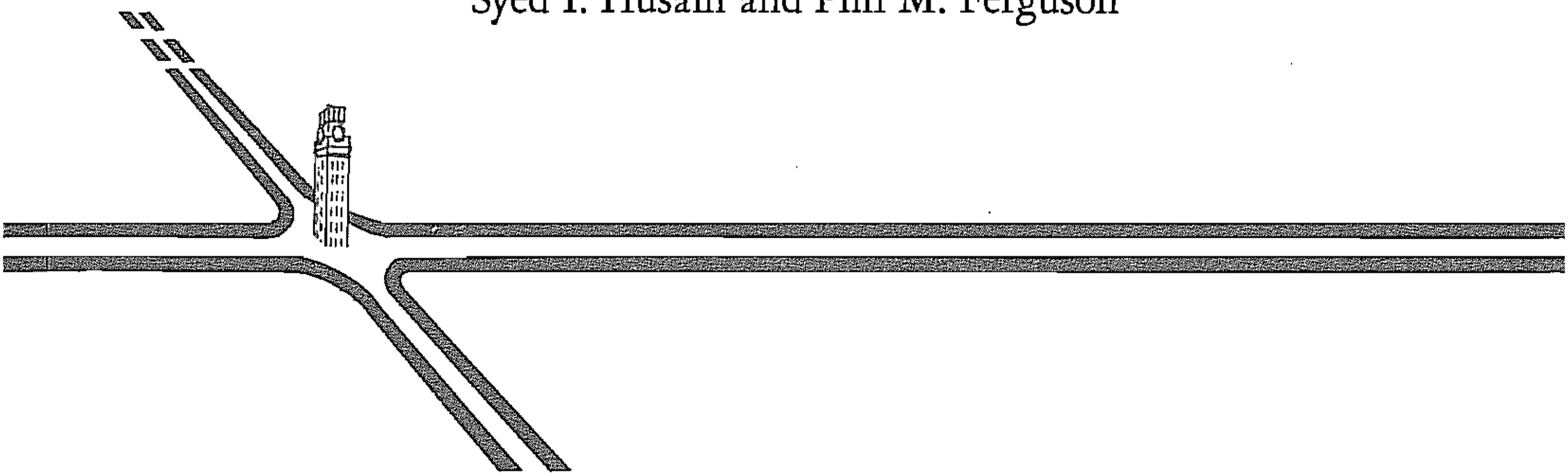
FLEXURAL CRACK WIDTH AT THE BARS IN REINFORCED CONCRETE BEAMS

By

Syed I. Husain and Phil M. Ferguson



RESEARCH REPORT 102–1F PROJECT 3–5–66–102
COOPERATIVE HIGHWAY RESEARCH PROGRAM
WITH TEXAS HIGHWAY DEPARTMENT
AND
U. S. DEPARTMENT OF TRANSPORTATION
BUREAU OF PUBLIC ROADS

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN
JUNE 1968

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FLEXURAL CRACK WIDTH AT THE BARS IN REINFORCED CONCRETE BEAMS

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Research Report Number 102-1F

Research Project Number 3-5-66-102
Crack Width Study

Conducted for

The Texas Highway Department

In Cooperation with the
U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

by

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

June 1968

P R E F A C E

This report introduces a general study of the effect of flexural beam cracking upon corrosion of reinforcement. The objective of this part of the program was to establish the flexural crack width at the bar and the relation of this width to the crack width at the beam surface. A method of filling these cracks with epoxy, sawing the beams to cut through the crack and exposing the epoxy filler for measurement was devised. The measured widths of the cracks at the bar were found to be quite small in comparison with the crack widths at the tension face of the beam.

The next step in the program, already under way, is the exposure of a series of stressed and unstressed beams to regular salt spraying and drying for an extended period until corrosion is general enough to differentiate the satisfactory from the unsatisfactory combinations of bar stress and cover.

Support has been provided by the Texas Highway Department and the Bureau of Public Roads, U. S. Department of Transportation. The encouragement and assistance of their contact representatives are also acknowledged with thanks.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

Syed I. Husain
Phil M. Ferguson

June 7, 1968

A B S T R A C T

As a preliminary to a study of the relation between bar stress, concrete cover, and corrosion, a method of injecting colored epoxy into loaded beams was developed. Later sawing of the beam exposed the filled internal crack for measurements. Crack width at the bar was found to be primarily influenced by bar stress and to average from 0.10 to 0.31 of the surface width. The clear cover over the bars also influenced crack proportions and crack spacing.

FLEXURAL CRACK WIDTH AT THE BARS IN

REINFORCED CONCRETE BEAMS

THE PROBLEM

Relation to corrosion

Deterioration of reinforced concrete is often accompanied by, or caused by, corrosion of the reinforcing steel. Under some conditions corrosion of steel can occur without any cracks in the concrete; that is, lack of concrete density or defective concrete covering can permit salts to penetrate the cover and set up conditions at the steel level favorable to rusting and corrosion, with resulting spalling of the concrete.

Cracks are also suspect, however, as a source of corrosion and spalling. Top concrete on bridge decks can crack due to plastic shrinkage (from a high surface evaporation rate) or from settlement of concrete around the bars. Under these conditions, with spots of high water-cement ratio concrete and low air-content concrete, corrosion can lead to severe deck deterioration. This report is not directed to this type of deterioration.

Flexural cracks have long been under discussion as a possible source of steel corrosion. Many engineers have hesitated to use high strength steel at increased stresses because wider flexural cracks might lead to a greater corrosion hazard. The question has remained more speculative than proven; real factual data on corrosion of this (or any) type are quite deficient.

If flexural crack width is a significant corrosion factor, the width where the concrete contacts the bar must be the most significant width. Broms and Lutz[1,2,3] measured a few internal crack widths, but in general the problem has been avoided because of its difficulty. The problem has remained unsolved except by simulated,[2,4] rather than direct, tests.

Objectives of investigation

The object of this investigation has been to measure actual crack widths at bars, as a first step towards a direct corrosion exposure test. To measure internal crack width it was first necessary to develop a new epoxy injection procedure, related to but not like Broms used,[1] to fix and define the internal crack structure.

Once a suitable technique was developed, the study was extended to studying the effect of bar cover and steel stress level on the width of cracks developing at the bar level. The variation in crack width from the bar outward and the ratio of crack width at bar to that at the surface was also studied. Some attention was given to variations in bar size, percentage of steel, beam depth, and a small number of stress cycles.

Scope of investigation

A total of 32 reinforced concrete beams were tested, although 9 of these were only modestly effective because they were used in developing the basic technique. The 9 preliminary beams were 24 in. deep and 16 of the other 23 were the same depth. In addition 7 members 7 in. deep were tested. Steel stresses ranging from 20 ksi to 40 ksi and covers from 0.75 in. to 3 in. clear were used. Bars were largely #11, but a few specimens with #8 or #6 bars were compared.

The details of these beams are tabulated in Table 1, with the preliminary beams numbered 1P to 9P, inclusive, placed at the end. The conclusions of this report are based chiefly on the other 23 beams, ignoring these preliminary beams where measurements were less satisfactory.

TABLE 1

PROPERTIES OF TEST SPECIMENS

Specimen	Width (in.)	Height (in.)	Depth d (in.)	p (%)	Conc. f'_c (psi)	Split Cyl. f_t (psi)	Clear Cover (in.)	Steel f_s (ksi)
10-24-8 (3-#8)*	12.2	24.30	21.50	0.90	4640	490	2.25	30-20**
11-24-11	12.2	24.20	21.30	1.20	4270	430	2.25	30
12-23.4-11	12.0	23.40	21.20	1.23	5150	560	1.50	20
13-24-11	12.1	24.20	20.50	1.26	5230	510	3.00	20
14-24-11	12.0	24.30	21.30	1.22	4260	450	2.25	20
15-24-11 (3-#11)	12.0	24.30	21.30	1.83	3560	420	2.25	30
16-7.75-6	12.1	7.80	5.90	1.23	3040	360	1.50	20
17-7-6	12.2	7.00	5.85	1.23	3540	360	0.75	30
18-7.75-6	12.1	7.70	5.83	1.25	4440	450	1.50	30
19-7-6	12.2	7.00	5.87	1.23	4460	510	0.75	20
20-24-11	12.1	24.30	21.30	1.20	3900	410	2.25	20
21-24-11	12.2	24.10	21.26	1.20	3670	390	2.25	30
22-24-11	12.2	24.25	21.30	1.20	3840	430	2.25	30-20
23-24-11	12.2	24.23	20.53	1.25	3720	400	3.00	30
24-24-11	18.1	24.30	21.30	0.81	4320	480	2.25	30
25-7.25-6	12.2	7.25	5.88	1.23	3720	430	1.00	30
26-24-11	12.1	24.30	21.35	1.20	4120	460	2.25	37
27-24-8 (4-#8)	12.1	24.30	21.55	1.21	3640	410	2.25	30-20
28-23.4-11	12.4	23.40	21.20	1.19	5160	580	1.50	30
29D-24-11***	12.1	24.20	20.50	1.26	5190	420	3.00	30
30-7.75-6	12.2	7.50	5.60	1.29	3280	370	1.50	33
31-7.25-6	12.0	7.90	6.50	1.13	3280	370	1.00	28
32-24-8 (4-#8)	12.3	24.20	21.40	1.19	4170	420	2.25	30
Preliminary beams generally excluded from report discussion								
1P-24-11	12.0	24.00	21.30	1.22	2990	310	2.00	30
2P-24-11	12.3	24.10	21.40	1.18	3080	350	2.00	30
3P-24-11	12.2	24.10	21.40	1.20	4150	460	2.00	40-30
4P-24-8 (4-#8)	12.3	24.20	21.40	1.19	3820	430	2.25	30-20
5P-24-11 (3-#11)	12.0	24.30	21.60	1.20	4510	440	2.00	30
6P-24-11	18.2	24.20	21.30	0.80	4300	430	2.25	30-20
7P-24-11	12.2	24.20	21.30	1.20	4260	440	2.25	20
8P-24-11	12.1	24.10	21.20	1.22	4790	500	2.25	20
9P-24-11	12.1	24.20	21.20	1.22	5350	490	2.25	20

*The last number always represents the bar size of reinforcing steel (40 ksi deformed bars). The beams were reinforced with two bars unless noted otherwise.

**A double entry indicates an initial stress level dropped to the second value before injection.

***This is a duplicate of beam 23-24-11.

P H Y S I C A L   T E S T S

Manufacture of beams

The bars used were intermediate grade deformed bars, since stresses in excess of 40 ksi were not planned. They were always cast in the bottom of the test member to avoid uncertainties surrounding concrete quality around top bars. High early strength cement was used, with a cement factor less than 5 sacks per cubic yard. In the first few beams, flint in the river gravel aggregate made sawing difficult. Thereafter, crushed limestone coarse aggregate was used with river sand. Concrete was delivered in a mixer truck, placed with a vibrator, and cured for several days under a plastic coating.

When the concrete attained a strength of 3500 psi, the beams were turned over, to place the tension steel on top, and then placed under load to produce cracks at the desired calculated steel stress.

Loading the beams

The test beam was mounted on top of an anchor beam on supports 7 feet apart, which left cantilevers with a 5 foot loading armat each end, as sketched in Fig. 1 and shown in Fig. 2. By means of steel loading yokes and hydraulic jacks, load was placed on each cantilever to develop the desired negative moment in the middle 7-ft. length. Mechanical jacks were then substituted for the hydraulic jacks to hold deformations constant. Crack widths on the surface of the beam were measured and the process of epoxy sealing and injecting completed. After the injected epoxy had cured, the jacks were removed and the beam moved for sawing.

Sealing and injecting epoxy

Injections of epoxy involved two separate steps, sealing and injecting.

The first step was to attach Alemite grease fittings over the cracks and to seal the cracks on the surface. For this purpose, the fittings were

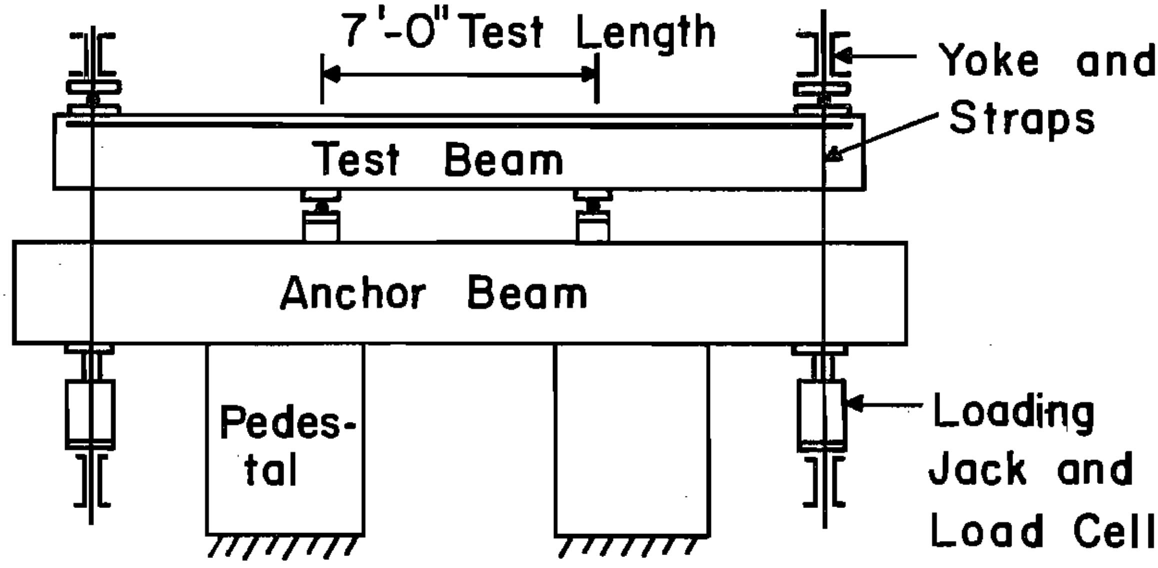

Fig. 1. Arrangement of loading rig.

