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ASSESSMENT FOR SEISMIC PERFORMANCE OF HEADED BAR ANCHORING IN INTERNAL BEAM-COLUMN JOINTS

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ABSTRACT

In this study, headed bars are adopted to replace traditional standard hooks for avoiding reinforcement crowding in the beam-column joints. A total of nine full-scale beam-column joint experiments were performed to evaluate the applicability of headed bars in beam-column joints. Not only to understand the anchorage behavior of headed bars in beam-column joints, but to comprehend the effect on flexure moment of beams. The issues on whether the performance of beam-column joints with different clear spacing and arrangements of headed bars satisfy the seismic requirement are also discussed.

For interior beam-column joints with two types of arrangement (butt and splices) and two types of clear spacing ($2.2d_b$ and $4d_b$), the strength and ductility of the beam-column joints are found to be satisfactory. Additionally, for butt arrangement with enough anchorage length, the yielding of reinforcement and crush of concrete at beam end are obvious during incremental loading vertically, the beam-column joint belongs to the strong column-weak beam pattern.

Keywords: reinforced concrete, beam-column joint, headed bar, butt and splice , clear spacing

1. INTRODUCTION

The connection point of column component and beam component (beam-column joint) is one of the structures bearing the most complex force mechanisms, especially for the beam-column joints of side columns, corner columns, top columns, discontinuous beam or column components. The traditional engineering method for the seismic design results in more congested reinforcement configuration in joints since the main reinforcement end adopts the hook for anchorage and all reinforced hooks are anchored to the center of joints, which easily causes poor concrete pouring due to difficult construction. Furthermore, it leads to the doubt about insufficient strength in beam-column joints. The specification ACI 318-11 (2011) suggests that the anchorage length of the hook should be greater than that of headed bar. If headed bars can be used to replace the reinforced hooks for anchorage, not only the embedded length can be shortened, but also the bars congestion

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issue in beam-column joints can be resolved. Additionally, it can improve the construction quality of beam-column joints.

If the anchoring of the reinforcement ends adopts the headed bars, it can be processed in the factory in advance to not only guarantee the accuracy of material size and quality but also improve production rate and reduce the cost if it is accompanied by mechanized mass production. It is also conducive to relieve the pressure of on-site manufacturing and to realize control in the construction quality. If it is performed by precast construction, the precast components are manufactured in factory and the connection of reinforcement at joint is not limited to be straight type (splice splices or butt splices) so as to improve the construction quality and efficiency.

The specification ACI 318-11 provisions for headed bars detail the development of headed and mechanical anchorage deformed bars , such as development length, maximum allowable concrete strength, bar and head size, as well as side cover and clear bar spacing. However, the restriction of ACI 318-11 hinders use of headed bars for the case where bar clear spacing is less than $4.0d_b$, which is in fact common for beam or column reinforcement of moment frames.

The related study on T-headed bar (Lin et al. 2010) indicated that as far as the development of anchoring strength is concerned, the anchoring capacity of the clear spacing of T-headed bar configuration is equal to that of $4.0d_b$ clear spacing. So it is suggested that the clear spacing of T-headed bar configuration can be decreased to $1.5d_b$. In this study, the interactive splice configuration is adopted in reinforcement of beam-column joints so that the clear spacing of T-headed bar configuration of the beam can only be controlled to $2.2d_b$, and closely shear stirrups will be configured in beam-column joints to guarantee the doubt of the clear spacing of headed bars while the seismic requirement is considered.

2. SHEAR FORCE REQUIREMENTS IN BEAM-COLUMN JOINTS

The concept of flexure design codes in America and Japan are both strong column and weak beam patterns. In earthquake, column components are required not to be destroyed before beam components and beam-column joints, so they must be elastic-plastic so that other components have enough time to dissipate the seismic forces, which means the shear strength V_n of beam-column joints should be greater than the shear force requirement V_{jh}. When there is a plastic hinge in beam end, the shear force requirements in joints is the horizontal shear force in beam-column joints passed from main reinforcement of the beam, which can be calculated by the following formula:

$$V_{jh} = 1.25\left(A_s + A_s^{'}\right) f_y - V_{col} \tag{1}$$

where A_s and $A_s^{'}$ are the sectional areas of the bottom and top layers reinforcements in beams, respectively; f_y is the yielding stress of the main reinforcement; and V_{col} is the shear force of the column. As for the shear force requirements in beam-column joints, America and Japan share the same idea in the codes but greatly differ in the design approach of beam-column joint.

