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CYCLIC BEHAVIOR OF RC BEAM-COLUMN JOINTS CONSTRUCTED USING CONVENTIONAL AND HEADED REINFORCEMENT

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ABSTRACT

A comparison is made of the reversed cyclic behavior of reinforced concrete exterior and knee joints constructed utilizing conventional reinforcement anchorages and headed reinforcement anchorages. The comparison is based on the experimental results of two exterior and five knee joint specimens tested as part of an extensive experimental program. An overview of the experimental study is presented prior to evaluating the effectiveness of the specimens constructed using headed reinforcement. Behavior of the specimens constructed using headed reinforcement eased specimen fabrication and concrete placement, as well, the behavior was as good as, or better than similarly constructed specimens constructed with standard 90 degree hooks. For knee joints, the test results indicate the need to provide transverse reinforcement at the heads to restrain.

KEYWORDS

Beam-column joints, joints, knee joints, headed reinforcement, T-headed bars, mechanical anchorage, experimental, cyclic loads, exterior joints, headed rebar.

INTRODUCTION

ACI-ASCE Committee 352 publication ACI 352-91 sets various design guidelines for achieving proper anchorage of longitudinal bars terminating within a 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 90 degree hooked anchorages be used when longitudinal reinforcement is terminated within the joint. The use of hooked anchorages tends to increase steel congestion, making the construction process more 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 reinforcement with mechanical anchorages has obvious advantages; however, the use of mechanical anchorages may produce high local stresses. Therefore, experimental studies of specimens constructed with mechanical anchorages are needed to assist in the development of design guidelines.

OBJECTIVES AND SCOPE

The overall research project involved experimental and analytical studies of beam-column joints subjected to slowly varying, reversed cyclic loads. A total of eighteen beam-column knee joint specimens and two beam-column exterior joint specimens were tested. The scope of this report is limited to evaluating: (1) joint shear strength requirements for knee joints and (2) the effectiveness of the specimens constructed with headed bars. Where possible, the performance of specimens constructed with headed reinforcement is compared with the test results of similarly constructed specimens in which anchorage within the joint was provided with standard hooks. Additional information on the studies is available in the following reports (Cote and Wallace, 1994; McConnell and Wallace, 1994; 1995; 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. Report 352-91 provides guidelines for both ``non-seismic" (Type 1) and ``seismic" (Type 2) design applications; emphasis is placed on Type 2 connections within this paper. 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." Specific requirements for Type 2 joints are reviewed in the following paragraphs.

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 to ensure that a majority of the inelastic deformations occur in the beam rather than the column (to avoid the formation of a ``soft-story"). It is noted that achieving this ratio is difficult for knee joints; however, this requirement need not be satisfied for knee-joints, because column hinging is typically no more critical than beam hinging.

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 a Type 2 exterior and corner (other) joints, γ is taken as 15 and 12 for f'_c in psi, and 1.2 and 1.0 for f'_c in MPa. No specific recommendations are given for knee joints; therefore, a value of 12 (for f'_c in psi) may be used, although no comprehensive studies have been conducted to establish if this is reasonable.

The ACI 352-91 report specifies that the critical section for development of reinforcement should be at the outside edge of the column core for Type 2 joints. Furthermore, all 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:

$$l_{dh} = \frac{\alpha f_y d_b}{75\sqrt{f_c'}} \ in. \quad = \quad \frac{\alpha f_y d_b}{6.225\sqrt{f_c'}} \ \mathrm{mm} \tag{2}$$

where f_y and f'_c are in terms of psi and MPa for l_{dh} in inches and mm, respectively. The term α represents a stress multiplier used to account for strain hardening and over strength of the reinforcing bars. A minimum value of α = 1.25 is recommended for Type 2 joints. For f'_c = 4000 psi (27.4 MPa), f_y = 60 ksi (420 MPa), and α= 1.25, the development length is approximately 15.8 bar diameters.

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

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

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 or 4 inches (101.6 mm). ACI 352 requirements were used to assist in the planning of the experimental research program as well as to evaluate the test results.

EXPERIMENTAL RESEARCH PROGRAM

The overall research program involved testing twenty beam-column joint specimens. A brief description of the specimens is provided in the following subsections. Design of specimen BCEJ2 was based on requirements for low seismic regions; therefore, results are not presented.

