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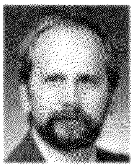
Cracking on the Side Faces of Large Reinforced Concrete Beams




by Gregory C. Frantz and John E. Breen

Test results and observations of several large reinforced concrete beams have questioned the effectiveness of the present design provisions concerning side face crack control reinforcement for large beams. Forty-four laboratory size specimens were tested to study how skin reinforcement affects side face cracking. Variables included amount, location, distribution, cover, and type of skin reinforcement, web width, and beam depth. Test results indicate that the present provisions are not adequate. Skin reinforcement affects only a narrow strip of concrete along each side face and is not dependent on the web width. The effectiveness of skin reinforcement in controlling cracking can be related to a simple skin reinforcement ratio. As the beam depth increases, the skin reinforcement ratio required to provide the same degree of crack control also increases.

Keywords: **beams (supports)**; bending; bridges (structures); **cracking (fracturing)**; **crack width and spacing**; loads (forces); maintenance; **reinforced concrete**; reinforcing steels; specimens; **tests**; welded wire fabric.

Almost all research on control of crack widths in beams has studied cracking in the vicinity of the main flexural reinforcement. However, observations of several 8 ft (approximately 2.4 m) deep inverted T-beams, designed according to the latest AASHTO specifications,[1] have shown that wide cracks developed on the side faces in the region between the neutral axis and the main tension reinforcement (Fig. 1). While the crack widths at the main reinforcement level were within acceptable limits, the side face cracks near middepth were as much as three times as wide, 0.037 in. (0.94 mm), unacceptable. Although it is uneconomical to attempt to prevent cracking in conventional reinforced concrete, it is desirable to limit the widths of cracks to avoid esthetic and durability problems.

Tests at the Portland Cement Association[2] have shown the effectiveness of longitudinal crack control (or skin) reinforcement in controlling side face cracking. Both "Building Code Requirements for Reinforced Concrete (ACI 318-77)"[3] and the AASHTO specifications[1] provide guidance in the design of skin reinforcement and require the skin reinforcement area to be at least equal to 10 percent of the main tension reinforcement area. However, in addition to the beams discussed in the previous paragraph, test results[4,5] have also questioned the effectiveness of these provisions. One study[5] suggested that the area of skin reinforcement should be directly proportional to the web area in the tension zone.

This paper summarizes the results of an experimental program that examined the effects of the following variables on the side face crack width: (1) amount, location, and distribution of skin reinforcement; (2) side cover over the skin reinforcement; (3) type of skin reinforcement — deformed bars or welded wire fabric mesh; (4) beam depth; and (5) beam web width. Reference 6 is the complete project report and includes a finite element study of the side face cracking problem (also see Reference 7), and presents a revised design method for skin reinforcement. Specific recommendations for needed code revision are made in a parallel paper in the October 1980 issue of ACI's *Concrete International: Design & Construction.*[8]

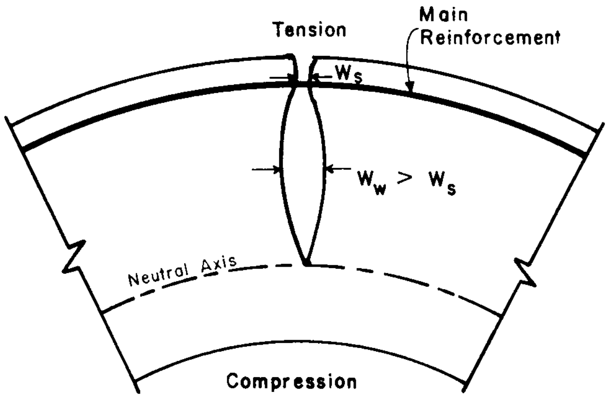


Fig. 1 — Side face cracking in large beam

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*ACI member **Gregory C. Frantz** is an assistant professor of civil engineering at the University of Connecticut.*

***John E. Breen**, FACI, is the J. J. McKetta Professor of Engineering at the University of Texas at Austin. He is a member of ACI Committees 318, Standard Building Code, and Joint ACI-ASCE 441, Reinforced Concrete Columns; and is past chairman of the Technical Activities Committee.*

