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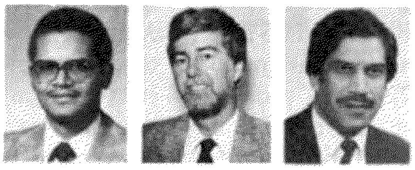
Investigation of "Top Bar" Effects in Beams



by Paul R. Jeanty, Denis Mitchell, and M. Saeed Mirza

An experimental study was performed on full-scale beam specimens to study the "top bar" effect on the responses. The behavior of beams containing top-cast bars is compared with companion beams containing bottom-cast bars. A top bar factor for these tests is derived and the results are compared with current ACI predictions and with the suggested provisions made by ACI Committee 408. In addition, the influence of transverse reinforcement is investigated.

Keywords: anchorage (structural); **beams (supports)**; bond (concrete to reinforcement); **position (location)**; reinforced concrete; **reinforcing steels**; structural design.

The influence of the casting position of reinforcing bars on bond characteristics has been recognized since 1913.[1] The top bar factor was introduced in the 1951 ACI Building Code for top bars defined as horizontal bars so placed that more than 12 in. (305 mm) of concrete is cast in the member below the bars. This factor and the definition of a top bar have remained essentially the same in the ACI Building Code for more than 30 years.

RESEARCH SIGNIFICANCE

There is a need for more research in this important area to provide a better understanding of the effects of casting position on the bond performance. The effects of water-cement ratio, the vertical position of bars in the casting height, the orientation of the bars, the presence of superplasticizers, and the use of large-diameter bars need to be investigated. This paper presents the results of a series of experiments on full-scale reinforced concrete beams to examine the top bar effects on the responses.

HISTORICAL DEVELOPMENT OF TOP BAR FACTOR

The effects of casting position on the bond characteristics were reported by Abrams;[1] Davis;[2] Clark;[3] Menzel;[4] Dutron;[5] Rehm;[6] and Ferguson, Breen, and Thompson.[7] These researchers performed experiments on pullout specimens that included reinforcing bars placed vertically in the formwork, bars placed horizontally at the bottom of the formwork (bottom-cast), and bars placed horizontally at the top of the formwork (top-cast). In addition, Soretz,[8] Leonhardt and Walther,[9] and Ferguson and Thompson[10] performed beam tests comparing the behavior of bottom-cast with top-cast specimens.

In the case of a vertically oriented reinforcing bar, it was concluded that the settlement of the concrete resulted in better consolidation of the concrete above the deformations than below the bar deformations. The bond resistance is therefore more favorable when the bar is pulled against the direction of casting rather than in the casting direction. The lower bond strength of top-cast compared to bottom-cast horizontal bars is attributed to the greater settlement of concrete immediately below the top-cast bar and to a 10 to 20 percent[11] lower tensile strength of the concrete at the top of the casting. The pullout tests enabled the following classification for casting position and loading direction of bars in order of decreasing bond strength:

1. Vertically oriented bar loaded in direction opposite to casting direction;
2. Horizontally oriented bottom-cast bar;
3. Horizontally oriented top-cast bar; and
4. Vertically oriented bar loaded in direction of casting.

From their pullout tests, Ferguson, Breen, and Thompson[7] observed that top-cast bars slipped at the unloaded end at relatively low loads and then continued to accept more load, whereas bottom-cast bars did not slip at the unloaded end until almost at their maximum load.

Recognition of this phenomenon was first introduced into the ACI Building Code[12] in 1951 in the form of allowable bond stresses at working loads based on the tests carried out by Clark.[3] The allowable bond stress for a top-cast bar was 0.7 times the allowable stress for a bottom-cast bar. Top bars were defined as

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Paul R. Jeanty is an engineer with the Commission des Services Electriques of the City of Montreal, Quebec, Canada.

Denis Mitchell, FACI, is a professor in the Department of Civil Engineering and Applied Mechanics at McGill University in Montreal. He is currently a member of ACI-ASCE Committee 445, Shear and Torsion, and ACI Committees 408, Bond and Development of Reinforcement; and E 901, Scholarships; and is a member of the Canadian Concrete Code Committee.

M. Saeed Mirza, FACI, is a professor in the Department of Civil Engineering and Applied Mechanics at McGill University. He is currently a member of ACI Committees 444, Models of Concrete Structures, and 435, Deflection of Concrete Structures.

