Use of Mechanically Anchored Bars in Exterior Beam-Column Joints Subjected to Seismic Loads

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INTRODUCTION

ACI-ASCE Committee 352 publication ACI 352-91 sets various design guidelines for achieving proper anchorage of longitudinal bars terminating within a beam-column joint. For high seismic zones, load reversals in the joint can lead to significant bond deterioration along straight bar anchorages; therefore, ACI 352-91 requires that standard hooks be used to anchor longitudinal reinforcement terminated within a joint. The use of standard hooks results in steel congestion, making the fabrication and construction difficult. In addition, geometric limitations often prevent the use of larger diameter reinforcing bars due to construction limitations arising from lengthy hook extensions and large bend diameters. In these cases, the use of mechanical anchors has obvious advantages; however, studies are needed to address the required embedment length for mechanically anchored bars as well as requirements for transverse reinforcement.

OBJECTIVES AND SCOPE

The research program consisted of testing two, full-scale, exterior beam-column joint sub-assemblages (Fig. 1). One of the specimens was subjected to cyclic load whereas the other specimen was subjected to essentially monotonic load. The objective of this paper is to provide a brief overview of the results. More detailed information is available in a report by Gupta and Wallace (1996).

OVERVIEW OF ACI-ASCE COMMITTEE 352 REQUIREMENTS

Design requirements for reinforced beam-column joints for typical structures are specified by ACI-ASCE Committee 352 Report 352-91 ("Recommendations", 1991). Report 352-91 provides guidelines for both "non-seismic" (Type 1) and "seismic" (Type 2) design applications. ACI 352-91 defines a Type 2 joint as a joint that "connects members designated to have sustained strength under deformation reversals into the inelastic range." ACI 352 requirements were used to assist in the planning of the experimental research program as well as to evaluate the test results. Specific requirements are reviewed in the following paragraphs.

Flexural Strength Ratio: ACI 352-91 recommends that the nominal moment strength of the columns be at least 1.4 times the nominal moment capacity of the adjoining beams for Type 2 joints. This requirement exists to ensure that a majority of the inelastic deformations occur in the beam to avoid the formation of a "soft-story". No similar requirements exist for Type 1 joints.

Joint Shear Strength: The ACI 352-91 requirements for joint shear strength are based on (1):

$$\phi V_n = \phi\gamma\sqrt{f_c'}\, b_j h \geq V_u \tag{1}$$

where ϕ=0.85, V_n is the nominal shear strength of the joint, b_j is the effective width of the joint, h is the depth of the column, and γ is a factor that depends on the joint type and classification. For exterior joints with transverse beams, γ is taken as 20 and 15 for f'_c in psi (1.67 and 1.2 for f'_c in MPa) for Type 1 and 2 joints, respectively.

The horizontal joint shear demand V_u is calculated based on the amount of beam reinforcement as (Fig. 2):

$$V_u = T - V_{column} = \alpha A_s f_y - V_{column} \tag{2}$$

where T is the tension force in the reinforcement, A_s is the area of tension reinforcement, f_y is the nominal yield stress of the tension reinforcement, and V_{column} is the shear in the column. Typically, inflection points are assumed at beam midspan and column midheight to compute the column shear (Fig. 1). The term α is a stress multiplier to account for over-strength and strain hardening of the reinforcement. Values of α = 1.00 and 1.25 (minimum) are recommended for Type 1 and 2 joints, respectively.

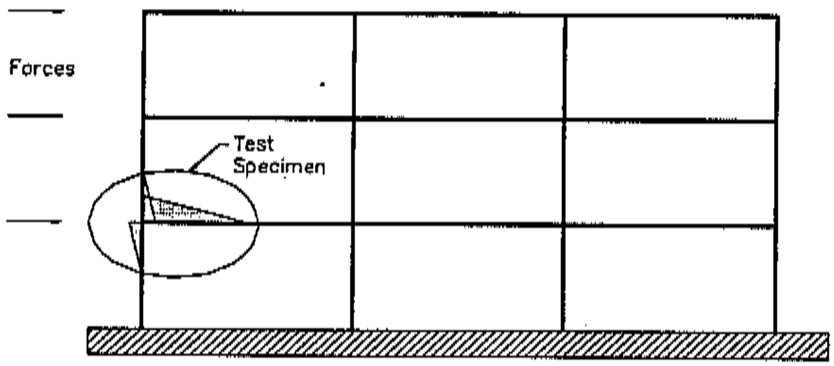

Fig. 1 Test Specimen Definition

Reinforcement Anchorage: The ACI 352-91 report specifies that the critical section for development of reinforcement should be at the outside edge of the column core (hoops) for Type 2 joints and at the beam-joint or column-joint interface for Type 1 joints.