2.1. Design of beam-column joints in ACI 318-11

As for the shear strength in beam-column joints, this study calculates it based on ACI 318-11. ACI 318-11 code specifies the nominal shear strength V_n in beam-column joints for the seismic design, as shown in follows:

$$V_n = 0.083\gamma\sqrt{f_c'}b_j h_c \tag{2}$$

where the shear capacity coefficient γ, which is related to the confinement conditions, is divided into the following classifications: (1) when joints are confined in all round, γ is 20; (2) when the joints are confined at three sides or at two opposite sides, γ is 15; (3) or else, γ is 12; $b_j \times h_c$ is the effective shear resistance area in joints (mm^2); b_j is the effective shear resistance width in joints; h_c is the depth (and the depth of the column) in the shearing direction in joints. To ensure the shear strength of beam-column joints, in the consideration of material uncertainties and other factors, the nominal strength is required to multiply to the strength reduction factor, as follows:

$$\phi V_n \geq V_{jh}, \quad \phi = 0.85 \tag{3}$$

To let beam-column joints meet the requirement of the strong column-weak beam in the seismic design, ACI 318-11 also specifies that the flexural strength ratio of the columns and the beams shall be checked and its value must be greater than 1.2 to ensure that the beam end firstly reaches the bending moment of plastic hinge before column ends under the seismic force. The flexural strength ratio of beam-column joints is defined as follows:

$$R_m = \sum M_{nc} \Big/ \sum M_{ng} \tag{4}$$

where ΣM_{nc} and ΣM_{ng} are the sums of nominal flexural strengths of column and beam ends of joints in the seismic force direction, respectively.

2.2. Design of beam-column joints in AIJ (1999)

According to the design codes of AIJ (1999), the shear force strength of beam-column joint V_n is defined as follows:

$$V_n = \kappa \times \varphi \times F_j \times b_j \times D_j \tag{5}$$

$$F_j = 0.8 \times \sigma_B^{0.7} \tag{6}$$

where the shape coefficient κ of joints is divided into the following classifications: (1) cross shape joint, κ is 1.0; (2) T shape joints, κ is 0.7; (3) L shape joint, κ is 0.4; φ is the modified factor of orthogonal connection beam: (1) if there are orthogonal connection beams on both sides, φ is 1.0; (2)

if there are none of above cases happen, φ is 0.85; F_j is the standard value of shear strength for concrete in joints; σ_B is the concrete compressive strength; b_j is the effective shear width in joints; D_j is the horizontal projection length of reinforcement 90 degrees perpendicular to the column.

3. EXPERIMENT PROGRAM

This study aims to evaluate the seismic performance of T-headed bar anchored in beam-column joints. It divides into nine groups of interior beam-column joints, focusing on the following research subjects:

(1) The bar configuration patterns in joints: to ensure T-headed bar can be effectively applied in reinforced concrete beam-column joints, the study will conduct experiments with nine interior beam-column joints to discuss the differences of seismic behavior in joints. The top layer reinforcement of the beam is straight type and the bottom one is splice or butt types.

(2) Different seismic performances with different reinforcement ratios: in considerations of the engineers' design demands, the amount of main reinforcement of beam components is one of the important factors. In order to understand the effect of reinforcement ratio on joint performance, the amount of reinforcement of beam component is divided into percentages of 1.0, 1.2, 1.5 and 2.0 in this study, so as to further verify whether the amount of reinforcement affects the bond performance among concrete.

(3) Bar clear spacing configuration of beam members: according to the provision that T-headed bar clear spacing is $4d_b$ in ACI 318-11 code, which directly influences the oversize components. Hence, to verify the feasibility of reducing clear spacing of headed bar, the study will conduct the specimen with four interior column joints to discuss the differences of seismic behaviors when bar clear spacing is respectively $4d_b$ and $2.2d_b$ by means of splice and butt.

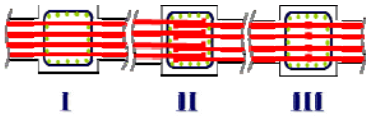
3.1. Details of specimens

This study totally performs nine tests on beam-column joints. The sectional-cross areas of column in all specimens are 650 mm × 650 mm, and the length is 3700 mm, the bearing center distance is 3200 mm; The sectional-cross areas of beam in all specimens are 400 mm × 700 mm, the individual beam length from the column center to the beam end of the specimen is 2700 mm, and the distance from column center to the force center of the beam end is 3000 mm.