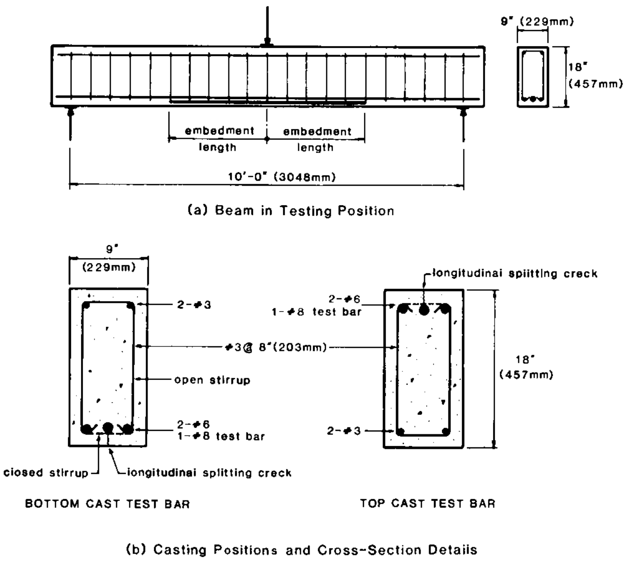

Fig. 1—Test set-up and positions of casting (1 in. = 25.4 mm)

"horizontal bars so placed that more than 12 in. of concrete is cast in the member below the bar." The 1963 ACI Building Code[13] introduced ultimate strength design and used an ultimate bond stress expression with the same top bar bond stress reduction factor as the 1951 ACI Code.

The 1971 ACI Building Code[14] replaced the traditional bond stress calculation with expressions for development length. In this code and the 1983 ACI Building Code,[15] the top bar effect is accounted for by multiplying the development length by a factor of 1.4, which corresponds to the top bar bond stress reduction factor of 0.7 in the 1951 ACI Building Code. Since the 1951 ACI Code, the top bar definition and the top bar factor have not been changed. Further research is needed to determine the influence of casting position on the bond performance in modern concrete construction.

OBJECTIVES OF EXPERIMENTAL PROGRAM

The objectives of this investigation are to test full-size beam specimens to study the effects on the responses of the following parameters, varied systematically, one at a time:

1. Top-cast versus bottom-cast bars;
2. Embedment length of the test bars; and
3. Presence of transverse reinforcement crossing the plane of potential splitting

The experimental results are compared with the current ACI Building Code (ACI 318-83) provisions[15] and the suggested provisions[16,17] of ACI Committee 408. By comparing the responses of top-cast specimens and companion bottom-cast specimens, a suitable top bar factor is suggested.

DESCRIPTION OF TEST SPECIMENS

The cross-sectional dimensions of all the test specimens were 9 in. (229 mm) wide by 18 in. (457 mm) deep. The specimens were tested over a simple span length of 10 ft. (3048 mm) with a central load, as shown in Fig. 1. The beams contained the following reinforcment:

1. A No. 8 reinforcing bar (25-mm diameter) with a clear concrete cover of 1.5 in. (38 mm) was placed with equal embedment lengths on both sides of the beam centerline. The yield stress f_y was 59.5 ksi (410 MPa).
2. Two No. 6 (19-mm diameter) reinforcing bars were provided in the corner of the stirrups running the full length of the beam. The yield stress was 58.5 ksi (403 MPa).
3. Two No. 3 (9.5-mm diameter) reinforcing bars were provided in the corners of the stirrups. The yield stress was 60.3 ksi (416 MPa).
4. Either open or closed No. 3 stirrups were placed at 8-in. (203-mm) spacing throughout the beam length.

The beams were cast in pairs, one with the reinforcing placed in the formwork to provide a bottom-cast test bar and the other with an inverted reinforcing cage to provide a top-cast test bar [see Fig. 1(b)]. All of the specimens were tested, as shown in Fig. 1(a), with the main tension steel on the bottom to enable a comparison of the performance of top versus bottom-cast bars. The embedment lengths were varied from 30 to 48 in. (762 to 1219 mm) to determine the embedment length necessary for yielding of the main tension reinforcement for both the top-cast and the bottom-cast specimens. Since bond failure was initiated by a longitudinal splitting crack in the concrete cover over the test bar, some of the stirrups were closed [see the dotted line in Fig. 1(b)] to study the effects of transverse reinforcement crossing the plane of splitting. Table 1 summarizes the important test specimen details. The odd-numbered specimens contain top-cast bars, while the even numbered specimens contain bottom-cast test bars.