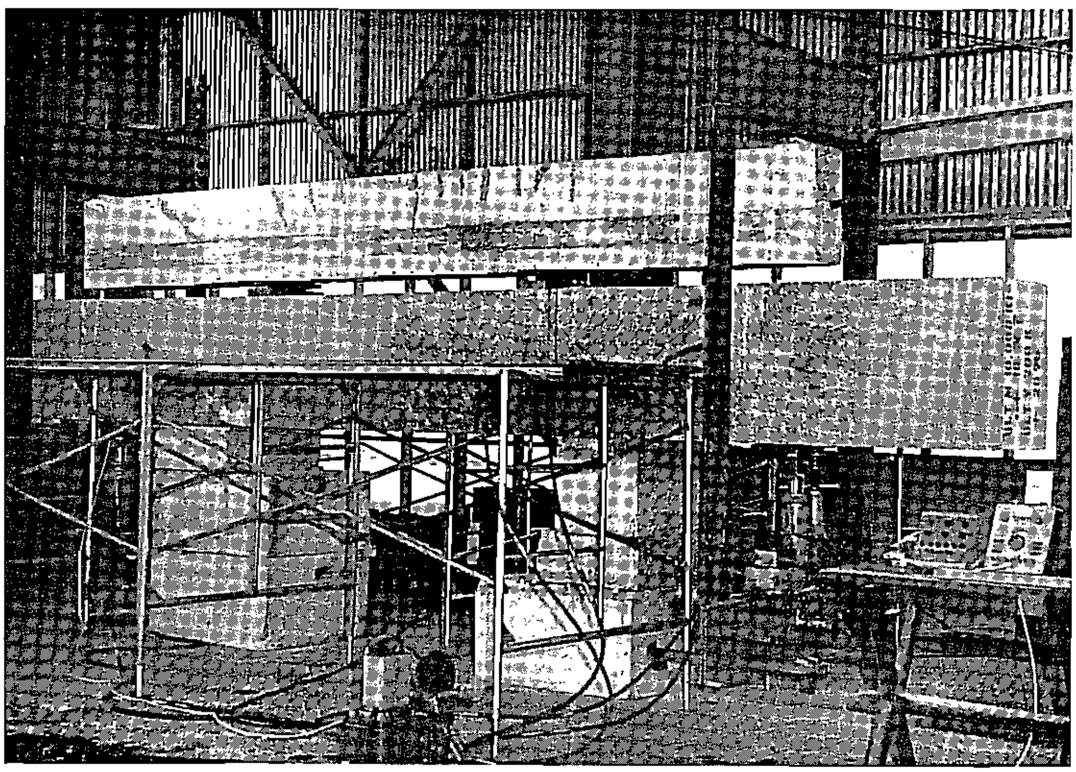

Fig. 2. Test setup with specimen on top.

each threaded into a hole in a small steel plate (1.5" x 1.5" x 1/8"). Then two of these plates were lightly attached to the concrete directly over the crack at the points where it crossed over the bars. The sealant (Epibond 150 with Hardener 947*) was mixed in the ratio 100:40 by weight and applied around the fitting plates and over the crack, sealing all across the tension face of the beam and down the sides beyond the level of the bars. To permit the escape of air, as the crack was later filled, a small (3/16") gap was left opposite the bar at each side of the beam. This epoxy seal cured fully in 4 to 5 hours, if the air was in the high eighties. In cool weather an electric blanket was used to hold a better curing temperature. The injections were started after 24 hours in warm weather and after 2 days in cool weather.

The injection itself was made with Epocast 530 and Hardener 9816, colored with carbon black dye and mixed in proportions which were varied with the temperature, from 100:40 by weight during summer to 100:15 in temperatures below 70°F. An electric blanket helped hold the specimen to near this temperature even when the air temperature was lower.

The Epocast was injected by pouring the mix into a hand-operated grease gun which could be attached to the Alemite fitting. A 10 or 15 minute interval was available to inject the mix before it became hot and too stiff. The injection was made through each of the two fittings, slowly in order not to build up high pressure which might break the seal or push off the fitting. Not all cracks were injected. Injection was stopped when a sufficient number of samples seemed to have been successful. No injection was attempted in cracks having a surface width of less than 0.002 in. Not all injections were successful; some broke the seal before injection was complete. Some were found incomplete when sawed; but usually when epoxy overflowed through the vent holes (Fig. 3) it had also penetrated around the bars. The successful injections represented from 35 to 100 percent of the total cracks, with half of the specimens in the 50 to 70 percent range.

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*Manufactured by Furane Plastics, Inc., Los Angeles, California

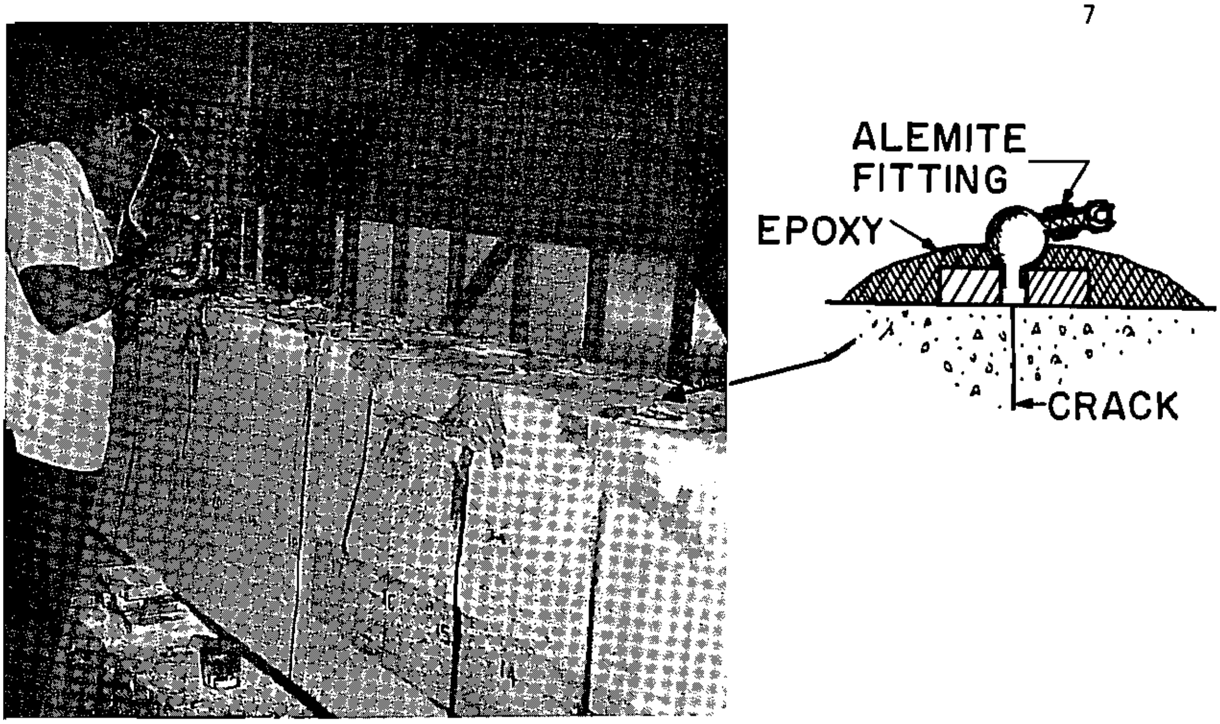


Fig. 3. Injection of colored epoxy. Note epoxy seal over upper part of crack and Alemite fittings for injection. The black streaks are overflow from vent holes.

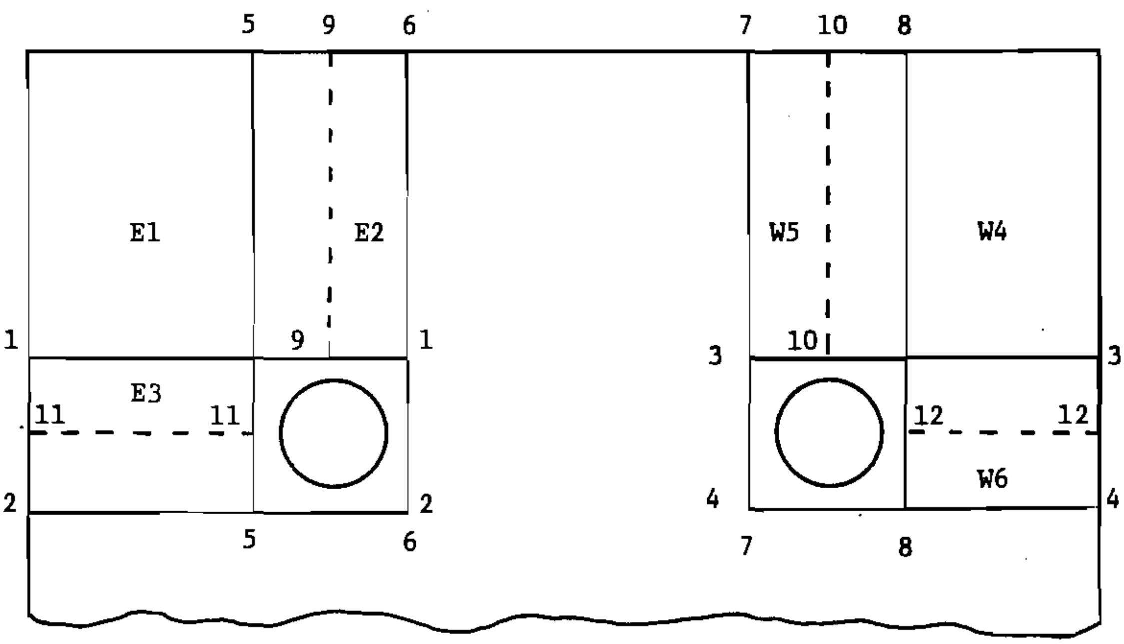


Fig. 4. Primary pattern of saw cuts. The cuts along the dotted lines were made later.

The Alemite fittings could be used only once and the grease gun only a few times.

The beam was left under load for at least a day after injection to cure the epoxy. Then it was unloaded and moved into position for sawing.

Sawing the beam

The objective of the test was to measure internal crack widths. To get inside the beam, diamond point saw cuts were made to form the channels indicated by the solid lines in Fig. 4. It proved too destructive of the saws to cut the bar itself, but the cuts were made as close beside the bar as possible.

A heavy saw was used initially (Fig. 5), but a lighter saw with a 1/4-in. thick blade proved satisfactory. The appearance of a beam after the vertical cuts had been made is indicated in Fig. 6 (which shows one more than the typical number of cuts on each side). The beam was turned on its side for the horizontal cuts. Further cuts of the concrete strips cut out were made with a bench type of diamond point saw, as shown by the dotted lines in Fig. 4, to give an exposed surface directly above the bars and directly opposite the bars.

After removal of the loose slices of concrete, the exposed bars were cut off (Fig. 7). The remaining thin cover on these bars could be pried loose to expose the epoxy in the crack at the bar surface.