As for material strength, concrete compressive strength is designed to be 41.2 MPa, the main reinforcement of bean and column and stirrup in joints respectively adopt D32-SD420W and D13-SD420 reinforcement. T-headed end plate material is made by friction welding of S45C with reinforcement. The detailed specimen design parameters are shown in Table 2. Table 2 indicates the internal beam-column joint specimens in this study.

Table 2: Design parameters for beam-column joints of internal column specimens

Spec	Config	Beam Bar			Connection Type	Spacing of Rebar (d_b)	Materials				Member Strength		Development Length	
							Design		Actual				Design	
		Num	d_b (mm)	ρ (%)			f_c' (MPa)	f_y (MPa)	f_{ca}' (MPa)	f_{ya} (MPa)	$\Sigma M_{nc} / \Sigma M_{nb}$	$V_{jh,u} / V_n$	L_{dt} (mm)	L_{dt} / d_b
T1	Top.	5	25	1.2	I	4.0	41.2	412	43.2	469	1.47	0.87	650	25.6
	Bot.				II								528	20.8
T2	Top.	5	25	1.2	I	4.0			42.3	469	1.47	0.87	650	25.6
	Bot.				III								309	12.2
T3	Top.	6	25	1.5	I	2.2			40.5	469	1.24	1.08	650	25.6
	Bot.				II								528	20.8
T4	Top.	6	25	1.5	I	2.2			46.3	469	1.26	1.01	650	25.6
	Bot.				III								309	12.2
T5	Top.	8	25	2.0	I	2.2			43.2	469	1.23	1.04	650	25.6
	Bot.	4		1.0	I								650	25.6
T6	Top.	8	25	2.0	III	2.2			42.0	469	1.22	1.06	309	12.2
	Bot.	4		1.0	III								309	12.2
TX1	Top.	4	25	1.0	I	2.2			44.8	489	1.83	0.51	650	25.6
	Bot.				II								528	20.8
TX2	Top.	4	25	1.0	I	2.2			44.4	489	1.83	0.64	650	25.6
	Bot.				III								309	12.2
TX3	Top.	4	25	1.0	I	2.2			43.4	489	1.83	0.64	650	25.6
	Bot.				II								325	12.8



3.2. Testing setup

In beam-column joints of internal columns in this study, E represents east and W represents west. The configurations of testing device are shown in Figure 1. Both beam and column ends can be regarded as the hinge bearing. In the tests of this study, a hydraulic jack connecting with the beam end is used to impose reverse and cyclic vertical loading that gradually increases to simulate the seismic force effect caused by earthquake. At the same time, to achieve the relatively critical force conditions of beam-column joints, the column axial force which facilitates the shear strength of beam-column joints is adjusted to $0.1A_g f_c'$.

In the tests, the loads are imposed to beam ends under the control of displacements. The beam end displacement is achieved by multiplying the drift ratio of the structure by the distance from the center of the column to the beam force point. And then the repeated displacements are imposed. The drift ratios of tests are 0.25 %, 0.375 %, 0.5 %, 0.75 %, 1.0 %, 1.5 %, 2.0 %, 3.0 %, 4.0 %, 6.0 % and 8.0 % respectively, which are gradually increased. Every drift ratio at the peak repeats three loops until the loop has completed or the strength is seriously reduced. In the tests, the loading program conforms to ACI 374.1 (2005) specifications. Every test finishes only when it is damaged or the strength is seriously reduced.

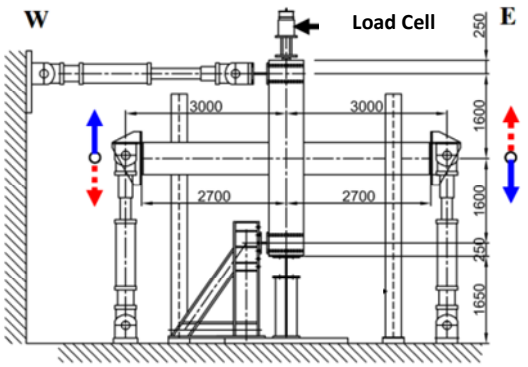


Figure 1: Testing system for beam-column joints of internal column

4. DISSCUSION OF RESULTS

Taking the engineering practice into account, in addition to referring to the specifications, the study also intends to understand the feasibility of design out of the codes. This chapter analyzes the effect of design conditions on seismic behavior in joints and compares the research variables thereinafter.

