Tests of Reinforcement Splices for Continuously-Reinforced Concrete Pavement

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Lap splices in reinforcement for continuously-reinforced concrete pavements were tested under longitudinally-applied static axial tensile loading to failure. Twenty-eight specimens, 8 in. thick, 13 in. wide, by 20 ft long were reinforced with two hardgrade No. 5 deformed bars (average yield strength 64,000 psi) and twenty-four specimens of similar size were reinforced with a strip of welded-wire fabric having 5/0 longitudinal wires (average yield strength 81,000 psi).

Observations were made for openings of the preformed crack under load, together with the occurrence and opening of additional cracks and the mode of failure. Results were evaluated in terms of several criteria that are significant to the function of reinforcement in continuously-reinforced pavement.

THE LONGITUDINAL reinforcement in continuously-reinforced concrete pavement consists of many lengths of either high-strength deformed bars or welded-wire fabric. Continuity of reinforcement in the longitudinal direction is provided by overlapping the ends of the steel to form a splice. The lapped splice transfers force from one bar to another through the surrounding concrete by bond and, in the case of welded-wire fabric, by bond and the anchorage offered by the transverse wires.

Laboratory experiments were made to evaluate the load-deformation characteristics of lap splices in deformed-bar and in welded-wire fabric reinforcement. Although laboratory tests cannot duplicate all conditions encountered in the field, such tests yield valuable information indicating the optimum splice length required to maintain reinforcement continuity. Static load tests to fracture, made at early concrete ages, constitute the most severe strength test of the splices and were chosen to cover the most critical conditions that might occur in the field.

The basic requirement for reinforcement in continuously-reinforced concrete pavement is to hold tightly closed all transverse cracks that may form. When cracks are prevented from opening more than 0.01 or 0.02 in., the subgrade is protected and spalling or deterioration at such cracks does not occur. When reinforcement is adequate to cause additional transverse cracks to form without allowing existing ones to open excessively, stresses will be relieved and a stable condition is reached. If reinforcement is overstrained at a crack so that yielding occurs, the crack may open enough to deteriorate. Obviously, if the reinforcement fails in tension or a splice opens all continuity is lost.

The splice must be capable of performing as well as the unspliced reinforcement. Three criteria for judging the adequacy of a splice are used in this investigation:

1. Is the lap length sufficient to produce other cracks away from the splice at all ages of concrete?
2. Is the lap sufficient to develop the yield strength of the reinforcement?
3. Is the splice strong enough to develop the ultimate strength of the reinforcement, or short of this, to cause other cracks to open to 0.1 in. or more?

It is recognized that the third criterion represents a condition that does not occur in pavements in actual service. However, it does serve to compare the strength of splices with the strength of unspliced reinforcement under the conditions of these tests.

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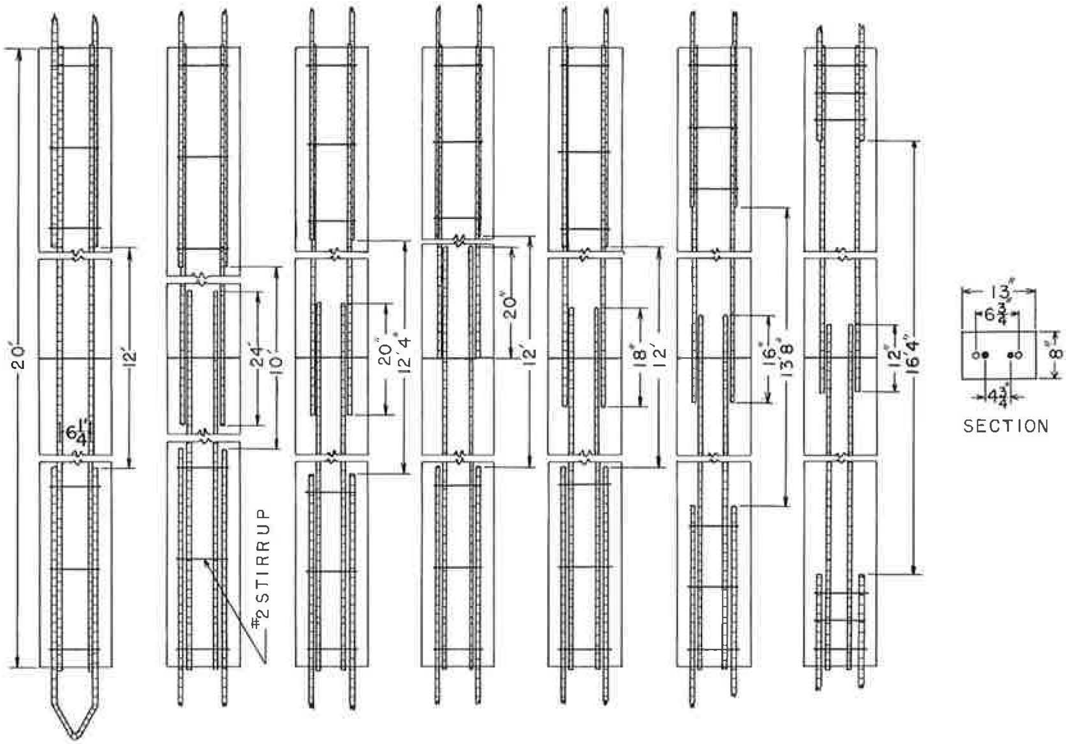