Measuring crack width

A typical exposed crack filled with the dark epoxy is shown in Fig. 8a, with the measured crack widths noted alongside at various depths. The notation 1.00"-120 means at 1 in. below the surface the crack measured 0.0120 in. The crack is neither perpendicular to the beam surface nor a smooth separation like a cut. It bends and twists and gradually gets narrower with depth. Under a microscope the faces are irregular and almost jagged. Exact crack width thus becomes a matter of definition or judgment in reading. At a magnification factor of six (with a pocket comparator)

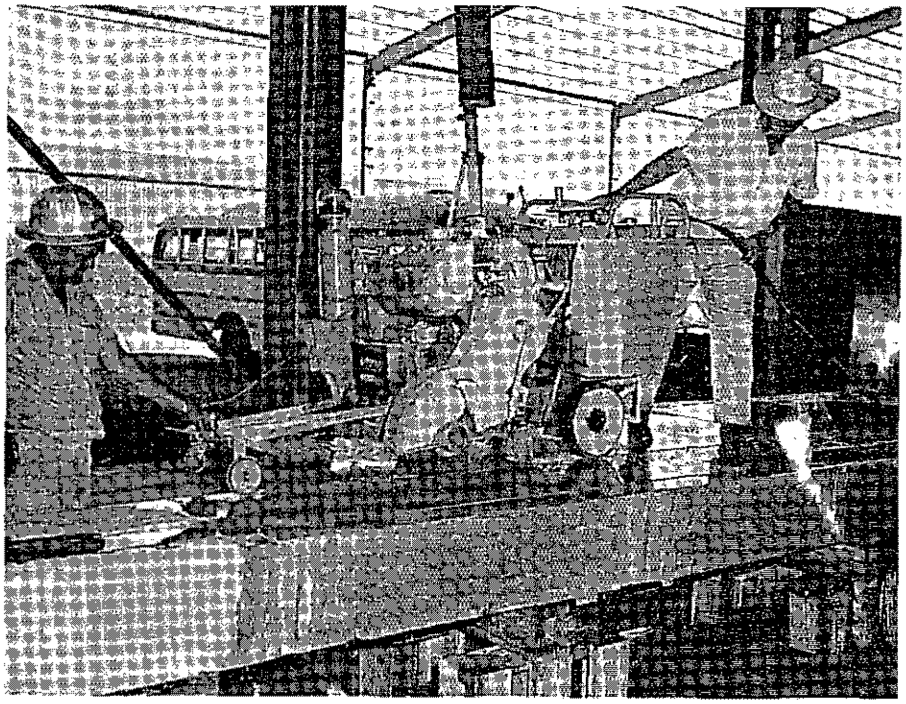


Fig. 5. Sawing out strips cutting across cracks.

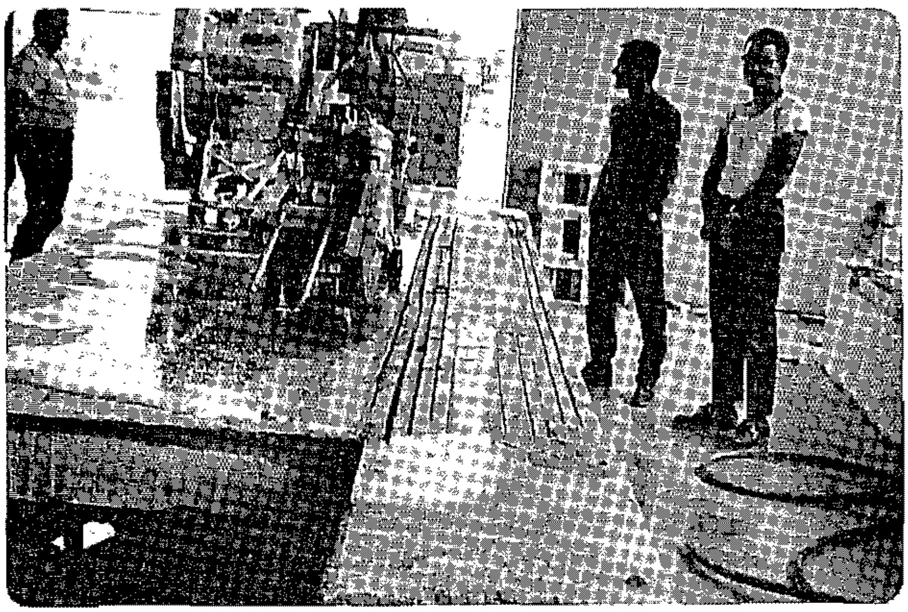


Fig. 6. Beam after sawing vertical cuts. More cuts were made here because this was a wide beam.

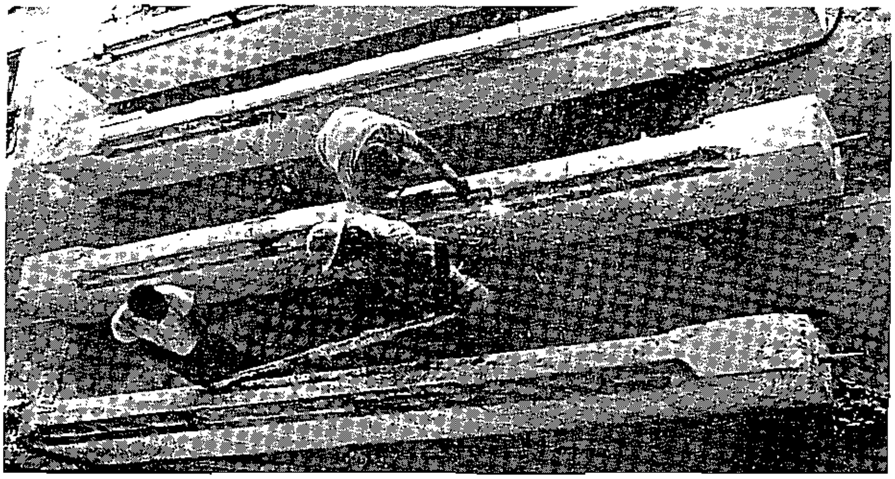


Fig. 7 Cutting out bar to permit examination of crack close to bar.

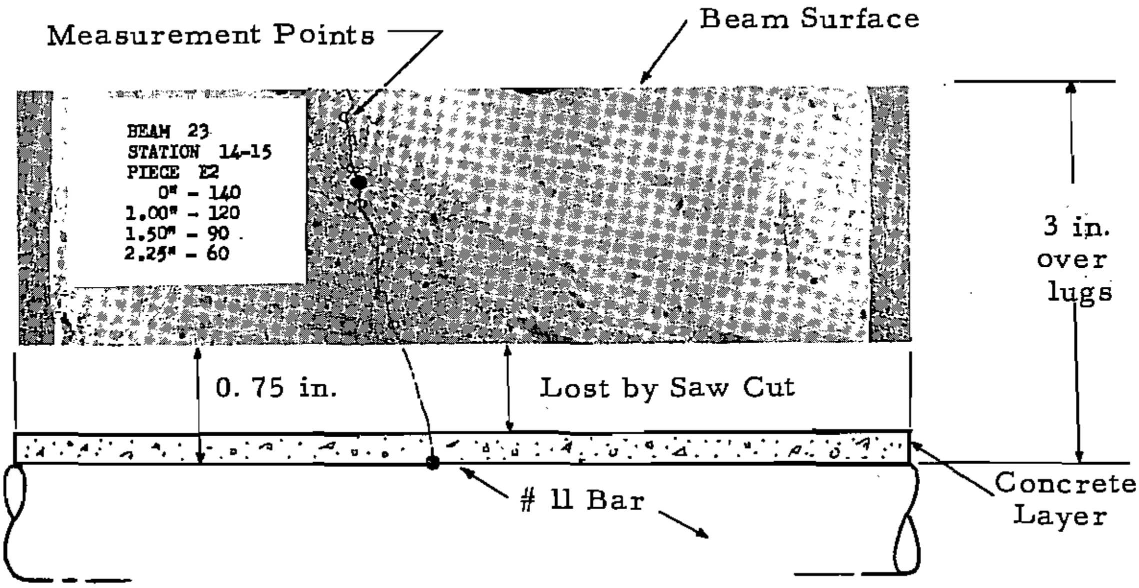


Fig. 8a. Typical variation in crack width.

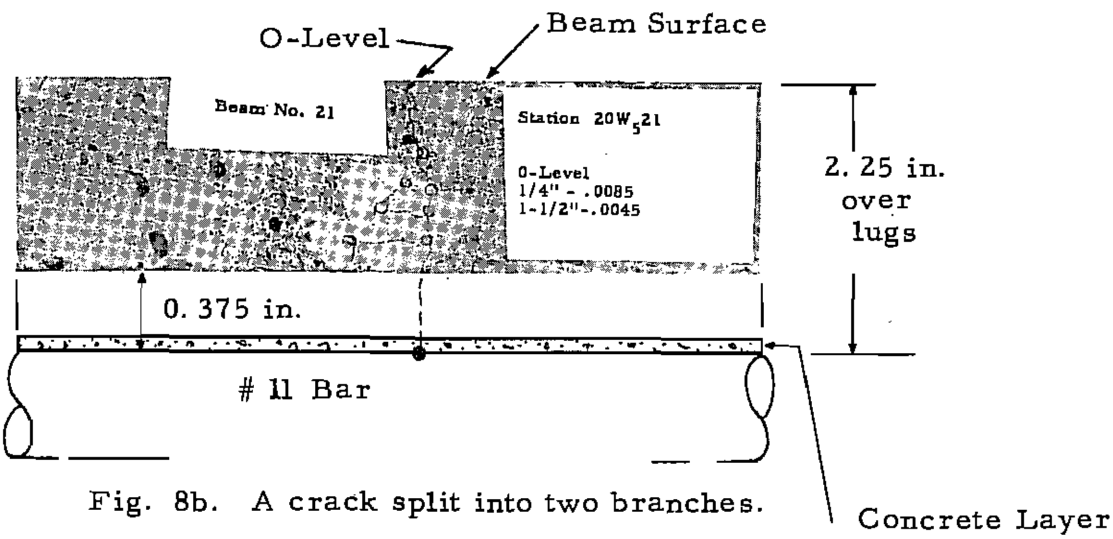


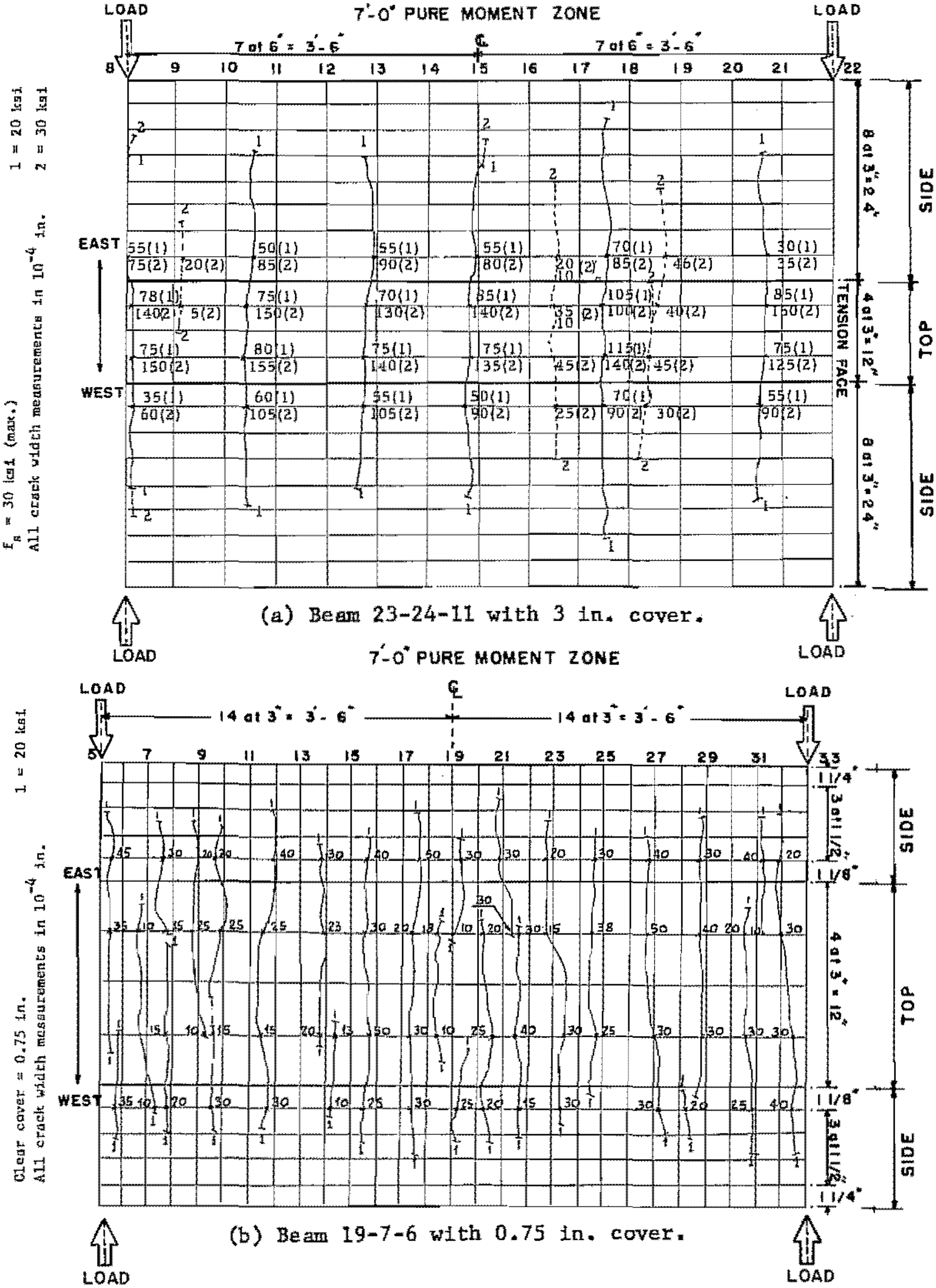
Fig. 8b. A crack split into two branches.

there was less problem in defining the crack, but it was difficult to read closer than 0.0005 in. and readings by two observers at nominally the same point could differ by 0.0010 in. A microscope with a 60-power magnification was more successfully used on the last 23 beams. This could be read more closely, but it made the crack face appear much more irregular. Differences as great as 0.0007 in. were still occasionally observed in checking readings. As a result, although crack widths have been recorded in units of 0.0001 in., no record is fully significant in the last place and, except in the smaller widths, readings were usually recorded only to the nearest 0.0005 in.