4.1. Seismic performance assessment using ACI 374.1-05

According to ACI 374.1-05 approved standards, the study assesses the seismic performance of beam-column joints when the drift ratio at the peak reaches 3.5% in the third loop, so as to verify the criteria of this joint specimen. But the 3.5% drift ratio of constraint displacement is not conducted in this study, so that seismic performance of 3% drift ratio in the third loop can be assessed. Generally, all specimens meet the approved standards in this study. The assessment criteria details can be classified into the following three aspects:

(1) Strength: the strength of drift ratio in positive or negative 3% of the third loop should not be less than the 0.75 times of the maximum strength for the specimen.

(2) Energy: the energy dissipation area of drift ratio in positive or negative 3% of the third loop should not be less than the 0.125 times of areas surrounded by energy area under the original stiffness tangent and strength horizontal line of drift ratio in positive or negative 3% ($\beta \geqq 0.125$, β is relative energy dissipation ratio).

(3) Stiffness: the stiffness of drift ratio in positive or negative 3% of the third loop should not be less than the 0.05 times of original stiffness of drift ratio in positive or negative 0.35%.

4.2. Beam moment versus lateral drift ratio relationship

In terms of the relationships between bending moment and drift ratio in this specimens, when drift ratio in hysteretic loop increases to 1.5~2%, the main reinforcement yields and steps into plastic stage; beam-end reaches the maximum bending moment when drift ratio is 4% and beam-end bending moment reduces significantly when drift ratio is 6%.

4.3. Different connection types and shear ratio for joints

The next step explores whether the seismic performance of joint specimens are affected when T-headed bars in beam-column joints are anchored with different joining modes. Figure 2 shows the comparison of envelope line of bending moment and energy dissipation between joint specimens T1 and T2, in which the bottom layer T-headed bars of two specimens are anchored in the joints by lap and butt types, respectively. From Figure 2(a), when clear spacing between T-headed bars of the two specimens is of $4.0d_b$, beam reinforcement ratio of 1.2% and shear ratio in the joints of 0.87, the envelope line of bending moment and drift ratio are nearly the same for two specimens. Besides, Figure 2(b) also clearly reveals that the total energy dissipation curves of two specimens are generally the same. Therefore, the seismic performance of adopting T-headed bars in joints are equivalent when they are anchored by splice or butt types.

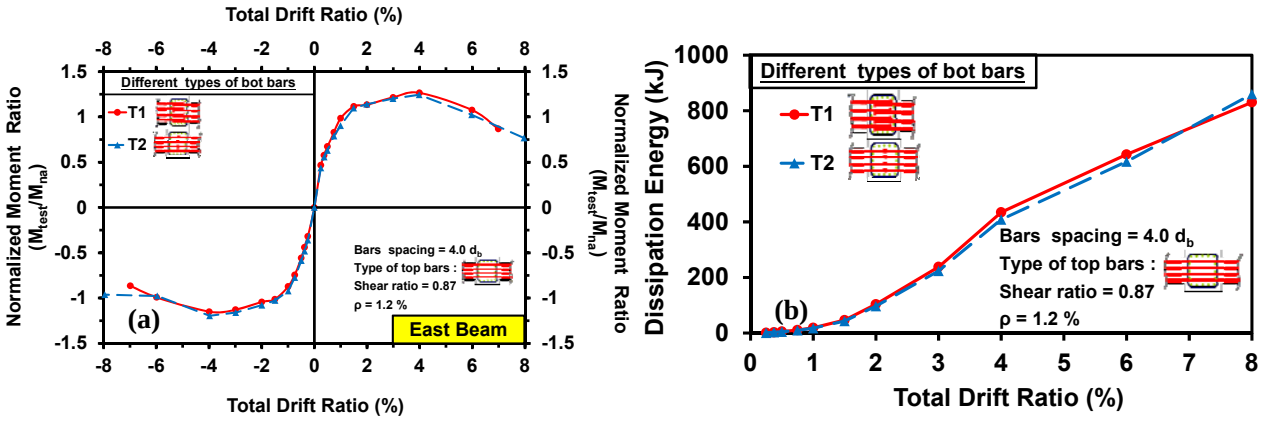


Figure 2: Comparison of envelope line and energy dissipation of specimen T1 and T2 by different connection types in joints