The concrete consisted of normal portland cement, natural sand, and crushed limestone for the coarse aggregate having a maximum size of ¾ in. (19 mm). A water-cement ratio of 0.54 was used, and a water-reducing admixture was included in the mix. The components of the concrete mix are given in Table 2. The compressive strength for each specimen was determined from six standard 6 x 12 in. (152 x 305 mm) test cylinders tested on the day after the beam was tested. The average compressive strength for each specimen is

Table 1 — Test specimen details

Embedment length, in. (mm)	Top cast		Bottom cast		Stirrup type
	Specimen	f'_c, psi (MPa)	Specimen	f'_c, psi (MPa)	
30 (762)	B1	4040 (27.9)	B2	3890 (26.8)	Open
36 (914)	B3	4070 (28.1)	B4	4240 (29.2)	Open
40 (1016)	B5	4030 (27.8)	B6	4070 (28.1)	Open
44 (1118)	B7	4000 (27.6)	B8	4000 (27.6)	Open
48 (1219)	B13	4560 (31.4)	—	—	Open
30 (762)	B9	4560 (31.4)	B10	4080 (28.1)	Closed
36 (914)	B11	4080 (28.1)	B12	4560 (31.4)	Closed

Table 2 — Concrete mix components for one cubic yard

Component	Weight
Fine aggregate: sand	1610 lb
Coarse aggregate: ¼-in. stone	510 lb
½-in. stone	840 lb
¾-in. stone	340 lb
Type I portland cement	500 lb
Water	270 lb
Water-reducing admixture	35 oz

1 lb. = 4.448 N.

given in Table 1. The average measured slump was 4½ in. (114 mm) for all of the test specimens.

The No. 8 (25-mm diameter) test bar was instrumented with electrical-resistance strain gages at a spacing of 4 in. (102 mm), while the No. 6 (19-mm diameter) bars were instrumented with strain gages at a spacing that varied from 6 to 12 in. (152 to 305 mm). Strain gages near the compression face of each beam were used to measure the concrete strains.

EXPERIMENTAL RESULTS

Effect of embedment length and position of casting on the responses

The measured load versus central deflection responses for the beams with top-cast test bars (B1, B3, B5, B7, and B13) and for the beams with bottom-cast test bars (B2, B4, B6, and B8) are shown in Fig. 2 and 3, respectively. All of these specimens contained open stirrups. The test bars in these beams had embedment lengths varying from 30 to 48 in. (762 to 1219 mm). If the responses of the companion top-cast and bottom-cast specimens having the same embedment lengths are compared, it is evident that the bottom-cast beams exhibited better overall behavior than the top-cast beams. The dashed lines shown in Fig. 2 and 3 are load-deflection predictions using the computed ultimate flexural strengths and the calculated average effective moments of inertia of the beams for different load levels, assuming perfect bonding between the concrete and the reinforcing bars.

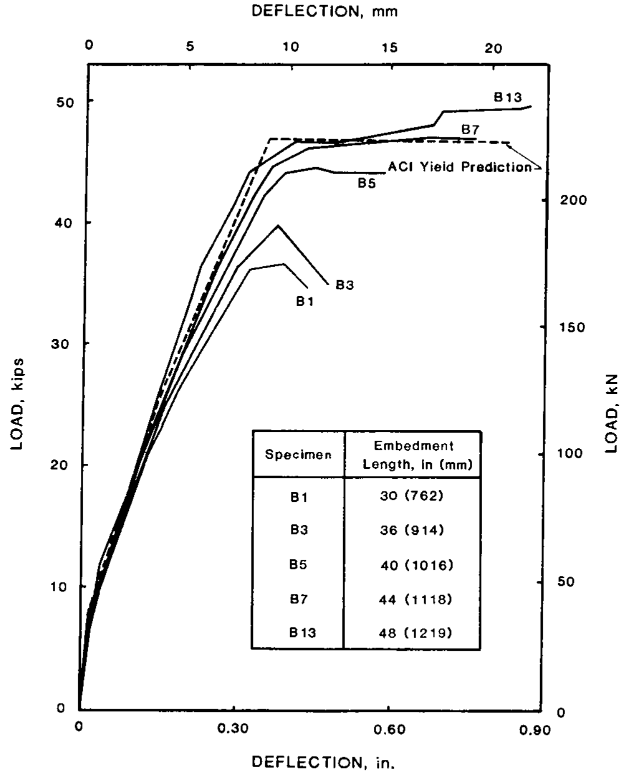

Fig. 2—Load-deflection responses of top-cast beams having different embedment lengths