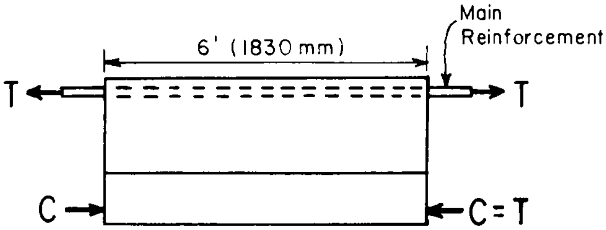


Fig. 2 — Beam segment

EXPERIMENTAL PROGRAM

Preliminary tests

The initial part of the project was directed at verifying the similitude of side face cracking in full size beams and in model beams of reduced size aggregate and deformed bars suitable for laboratory study. Test results indicated that satisfactory cracking similitude was obtained in crack spacing, crack width, and crack shape by geometric scaling. Cracks in the shear span were not significantly larger than cracks in the constant moment region. Even with the skin reinforcement required by the ACI Building Code or AASHTO specifications, cracks on the side faces were well over twice as wide as cracks at the main reinforcement level.

A simplified 6 ft (approximately 2 m) long model beam segment was developed to permit testing a region of constant moment (Fig. 2). Using one hydraulic system, tensile forces were applied to the main reinforcement extending from each end of the segment, and compressive forces were applied in the compressive zone of the concrete, thus creating a bending moment within the segment. The ends of the segment approximated long flexural cracks. Results from a preliminary series of segment tests indicated that these simplified specimens accurately simulated the deformation and cracking behavior of the constant moment region of the full length beam. These preliminary tests are fully discussed in the complete report.[6]

Specimen details

Forty-four T-beam specimens, consisting of 42 segments and 2 full-length beams, were tested. Fig. 3 and Table 1 give specimen details. Two-thirds scale models of the 47.1 in. (1200 mm) deep specimens of Series D were used to avoid requiring a longer test length for this deep specimen. The Series M specimens had sheets of welded wire fabric mesh bent into a U-shape so that longitudinal bars were uniformly distributed along the extreme tension face and throughout the depth. Series W specimens were designed so the crack width at the main reinforcement level, as calculated by the Gergely-Lutz equation,[9] was the same in each specimen. Concrete strength was approximately 5000 psi (approximately 34 MPa). Reinforcement was Grade 60 (or Grade 77 for the 6 mm bars).

Test procedure

Approximately six load stages were used between the first cracking load and the ultimate capacity of the specimen, which occurred at yielding of the main reinforcement extending out of each end of the specimen. Upon reaching the desired load, valves were closed at the four hydraulic rams at the segment ends. All visible cracks were located and marked; however, only cracks in the center 4 ft of the specimen were measured, omitting 1 ft at each end because of pos-

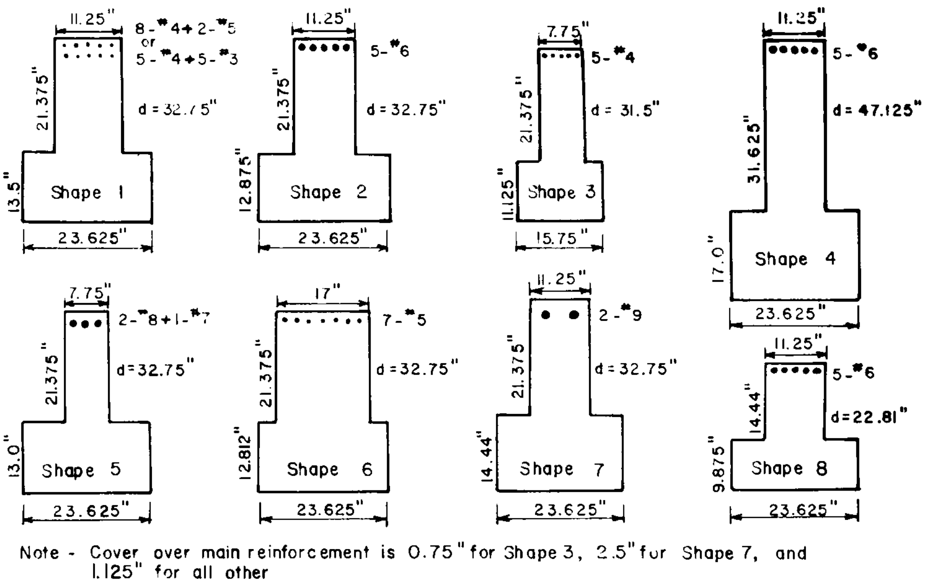


Fig. 3 — Specimen cross section details; see Table 1 for skin reinforcement details (1 in. = 25.4 mm)

sible localized effects of the loading system. Cracks were measured at about 2 in. (approximately 5 cm) intervals down the side faces. Crack patterns were recorded at each stage.