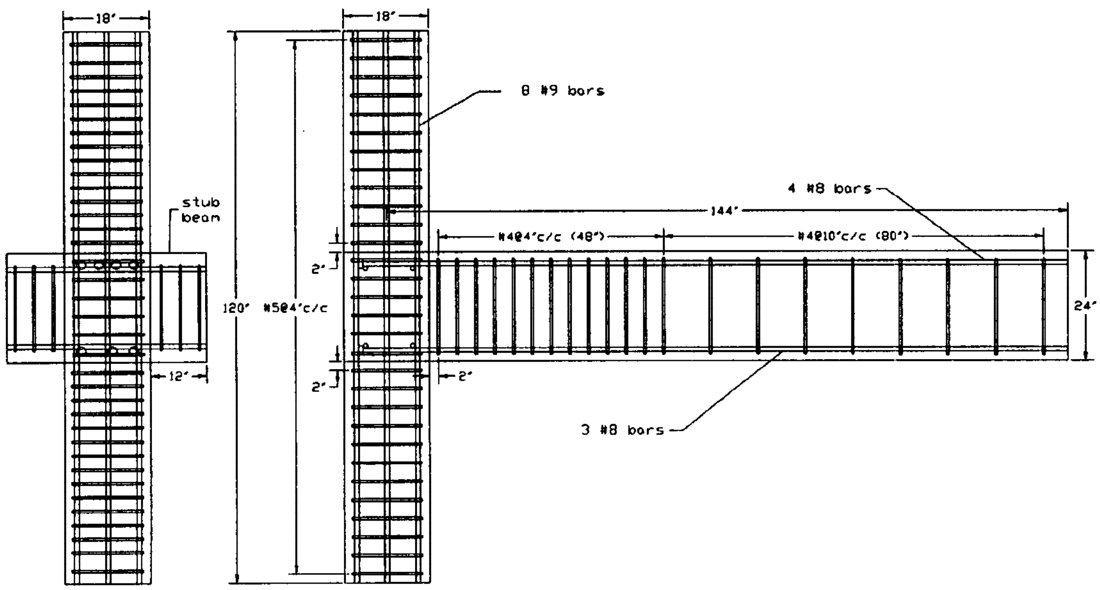

Fig. 1. Specimen BCEJ1 Reinforcing Details

Specimen Description

Overall dimensions for the exterior and knee joint specimens tested are shown in Figure 1 - 3. For all specimens, 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.

In specimens KJ1-KJ13, hooked beam and column anchorages were provided within the joint as required by ACI 352-91. In specimens KJ16-KJ18 headed bars were used to anchor both column and beam reinforcement