Figure 3 shows the comparison of envelope line of bending moment and energy dissipation between joint specimen T3 and T4, in which the bottom layer T-headed bars of two specimens are anchored in the joints by splice and butt types, respectively. From Figure 3(a), when clear spacing between T-headed bars of the two specimens is of $2.2d_b$, beam reinforcement ratio of 1.5% and shear ratio in the joints of 1.05, and the anchoring mode in joint adopts butt type, the envelop line of bending moment goes down significantly when drift ratio reaches 3%; in addition, Figure 3(b) reveals that the energy dissipation of specimen by means of adopting splice type in joint is better than that of butt. Through observing the crack propagation of the two specimens, it indicates that the drift ratio of specimen T4 is up to 3%, noticeable shearing crack occurs in the joints, which may further decrease the anchoring capacity of T-headed bars and then result in reinforcement sliding in experiments.

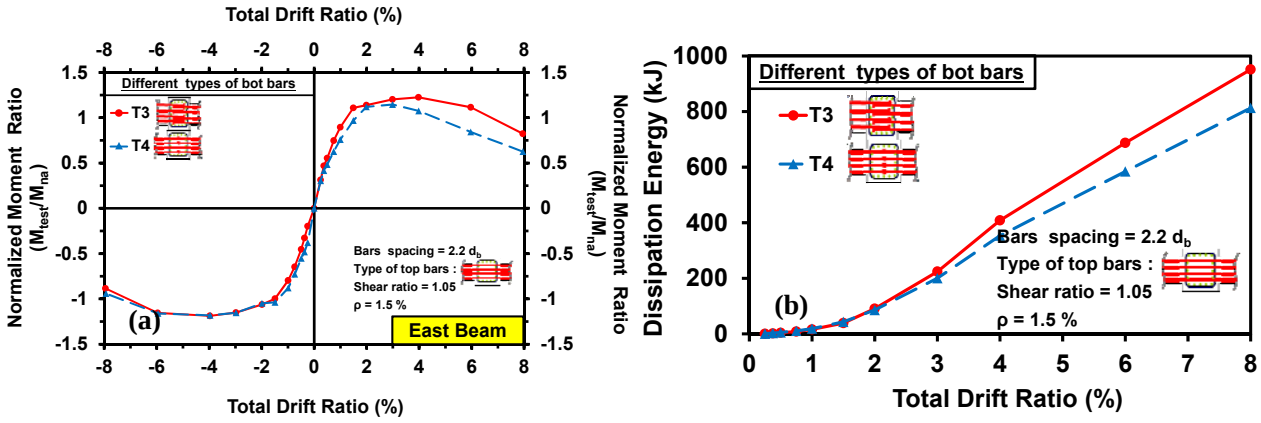


Figure 3: Comparison of envelope line and energy dissipation of specimen T3 and T4 by different connection types in joints

Comparison of envelope line and energy dissipation of joint specimen TX1 and TX2 is shown in Figure 4, in which the bottom layer T-headed bar of two specimens are anchored in the joints by splice and butt types, respectively. From Figure 4(a), when clear spacing between T-headed bars of the two specimens is of $2.2d_b$, beam reinforcement ratio of 1.0%, shear ratio in the joints of 0.58, the anchoring mode in joint adopts splice type, moment envelop line goes down significantly when drift ratio reaches 6%; in addition, Figure 4(b) clearly indicates the energy dissipation of specimen by means of adopting splice type is not as good as that of butt when drift ratio is up to 4%.