TEST RESULTS

Analysis of data

Test results of different specimens were compared in several ways: (1) by comparing crack patterns; (2) by comparing the crack widths measured on the side face; and (3) by comparing the crack magnification ratios (CMR), the ratio of the crack width in the web to the crack width at the main reinforcement level. Skin reinforcement, at least in the amounts used in this study, did not significantly affect crack widths at the main reinforcement level. The crack magnification ratio remained fairly constant above a main reinforcement stress of about 30 ksi (approximately 210 MPa), a typical service load level. Using the crack magnification ratio permitted a better comparison between data measured by different people than using absolute crack widths. Skin reinforcement affected both the maximum and average crack widths equally. Since the sample size of crack widths was small, the average crack width was used as a more reliable indicator of cracking severity.

General concepts of side face cracking

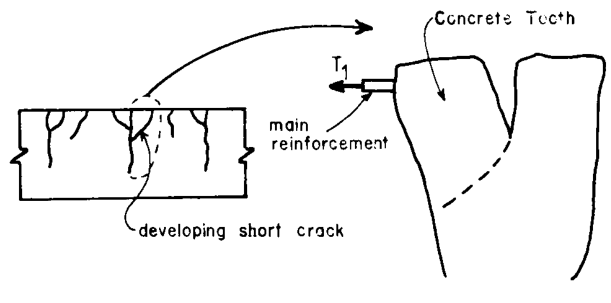
Why cracks are not wedge shaped. Fig. 1 shows a section of a beam containing a crack. The main reinforcement supplies a restraining force across the crack. Using elementary strength of materials concepts, the deformation of the crack edges would be assumed as a straight line. However, because of the phenomenon of diffusion or shear lag, the actual deformation lags behind the simple theory predictions. It is maximum at the load, but it decreases rapidly away from the load. Thus, the resulting crack opening is narrow at the main reinforcement and larger towards the neutral axis.

How skin reinforcement affects side face cracking. As the amount of skin reinforcement increases, the crack pattern gradually changes from the tree branch pattern shown in Fig. 4(a) with fewer cracks running deep into the web and multiple branching short cracks to the one shown in Fig. 4(b) where more cracks remain vertical and extend into the web. As discussed by Beeby[4] for a beam without skin reinforcement, the concrete tooth of Fig. 4(a) is loaded like a cantilever, causing the short developing crack to curve towards the nearest long crack. If skin reinforcement is present, tensile stresses created by the anchorage of the skin bar into the concrete tend to extend the crack perpendicular to the skin reinforcement [Fig. 4(b)]. With more "long" cracks, the average width per crack decreases, a desirable result. In addition to increasing the number of long cracks, the skin reinforcement also provides additional restraining forces across the crack that reduces the crack width (Fig. 5).