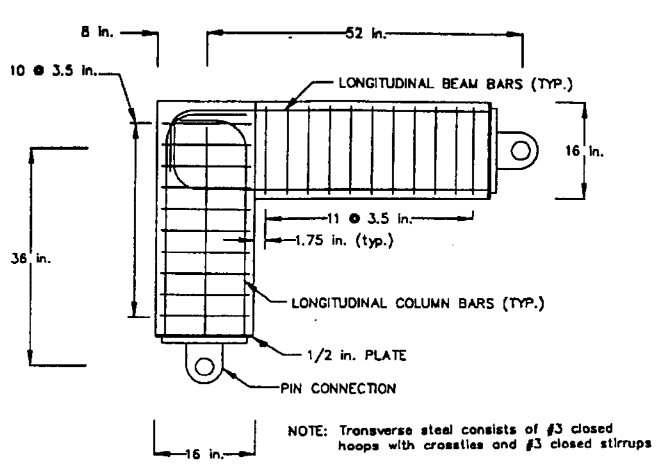

Fig. 2a. Knee Joint Specimen Geometry

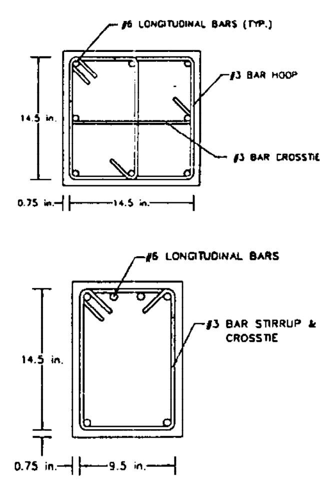

Fig. 2b. Knee Joint Specimen Cross Sections

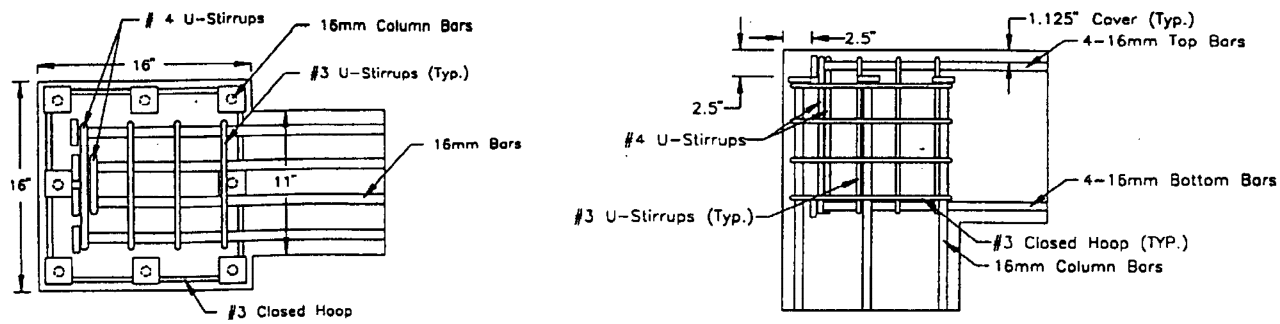

Fig. 3. Reinforcing Details for Specimen KJ17

within the joint, whereas in specimens BCEJ1 and BCEJ2 headed reinforcement was used to anchor beam longitudinal reinforcement. For specimens KJ16-KJ18, the headed anchorages were fabricated by Headed Reinforcement Canada using a friction welding technique to attach steel plates to the reinforcement (Norwegian Tempcore steel). For the reinforcement used in these specimens (16 and 20 mm diameter bars), the steel plates were approximately 2" x 2" x 1/2" (50 mm x 50 mm x 12 mm). For specimens BCEJ1-BCEJ2, a tapered, threaded connection provided by ERICO, INC was used to anchor circular plates (diameter = 2.25 in.; thickness = 1.375 in.) to the longitudinal reinforcement. Figures 3 shows the plan and elevation joint details for KJ17; details for BCEJ1 are provided in Figure 1. A 12 in. (25.4 mm) long beam stub was cast on either side of the joint to represent the confinement provided by the transverse beams that typically frame into the joint.

The ratio of the beam flexural strength to the column flexural strength was approximately unity for the knee joint specimens and 1.65 for BCEJ1. The joint shear demand was approximately 6, 9, and 12 $\sqrt{f_c'}$ psi (0.5, 0.75, and 1.0 $\sqrt{f_c'}$ MPa) for the knee joint specimens KJ1-KJ15, depending on the amount of beam longitudinal reinforcement. The design joint shear stresses were approximately $6\sqrt{f_c'}$ psi for specimens KJ16-KJ17, $9\sqrt{f_c'}$ psi for specimen KJ18, and $12\sqrt{f_c'}$ psi BCEJ1.

The tension development length provided within the joint core slightly exceeded that required for a standard hook for specimens KJ16 and KJ17, was approximately equal to that required for a standard hook for specimen KJ18, and was slightly less than that required for a standard hook for specimen BCEJ1 ($12.5d_b$ versus a required length of $15.8\ d_b$) the compression development length provided was 84%, 67%, and 88% of that required by ACI 318 Section 12.3 (including a multiplier of 0.8 to account for confinement) for specimens KJ16-KJ17, KJ18, and BCEJ1, respectively.

Horizontal transverse reinforcement within the joint region for specimens KJ4 and KJ7, and KJ16-KJ18 consisted of #3 (9.5 mm) US Grade 60 hoops with two crossties spaced at 3.5 inches (88.9 mm). Double leg, inverted, ``U-shaped" stirrups were also provided at a spacing of 3.5 in. (88.9 mm) in KJ4, KJ7, and KJ16 to confine the top face of the joint. For specimens KJ17 and KJ18, an additional U-shaped stirrup was used at the heads to restrain pullout (Fig. 3). For specimen BCEJ1, the spacing of transverse reinforcement in the joint region (hoop and two crossties) was approximately 4 inches (101.6 mm).