Figure 1. Deformed-bar specimens, series D.

PROGRAM OF TESTS AND TEST SPECIMENS

Two series of tests were made: (a) 28 specimens were reinforced with high-strength deformed bars, and (b) 24 specimens with welded-wire fabric. Six splice arrangements were tested and compared with an unspliced control in the deformed-bar series; five splices and an unspliced control were tested in the welded-wire fabric series. Four identical specimens for each splice arrangement were cast from one concrete batch for test at 1-, 3-, 7-, and 14-day ages. A single class of concrete was used. The test specimens were 8 in. deep by 20 ft long, with 0.6 percent steel reinforcement located at mid-depth. The specimens were designed to represent a length of pavement containing a transverse crack at the lap splice. The crack was formed by inserting a sheet metal separator at the splice to prevent load transmission through the concrete at this point.

Details of the specimens reinforced with deformed bars, series D, are shown in Figure 1. Specimen width was 13 in. to accommodate two No. 5 bars (0.57 percent steel). Unspliced control specimens, DC, had a 12-ft test length between ends of yokes, with separator at midlength. Splice lengths of 24, 20, 18, 16, and 12 in., with separator at midlength of splice, were tested in specimens D24, D20, D18, D16, and D12, respectively. Specimen D20E had a 20-in. splice with separator at the end of the splice. Reinforcement was placed symmetrically in plan to avoid eccentricity of load. Test lengths between the yokes varied from 10 ft to 16 ft 4 in. The shorter yoke embedments were sufficient for the lower loads resisted by the shorter splices. No transverse reinforcement was used within the test length. Stirrups were used around the yokes to prevent failure in the yoke regions.

The welded-wire fabric reinforcement, series WWF, consisted of four 5/0 gage longitudinal wires on 3-in. centers welded to No. 1 gage transverse wires on 12-in. centers. The longitudinal wires extended 6 in. beyond the last transverse wire. Specimens of this series