Sometimes cracks subdivide either near the bar or the surface, as in Fig. 8b. In such cases the recorded width has been taken as the sum of the two (occasionally more) cracks, which may or may not be significant with regard to corrosion.

Flexural cracks are not uniformly spaced, nor of uniform width at the surface, even along a constant moment length of a given beam, as can be seen in the developed crack sketches of Fig. 9, drawn to the same longitudinal scale (but different width scales). Broms[2,3] has suggested that crack spacing at stresses above 20,000 to 30,000 psi is given by twice the concrete cover to center of bar, which would give 7.4 in. and 2.9 in. for these two beams, which do not quite meet this stress limitation. The average spacings in Fig. 9 are about 9.4 in. and 4.6 in., with some questions about how to count partial cracks.

Broms[2,3] also suggested that average crack width is given by the product of the crack spacing and the average steel strain, which is roughly true. In Fig. 9 the numbers alongside a crack are widths in units of 10^{-4} in., those with the parenthesis alongside meaning 20 ksi steel stress when marked 1 and 30 ksi when marked 2. The dotted crack lines represent cracks observed at 30 ksi, but not present (or observed) at 20 ksi. The crack widths recorded were taken directly over the bars. Wider portions would exist between bars and at the corner edges, because the bar is a restraint on crack width. Even under a given set of conditions, crack width typically ranges at least 50 percent each way from the average.



(a) Beam 23-24-11 with 3 in. cover.

(b) Beam 19-7-6 with 0.75 in. cover.

Fig. 9. Unfolded view of beam crack patterns on surface, with crack widths noted in 0.0001 in. units.

A surface crack could be defined in many ways, average crack width or maximum crack width for a single crack, or for a group of cracks. Unless there were some systematic approach, each investigator might get a different value when observing even one of the above limitations, because cracks vary so much from point to point and crack to crack. In this report several values are used in the discussion. Average crack width in this report relates to measurements made only at points directly over the bars, but may be at beam surface, at bar, or intermediate level, as stated. Surface crack averages include only cracks successfully injected, unless specifically noted otherwise. The maximum crack width is the maximum reading observed over the bars. At times the "probable maximum" at two standard deviations from the mean value seems meaningful. It should be noted that with very small cracks not injected, some cracks omitted, and some injections not successful, the averages are probably all on the high side.

Cracks were measured at each quarter-inch of depth below the surface, but a "good" reading place close by was used in preference to this exact depth, as shown by the circles around reading points in Fig. 8. Since a typical beam involved between 70 and 200 crack width readings, the project involved a great amount of detail.

Data

Aside from concrete properties (Table 1), the chief data taken included maps of cracking in the constant moment length and many crack width readings, both on the beam surface and on the faces exposed by the sawing.* The data are summarized in Table 2, with the average surface crack recorded first for all cracks and then the larger value for cracks which were successfully injected.

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*The 32 pages of crack sketches (similar to Fig. 9) and the like number of tables of crack widths can be reproduced for anyone interested in that detail.

TABLE 2

SUMMARY OF TEST RESULTS

Specimen	Steel Stress f_s (ksi)	f'_c (psi)	Clear Cover (in.)	Aver. Crack Spcg. (in.)	Average Crack Width, Beam Surface, All Cracks (in.)	Average Crack Width, Beam Surface, Successful (10^{-4}in.)	Average Crack Width, At Bar (10^{-4}in.)	Crack Ratio	Maximum Crack Width, Surface (10^{-4}in.)	Maximum Crack Width, Bar (10^{-4}in.)	Remarks
10-24-8 (3-#8)	30-20	4640	2.25	8.0	33	37	7	0.19	55	10	
11-24-11	30	4270	2.25	7.6	67	66	10	0.15	100	15	20 cycles
12-23.4-11	20	5150	1.50	7.0	31	40	10	0.25	50	17	
13-24-11	20	5230	3.00	12.0	63	63	7	0.11	120	10	
14-24-11	20	4260	2.25	11.2	58	57	6	0.10	76	10	20 cycles
15-24-11(3-#11)	30	3560	2.25	8.4	71	77	10	0.13	130	18	
16-7.75-6	20	3040	1.50	6.0	44	43	8	0.19	80	12	shallow
17-7-6	30	3540	0.75	4.4	33	43	12	0.28	57*	25	shallow
18-7.75-6	30	4440	1.50	6.0	60	69	11	0.16	120	25	shallow
19-7-6	20	4460	0.75	4.9	25	32	10	0.31	50	21*	shallow
20-24-11	20	3900	2.25	10.5	43	51	7	0.14	75	10	
21-24-11	30	3670	2.25	9.3	68	81	13	0.16	105	27	
22-24-11	30-20	3840	2.25	12.0	61	62	12	0.19	95	20	
23-24-11	30	3720	3.00	11.2	113	146	36	0.24	150	45*	
24-24-11	30	4320	2.25	9.4	61	72	16	0.22	95	30	
25-7.25-6	30	3720	1.00	6.0	53	67	15	0.22	100	20	shallow
26-24-11	37	4120	2.25	9.3	99	108	22	0.20	130	37**	
27-24-8(4-#8)	30-20	3640	2.25	7.0	44	48	10	0.21	78	25*	
28-23.4-11	30	5160	1.50	7.0	52	58	16	0.28	75	29*	
29D-24-11	30	5190	3.00	9.9	99	125	22	0.18	170	33*	
30-7.75-6	33	3280	1.50	5.6	73	76	21	0.28	120	40	shallow
31-7.25-6	28	3280	1.00	5.6	50	53	16	0.30	75	25	shallow
32-24-8(4-#8)	30	4170	2.25	6.5	60	65	15	0.23	100	25*	
				Preliminary beams generally excluded from report discussion							
1P-24-11	30	2990	2.00	9.3	-	75	25	0.33	100	30	
2P-24-11	30	3080	2.00	7.6	40	48	20	0.42	60	30	
3P-24-11	40-30	4150	2.00	8.4	73	82	26	0.32	100	30	
4P-24-8(4-#8)	30-20	3820	2.25	6.5	46	44	22	0.48	80	30	
5P-24-11(3-#11)	30	4510	2.00	8.0	58	58	23	0.40	80	30	
6P-24-11	30-20	4300	2.25	9.9	42	44	27	0.61	60	30	
7P-24-11	20	4260	2.25	14.0	42	47	18	0.44	50	30	
8P-24-11	20	4790	2.25	10.5	40	39	14	0.36	60	20	3 cycle
9P-24-11	20	5350	2.25	8.4	29	39	12	0.31	45	20	20 cycle

*Sum of two cracks forming close together.

**Sum of three cracks forming close together.

In comparisons of data the numbering code used for the specimens will be helpful. The first number is a serial number (P added for preliminary specimens), the second is the nominal overall height of the member, and the last the bar size used. All beams contained two bars, unless noted differently.

The bar chart of Fig. 10 provides a more convenient display of crack width for the 23 beams which were made after the techniques were better developed. The surface crack widths are the average of the cracks successfully injected. (It will be noted that the average of all surface cracks, Fig. 12, will be lower, notably so for the 30 ksi beams with 3 in. clear cover.) It should also be noted (from Table 2) that several of the maximum cracks recorded for 30 ksi steel stress represented 2 or even 3 closely spaced cracks which were totaled.

General results

The major results are indicated in Figs. 11 and 12, which show the average and maximum crack widths, respectively. Such data are discussed in more detail in the following sections, but some general comparisons may be made here.

In these figures the curve of crack widths at the tension face of the beam is marked "surface" and that at the near surface of the bar is marked "at bar." There is a major difference between these two sets of values and some increases (smaller differences) with increasing cover. A few cracks measured at other stresses have been plotted as having some interest. For comparison, the Portland Cement Association equation (marked PCA) for average surface crack width at the level of the bar is plotted in Fig. 11. This equation is

$$w_{t\ avg} = 77(A)^{\frac{1}{4}} f_s \times 10^{-9} \text{ in.}$$

where A = average effective concrete area around a reinforcing bar in in.^{2}

f_s = steel stress calculated by elastic cracked section theory, ksi

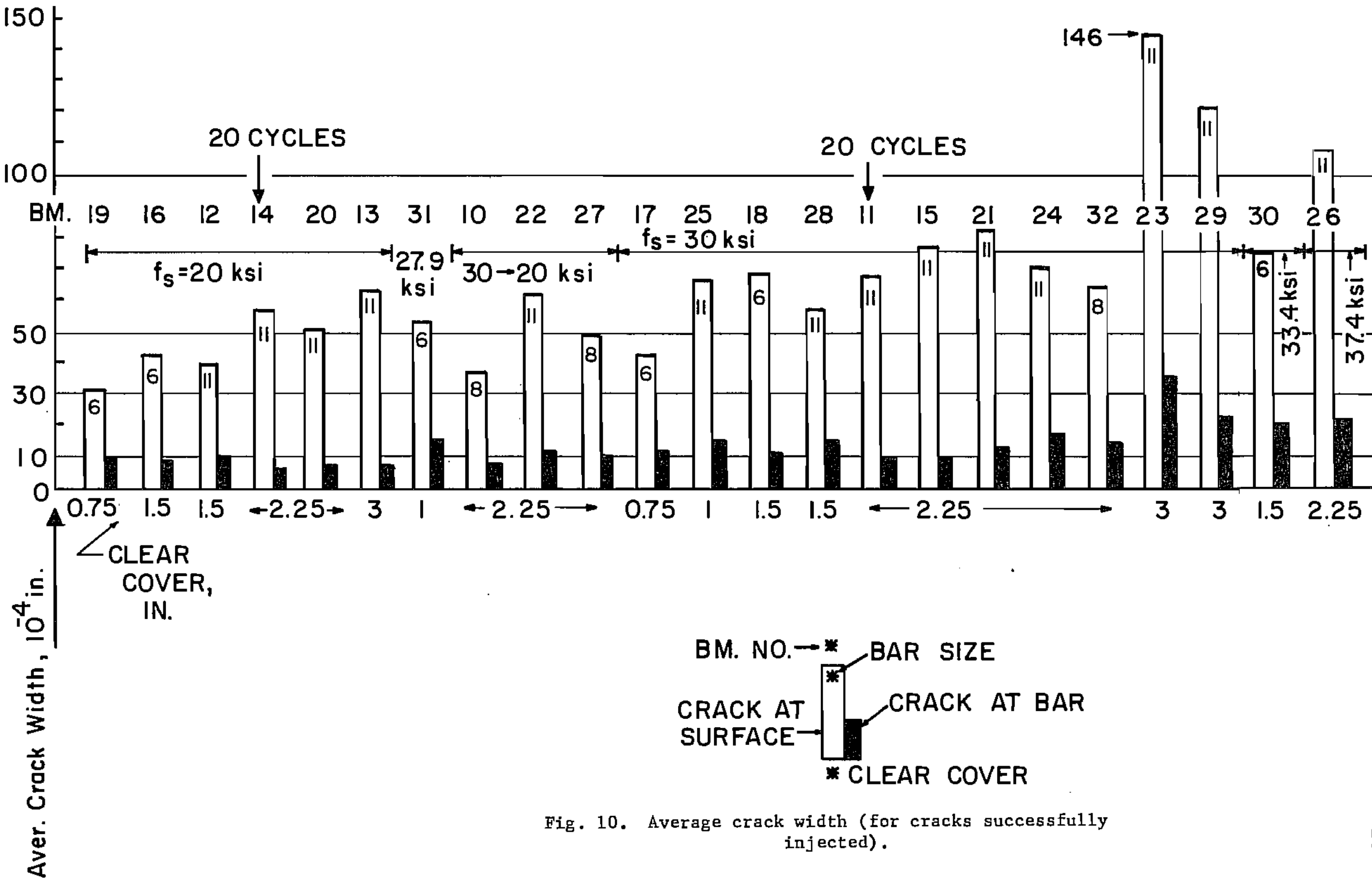
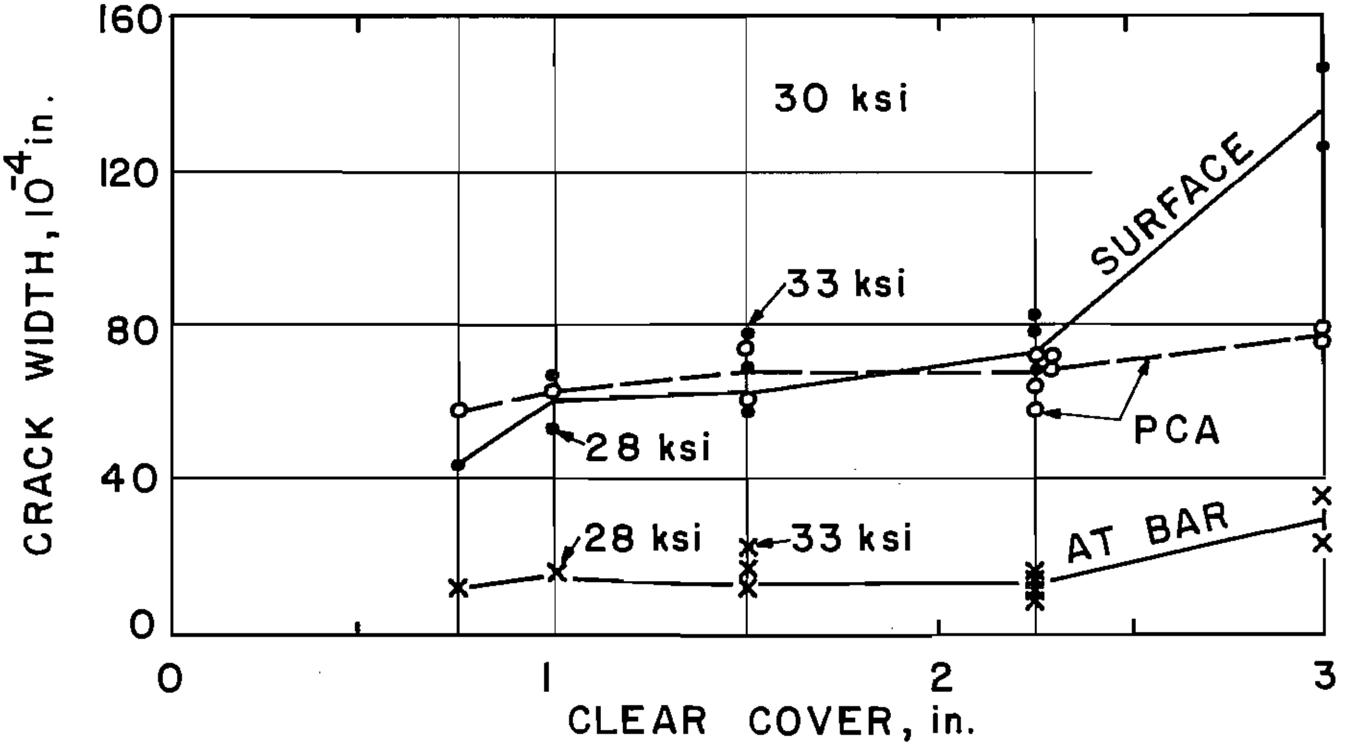