The average concrete compressive strengths at the testing date were: 7480, 4765, 5390, 5450, 5540, and 5190 psi (51.6, 32.9, 37.2, 38.2, 35.8 MPa) for specimens KJ4, KJ7, KJ16-KJ18, and BCEJ1, respectively. It should be noted that the stress-strain characteristics of the US Grade 60 reinforcement differ slightly from that of the Norwegian Tempcore reinforcement used for specimens KJ16-KJ18 (relatively little strain hardening occurred in the Tempcore steel), and that stress strain relations are not yet available for the reinforcement used in BCEJ1. Yield strength of the US Grade 60 longitudinal and transverse reinforcement used in the knee joints was approximately 65 ksi (44.8 MPa) for all specimens and bar sizes, whereas the yield stress was 71 (49.0 MPa) and 77 ksi (53.1 MPa) for the 16 mm and 20 mm bars, respectively, used in specimens KJ16-KJ18.

Specimen Testing and Instrumentation

The knee joints were tested in a statically determinate test setup with the column in an upright position. A schematic of the testing apparatus is shown in Figure 4. With this setup, the axial load in the beam and column varies in proportion with the applied load. The affects of axial load on member capacity were included in the specimen design and analysis. The exterior joints were also tested in an upright position (Figure 5). No axial load was applied to the column.

Instrumentation was used to measure lateral load, lateral displacement, rotations, concrete cover and joint core strains, and strain in the longitudinal and transverse reinforcement. Reversed cyclic loading was applied under displacement control. A minimum of two complete cycles were performed at each drift level in all specimens. The strain in the longitudinal and transverse reinforcement was measured through the use of strain gages. Several gages were provided along the top beam bars for specimens KJ16-KJ18 to evaluate the effectiveness of the headed reinforcement.

EVALUATION OF EXPERIMENTAL RESULTS

The primary objectives of this paper are to evaluate the potential of using headed anchorages with beam-column joint regions; therefore, only selected results from the overall research program are presented. For the knee joint specimens, a direct comparison between specimens constructed with headed reinforcement and similarly reinforced specimens where the anchorage within the joint was provided with 90 hooks (referred to as conventionally reinforced) is available. The conventionally reinforced specimen most comparable to specimens KJ16 and KJ17 is KJ4; whereas, specimen KJ7 most closely resembles the reinforcement placed in specimen KJ18. Specimen behavior and performance are discussed in the following subsections. Conclusions are based on the observed behavior as well as comparative evaluations. Some general results of the overall research program are presented first, followed by specific observations for the specimens with headed reinforcement.

Joint Shear Capacity

One objective of the knee joint research program was to evaluate joint shear capacity by varying the amount of longitudinal reinforcement provided in the beams and columns. Results indicate that if the joint shear demand is kept below $6\sqrt{f_c'}$ psi ($0.5\sqrt{f_c'}$ MPa), then good joint performance was achieved with little damage observed within the joint (KJ1-KJ4, KJ14-KJ17). Beam flexural hinging was typically observed for these specimens and good load deformation behavior was measured (Fig. 6). For specimens with sufficient