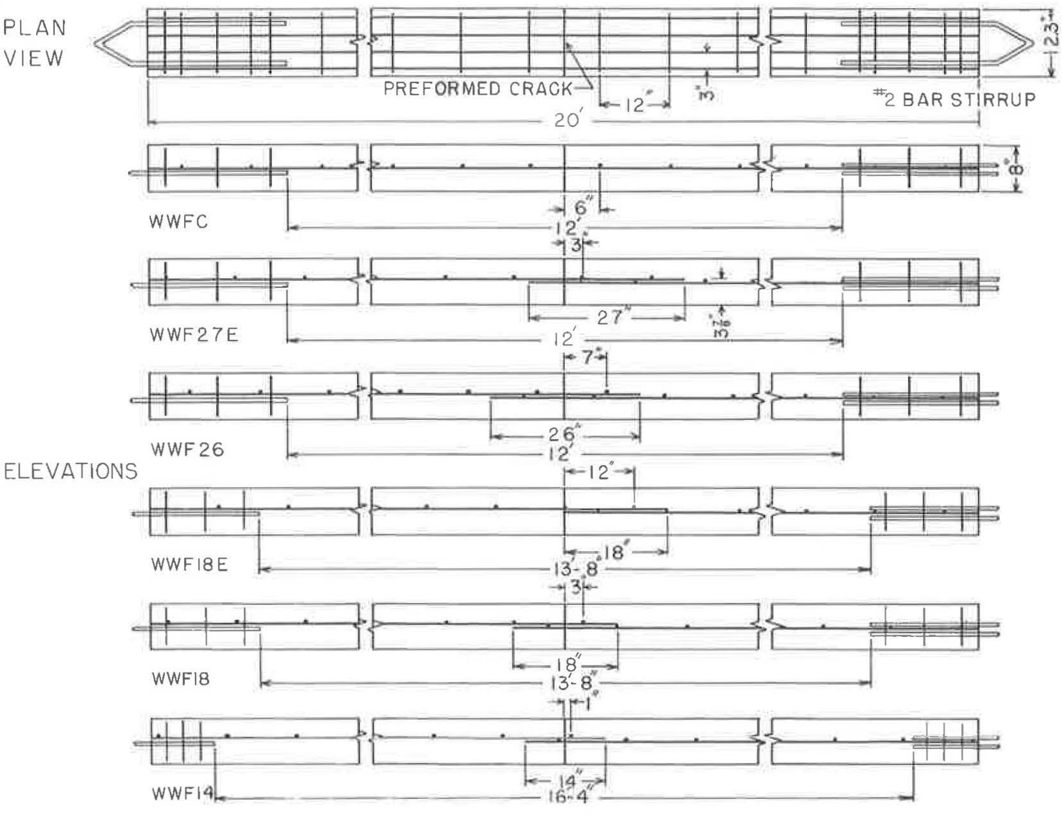


Figure 2. Welded-wire fabric specimens, series WWF.

were 12.3 in. wide (0.60 percent steel) with transverse wires cut to the full width.

Unspliced control specimens, WWFC, were reinforced with a single length of fabric at mid-depth, Figure 2. The separator for the preformed crack was located at mid-length, and was midway between transverse wires. Specimen WWF27E was made with a 27-in. splice, with the preformed crack located at the end transverse wire of one length of reinforcement. The overlapped reinforcement length was thus anchored by two transverse wires beyond the preformed crack, the second wire from the end of the fabric being 3 in. from the crack. WWF26 had the end transverse wires of each fabric length 7 in. beyond the preformed crack. In WWF18E, the end transverse wires lap 6 in., with the preformed crack at the second transverse wire of one fabric length and at the end of the other fabric length. WWF18 and WWF14 had 6-in. and 2-in. laps between end transverse wires, respectively, and corresponding embedments of 3 in. and 1 in. beyond the preformed crack.

MATERIALS

The concrete mix was designed for 4,000-psi compressive strength at 28 days, 6.25 sacks of cement per cu yd, with 2½-in. slump and 5 percent entrained air. Concrete was made from high-quality quartz-sand fine aggregate, well-graded quartz-gravel coarse aggregate and Type I portland cement. Maximum aggregate size was ¾ in. An air-entraining agent was added to the mixing water. Measurements made on the concrete batches at the time of casting specimens and standard strength tests results on 6- by 12-in. compression cylinders, 6- by 6- by 20-in. flexure beams and 3- by 6-in. splitting tension cylinders are given in Table 1.