For Type 1 and Type 2 joints, terminating bars should be hooked within the transverse reinforcement of the joint using a 90 degree standard hook. The development length should be computed as:

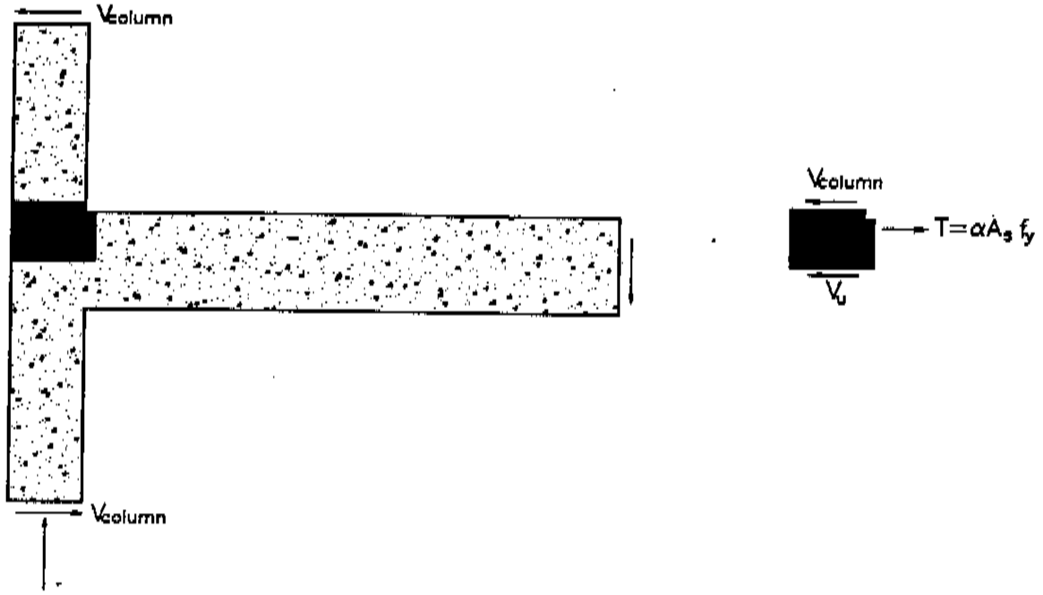

Fig. 2 Horizontal Joint Equilibrium

$$l_{dh} = \frac{\alpha f_y d_b}{50\beta\sqrt{f_c'}}\ in. \quad = \quad \frac{\alpha f_y d_b}{6.2\beta\sqrt{f_c'}}\ \text{mm} \tag{3}$$

where f_y and f'_c are in terms of psi and MPa for l_{dh} in inches and mm, respectively. Values of β are 1.0 and 1.5 for Type 1 and 2 joints, respectively. For a Type 2 joint with f_y = 60 ksi (414 MPa) and α= 1.25, the development length is 15.8d_b and 12.9d_b for f'_c = 4,000 psi (27.4 MPa) and 6,000 psi (41.4 MPa), respectively.

Transverse Reinforcement within the Joint: The 352 committee report also makes recommendations for providing adequate transverse reinforcement in the form of spirals or rectangular hoops with crossties for both Type 1 and Type 2 joints.

For Type 1 joints that are part of the primary system for resisting non-seismic lateral loads, the center-to-center spacing of hoops and cross-ties are limited to six inches. As well, at least two layers of transverse reinforcement must be provided between the top and bottom layers of beam longitudinal reinforcement of the deepest member framing into the joint.

For Type 2 joints, the total cross-sectional area of transverse reinforcement within the joint in each direction should be:

$$A_{sh} = 0.3\,\frac{s_h h'' f_c'}{f_{yh}}\left(\frac{A_s}{A_c} - 1\right) \geq 0.09\, s_h h''\,\frac{f_c'}{f_{yh}} \tag{3}$$

The center-to-center spacing between layers of transverse reinforcement, s_h, should not exceed the least of one-quarter of the minimum column dimension, six times the diameter of the longitudinal column bars to be restrained, or 6 inches.

EXPERIMENTAL RESEARCH PROGRAM

The research program involved testing of two exterior beam-column joint specimens. The specimens were sub-assemblies from a building subjected to lateral loads (Fig. 1). Stub beams were used to represent the three-dimension effects of transverse beams (Fig. 3); however, no loading was applied to the stub beams.

Specimen Geometry and Materials:

Overall dimensions for the specimens are shown in Figure 3 and 4. The beam and column cross sections were 18"x24" (457 mm x 610 mm) and 18"x18" (457 mm x 457 mm), respectively. Eight bars (#9, d_b =1.127 in. or 28.6 mm) were used in the column and seven bars (#8, d_b =1.0 in. or 25.4 mm) were used in the beam (four top, three bottom). A concrete compressive strength of 4,000 psi (27.6 MPa) and a reinforcement yield stress of 60,000 psi (413.7 MPa) were used for design purposes. For BCEJ-1, longitudinal and transverse reinforcement consisted of A706 and A615, respectively. For BCEJ-2, all reinforcement was A615. Actual material properties varied slightly from the design values. The average concrete compressive strengths at the testing date were 5190 psi and 4,870 psi (35.8 and 33.6 MPa) for specimens BCEJ1 and BCEJ2, respectively. Actual reinforcement properties were typical for Grade 60 reinforcement, with yield stresses of approximately 67 ksi (Gupta and Wallace, 1996).