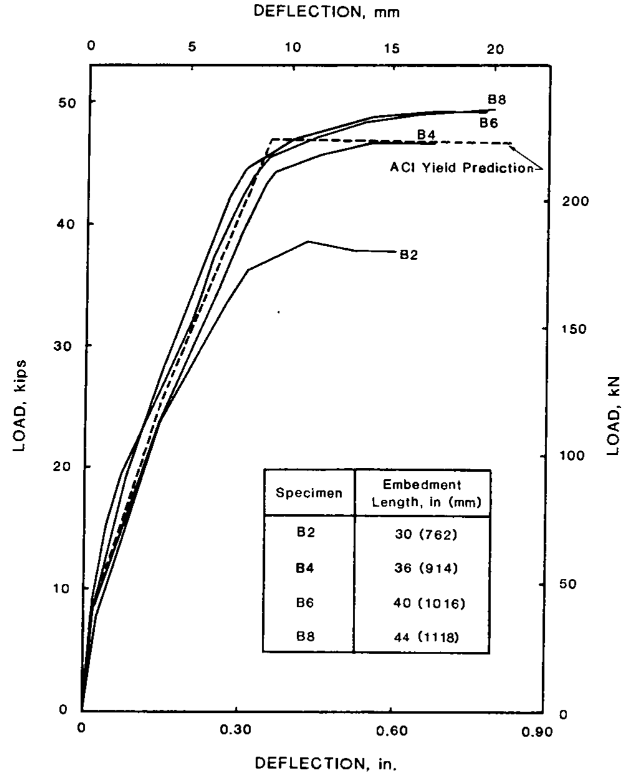

Fig. 3—Load-deflection responses of bottom-cast beams having different embedment lengths

Fig. 4 and 5 compare the variations in the measured strains in the No. 8 bar for top-cast specimens (B1, B3, B5, and B7) with those measured in the bottom-cast

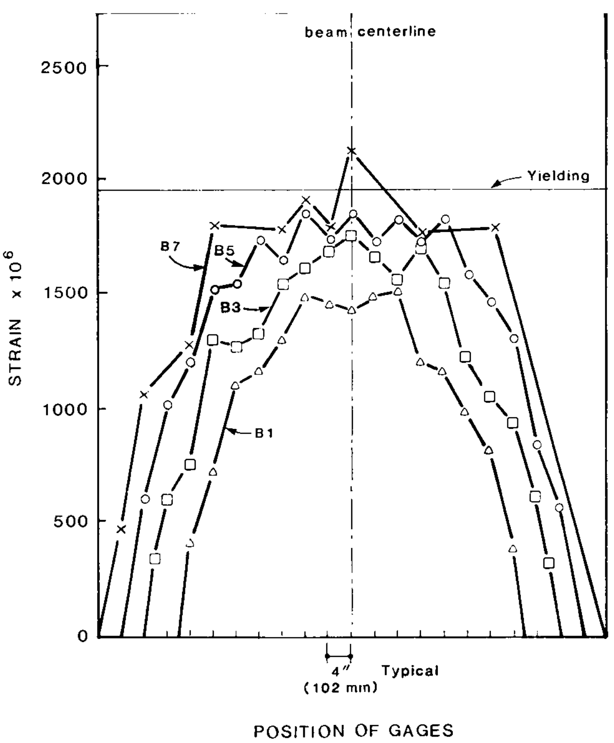

Fig. 4—Measured tensile strains in No. 8 bar at failure for specimens B1, B3, B5, and B7

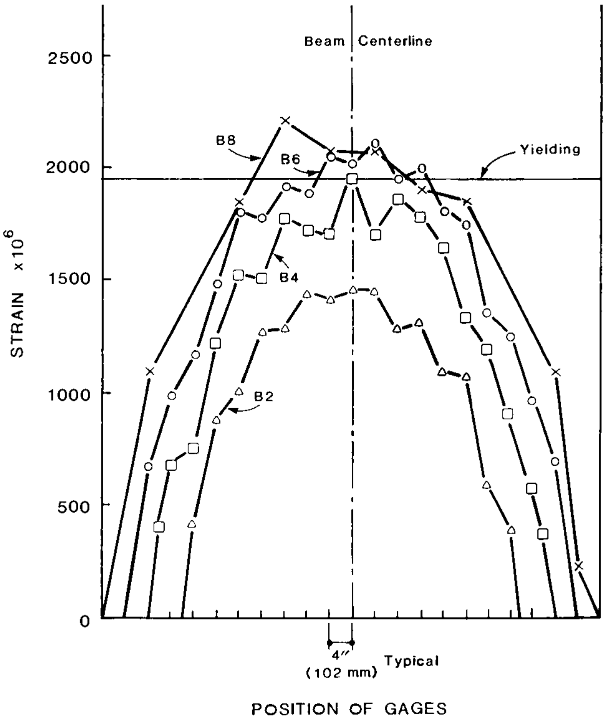

Fig. 5—Measured tensile strains in No. 8 bar at failure for specimens B2, B4, B6, and B8

specimens (B2, B4, B6, and B8). As expected, larger strains are developed in the No. 8 bar as the development length is increased. It is clear from these two figures that the top-cast bars required an embedment length of 44 in. (1118 mm), while the bottom-cast bars required only 36 in. (914 mm) to yield the reinforcement.