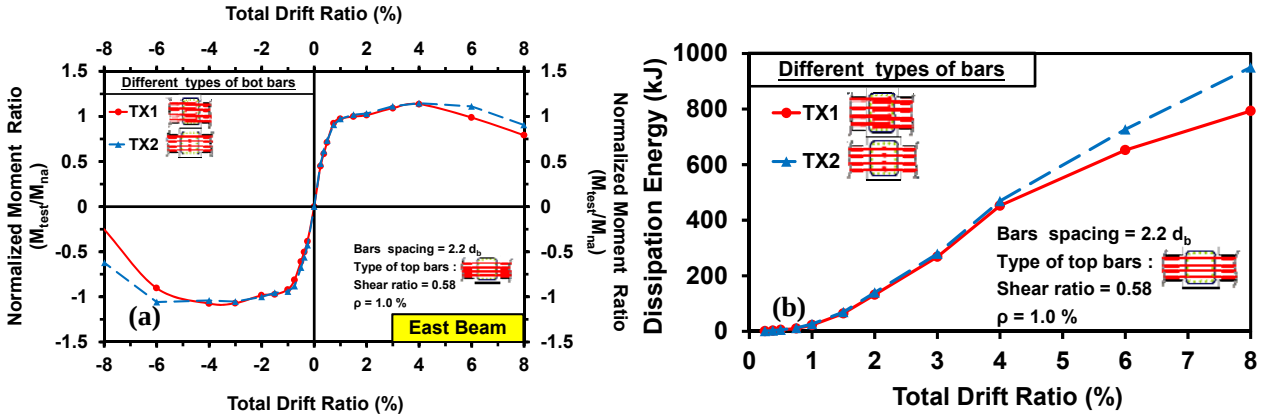


Figure 4: Comparison of envelope line and energy dissipation of specimen TX1 and TX2 by different connection types in joints

In Figure 5, comparison of envelope line of bending moment and energy dissipation of joint specimen TX2 and TX3 is clearly shown, in which the bottom layer T-headed bar of two specimens are anchored in the joints by splice and butt types, respectively. Although the joints of specimen TX3 is anchored by means of splice type, it is actually tightly fastened in the end plate of T-headed bars. From Figure 5(a), when clear spacing between T-headed bars of the two specimens is of $2.2d_b$, beam reinforcement ratio of 1.0% and shear ratio in the joints of 0.58, envelop lines of bending

moment and drift ratio are generally the same; according to Figure 5(b), the curves of total energy dissipation of both specimens are also generally the same.

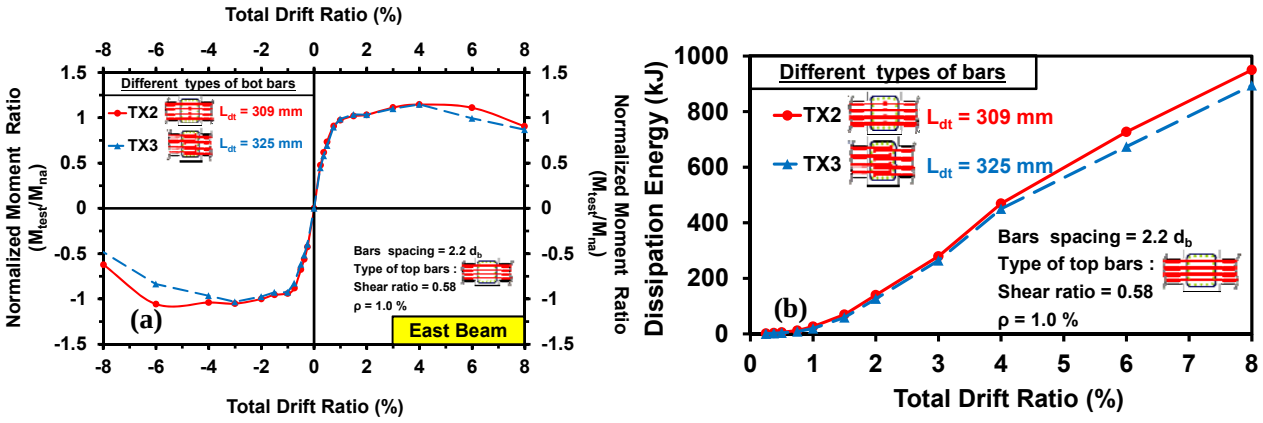


Figure 5: Comparison of envelope line and energy dissipation of specimen TX2and TX3 by different connection types in joints

Figure 6 shows the comparison of reduction ratios of bending moment in joints by different connection types, which refers to the reduction ratios of bending moment of any drift ratio at the third loop to that at the first loop. From Figure 8, the moment reduction by means of adopting in straight, splice and butt types are quite equivalent when bar spacing is of $2.2d_b$, reinforcement ratio of 1.5% and shear ratio at joint of 1.08; besides, the beam bending moment reduces to 80% below when drift ratio reaches to 6%. As a result, equivalent seismic performance can be obtained regardless of any connection types (splice, splice and straight) is adopted.