Deformed-bar reinforcement was furnished in two lots. The results of tensile

TABLE 1

PROPERTIES OF SERIES D AND WWF CONCRETE

Batch	Slump (in.)	Air (%)	Test Age (day)	Compressive Strength (psi)	Modulus Rupture (psi)	Splitting Tensile Strength (psi)
DC	2.4	4.0	1	1,715	339	223
			3	3,320	533	474
			7	4,350	679	584
			14	5,075	695	584
D24	6	4.0	1	1,052	235	151
			3	2,360	446	296
			7	3,583	519	385
			14	4,410	544	382
D20	2.1	5.2	1	1,798	377	207
			3	2,644	495	330
			7	3,392	521	376
			15	4,268	564	440
D20 E	3	3.5	1	1,650	378	326
			3	2,635	467	440
			7	3,200	532	453
			14	3,995	620	473
D18	2.5	5.8	1	1,897	475	285
			4	3,060	567	458
			7	3,800	594	352
			14	4,138	608	446
D16	3	5.5	1	1,123	274	147
			3	2,478	486	326
			7	3,406	555	458
			14	3,864	607	378
D12	2.5	4.6	1	1,418	315	212
			3	2,504	453	332
			7	3,390	512	454
			14	3,855	553	460
WWF C	3.5	6.5	1	1,261	288	199
			3	2,810	498	405
			7	3,628	609	414
			14	4,041	644	480
WWF 27E	6	6.7	1	1,660	335	260
			3	3,006	507	377
			7	3,519	580	373
			14	3,961	642	505
WWF 26	3	5.8	1	1,001	271	179
			3	2,785	485	404
			7	3,589	573	453
			14	4,028	566	470
WWF 18E	3	5.9	1	1,469	328	262
			3	2,894	451	384
			7	3,953	573	424
			14	4,050	568	468
WWF 18	5	6.0	1	1,519	328	198
			3	2,508	455	427
			7	3,555	528	409
			14	4,163	550	506
WWF 14	3	5.6	1	1,541	320	214
			4	2,880	508	319
			7	3,329	563	387
			14	3,688	587	367

TABLE 2

PROPERTIES OF REINFORCEMENT NO. 5 DEFORMED BARS, SERIES D

Test No.	Area (sq in.)	Yield Point (psi)	Yield Strength 0.2% Offset (psi)	Tensile Strength (psi)	Modulus of Elasticity (psi)	Elongation (% in 2 in.)
First Lot Used in Specimens DC, D24, D20, D12						
1	0.295	65,080	65,100	109,830	31,200,000	—
2	0.295	65,080	65,100	110,060	31,300,000	24
3	0.295	65,080	65,150	110,850	31,900,000	25
Avg.		65,080	65,120	110,250	31,500,000	24.5
Second Lot Used in Specimens D20E, D18, D16						
1	0.295	63,390	64,100	104,750	30,300,000	27
2	0.295	62,710	63,050	105,080	28,300,000	19
3	0.295	62,710	63,050	104,070	31,200,000	26
Avg.		62,940	63,400	104,630	29,900,000	24