The measured load versus central deflection responses for Specimen B3 (top-cast) and B4 (bottom-cast) are shown in Fig. 6. The various stages of behavior, such as cracking at the bar cut-offs, the initiation of longitudinal splitting cracks, and the appearance of major shear cracks close to maximum load, are shown in this figure. It is interesting to note that the top-cast specimen displayed flexural cracking at slightly lower loads than the bottom-cast specimen, indicating that the tensile strength of the concrete at the top of the casting is lower than that at the bottom of the casting.

The effects of increasing the embedment length to 44 in. (1118 mm) for Beam B7 (top-cast) and Beam B8 (bottom-cast) are apparent from Fig. 7. The test bar in the top-cast specimen just reached yield at maximum load (see Fig. 4). Beam B8 displayed yielding of the test bar along a length of about 28 in. (711 mm), as can be seen from Fig. 5.

Only one beam, top-cast Specimen B13, had an embedment length of 48 in. (1219 mm). Due to the significant yielding displayed in Beams B6 and B8 having embedment lengths of 40 and 44 in. (1016 and 1118 mm), respectively, it was unnecessary to test a companion bottom-cast specimen with a longer embedment length. As can be seen from the load-deflection response in Fig. 2, Beam B13 displayed an extremely ductile response similar to that for bottom-cast Beam B6 having a test bar embedment length of 40 in. (1016 mm).

Photographs of the side faces and tension faces of Beams B3 and B4 are shown in Fig. 8. For these beams, and in general for all the beams tested, the bottom-cast specimens displayed better cracking response (i.e., a larger number of more evenly spaced smaller cracks) than the companion top-cast specimens due to the larger tensile strength of the bottom-cast concrete. In addition, the top-cast specimens exhibited more severe longitudinal splitting cracks than the bottom-cast specimens (see tension faces of Beams B3 and B4 in Fig. 6).

From this series of tests on companion beams with top-cast and bottom-cast No. 8 (25-mm diameter) bars and an average concrete strength of 4170 psi (28.8 MPa), it can be seen that a development length of 36 in. (914 mm) is required for a bottom-cast bar, while a length of 44 in. (1118 mm) is required for a top-cast bar. This implies a top bar factor of 44/36 = 1.22 for these tests. It is noted that the top-cast test bar had 15.5 in. (394 mm) of concrete cast below it (see Fig. 1).

Effect of transverse reinforcement and position of casting on the responses

Fig. 9 compares the responses of bottom-cast Beam B2, without transverse reinforcement crossing the plane of splitting, and bottom-cast Beam B10, containing No. 3 closed stirrups at 8-in. (203-mm) spacing crossing the plane of splitting. The significant difference in the responses of these two beams in terms of their overall be-

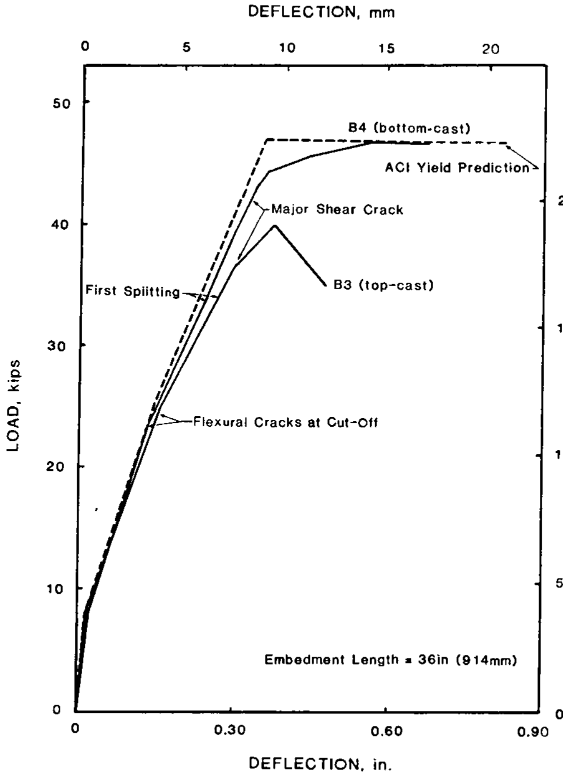

Fig. 6—Effect of casting position of the reinforcement on the load-deflection responses of Beams B3 and B4