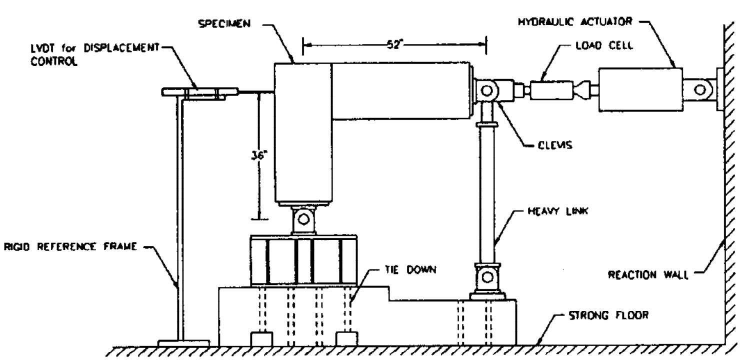

Fig. 4. Knee Joint Test Setup

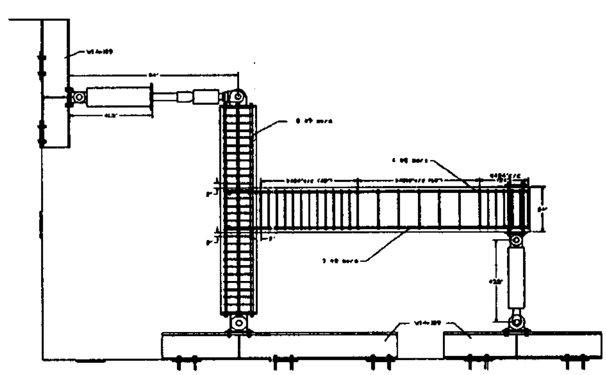

Fig. 5. Exterior Joint Test Setup

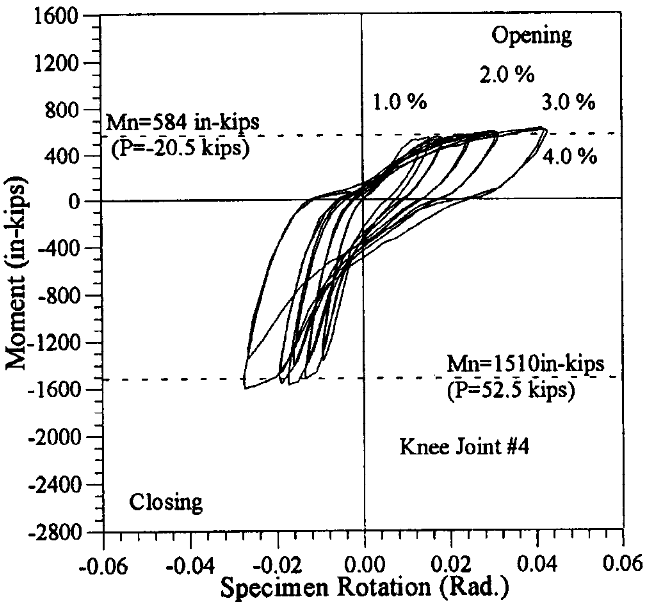

Fig. 6. Beam Moment vs. Specimen Rotation: KJ4

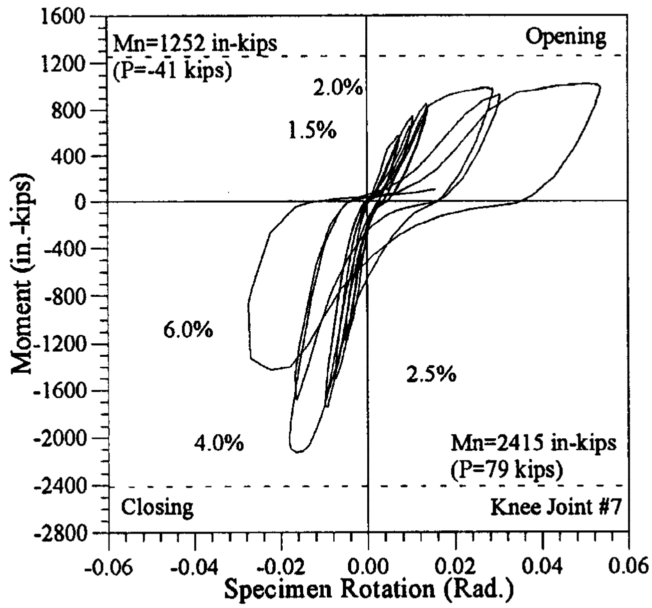

Fig. 7. Beam Moment vs. Specimen Rotation: KJ7

beam flexural reinforcement to achieve joint shear stresses of 9 to $12\sqrt{f_c'}$ psi (0.75 to $1.0\sqrt{f_c'}$ MPa), the maximum joint shear stress under closing moments obtained ranged from 7.4 to $9.2\sqrt{f_c'}$ psi (0.62 to $0.77\sqrt{f_c'}$ MPa), with an average value of $8.0\sqrt{f_c'}$ psi ($0.67\sqrt{f_c'}$ MPa). For all of these specimens, the full moment capacity of the beam could not be reached and substantial joint damage was observed. As a result, somewhat poor overall performance was observed (KJ7, Fig. 7). The horizontal dashed lines in Fig. 6 and 7 indicate the nominal moment capacities of the beam under both positive and negative bending. Due to joint deterioration, the specimens were unable to achieve the full flexural capacity of the beams. Based on the test results, beam-column knee joints without transverse beams are not capable of achieving a joint shear level of $12\sqrt{f_c'}$ as would be suggested in the Committee 352 report. For a knee joint with 4 adjacent unrestrained sides (the knee-joints were tested without transverse beams), a γ factor of 8 is probably a realistic limiting value.