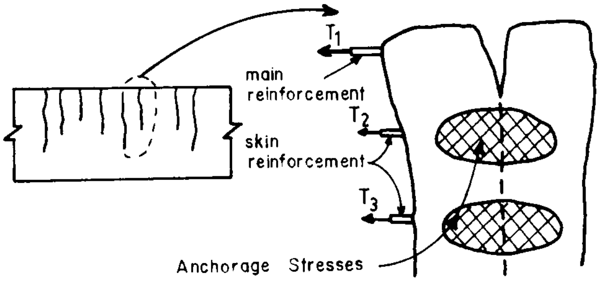
Table 1 — Specimen details

	Skin reinforcement					
Specimen ID/shape* (1)	Area, in.^{2} (2)	Bars (3)	Cover, in. (4)	d_{sk}, in. (5)	100 × ϱ_{sk}, percent (6)	f'_c, psi (7)
Series variable: Verify test method						
RS-1† 1	0.26	6-6 mm at 6 in.	1.125	24.0	0.22	2944
RS-2† 1	0.26	6-6 mm at 6 in.	1.125	24.0	0.22	3183
RS-3† 1	0.26	6-6 mm at 6 in.	1.125	24.0	0.22	4920
RS-4-0 1	0	—	—	—	0	4890
Series variable: Full length beam specimens						
BC-1† 1	0.26	6-6 mm at 6 in.	1.125	24.0	0.22	5739
BC-2† 1	0.88	8-#4 at 3.5 in.	1.125	17.5	0.96	4613
Series variable: Amount and distribution of skin steel						
A-1-0 2	0	—	—	—	0	4913
A-2-0 2	0	—	—	—	0	4975
A-3 2	0.53	12-6 mm at 3.875 in.	1.125	27.1	0.39	5320
A-4 2	0.88	20-6 mm at 2.375 in.	1.125	26.1	0.68	6062
A-5 2	0.88	8-#3 at 5.25 in.	1.125	26.2	0.64	6310
A-6 2	0.88	2-#6 at 13.375 in.	1.125	26.8	0.56	4669
A-7 2	0.35	8-6 mm at 4.125 in.	1.125	20.6	0.34	5521
A-8 2	0.88	8-#3 at 4.125 in.	1.125	20.6	0.81	4580
A-9 2	1.60	8-#4 at 4.125 in.	1.125	20.6	1.41	5231
A-10 2	0.80	4-#4 at 6.75 in.	1.125	20.2	0.72	5438
A-11 2	0.53	12-6 mm at 2.25 in.	1.125	15.8	0.67	5416
A-12 2	1.54	14-#3 at 2.063 in.	1.125	16.5	1.80	5320
A-13 2	0.88	2-#6 at 8.5 in.	1.125	17.0	0.86	4810
A-14 2	0.84	2-#4+4-#3 at 2.875 in.	1.125	11.5	1.37	4810
A-15† 1	0.88	8-#3 at 3.5 in.	1.125	17.5	0.96	4636
Series variable: Skin steel cover						
C-1 2	0.88	8-#3 at 4.125 in.	0.75	20.6	1.14	4878
C-2 2	0.88	8-#3 at 4.125 in.	1.50	20.6	0.63	5290
C-3 2	0.88	8-#3 at 4.125 in.	2.00	20.6	0.49	4783
C-4 2	0.88	8-#3 at 4.125 in.	3.00	20.6	0.38	4768
C-5 2	0.88	8-#3 at 4.125 in.	3.00	20.6	0.38	4386
Series variable: Beam depth						
D-1-0 8	0	—	—	—	—	3876
D-2-0 4	0	—	—	—	—	3979
D-3-0 4	0	—	—	—	—	5330
D-4-0 3	0	—	—	—	—	5000
D-5 3	0.44	10-6 mm at 2.75 in.	0.75	16.5	0.76	3339
D-6 3	0.88	8-#3 at 3.375 in.	0.75	16.9	1.39	4969
D-7 3	1.54	14-#3 at 2.063 in.	0.75	16.5	2.52	3410
Series variable: Welded wire fabric mesh as skin steel‡						
M-1 2	0.17	12.5 gage at 2x4 in.	1.125	26.8	0.15	4780
M-2 2	0.50	5 gage at 4x3 in.	1.125	26.8	0.42	5960
M-3 2	0.70	5 gage at 3x4 in.	1.125	26.8	0.58	6085
M-4 2	1.10	5 gage at 2x1.5 in.	1.125	26.8	0.91	4740
Series variable: Full size beam						
T-1-0 7	0	—	—	—	0	4693
T-2 7	0.35	8-6 mm at 4.125 in.	1.125	20.6	0.34	5009
T-3 7	0.88	8-#3 at 4.125 in.	1.125	20.6	0.81	4269
Series variable: Web width						
W-1-0 5	0	—	—	—	0	4025
W-2 5	0.88	8-#3 at 4.125 in.	1.125	20.6	0.81	3418
W-3-0 6	0	—	—	—	0	4480
W-4 6	0.88	8-#3 at 4.125 in.	1.125	20.6	0.81	3433

*See Fig. 3.
†With double 6 mm stirrups at 3 in.
‡Grid spacing is horizontal bar spacing by vertical bar spacing
Note: 1 in. = 25.4 mm; 1 sq in. = 6.45 cm^2; 1 psi = 6.895 KN/m^2.