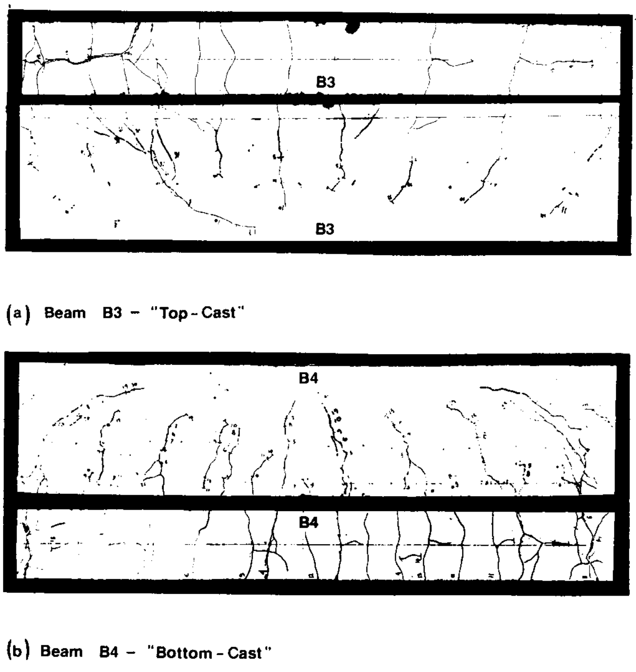

Fig. 8—Effect of casting position on the crack patterns on side faces and tension faces of Beams B3 and B4

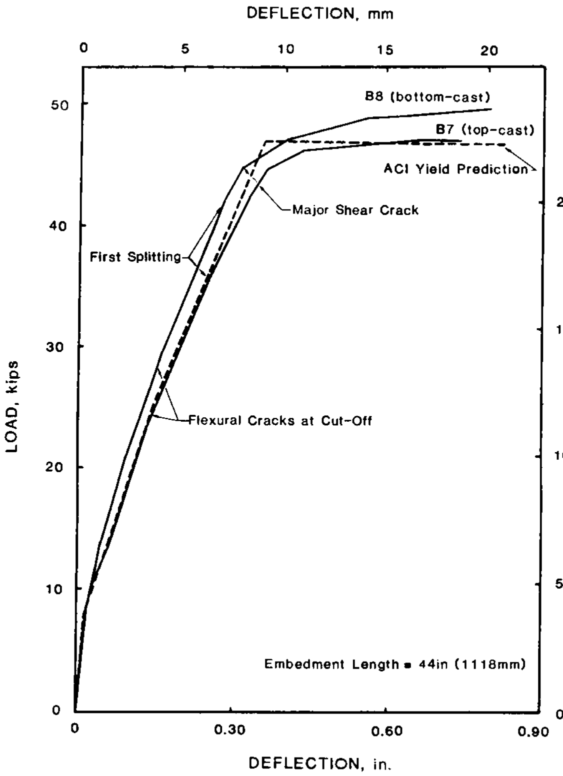

Fig. 7—Effect of casting position of the reinforcement on the load-deflection responses of Beams B7 and B8

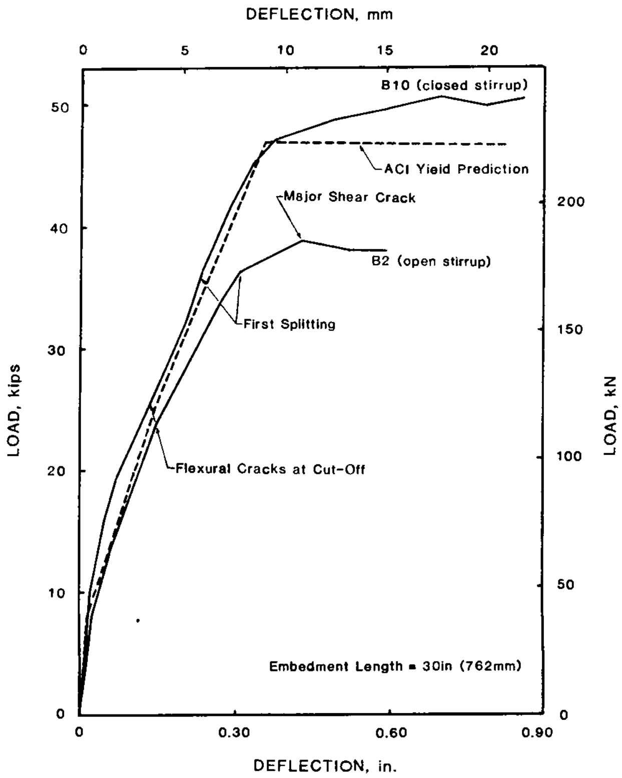

Fig. 9—Effect of transverse reinforcement on the load-deflection response for bottom-cast beams