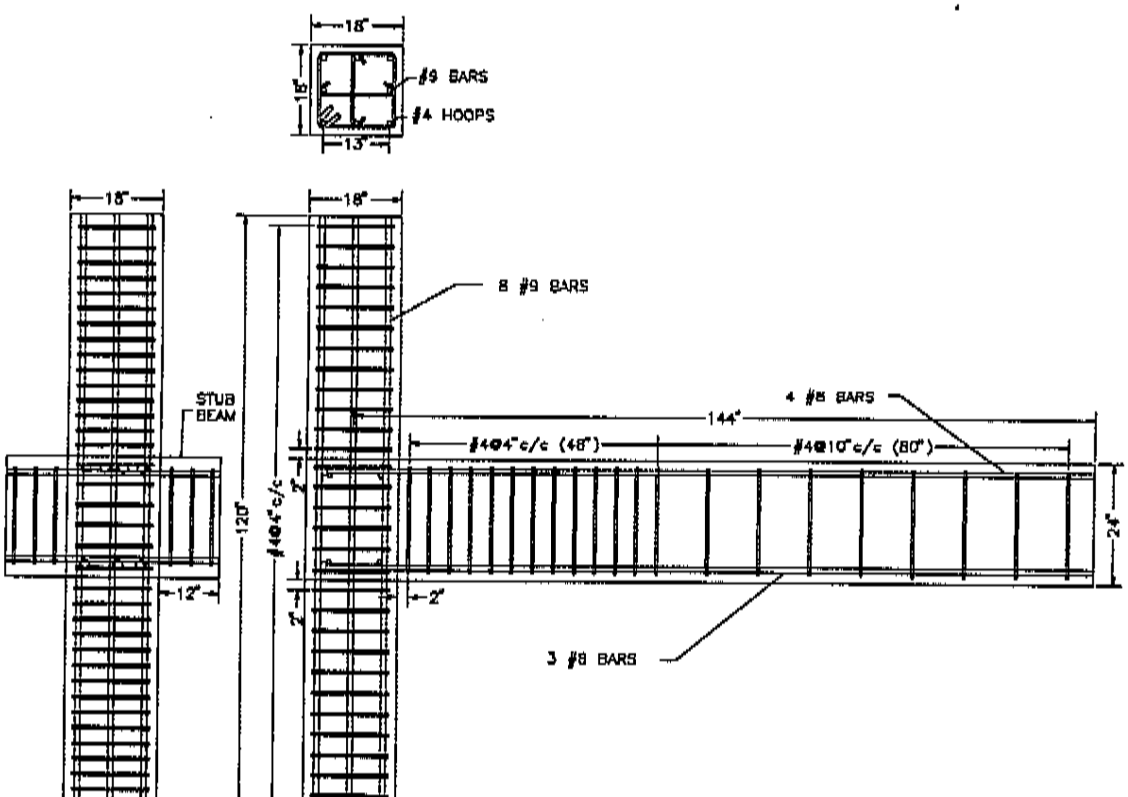

Fig. 3. Specimen BCEJ1 Reinforcing Details

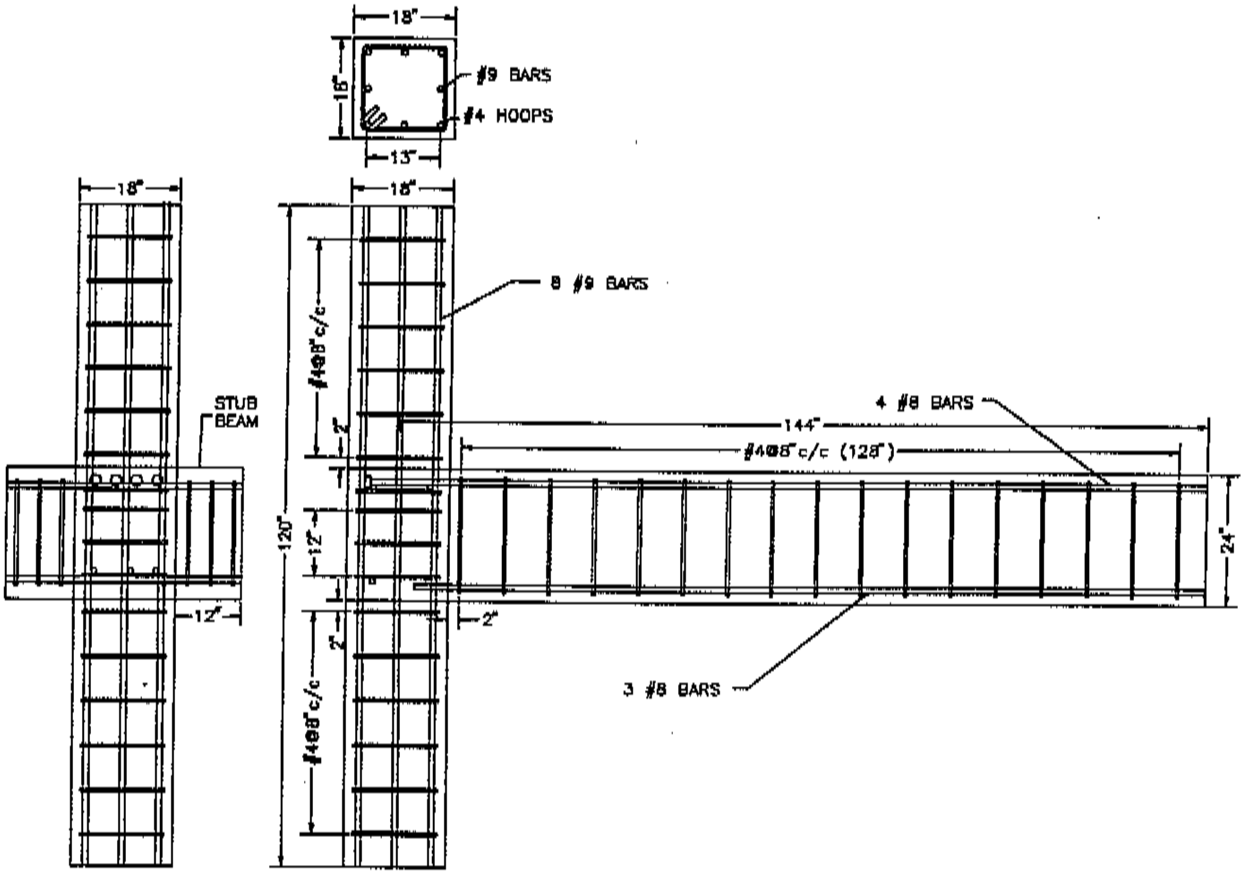

Fig. 4 Specimen BCEJ2 Reinforcing Details

Specimen design was based primarily on ACI Committee 352 requirements; however, additional information from prior test programs on beam-column joints constructed with mechanically anchored bars (McConnell and Wallace, 1994; 1995) was also used to assess anchorage requirements for the beam reinforcement.

Design Summary: BCEJ-1

The ratio of the beam flexural strength to the column flexural strength was 1.72 (minimum of 1.4 required) and the joint shear demand V_u was approximately $12\sqrt{f_c'}$ psi ($1.0\sqrt{f_c'}$ MPa) compared with a design limit of $\phi V_n = 12.75\sqrt{f_c'}$ psi ($1.06\sqrt{f_c'}$ MPa). Based on the specimen design, inelastic actions were expected within the beam adjacent to the joint. Hoops with two perpendicular cross-ties were spaced at 4 inches (102 mm) within the joint region. The provided area of transverse reinforcement $(A_{sh})_{provided} = 0.60$ in^2 (387 mm^2) exceeded that required $(A_{sh})_{req'd} = 0.51$ in^2 (329 mm^2) by approximately 17%.

The column reinforcing bars were continuous over the height of the column (Fig. 3, 4). In place of 90 degree standard hooks, a tapered, threaded connection provided by ERICO, Inc. was used