Fig. 10. Average crack width (for cracks successfully injected).



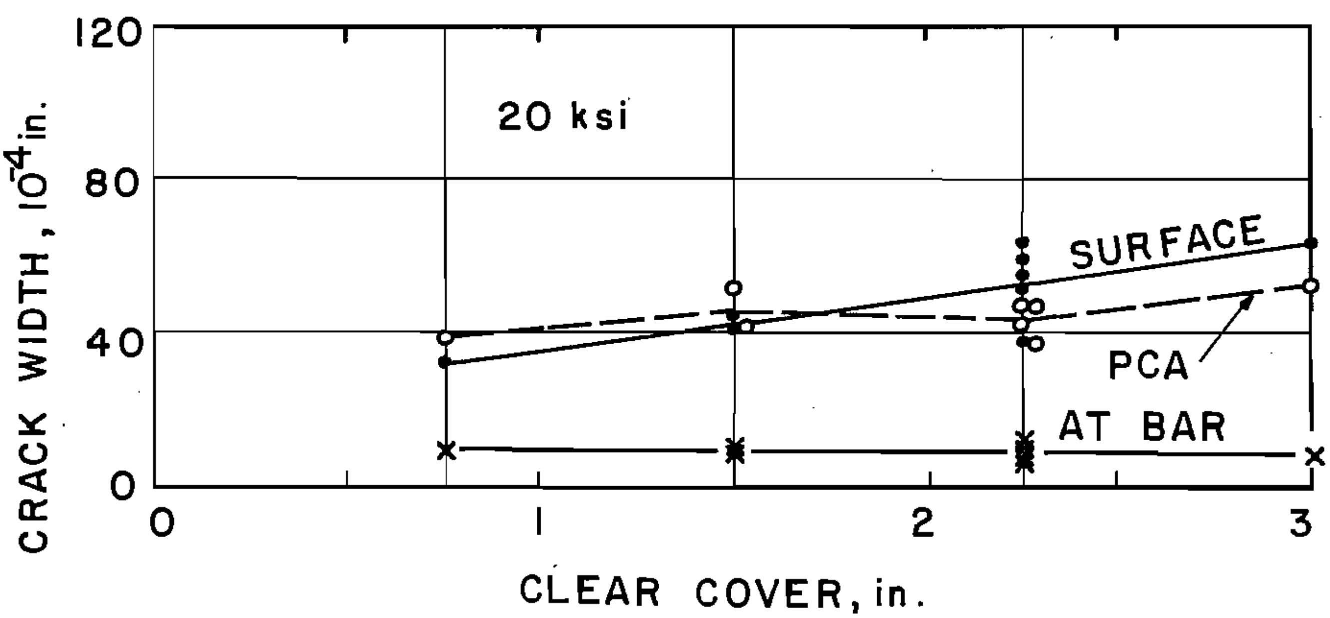


Fig. 11. Average crack widths at 30 ksi and 20 ksi steel stress.

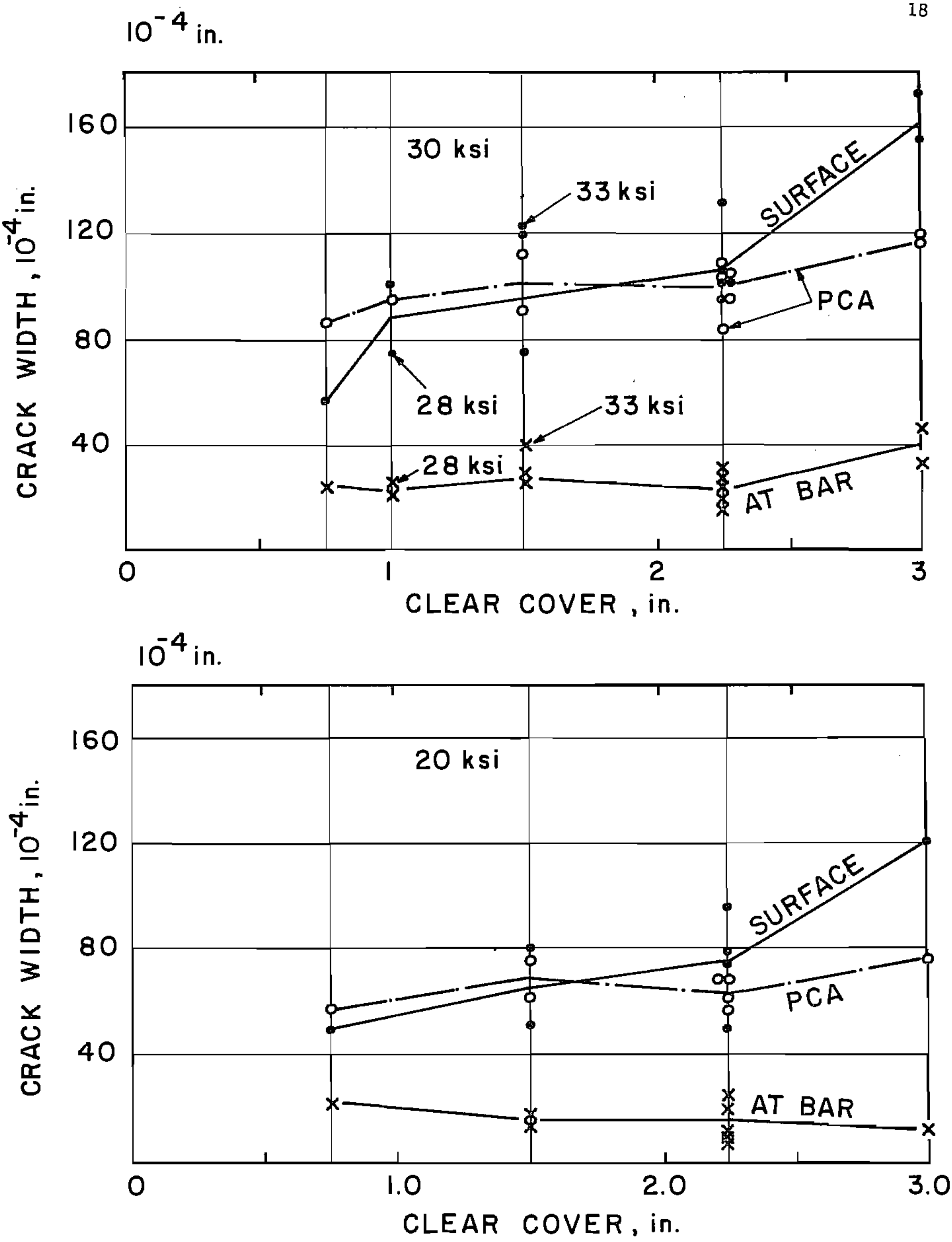


Fig. 12. Maximum crack widths at 30 ksi and 20 ksi steel stress, unless noted.

The agreement generally is satisfactory.

The maximum crack widths have been similarly plotted in Fig. 12 and compared with the PCA equation for maximum crack width at the level of the bar in a constant moment region:

$$w_{t\ max} = 115(A)^{\frac{1}{4}} f_s \times 10^{-9} \text{ in.}$$

where the symbols are the same as above. The PCA equation is the one suggested in the BPR criteria.[8] Again, the difference between the surface crack and the crack at the bar is quite striking.

E V A L U A T I O N   O F   D A T A

Width of cracks at bar surface

Since crack widths scatter considerably, the crack width at the bar will be discussed in terms of average values for specific covers and nominal steel stresses, and to a minor degree bar sizes. The average width at the bar at a 20 ksi stress shows in Fig. 13 to be 0.0010 in. or less, with a slight tendency to decrease with larger cover.* In general, bar size seems to be of small consequence in that the smaller cover represents slabs (d = 6.25 in.) with #6 bars, while the 3 in. cover represents beams (d = 20.3 in.) with #11 bars, and #8 bars were used in some specimens. It is rationalized that the thicker cover held the bars tighter at this

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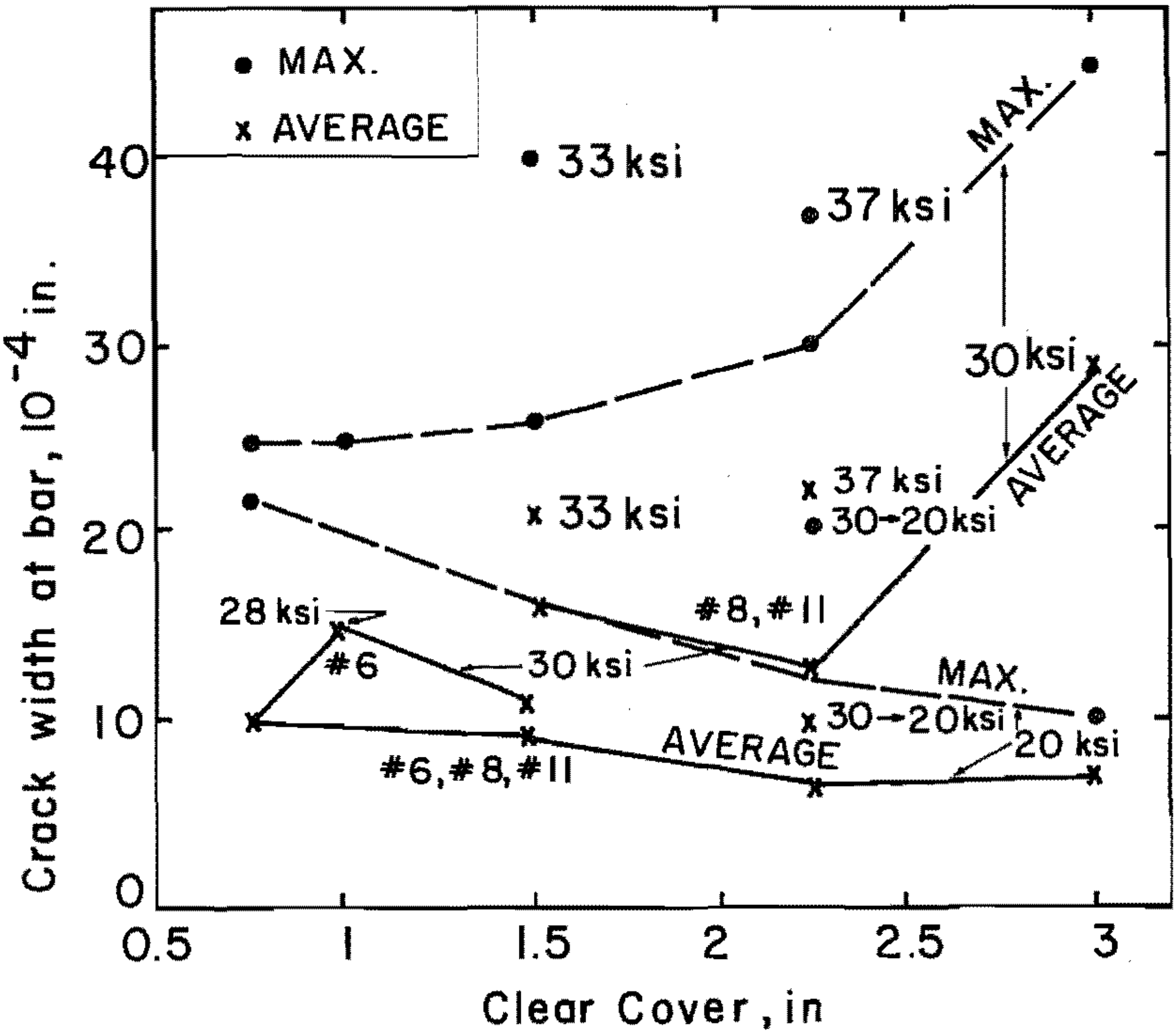
*Since the smallest cracks were not injected, this value overstates the true average of all cracks.