(a) Without skin reinforcement



(b) With skin reinforcement

Fig. 4 — Mechanics of side face crack development

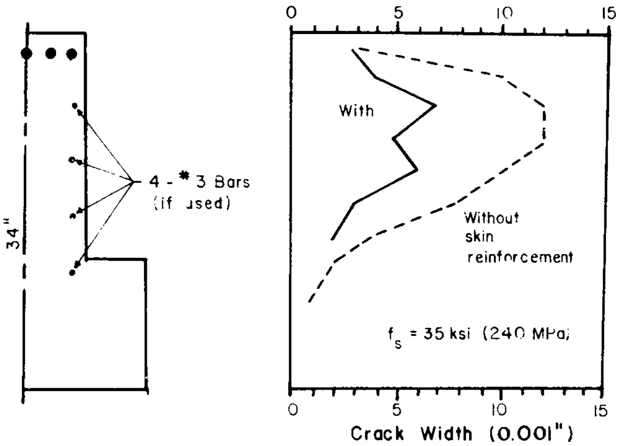


Fig. 5 — Side face crack profile of a single crack (1 in. = 25.4 mm)

Web width

Examining Series W test results of crack patterns, web crack widths and crack magnification ratios showed no significant correlation between the web width and the web crack width, especially in specimens with skin reinforcement (Fig. 6). Skin reinforcement along one side face did not significantly affect the crack widths on the opposite side face. It apparently is effective in a narrow strip of concrete along each side face.

Skin reinforcement cover

Crack patterns for the Series C specimens were all very similar. The cover, at least in the range tested here, did not affect the crack development mechanism shown in Fig. 4(b). However, as the skin reinforcement cover increased, the effectiveness of the

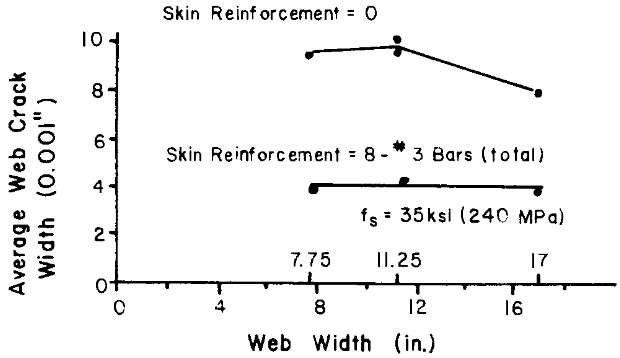


Fig. 6 — Effect of web width on web crack width (1 in. = 25.4 mm)

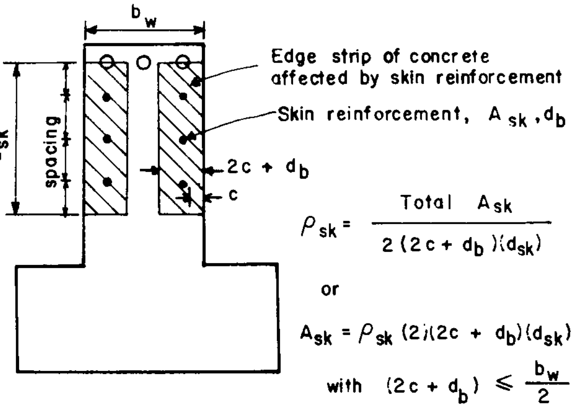


Fig. 7 — Skin reinforcement ratio

skin reinforcement in controlling the side face crack widths decreased. The same effect is seen in cracking at the main reinforcement level.[9] The results of Series W and C indicate that it may be possible to rate the effectiveness of skin reinforcement in controlling side face cracking on the basis of a skin reinforcement ratio ρ_{sk}, the area of skin reinforcement in relation to the area of an edge strip of concrete along each side face that is primarily affected by the reinforcement (Fig. 7). From these tests it appears reasonable to specify this edge strip as twice the distance from the center of the skin reinforcement to the side face but not more than one-half of the web width.

Location and distribution of skin reinforcement

Skin reinforcement variables for Series A were (1) area, (2) number of bars, and (3) depth of the tension zone in which the skin reinforcement is distributed. Since a relatively small number of specimens was tested, it was not possible to get quantitative results concerning the location and distribution (spacing) of skin reinforcement. However, comparison of specimens with the same area of skin reinforcement (Fig. 8), 0.88 sq in. (5.7 cm²), but with 1, 4, or 10 bars per side face indicated that increasing the number of bars increased the percentage of cracks extending into the web and decreased the side face crack width. Four bars were as good as ten bars; one bar per face reduced the crack width in the vicinity of the bar but did not control the crack width in the other regions.