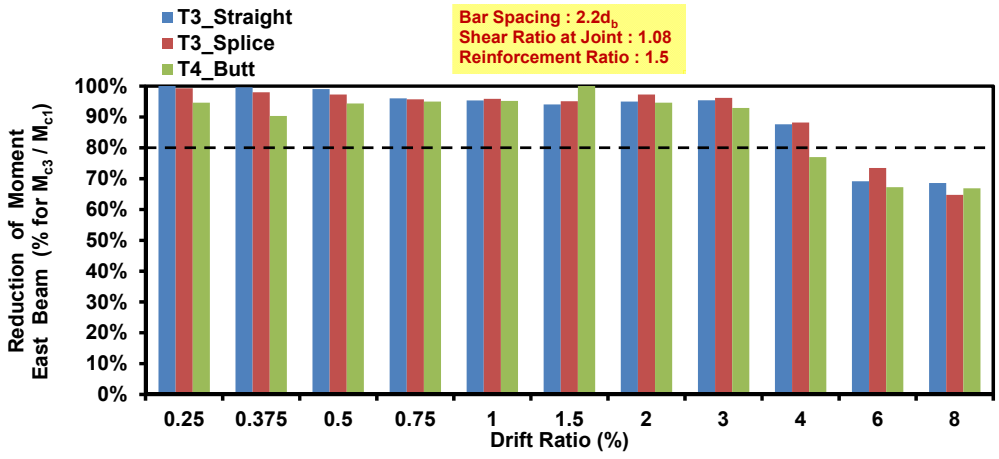


Figure 6: Comparison of reduction of moment in joints by different connection types in joints

4.4. Different reinforcement ratio for joints

Since reinforcement ratio is one of the engineers' considerations in design, it is necessary to confirm whether reinforcement ratio is a factor affecting the beam-column joint, as discussed in the following. Figure 7 shows the envelope lines of bending moment of joint specimen T5 and T6,

among which T5 adopts straight bars to anchor its main reinforcement at both top and bottom layers into the beam-column joint, while T6 uses butt with T-headed bars. The top and bottom layers reinforcement ratios of the two specimens are 2% and 1% respectively. From Figure 7(a), specimen T5 is anchored in joints by means of straight bars, the beam at both top and bottom layers have equivalent bending moment and deformability, namely, reinforcement ratio has no direct influences on the seismic performance of beam-column joints. Moreover, Figure 7 (b) has another situation that, specimen T6 uses T-headed bar to anchor in joints by means of butt type. It reveals that the deformability of bending moment of the top layer with a reinforcement ratio of 2.0% performs not so well as that of the bottom layer with a reinforcement ratio of 1.0%. Besides, through observing the damages in specimen T6, noticeable shear crack appears at the beam-column joints, which may reduce the anchoring capacity of T-headed bars at the joints and then result in reinforcement sliding in experiments.

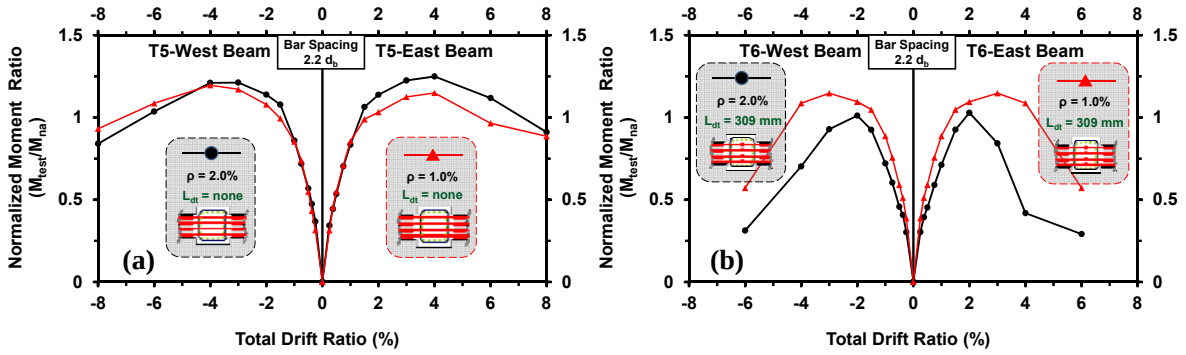


Figure 7: Comparison of reinforcement connection types of specimen T5 and T6 under different designs of reinforcement ratio