No. of readings					
20 ksi	14	--	27	23	9
27.9	--	25	--	--	--
30	18	--	44	58	18
30-20	--	--	--	22	--
33.4	--	--	18	--	--
37.4	--	--	--	9	--

Fig. 13. Crack width at bar surface for cracks successfully injected.

stage, because the maximum cracks observed also decreased from (a slightly questionable double crack) 0.0022 in. at 0.75 in. cover to 0.0010 in. at 3 in. cover.

At 30 ksi there is more scatter in the results with the average crack width ranging between 0.0010 in. and 0.0015 in. for a 2.25 in. cover or less. There is some indication at 1.5 in. cover that #6 bars gave smaller cracks than #11, but maximum crack width differed little between the two. At 30 ksi and above, the average crack width at the bar increases rapidly to 0.0029 in. at 3 in. cover. Possibly significant is the fact that both values represented the sum of two cracks close together, as in Fig. 8b. Other individual beams at 34 ksi and 37 ksi show a similar increasing trend at less cover. Maximum individual crack width also shows this increase with cover thickness.

The points marked 30-20 ksi represent beams first loaded to 30 ksi and then reduced to 20 ksi before epoxy was injected. They fall intermediate between the initial 20 ksi and 30 ksi curves. It is logical that the crack width at the bar decreases less than the load upon release. Crack width is a function of slip of the bar and friction reduces the reversibility of this action.

Attention is called to the listing below Fig. 13 of the number of individual cracks which were measured, grouped for the several points in this figure. Each beam was represented by from 7 to 25 readings on successfully filled cracks. The wide range in number of readings results in part from the large range in clear cover. A thick cover gives a few wide cracks, especially at 30 ksi steel stress, while a thin cover gives many narrow cracks, even at 20 ksi, as shown in Fig. 9.

It will be noted later that the crack width at the extreme surface of the beam varies almost linearly with the cover and slightly more than linearly with the bar stress. Relatively, the average crack width at the bar is less a variable, except with the 3 in. cover or with stresses over 30 ksi.

Widths of cracks at exterior beam face

Cracks at the surface, that is, at the tension face of the beam, vary considerably in spacing and greatly in width. The width discussed here and plotted in Fig. 14 is the average width of all cracks observed directly over the bars for each particular beam. This is a smaller width than the average surface crack plotted in Fig. 10 and used for Fig. 15, which is the one read before injection* on only those cracks which were successfully injected. Later, in plotting the variation of crack width with depth (Figs. 16-20, incl.), measurements after injection have been used.

Figure 14 indicates that crack width increases almost linearly with concrete cover but f_s is nearly as important. Crack widths are roughly proportional to steel stress, except that the combination of 30 ksi and a cover of 3 in. gave a crack width much worse (based on two beam tests). For comparison, the Broms and Lutz[3] value of $2 \epsilon_s t$ **has been plotted; it falls considerably lower. The comparison is not quite fair to Broms and Lutz, who derived this relation for higher stresses and limited it to "stresses exceeding 20,000 to 30,000 psi;"

The maximum cracks tabulated in Table 2 are typically 50 percent larger, or more, than the average.

---

*Slight differences did exist between initial crack width before injection and the corresponding measured epoxy thickness at supposedly the same points. These were in part errors in readings (larger widths after injection). The average was 3.8×10^{-4} in. smaller after injection, which may be a good measure of the inaccuracies inherent in this process. Half of this total resulted from three specimens, which are difficult to explain:

21-24-11	Epoxy measured	14×10^{-4} in. less
29-24-11	Epoxy measured	19×10^{-4} in. less
32-24-8	Epoxy measured	11×10^{-4} in. less

**Where ϵ_s is the average steel deformation (taken here simply as f_s/E_s as though the concrete did not lower ϵ_s) and t is the cover, from the center of bar, to the point where the crack is measured.

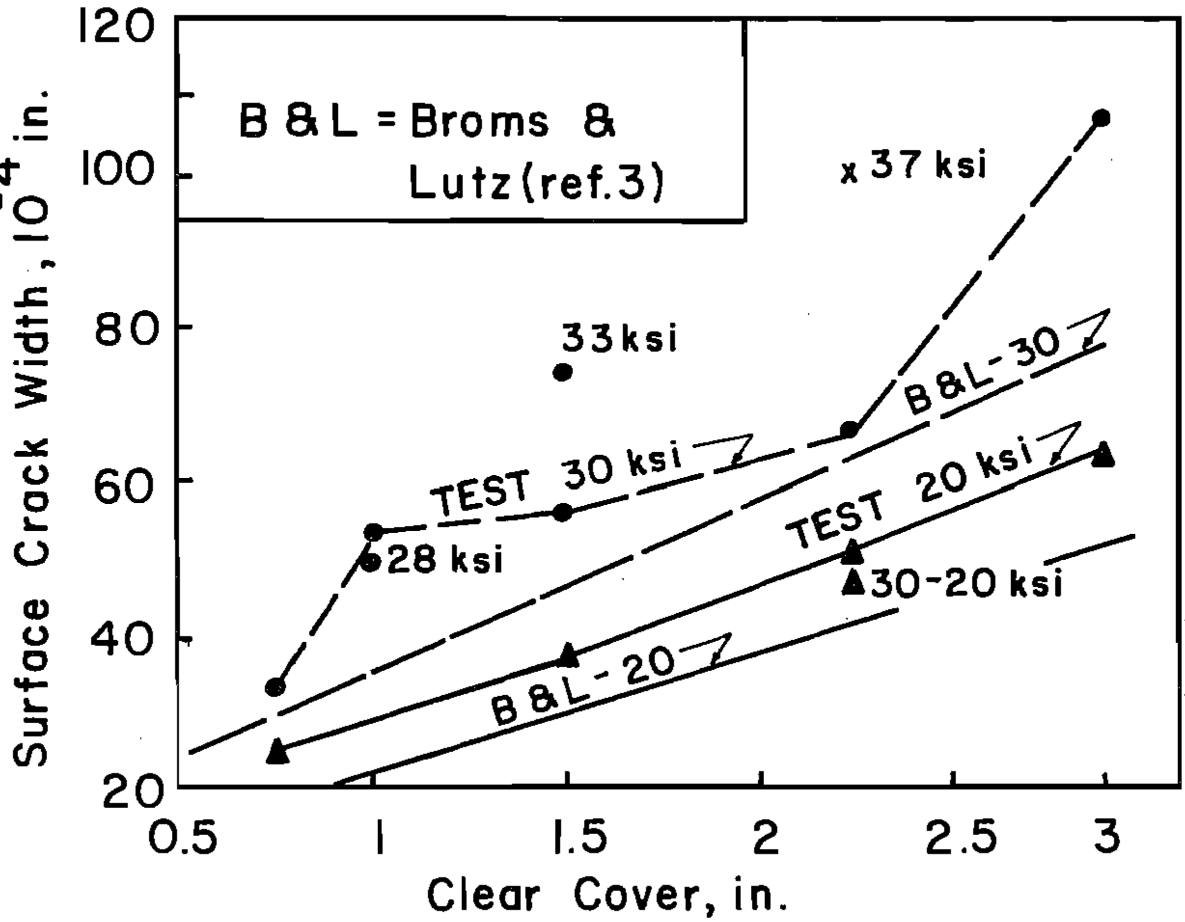


Fig. 14. Average crack width at tension face of beam (all cracks).

Ratio of crack thickness at bar to that at surface

To shorten references, the ratio of average crack at the bar to the average at the surface for the same cracks is here called simply the crack ratio for that beam. The ratio ranged between 0.10 and 0.31, being largest in a shallow member having 0.75 in. clear cover. For the 23 beams the crack ratio in Fig. 15 shows some influence of clear cover, dropping in the range from 0.75 in. to 2.25 in. in such a manner as to keep a near constant crack width at bar as indicated in Figs. 10 and 13. Although steel stresses of 20 and 30 ksi lead to slightly different average curves, the scatter in individual beams indicates that the general trend must be considered much the same within these limits. Possibly the lower ratio for 20 ksi stress at 2.25 in. cover is significant, since the trend continues to 3 in. cover, where it can be rationalized. At this cover the bar is tightly gripped by a considerable mass of concrete; the bar slip (which produces the crack width at the bar) apparently can be kept quite low at 20 ksi, but increases more rapidly at higher stresses. This would be consistent with bond-slip observations on other type specimens.

Cycling the loading from zero to maximum for 20 cycles did not seem to increase either the crack ratio of the crack width at the bar. Beams No. 11 and 14 under such loading show small crack widths at the bar (Fig. 10); they are noted specially in Fig. 15, but are also included in the averages. In Table 2, Beams No. 8P and 9P, for 30 and 20 cycles of loading, respectively, each show a much larger crack ratio; but so do the other preliminary beams without any repeated cycles. This probably reflects inadequate measurement techniques. (The preliminary beams have been ignored all through this report.)

Variation in crack thickness with depth

Reference to Fig. 2 indicates that a crack has very irregular boundaries; but one can plot crack thickness at different depths and obtain a reasonably smooth curve or profile. The irregularity still present may be caused only by measurement limitations, but it seems to represent also some

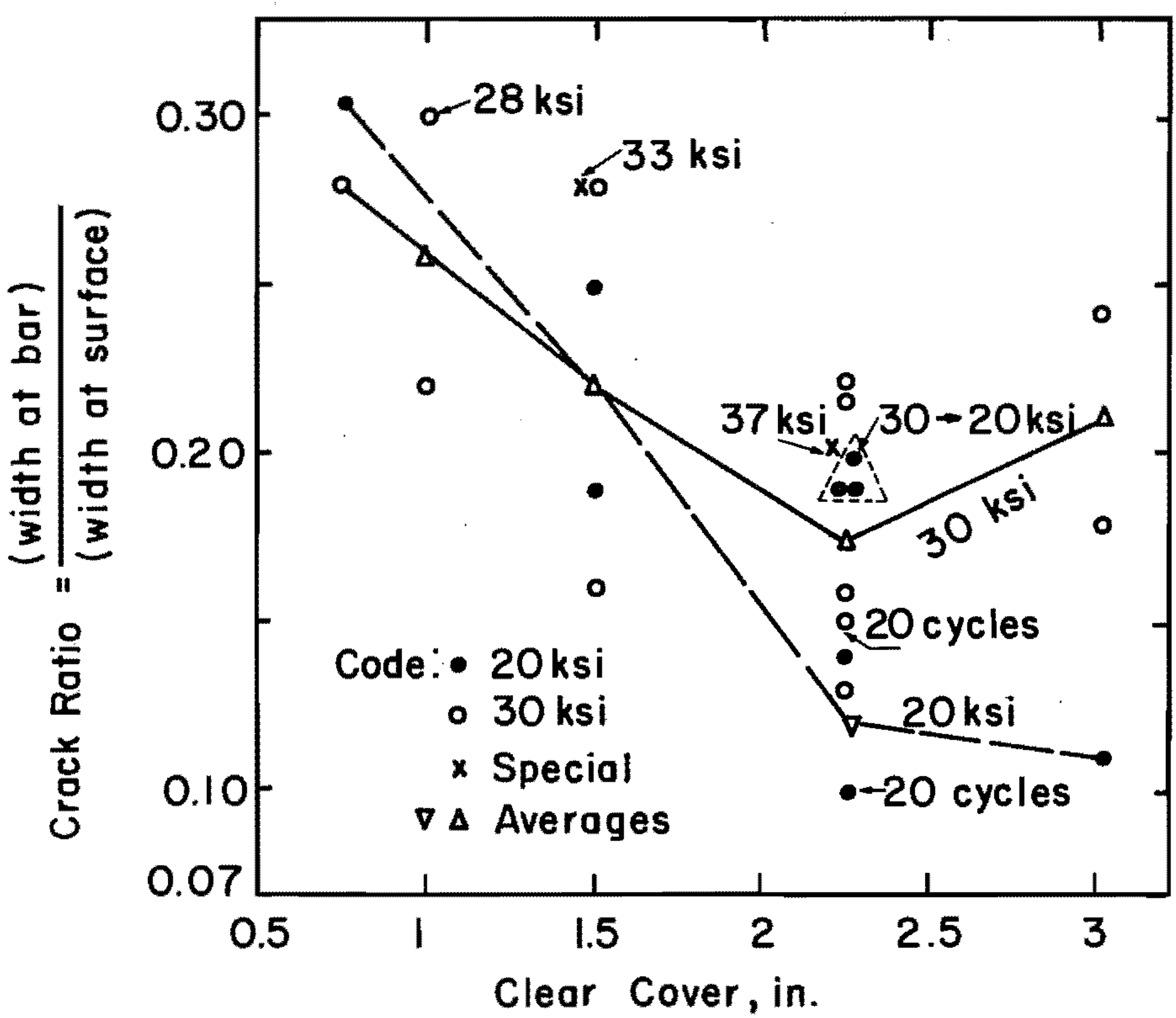


Fig. 15. Variation of crack ratio with clear cover over bars, for cracks successfully injected.