havior (i.e., cracking, stiffness, maximum strength, and maximum deformations) is clearly evident in Fig. 9. Both beams have embedment lengths of 30 in. (762 mm). The improved response of Beam B10 is due to the

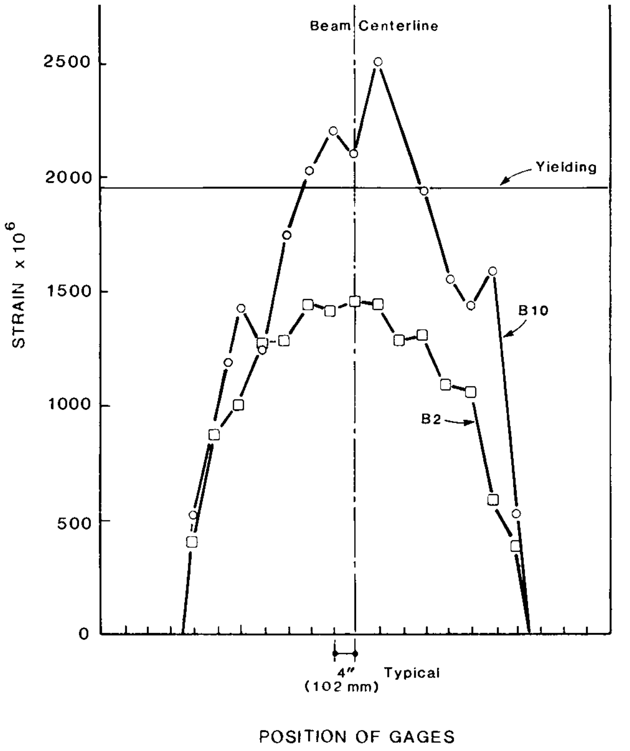

Fig. 10—Measured tensile strains in No. 8 bar at failure for specimens B2 and B10

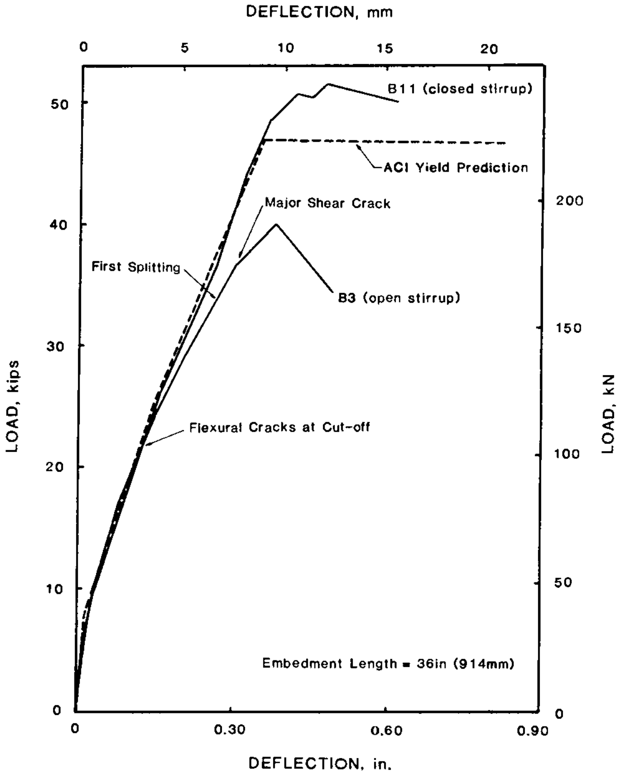

Fig. 11—Effect of transverse reinforcement on the load-deflection response for top-cast beams

presence of transverse reinforcement crossing the plane of splitting. As can be seen from Fig. 10, significantly larger strains were attained in the No. 8 bar of Specimen B10. Specimen B10 experienced significant yielding, whereas Specimen B2 did not reach yield, indicating a bond failure.