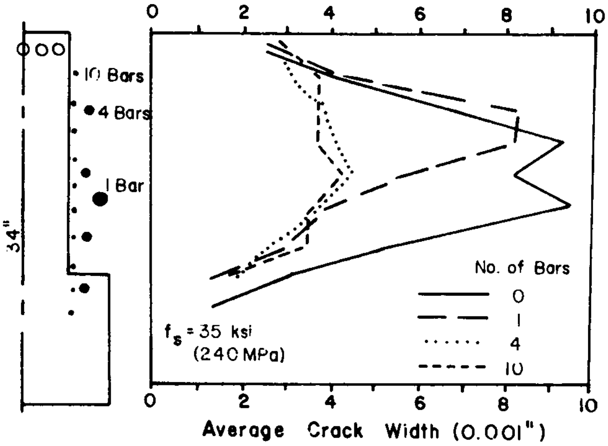


Fig. 8 — Effect of skin reinforcement distribution on crack profiles (1 in. = 25.4 mm)

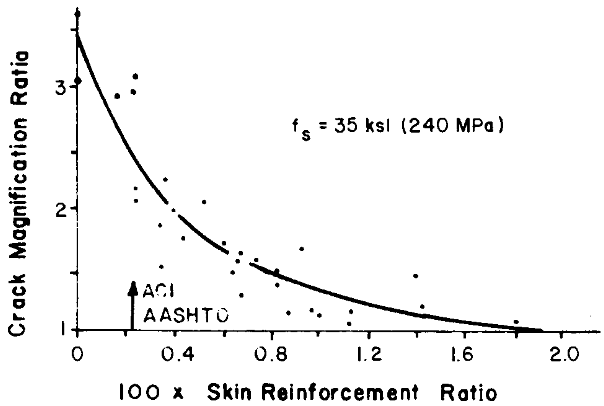


Fig. 9 — Effect of skin reinforcement ratio on crack magnification ratio, Series RS, BC, A, M, C

The reinforcement was most effective if distributed within about ⅝ of the tension zone closest to the main reinforcement. A finite element analysis also indicated similar results.[6,7]

Skin reinforcement ratio

The results from Series RS, BC, A, M, and C, all of which had similar cross sections, were analyzed by grouping the data by average side face crack widths and crack magnification ratios at stress levels of 25, 30, 35, and 40 ksi (170, 210, 240, and 280 MPa) and average crack magnification ratios in the range of 30-40 ksi. The effect of the skin reinforcement ratio described the data trend as well as more complicated variables. Fig. 9 shows that as the amount of skin reinforcement increases, the crack magnification ratio (and also the side face crack width) decreases but at a decreasing rate. To avoid requiring uneconomical amounts of skin reinforcement it is necessary to prescribe realistic values of the permissible crack magnification ratio.[6] For comparison, the ACI and AASHTO required amount of skin reinforcement for these specimens is also shown and results in an unacceptable crack magnification ratio of 2.5. The data was also plotted using the inverse of the skin reinforcement ratio, a more convenient form for the regression analysis (Fig. 10). The analysis described the mesh and cover series data reasonably well. The regression analysis indicated that 68 percent of all measured CMRs would be expected to be within ± 15 percent of the predicted CMRs. If it is desired to limit the average side face crack width in these ⅜ scale model beams to 0.0038 in. (0.097 mm), which is the same as limiting the CMR to 1.4, Fig. 10 predicts a skin reinforcement ratio of 0.0091. Analyses using either the actual side face crack width or the CMR gave comparable results.