4.5. Different spacing of headed bars for joints

To verify the clear spacing of T-headed bars can be further narrowed and be efficiently applied in engineering practices, the consideration of clear spacing of T-headed bars definitely becomes the topic urgently to be solved. From Figure 8, it clearly shows that, when bar spacing is $4.0d_b$ or $2.2d_b$ and top layer reinforcements are anchored in joints by straight type, the bending moment and deformability won't be affected if the bottom layer T-headed bars are anchored by splice or butt type, namely, the seismic performance of joints at a clear spacing of $2.2d_b$ equals that at a spacing of $4.0d_b$.

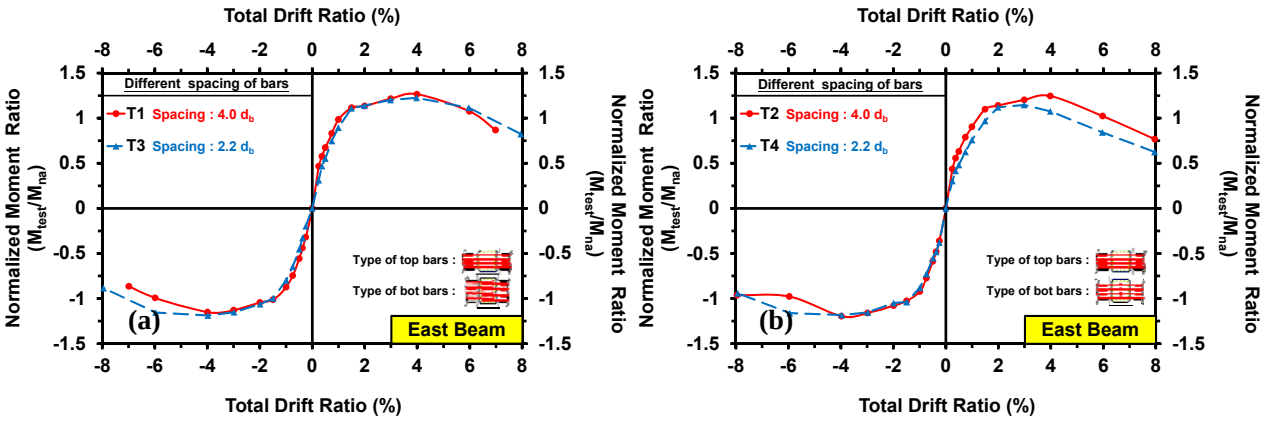


Figure 8: Comparison of envelope line of specimen T1 & T3 and T2 & T4 at different clear spacing of T-headed bars

5. SUMMARY AND CONCLUSIONS

This study aims to evaluate the seismic performance of beam joints anchored with T-headed bars. In this experiment, 9 groups of cyclic loading experiments for interior beam joints are conducted, with findings concluded into six articles as follow:

(1) Under the principle of strong column and weak beam, when shear ratio at joints is relatively low ($V_{jh,u}$ / V_n = 0.58), the seismic performance of T-headed bar at joints adopting butt performs better than that adopting splice; equivalent seismic performance can be obtained if shear ratio is medium ($V_{jh,u}$ / V_n = 0.87) regardless of splice and butt adopted at joints; but when shear ratio is large ($V_{jh,u}$ / V_n = 1.05), splice performs better than butt anchoring T-headed bar at joints.

(2) Under the principle of strong column and weak beam, when shear ratio at joints is relatively large ($V_{jh,u}$ / V_n = 1.05), the main reinforcement at joints adopting straight bars, splice or butt with T-headed bars will produce the same bending moment strength and deformability.

(3) When main reinforcement is anchored in beam-column joints by straight type, the reinforcement ratio has no impacts on its anchoring performance; while if it is anchored by butt type with T-headed bar, the larger reinforcement ratio results in easier reinforcement sliding due to the cyclic loads, which then influences the anchoring performance.

(4) When the bottom layer reinforcement is anchored in beam-column joints by splice or butt type with T-headed bars, the seismic performance of T-headed bars at a clear spacing of $2.2d_b$ equals to that at a spacing of $4.0d_b$. Therefore, the specifications for clear spacing of T-headed bars in code ACI 318-11 can be appropriately adjusted.

6. ACKNOWLEDGMENTS

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