real differences. The data show definitely that the widest surface crack usually will not develop the widest crack at the bar, nor will the widest crack at the bar commonly give the widest surface crack. Some variations found in a given beam for apparent identical surface crack are shown in Fig. 16. Individual width measurements are plotted with small cross marks such that a line could be traced through these marks to define a crack width profile. In several cases the abscissas show wide scatter at a given level, for example, maximum values double the minimums at levels 0.75 in. to 1 in. above the bar in the case of beam #26 in the upper right.

Crack width profile

A typical crack shape or profile, to be very meaningful, must be in terms of an average shape with the realization that there will be large variations crack to crack. As an example, Fig. 17 shows readings from beam #21 plotted as points, along with a second order best-fit curve marked by the circles and limits set at two standard deviations from this curve. If a normal distribution of the scatter were assumed, there would be a 95 percent probability that any crack profile under these stress conditions would fall within these limits.

The best fit curves similarly established for each of the beams are shown in Figs. 18 and 19, except that data of any two beams under the same stress and cover conditions have been combined. (The letter W has then been added to the beam number, as 29W.) Some of the data from the preliminary beams were read again with the 60 power microscope and treated likewise. However, in most of these cases the chips of concrete removed from the bar were no longer available for rereading and thus data at the bar were not improved.*

*These preliminary cases of partial data were weighted less in order to make a more logical combination. Sometimes, because of the smaller number of cracks, or because of seemingly erratic data, the weighting assigned was very small.

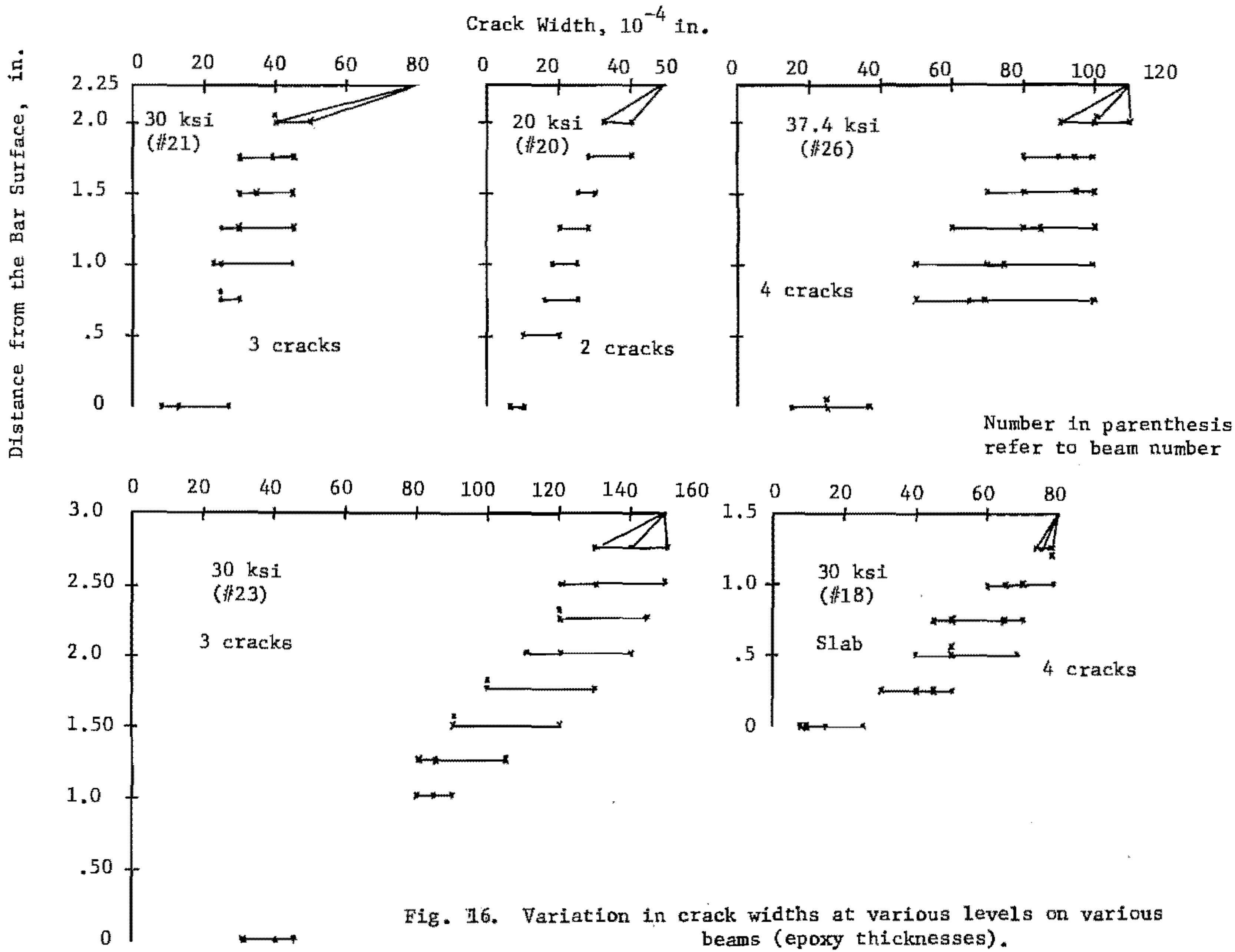


Fig. 16. Variation in crack widths at various levels on various beams (epoxy thicknesses).

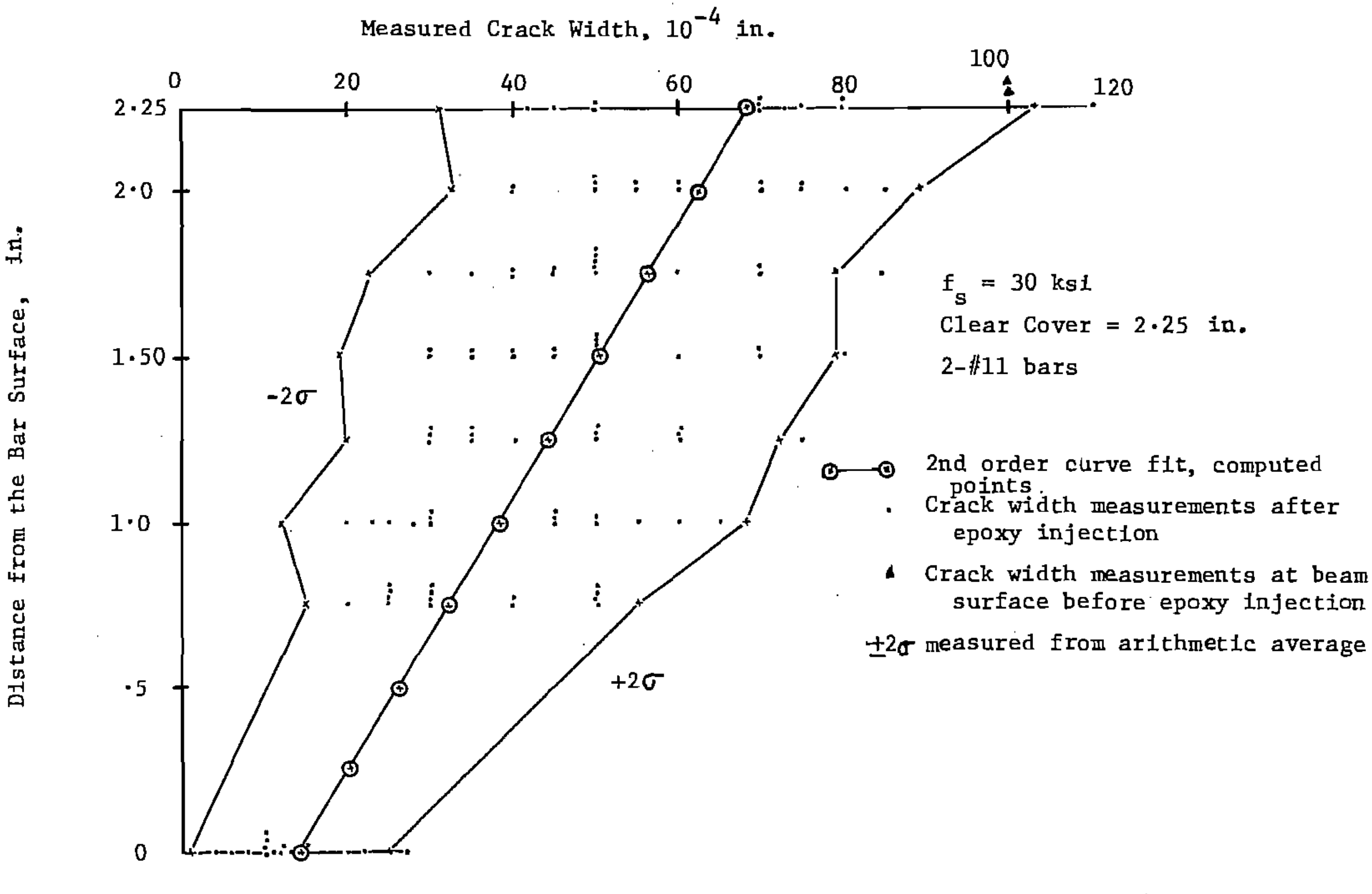


Fig. 17. Best fit crack shape for 30 ksi beam (21-24-11)

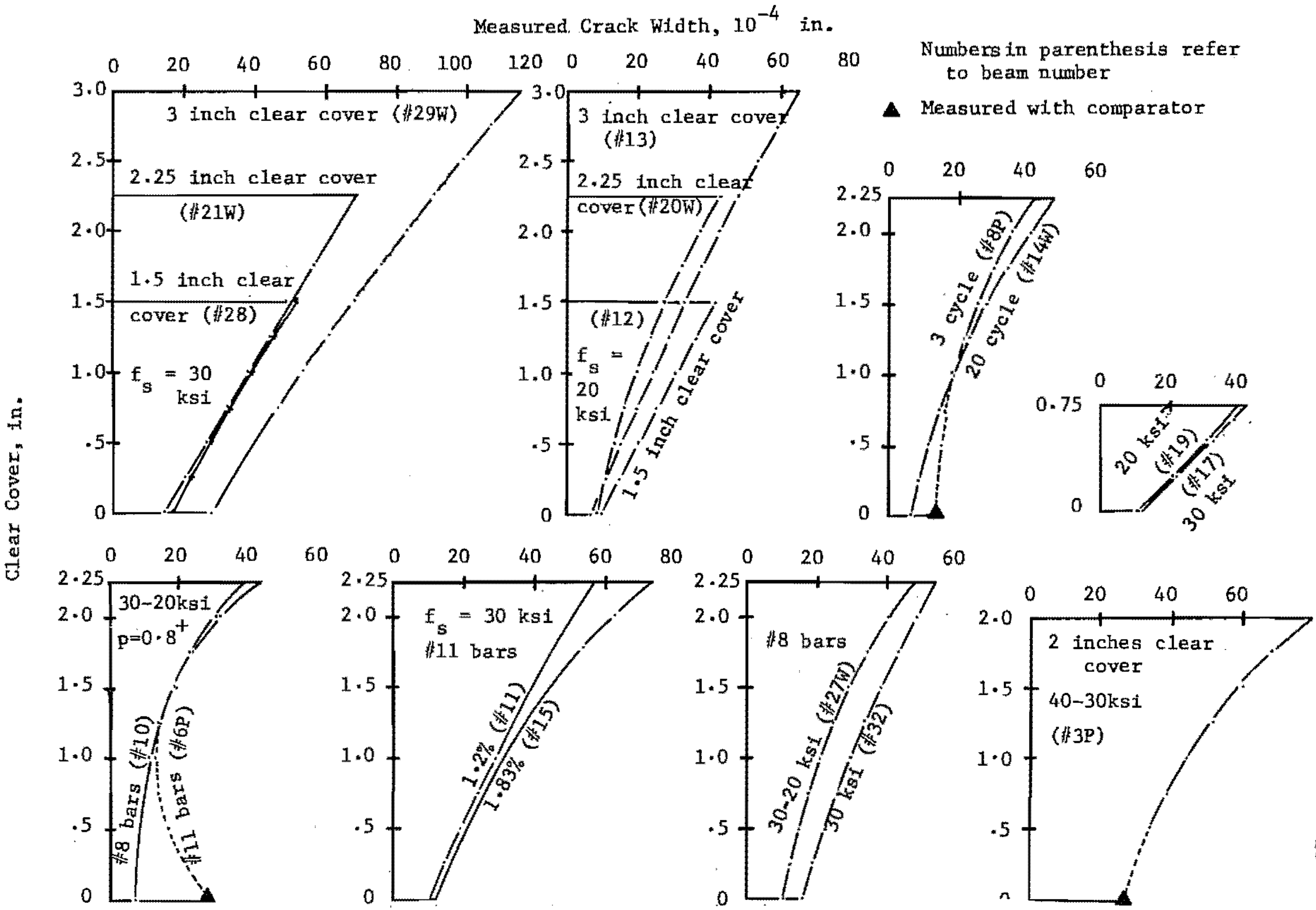


Fig. 18. Best fit curves for crack profiles.