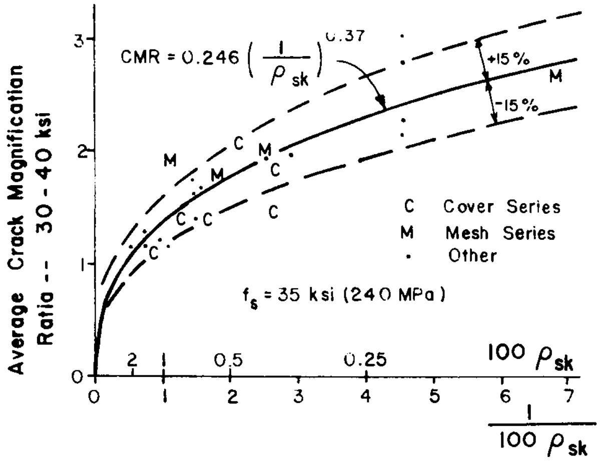


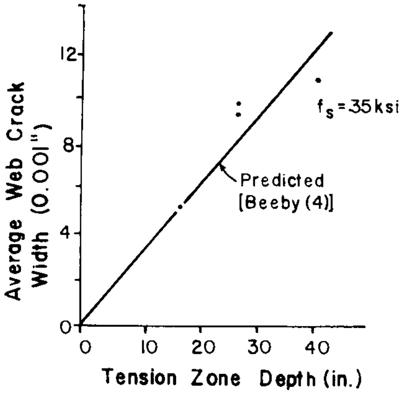
Fig. 10 — Regression analysis of data, Series RS, BC, A, M, C (1 ksi = 6.895 MPa)

Beam depth

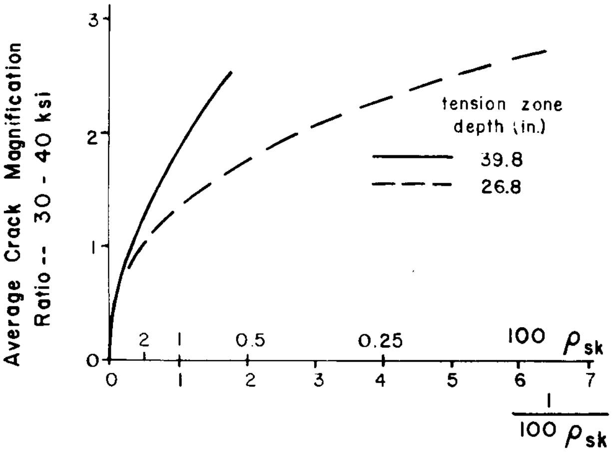
Series D specimens were designed to have the same size crack width at the main reinforcement level, 0.0055 in. (0.14 mm) calculated using the Gergely-Lutz equation.[9] As the depth of the tension zone at service load (d_t) increased in specimens without skin reinforcement, the side face crack width also increased [Fig. 11(a)]. The same trend is obtained from Beeby's cracking equation.[4] The results shown for the specimens with the 39.8 in. (1010 mm) deep tension zones were scaled from the test results of the 2/3 scale models of these specimens.

To limit the crack magnification ratio to 1.4 in model specimens with tension zone depths of 26.8 and 39.8 in. (681 and 1010 mm) required skin reinforcement ratios of 0.0091 and 0.0168, respectively [Fig. 11(b)]. These values of d_t and ϱ_{sk} are plotted in Fig. 12. Using Beeby's equations, it can be shown that a model specimen with no skin reinforcement and with a tension zone depth of about 11 in. (280 mm) would have a CMR of 1.4. This value is also plotted in Fig. 12. A straight line adequately explains the laboratory results.

To extend the range of these model specimens, a finite element model of the side face cracking problem was developed.[6,7] Analytical model specimens with tension zone depths from 26.5 to 79 in. (673 to 2010 mm) were studied. The computer data was analyzed in the same way as the laboratory data, with the results shown in Fig. 12. The finite element results indicate



(a) Without skin reinforcement



(b) With skin reinforcement

Fig. 11 — Effect of depth on side face cracking (1 in. = 25.4 mm, 1 ksi = 6.895 MPa)

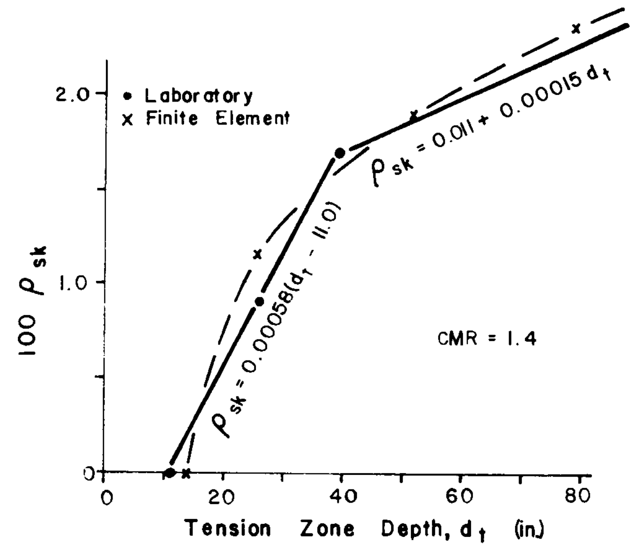


Fig. 12 — Relationship between tension zone depth and skin reinforcement ratio, model specimens (1 in. = 25.4 mm)