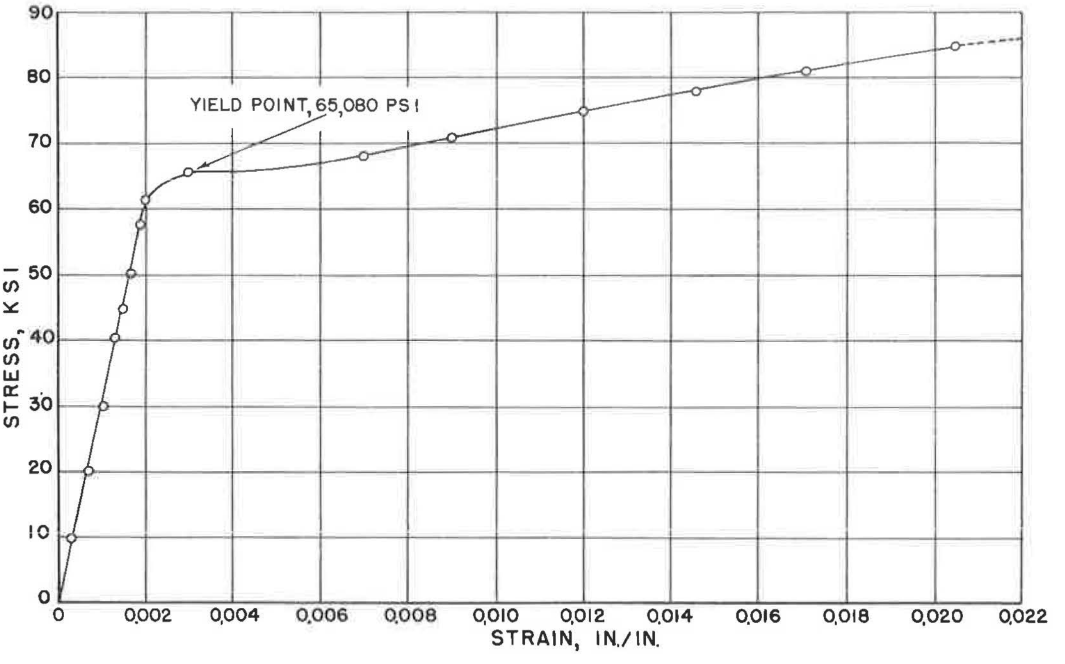


Figure 3. Initial portion of stress-strain curve, No. 5 deformed bar.

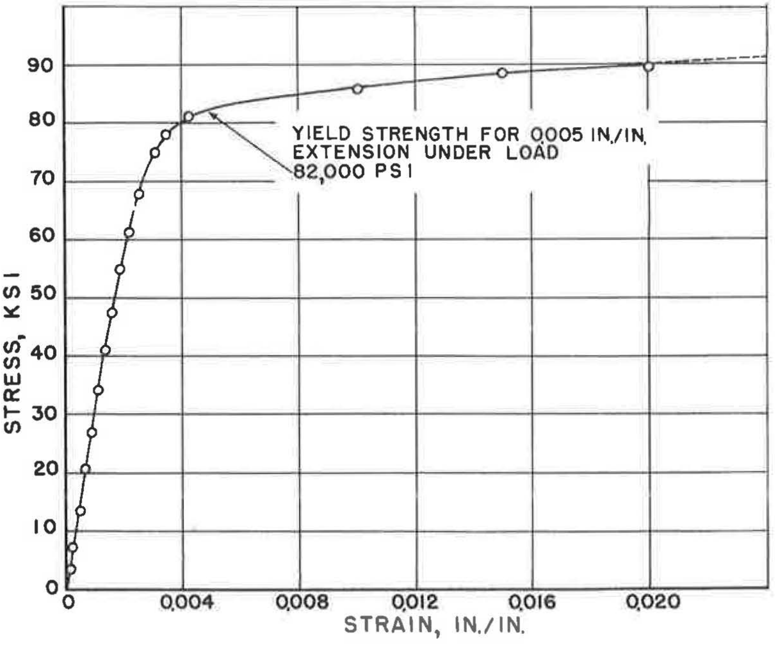


Figure 4. Initial portion of stress-strain curve, 5/0 wire.

TABLE 3

PROPERTIES OF WELDED-WIRE FABRIC

	Tensile Tests						Weld Shear Tests	
Gage Length	Test No.	Area (sq in.)	Yield Strength 0.005 in./in. Ext. Under Load[1] (psi)	Tensile Strength (psi)	Modulus of Elasticity (psi)	Elongation (% in 2 in.)	Test No.	Shear Strength (lb)
Across Welds	1	0.147	82,000	87,990	27,800,000	6	1	2,640
	2	0.147	81,000	86,220	26,300,000	6	2	4,040
	3	0.147	81,500	88,940	28,600,000	10	3	2,600
	Avg.		81,500	87,720	27,600,000	7	4	3,600
							5	3,200
Between Welds	1	0.147	81,000	87,440	31,300,000	10	6	2,380
	2	0.147	80,000	85,880	28,600,000	-	7	2,540
	3	0.147	82,000	89,610	30,000,000	11	8	3,640
	Avg.		81,000	87,680	29,900,000	10.5	9	3,160
							10	3,140
							Avg.	3,094

[1]ASTM A82-61T.

strength tests on each lot are given in Table 2. A typical tension-test stress-strain curve for a sample from the first shipment is shown in Figure 3. Elongations measured in a 2-in. gage length are higher than the specification values based on 8-in. gage length.