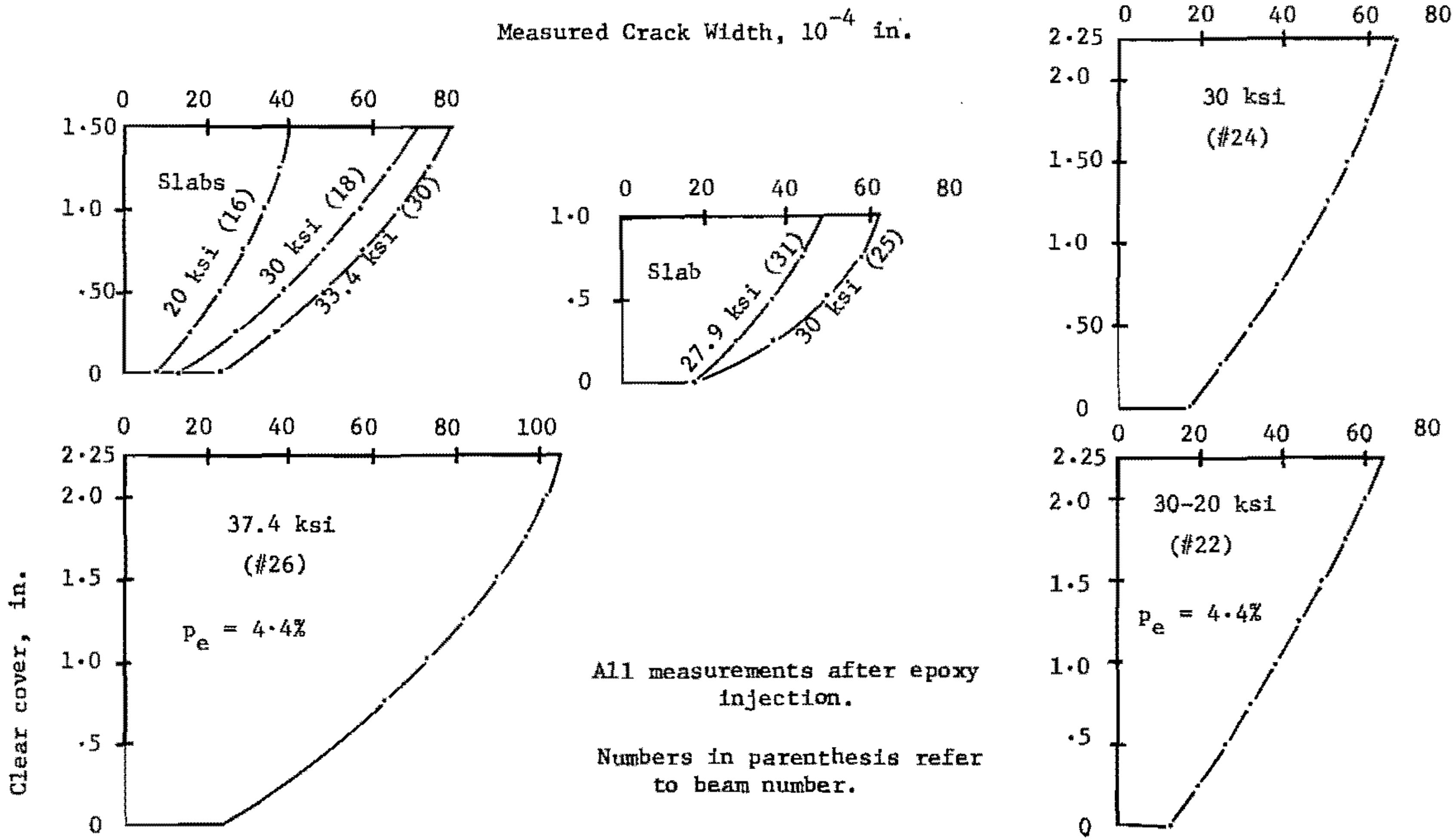


Fig. 19. Best fit curves for crack profiles.

Crack widths at the side of the beam were also measured with similar variations noted from point to point. The average crack widths for one beam are shown in Fig. 20, with the crack width along the lateral line x-x similar to, but smaller than along the vertical line y-y. It should be noted that the crack y-y starts closer to the tension face of the beam and thus should be wider than at face x on the bar.

Variation of crack profile with depth of cover

The display of crack width profiles in Fig. 18 permits some comparison of the effect of cover. The sketches in the upper left show that the profile for the thicker cover can be considered roughly a linear extension of the profile for the thinner covers. Surface crack width varies, again roughly, as the distance from the center of the bar, since these profiles would project nearly to zero at the center of the bar (a distance D/2 below the plotted diagrams).

The profiles or shapes shown in Figs. 18 and 19 are approximately trapezoids, with some superimposed curvature in some cases. In general the slab specimens, especially beams Nos. 16, 18, 25, 30, and 31, show a curved outline with greater center abscissas. This may reflect the sharper curvature taken by these thin members at a given stress level. It might be hypothesized that this sharper curvature causes the crack to overcorrect and to throw the surface concrete between cracks into a slight compression. No measurements were taken to clarify the reasons for this different crack profile.

Other variables

Crack widths on the face of beams agreed reasonably well with the maximum width equation proposed by Gergely and Lutz[5] and the PCA average width equation,[6] but wide scatter was always present.

Small bars tended, under similar conditions, to give smaller average crack widths than large bars.

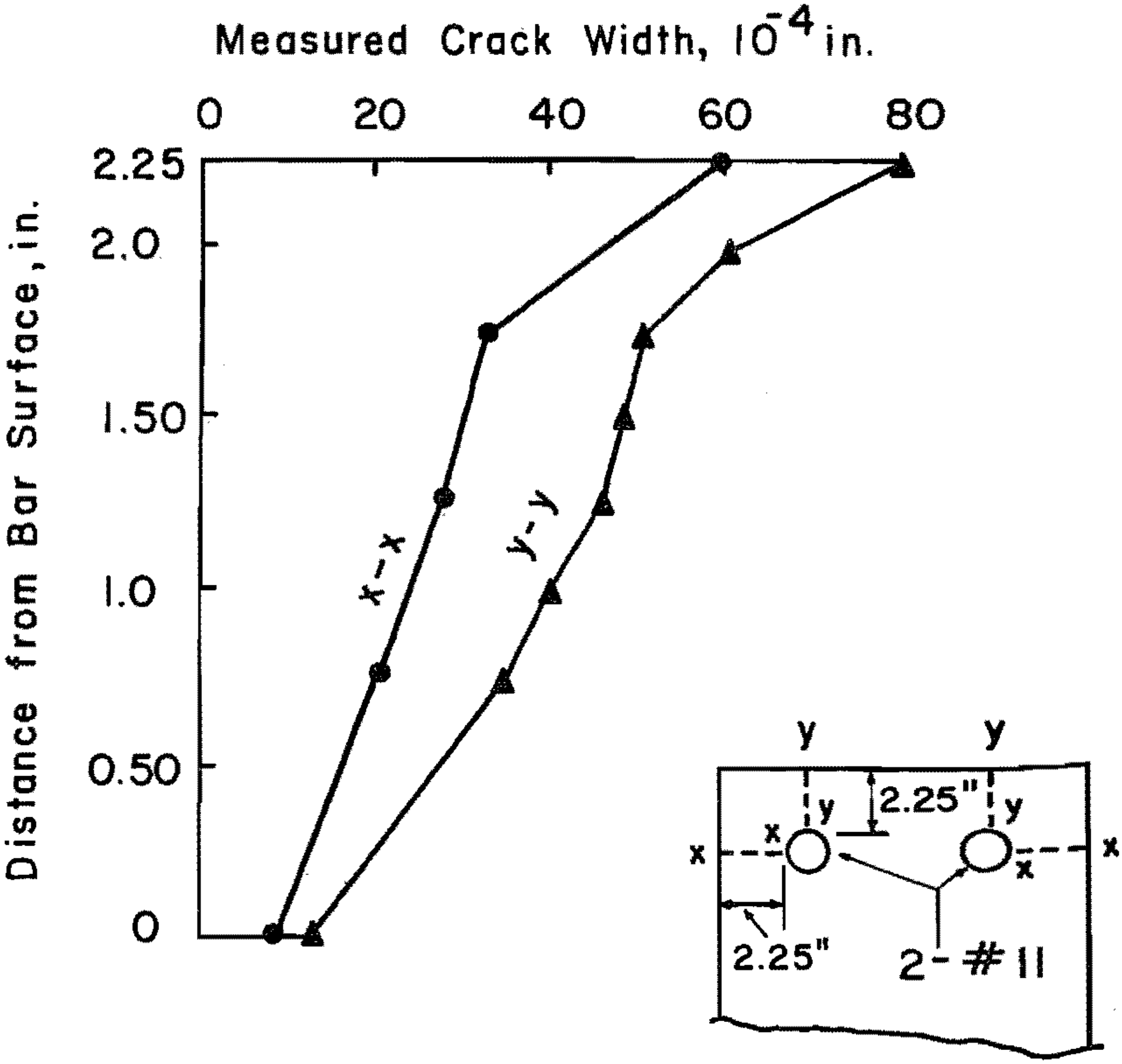


Fig. 20. Average crack width on lateral and vertical planes, at f_s = 30 ksi (#21-24-11).

The rather wide variations in concrete strength, which resulted from poor control over transit mixed concrete, seem not to have a large influence on the crack width measurements. Concrete strength should influence primarily the bar slip which fixes the crack width at the bar. Since this width is always small and varies from crack to crack, the effect of concrete strength may have been lost in the limited accuracy of a measurement of this small quantity.

There was some indication that a small percentage of steel leads to a larger average crack width at the bar.

C O N C L U S I O N S

A new technique has been developed for measuring the width of cracks within the concrete covering the bars. The tests have clarified the relation between crack width at the bar and at the surface and have given some measure of the width variation within the cover.

With this technique the following crack characteristics have been noted.

1. The crack spacing and the crack width at any level vary from average values by at least $\pm$ 50 percent. Average widths are used here for comparisons between cases.

2. Steel stress was the most important variable influencing crack width at the bar.

   (a) Average crack widths at the bar surface at 20 ksi steel stress range downward from 0.0010 in., the smaller values being associated with thicker bar cover.

   (b) At 30 ksi the average crack width at the bar is about 50 percent greater than at 20 ksi, except that at a cover of 3 in., the average jumps suddenly to 0.0029 in. Since no such increase occurs at a cover of 2.25 in. (where the average is only 0.0013 in.), it appears that the extra heavy cover is not actually helpful insofar as cracking is concerned.

3. For other conditions equal, crack width at the beam tension face varied almost linearly with the cover. However, at 30 ksi and 3 in. cover the width was greater than this ratio would suggest.

4. Surface crack width at 30 ksi was (very roughly) 50 percent greater than at 20 ksi, except that at 3 in. cover it was more than doubled.

5. The ratio of crack width at the bar to that at the surface varied from 0.10 to 0.31, being largest in a shallow member with clear cover of 0.75 in.

6. The crack thickness from bar to surface plotted approximately as a trapezoid, except that shallow members had relatively greater widths at middepth of the cover. A similar nearly linear variation in crack width existed laterally from the bar to the edge of the beam, with slightly smaller crack widths (possibly because nearer the beam neutral axis).

7. Repetitions of load for 20 cycles had no noticeable influence on measured crack dimensions.

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