The responses of top-cast Beams B3 (without closed stirrups) and B11 (with closed No. 3 stirrups at 8-in. [203-mm] spacing) are compared in Fig. 11. Both of these beams had embedment lengths of 36 in. (914 mm). Once again, the improved response of the member with the transverse reinforcement crossing the plane of splitting (Beam B11) is noted.

From the results of tests on specimens with closed stirrups (B9, B10, B11, and B12), it can be seen that a development length of 30 in. (762 mm) is required for the bottom-cast No. 8 test bar while a length of 36 in. (914 mm) is needed for the top-cast No. 8 test bar.

It is important to emphasize that the provision of transverse reinforcement crossing the plane of splitting reduces the development length required from 36 to 30 in. (1016 to 762 mm) for a bottom-cast bar and from 44 to 36 in. (1219 to 914 mm) for a top-cast bar. These results show that this amount of transverse reinforcement reduces the required development length by about 20 percent. These results also imply a top bar factor of approximately 1.20.

Comparison of development length provisions with test results

Table 3 compares the development lengths computed from the ACI Building Code (ACI 318-83) expressions[15] and from the ACI Committee 408 expressions[16] with the development length required to produce yielding of the test bar. In the calculations, the average concrete strength of 4170 psi (28.8 MPa) was used. For the cases with no transverse reinforcement crossing the plane of splitting, the ACI predictions are unconservative (by 19 percent for the bottom-cast bar and 7 percent for the top-cast bar), while the predictions using the recommendations of Committee 408 are conservative (by 16 percent for the bottom-cast bar and by 23 percent for the top-cast bar).

For those cases with transverse reinforcement crossing the plane of splitting, the ACI method does not directly account for the presence of this reinforcement, while the ACI Committee 408 provisions account for the size, yield strength, and spacing of the transverse reinforcement. Once again, the ACI Committee 408 predictions are conservative for both top-cast and bottom-cast bars, and this approach provides a good prediction of the beneficial effects of the transverse reinforcement.

CONCLUSIONS

This paper presents experimental data on the effects of top- versus bottom-cast bars on the response of full-scale beams. An examination of the test results has led to the following conclusions.

1. Beams with bottom-cast bars showed improved behavior in terms of the cracking, stiffness, strength, and deformation response over the companion top-cast beams.

2. For this test series of beams, both with and without transverse reinforcement crossing the plane of splitting, the top bar factor was found to be about 1.22.

3. The presence of transverse reinforcement across the plane of potential splitting can reduce significantly the required development length for both bottom-cast and top-cast bars. This reduction was 20 percent for this test series.

4. The provisions suggested by Committee 408 provide more accurate predictions of development lengths required than the provisions of the ACI Building Code. In comparing these two methods it must be noted that a Φ factor of 0.8 was used in making the predictions using the Committee 408 expression.

The aim of this experimental program is to provide additional data on the behavior of beams with top-cast and bottom-cast bars. Further research is needed to develop more appropriate treatment of this important phenomenon in codes.

Table 3 — Comparison of required development lengths computed by ACI method and Committee 408 method with test results

Casting position	Transverse reinforcement	Required development length, in. (mm)		
		ACI method[15]	Committee 408 method[16]	Test
Bottom	None	29 (737)	42 (1067)	36 (914)
Top	None	41 (1041)	54 (1372)	44 (1118)
Bottom	No. 3 at 8 in. (9.5 mm diameter at 203 mm)	29 (737)	33 (838)	30 (762)
Top	No. 3 at 8 in. (9.5 mm diameter at 203 mm)	41 (1041)	43 (1092)	36 (914)

Note: Average f_c' taken as 4170 psi (28.8 MPa). Capacity reduction factor of 0.8 was used in Committee 408 expression for development length.

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V = shear force acting on beam section
y = distance from top of beam section
$\bar{y}$ = distance from top to centroid of section
ϵ_1 = principal tensile strain in concrete
ϵ_2 = principal compressive strain in concrete (negative quantity)
ϵ_b = bottom fiber strain in beam section
ϵ_c' = strain in concrete cylinder at peak stress f_c' (negative quantity)
ϵ_s = strain in reinforcement
ϵ_t = top fiber strain in beam section
ϵ_x = strain in longitudinal direction
ϵ_y = strain in transverse direction
θ = angle of inclination of principal strains
θ_c = angle of inclination of principal stresses in concrete
ρ_v = reinforcement ratio for steel in transverse direction
$\Delta\epsilon_p$ = difference between strain in prestressing tendon and strain in an adjacent fiber of concrete

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