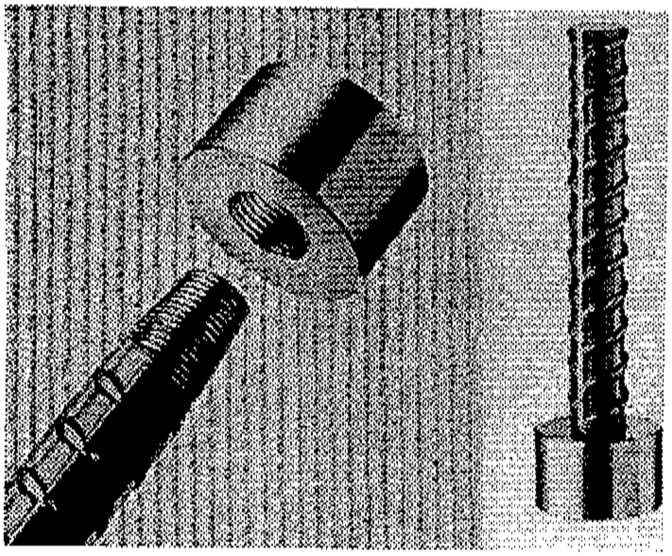

Fig. 5 ERICO Lenton Terminator Anchor

to anchor circular plates (diameter = 2.25 in. or 57 mm; thickness = 1.375 in. or 34.9 mm; Fig. 5) to the longitudinal beam reinforcement terminating within the joint (Fig. 3, 4). The contact area of the head is approximately four times the area of the reinforcing bar (#8, A_b = 0.79 in^2 or 509 mm^2) for tension in the bar. The development length of a 90 degree standard hook for a Type 2 joint is $15.8d_b$ for f'_c = 4000 psi (27.4 MPa) and f_y = 60 ksi (413.7 MPa). The tension development length provided within the joint core for the mechanically anchored bars was only $12.5d_b$, or approximately 80% of that required for a 90 degree standard hook. This value was considered acceptable based on tests of wedge anchors and "plate" anchors, where an embedment of 8 to $10d_b$ is sufficient to develop the yield stress of the anchor (Bode and Roik, 1987). Use of shorter embedments (e.g., less than approximately $12d_b$ for this design) is not realistic since flexural strength ratio or joint shear will control the joint dimensions and the terminating beam bars should be embedded the full depth of the joint core for ease of construction and inspection.

Compression anchorage of the headed bar should also be checked to ensure that the head will not push-out prematurely (Fig. 6). Push-out of the headed bar in compression does not typically decrease the flexural capacity of the beam significantly since the compression resisted by the bar will be redistributed to the concrete; however, push-out is likely to cause "pinching" of the load-deformation response, and thus should be minimized. Based on tests of beam-column knee joints (McConnell and Wallace, 1994; 1995), the anchorage length of the headed bar should be greater than 65% of the compression development length of a straight bar according to ACI 318-95 Chapter 12 requirements. For BCEJ-1, an anchorage length equal to 83% of that required by ACI 318 Section 12.3 (including a multiplier of 0.8 to account for confinement) was provided from the outside of the hoops.

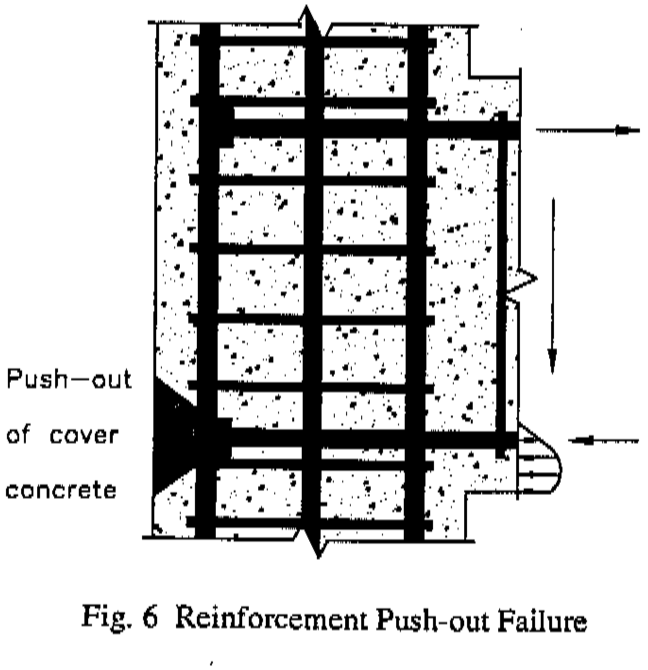

Fig. 6 Reinforcement Push-out Failure

Design Summary: BCEJ-2

The ratio of the sum of the beam flexural strengths to the column flexural strength was 1.72 and the joint shear demand was approximately $9.6\sqrt{f'_c}$ psi ($0.8\sqrt{f'_c}$ MPa), or 57% of the joint capacity $\phi V_n = 17\sqrt{f'_c}$ ($1.41\sqrt{f'_c}$ MPa). Based on the specimen design, inelastic actions were expected within the beam adjacent to the joint. Four hoops, spaced at a little less than 6 inches on center, were provided within joint region to satisfy design requirements (Fig. 4).

Mechanically anchored bars was used to anchor the beam top reinforcement; however, the bottom reinforcement was embedded only 6 inches (152 mm) into the column as required by ACI 318-95 Section 12.11.1 (Fig. 4). For the beam top bars, the development length of a 90 degree standard hook is $18.97(0.7)d_b = 13.3d_b$ for $f'_c = 4{,}000$ psi (27.4 MPa) and $f_y = 60{,}000$ psi (413.7 MPa). The tension development length provided from the beam-joint interface was $14d_b$; therefore, adequate anchorage was provided in comparison with a 90 degree standard hook. The required compression development length for anchorage of the headed bar was 92% of that for ACI 318-318-95 Section 12.3.3 (from the beam-joint interface).