The results of tensile tests of longitudinal wire samples cut from the welded-wire fabric are given in Table 3. Three samples were tested with the 2-in. gage length between welds, and three with the gage length spanning a weld. The transverse wire in the latter case was cut an inch away from the longitudinal wire, so that the weld was not disturbed prior to these tests. A typical stress-strain curve for the longitudinal wire between welds is shown in Figure 4.

Ultimate shear strength of welds was found by supporting the transverse wire on a bearing plate and pulling the longitudinal wire through a 5/8-in. hole in the plate. Results of these tests (Table 3) probably are lower than would be obtained from tests made with a fixture that holds the transverse wire against rotation.

TESTING APPARATUS

The 20-ft specimens were tested under tensile loading applied in the longitudinal direction. Test loads were applied through yokes made of reinforcing bars embedded in the concrete at each end of the specimen. The loading frame was built of structural steel members (Fig. 5). Load was applied through a pulling head actuated by a hand-operated hydraulic jack. The yoke at one end of the specimen was connected to the

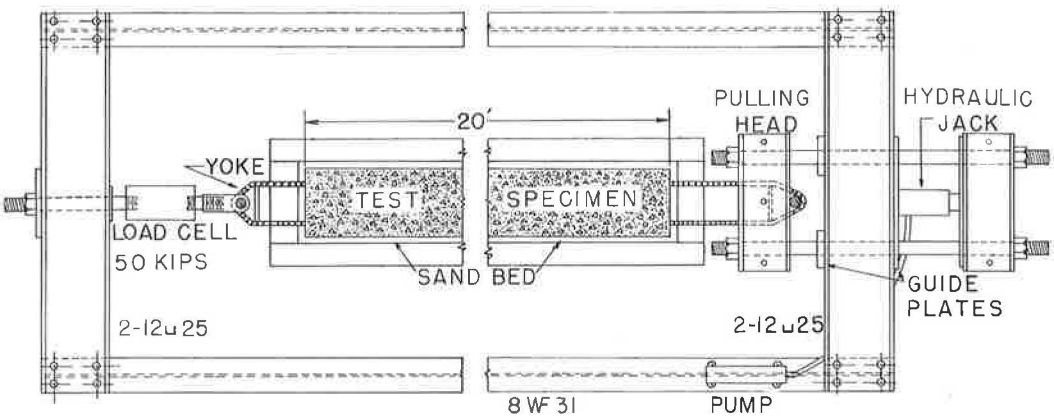


Figure 5. Plan of loading frame.

pulling head. The other end of the specimen was connected to the frame through a yoke, clevis, and strain-gage load cell. The load cell and the SR-4 strain indicator were calibrated in a universal testing machine.

Four 0.0001-in. dial gages, located symmetrically on the side faces of the specimen near the top and bottom were used to measure the preformed crack openings. They were mounted on brackets attached to bolts cast into the concrete 3 in. from the preformed crack. The widths of additional transverse cracks formed during the test were measured on the top surface of the specimen with a low-power microscope equipped with an optical scale.

The specimens were supported during testing on the base section of the form in which they were cast. A 1-in. thick bed of fine sand covered with two layers of 4-mil polyethylene sheeting below the specimen served to minimize frictional resistance.

FABRICATION OF SPECIMENS

Plywood forms were prepared for casting four specimens from each batch of concrete. The base form was 2 ft wide and was supported on four 20-ft long, 2- by 6-in. timbers. A 1-in. bed of sand, graded to pass a No. 16 sieve, was carefully compacted in a recess in the top of the base form and brought to a smooth surface by a straightedge. A 4-mil sheet of polyethylene stretched taut over the sand bed was stapled to the base form. A second sheet of polyethylene wide enough to wrap around the specimen was spread over this base, and side forms were bolted on top of this second sheet to the edge of the base.

At midlength of the specimens, the side forms had 12-in. long removable plywood pieces. A sawed slot in these pieces held the $1/16$-in. thick sheet metal separator at the position of the preformed crack. Machine bolts ($1/4$- by $1\,1/2$-in.) were used to secure the dial indicator brackets to these pieces 3 in. away from the slot, with 1-in. length to be embedded in the concrete.

