS

Based on the cyclic load tests of 6 exterior beam-column joints, and within the limitations of those test data, the following conclusions are made:
1. The joint hoops are found to act as a tension tie as well as to constrain the crack width. The current ACI requirements, viewing the joint hoop as confining the concrete core, are unnecessary and very difficult for construction. The test results indicate that a lesser amount of hoop reinforcement with wider vertical spacing up to 300 mm could be used without significantly affecting the performance of joints.

2. Without high axial load in the column, a beam-column joint without hoop can possess satisfactory seismic behavior, as long as the joint is provided with adequate shear strength according to the SST model.
3. The deterioration of beam-column joint under displacement reversals could be effectively restrained by the elastic joint hoops. For beam-column joints, where there is a need for sustained strength under deformation reversals, it is recommended to design the joints with adequate shear strength and with sufficient amount of hoops to remain in elastic range under earthquake loading. The required amount of hoops can be determined by viewing joint hoops as tension tie and using the equation of $A_{th}f_{yh} = \gamma_h V_{jh,u}$ according to SST model.
4. The SST design philosophy is equally applicable to the seismic joints using both the normal and the high strength concrete.

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