Specimen Construction

Use of mechanically anchored bars allowed the beam and column cages for each specimen to be fabricated independently. A crane was used to lift the column cage into the forms, and then the beam cage was lifted and slid into place. Congestion of reinforcement within the joint region was reduced, and placement of concrete was completed with relative ease.

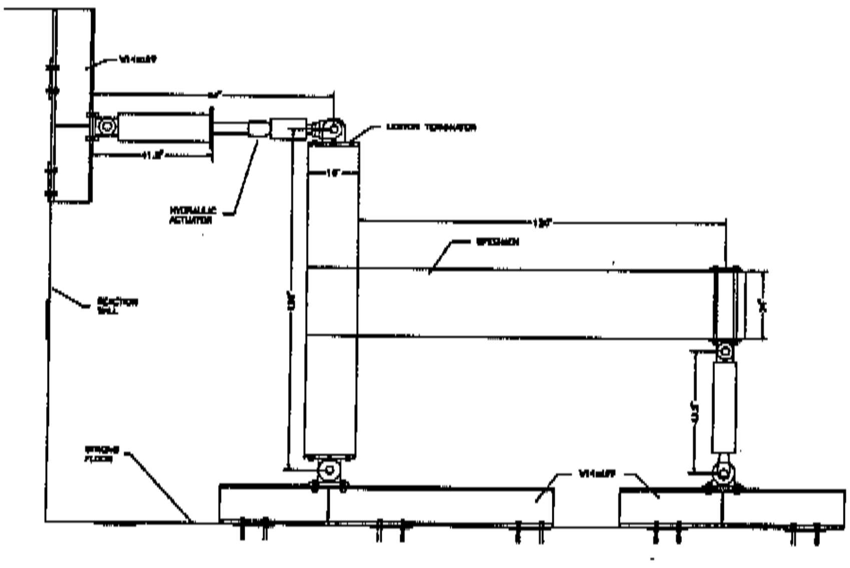

Fig. 7. Exterior Joint Test Setup

Specimen Testing and Instrumentation

The exterior joints were tested in an upright position (Fig. 7). No axial load was applied at the top of the column. Although column axial load reduces column deformation capacity, it would be expected to have a beneficial effect on the headed anchors by providing compression in the joint region.

Instrumentation was used to measure lateral load, lateral displacement, rotations, concrete cover and joint core strains, and strain in the longitudinal and transverse reinforcement. Loading was applied under displacement control as indicated in Fig. 8. For cyclic loads (BCEJ-1), a minimum

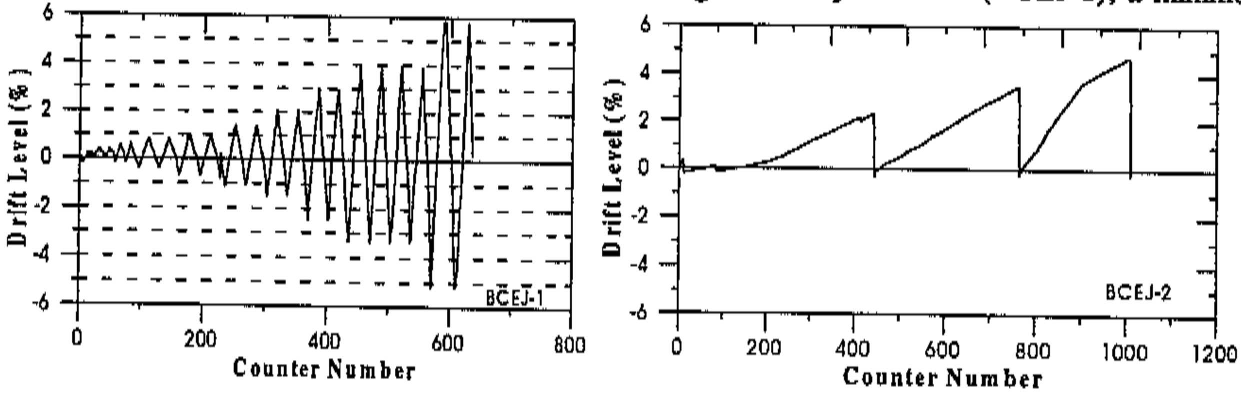

Fig. 8 Applied Displacement Routine

of two complete cycles were performed at each drift level. More detailed information on measured responses is contained in the report by Gupta and Wallace (1996).

EVALUATION OF EXPERIMENTAL RESULTS

The primary objectives of this paper are to evaluate the potential of using mechanically anchored bars in place of standard hooks within an exterior beam-column joint. General observations and measured responses are discussed in the following paragraphs.