Headed Reinforcement Anchorages

Specimen BCEJ1 was designed to meet ACI Committee 352 requirements except that headed reinforcement 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 pushout. Experimentally measured moment-rotation behavior (moment at column face versus the rotation measured over the 24 in. (609.6 mm) of the beam) is plotted in Fig. 8. Excellent behavior was observed, with little deterioration in flexural strength noted even at 6% lateral drift (note that no axial load was applied to the columns). Based on the test results, it is apparent that the use of headed reinforcement is a viable alternative to the use of standard hooks in exterior beam column joints. It is noted that the headed reinforcement was anchored approximately 13 beam bar diameters into the joint (roughly equivalent to the embeddment required for a standard hook). It is likely that shorter embeddments could be used as test results on isolated anchors (Bode and Roik, 1987) indicate that an embeddment of 8 to 10 bar diameters is adequate; however, additional testing is needed to verify this for bars anchored within a joint region. Pushout of the column cover concrete did not affect the lateral load capacity of the specimen even though only 88% of the compression development length was provided.

Testing of the knee joint specimens with headed bars was conducting in two phases due to the special problems associated with this joint configuration (four unrestrained joint faces). Specimen KJ16 was constructed to be essentially the same as the conventionally reinforced specimens (except with headed bars replacing the standard 90 degree hooks). Test indicated the need to provide additional reinforcement to restrain pullout of the beam top bars. Based on the test results for KJ16, additional reinforcing was provided in specimens KJ17 and KJ18 to restrain the heads of the beam top bars (Fig. 3). The area of the U--stirrups at the heads of the beam top bars was selected such that the stirrups would be capable of resisting one half of the total tension force developed in the beam top bars. The resistance provided by the three remaining single U-stirrups and by the cover concrete were neglected. No additional transverse reinforcement was used in the column.

The moment-rotation hysteresis loops for specimen KJ17 are plotted in Fig. 9 and indicate that large ductilities were achieved under both opening and closing moments. For specimen KJ17, the horizontal shear demand placed on the joint was kept below $6\sqrt{f'_c}$ psi ($0.5\sqrt{f'_c}$ MPa); therefore, good joint behavior was expected based on the results of the specimens constructed with conventional reinforcement anchorages. For this joint shear stress level, flexural hinging occurred in the beam adjacent to the column face.

Compared with KJ4 (Fig. 6), the relations for KJ17 reveal that the performance of the specimen constructed with headed reinforcement is as good as the specimen constructed with conventional reinforcement. Slight differences are evident in Fig. 6, compared with Fig. 9. These differences include: (1) KJ17 exhibits slightly greater stiffness than KJ4, probably due to less slip of the reinforcement, and (2) KJ17 achieves slightly lower flexural capacity than KJ4, likely due to the differences in the strain-hardening characteristics of the bars.
In specimen KJ17, some pushout of the concrete at the back of the joint occurred due to compressive forces in the beam bottom bars and localized bending of the column bar at the middle of the back face was noted. However, the concrete spalling and column bending mentioned above did not occur until very high drift demands (6%) were imposed on the specimen. This behavior was not evident in specimens KJ16 and KJ18 which were not subjected to such extreme deformation demands, indicating that the provided compression development length (85% and 67% of the ACI required compression development length for KJ17 and KJ18, respectively), detailing, and concrete cover are sufficient under the maximum displacement demands reasonably expected to occur in structural systems.

Specimen KJ18 performed noticeably better than specimen KJ7, which was reinforced using conventional 90 degree hooks. This is primarily due to less reinforcement slip occurring when the headed anchorages are used. Excessive anchorage slip occurred in the top beam bars under large displacement demands in KJ7. Initial crack formation occurred along the straight portion of these bars and eventually extended around the bends as the hook extensions pushed outward on the concrete cover at the back of the joint.