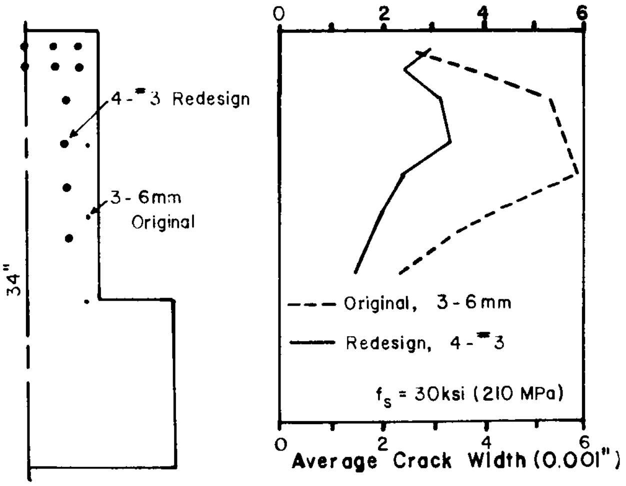


Fig. 13 — Crack profiles, original and redesigned beams (1 in. = 25.4 mm)

that the $d_t - \varrho_{sk}$ relationship should not be assumed as linear over the entire range. Based on the results of the finite element analysis and the generally good agreement with the experimental program in the range where both did apply, a bilinear relationship is proposed for these models: one branch describing the laboratory results and the other branch describing the trend observed in the finite element analysis for larger depths:

for $d_t \leq 40$ in. (1020 mm), $\varrho_{sk} = 0.00058\ (d_t - 11.0)$
for $d_t > 40$ in. (1020 mm), $\varrho_{sk} = 0.011 + 0.00015\ d_t$

with d_t expressed in in. Similar relationships can be derived for other values of CMR. It is emphasized that these relationships are valid for the model specimens which have a predicted Gergely-Lutz type maximum crack width at the main reinforcement level of 0.0055 in. (0.14 mm) and in which the side face crack magnification ratio is limited to 1.4.

To verify these results, a redesigned full-length model of a beam that had been observed to have a serious side face cracking problem was built and tested. Fig. 13 shows the side face crack profiles in each specimen. The redesigned beam had a crack magnification ratio of 1.2 (even better than the desired 1.4), a substantial improvement over the unacceptable crack magnification ratio of 2.5 in the original beam. Even though the skin reinforcement area had to be substantially increased, the total area of reinforcement was the same in each beam. The companion paper presents the design method in greater detail.

CONCLUSIONS

Design recommendations and suggestions for code revisions are made in a parallel paper.[8] This paper summarizes the results of an experimental study which supports the following major conclusions:

1. The existing ACI and AASHTO code requirements for side face crack control reinforcement for large members are not adequate.

2. Skin reinforcement affects only a narrow strip of concrete along each side face of the web.

3. The effectiveness of skin reinforcement in controlling side face crack widths can be related to the skin reinforcement ratio, the area of skin reinforcement in relation to the area of strips of concrete along the side faces affected by the reinforcement.

4. Increasing the tension zone depth also increases the skin reinforcement ratio required to reduce the crack magnification ratio to some specified value.

5. It is most effective to distribute the skin reinforcement as many small bars rather than as a few large bars. Generally, four bars distributed along each side face in about ⅝ of the tension zone closest to the main reinforcement are adequate.

ACKNOWLEDGMENTS

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NOTATION

b_w	= web width
c	= side cover over skin reinforcement
C, T	= compression, tension force applied to ends of segment
CMR	= crack magnification ratio w_w/w_s
d	= distance from extreme compression face to centroid of main tension reinforcement
d_b	= bar diameter
d_{sk}	= depth of beam in which skin reinforcement is distributed
d_t	= distance from neutral axis to centroid of main tension reinforcement at service load
f_c'	= concrete compressive strength
f_s	= main reinforcement stress, based on transformed section calculation
T_1, T_2, T_3	= forces in reinforcement
w_s	= crack width at the main reinforcement level
w_w	= crack width on the side face
ϱ_{sk}	= skin reinforcement ratio