Specimen: BCEJ-1:

Specimen BCEJ1 was designed to meet ACI Committee 352 requirements except that mechanically anchored bars was used to anchor the beam top and bottom bars. No other alterations were made, although an attempt was made to place column hoops in line with the heads of the beam bars to provide additional restraint against push-out (Fig. 6). Yield of the beam longitudinal reinforcement was observed at approximately 1.5% lateral drift. Damage was concentrated within the beam, as expected, and consisted of flexural and "shear" cracks. The crack at beam-joint interface at the extreme tension fiber had opened approximately 0.18 in. (4.6 mm) at 1% lateral drift. At the latter cycles of 4% lateral drift, cracking of the concrete over the heads of the bottom beam bars was observed, indicating that bond along the bars had been lost. However, when the loading was reversed, the full moment capacity of the beam was achieved,

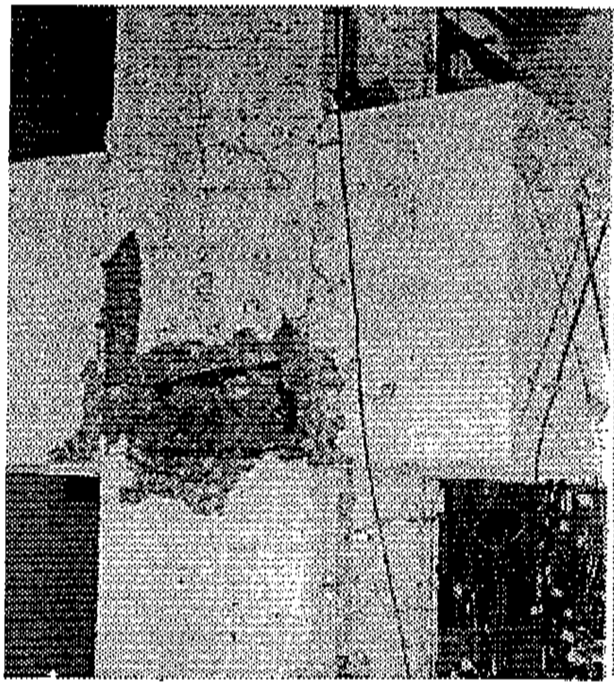

Fig. 9 Push-out of Heads on Bottom Beam Bars

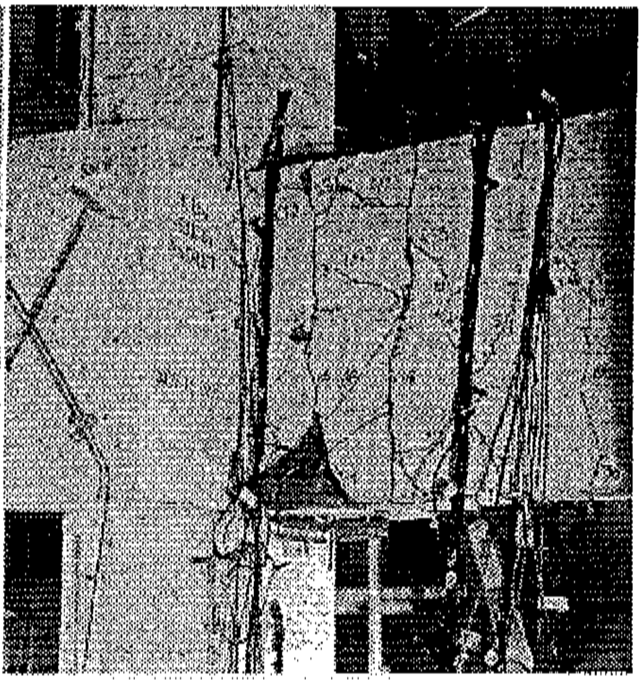

Fig. 10 Observed Beam Damage

indicating that the heads adequately anchored the bars in tension. Eventually, the concrete over the heads was pushed-off (Fig. 9). Observations after the tests indicated that crushing of the compressed concrete in front of the heads did not occur. Figure 10 presents a photograph of the beam region adjacent to the joint at 2% lateral drift.

Experimentally measured moment-rotation behavior (moment at beam-joint interface versus the rotation measured over a 24 in. or 609.6 mm gage length of the beam) is plotted in Fig. 11. Excellent behavior was observed, with little deterioration in flexural strength noted even at 6% lateral drift. The design beam moment capacity was reached for both directions of loading. Significant "pinching" of the moment-rotation relation is not observed until the cycles with peak drift levels of 6%. Based on the test results, it is apparent that the use of mechanically anchored bars is a viable alternative to the use of standard hooks in exterior beam column joints.