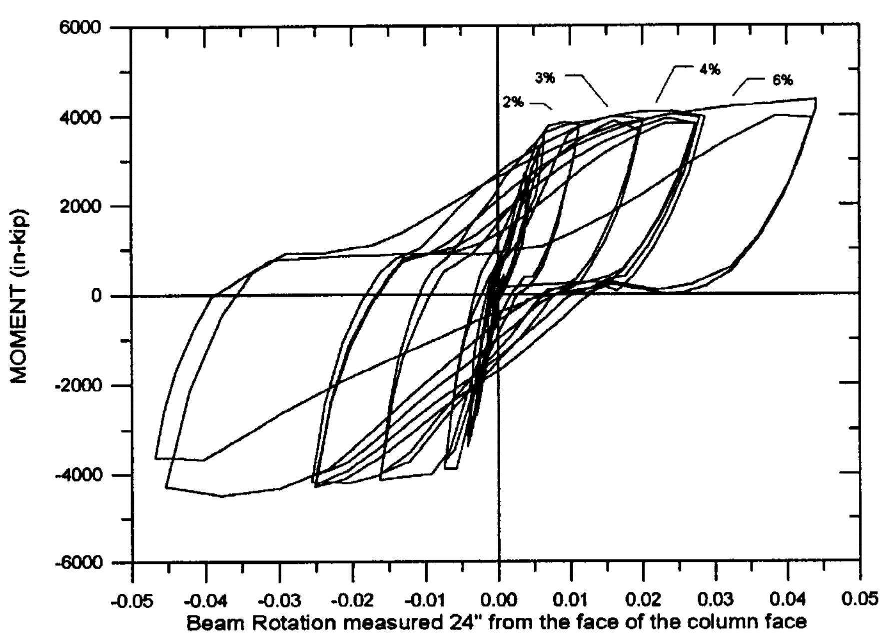

Fig. 8. Beam Moment vs. Rotation: BCEJ1

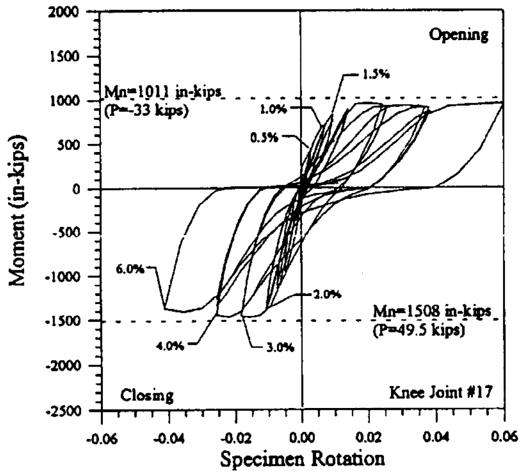

Fig. 9. Beam Moment vs. Specimen Rotation: KJ17

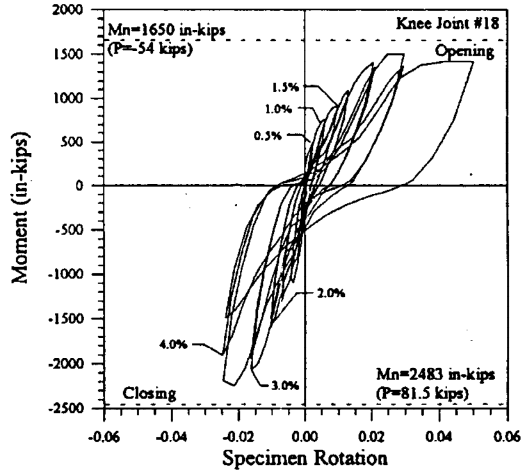

Fig. 10. Beam Moment vs. Specimen Rotation: KJ18

CONCLUSIONS

Results of a experimental and analytical study of knee and exterior joints was summarized and ACI Committee 352 recommendations were assessed. Based on this study, the following conclusions were reached: (1) The joint shear strength value implied for knee joints in ACI 352-91 ($12\sqrt{f_c'}$ psi; $1.0\sqrt{f_c'}$ MPa) is unconservative for the case where no transverse beams are provided. Based on test results, a limiting value of $8\sqrt{f_c'}$ psi ($0.67\sqrt{f_c'}$ MPa) should be used. (2) The use of headed reinforcement in exterior beam-column joints is a viable option and presents no significant design problems. (3) Performance of beam-column knee joints constructed with headed reinforcement performed as well as similar specimens with 90 degree hooks; however, additional transverse reinforcement may be needed to ensure that the heads are adequately restrained against pullout. (4) The use of headed reinforcement allows for easier construction by alleviating congestion of joint reinforcement, and thus easing concrete placement.

ACKNOWLEDGEMENTS

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