Test results indicate that mechanically anchored bars with tension bearing area equal to four times the bar area, and embedded approximately 13 beam bar diameters into the joint core (column cage measured from the outside of the column hoop), perform satisfactory. Based on this result, for bar sizes close to that used in this test (U.S. #8 bars, 25 mm), it is recommended that the mechanically anchored bars be embedded at least $12d_b$ into the joint core. It is possible that shorter lengths could be used as test results on isolated anchors (Bode and Roik, 1987) indicate that an embedment of approximately 10 bar diameters is adequate; however, additional testing is needed to verify this result for bars anchored within a joint. It should also be noted that shorter embedment lengths may not be possible for Type 2 joints due to requirements for flexural strength ratios and joint shear strength.

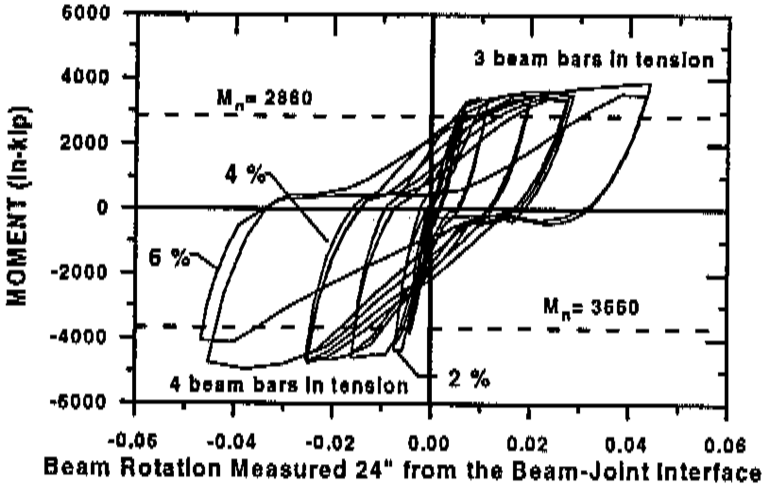

Fig. 11a. Beam Moment-Rotation Relation for BCEJ1

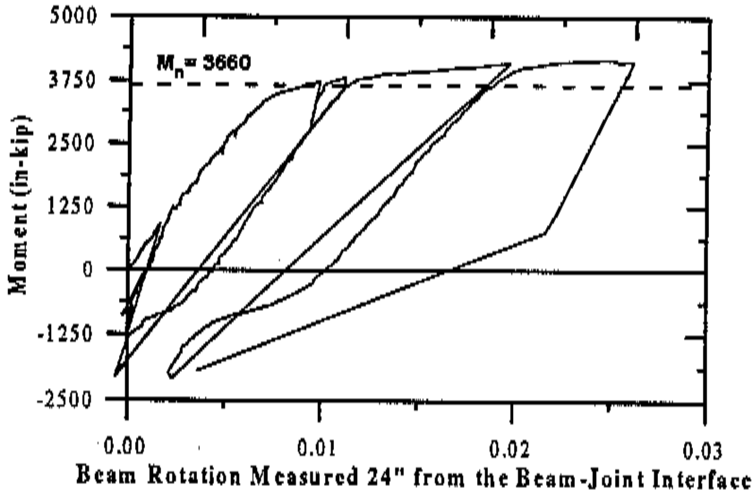

Fig. 11b Beam Moment-Rotation Relation for BCEJ-2

Push-out of the column cover concrete on the back of joint did not affect the lateral load capacity of the specimen , even for drift ratios approaching 6%. Based on this test, as well as similar tests (McConnell and Wallace, 1995), an embedment length of the headed bar should exceed 65% of the compression development length specified by ACI 318-95 Section 12.3.3.

Specimen: BCEJ-2:

Moment-rotation response is plotted in Fig. 11b for BCEJ-2. Excellent behavior was observed, even for drift ratios of 10% (instrumentation was removed and testing continued beyond that indicated in Fig. 11b). Joint distress was observed for drift ratios exceeding 4%, apparently due to a "cone" failure emanating from the rebar heads. However, once the cracks opened, the reinforcement crossing the cracks (longitudinal reinforcement in the stub beams and transverse reinforcement in the column and stub beams) arrested crack growth such that the load capacity of the specimen was not significantly affected. The results indicate the importance of providing transverse reinforcement for Type 1 joints, especially where the heads are tightly grouped as was done intentionally for this test program.

CONCLUSIONS

Results of an experimental study of exterior joints was summarized. Based on this study, the following conclusions were reached: (1) The use of mechanically anchored bars in place of standard hooks within an exterior beam-column joints is a viable option and presents no significant design problems, (2) The use of mechanically anchored bars allows for easier fabrication and construction, alleviates reinforcement congestion, and eases concrete placement, (3) a minimum anchorage length of $12d_b$ is recommended for reinforcement terminated within a beam-column joint provided the head bearing area in tension is at least four times the bar area, and (4) one layer of the transverse reinforcement within the joint region should be positioned essentially in-line with the mechanically anchored bars to restrain the heads from pushing off the cover concrete as well as to provide lateral stability to the column vertical bars.

ACKNOWLEDGEMENTS

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