For deformed-bar test specimens, holes at the mid-depth of the sheet metal separator supported the reinforcement. The holes were drilled $1/8$ in. larger than bar diameter to allow wrapping the bar with a $1/4$-in. wide rubber ring to prevent possible locking of the bar deformations in the separator. For WWF specimens, $3\,3/8$-in. deep separators wide enough to be held in the slots were placed above and below the wire fabric and taped together.

At the ends of the specimens, the reinforcement and the yokes were supported on plywood end forms having holes for accurate steel location. Wire ties attached to the side forms supported the reinforcement at several points along the specimen length.

The welded-wire fabric was exposed to the weather to rust for four weeks to simulate the reinforcement surface conditions usually encountered in the field. To avoid using possibly damaged welds at the splice, a 25-ft length of wire fabric was cut in half and the interior ends were placed in the splice region of the test specimen. The specimen to be tested at 1-day age was cast in the loading frame. Other specimens were cast at nearby locations on the laboratory floor.

The concrete was supplied by a local ready-mix plant. The designated quantities of sand, cement, and gravel were delivered to the laboratory in a horizontal-axis truck mixer. Mixing water and the air-entraining agent were added at the laboratory. Inasmuch as it was not possible to determine the exact moisture content of the aggregate at the plant, the following mixing procedure was adopted. A portion of the mixing water and all air-entraining agent were placed in the mixer and the concrete was mixed sufficiently to permit making a slump test; slump was invariably low. Water was then added to bring the slump to the desired value, and the concrete was thoroughly mixed.

The concrete was cast directly into the forms from the truck mixer. An internal vibrator was used to consolidate the concrete in the forms. Specimens were finished by striking off the top surface, covering with wet burlap, and wrapping in the polyethylene sheet. Within 24 hours the side forms were removed so that the specimens could be covered closely with wet burlap and polyethylene wrapping. Occasional spraying with water served to keep the specimens thoroughly wet. Curing temperatures were the ambient laboratory temperatures.

At intervals during the placing process, concrete was taken from the truck discharge to form a composite batch sample for preparation of the specimens for concrete strength tests. This concrete was remixed by hand to obtain uniformity. The air content was measured by air meter. Cylinder and beam test specimens were cast in metal forms following standard procedures. At 24 hours, the forms were stripped and the samples placed in a 70 F, 100 percent humidity curing room.

TEST PROCEDURE

Two to three hours before testing, the curing wrapping was removed and the polyethylene sheeting beneath the specimen was cut free from the base form. A coat of whitewash was then applied to the top and side surfaces of the specimen to permit easy crack detection. The specimen was moved into the testing frame on the base form, which was lifted by slings with an overhead crane. The lifting points were located in the form at the quarter points of the specimen length to avoid bending at the splice. To center the specimen in the testing frame, the base was adjusted by shims.

The specimen was moved longitudinally to break the initial restraint of the sand bed on the bottom surface and to minimize the frictional resistance during test. Using a small hydraulic jack, the specimen was twice pushed about 3/8 in. in each direction with the final movement being toward the load cell end. Thus, protruding irregularities in the bottom of the specimen moved into recesses in the sand bed as the specimen was strained during test.

Frictional resistance was measured on 11 specimens. Load readings were taken from a proving ring placed between the small hydraulic jack and one end of the specimen; movement readings were obtained by a 0.001-in. dial indicator at the other end of the specimen. After a consistent relationship between frictional resistance and movement had been established, these measurements were discontinued.

After breaking the initial sand bed restraint, the specimen was connected to the testing frame and dial gages were attached. The longitudinal tensile loading was begun in 1,000- to 2,000-lb increments, depending on specimen strength. The dial gages were read at each increment. When transverse cracks or any signs of splice failure developed, the test was stopped and load value recorded. Specimen conditions were noted and measurements of openings of all transverse cracks were made. The loading was then resumed until the next increment was reached or additional cracks developed. Following this procedure, the load was increased until the specimen failed. The final crack pattern was recorded in detail and photographs of the splice region were taken. The cracked concrete around the failed splice was removed to examine the failure pattern and to detect weld failures when such occurred with welded-wire fabric. Strength tests of concrete control samples were made immediately before or after testing each specimen.

TEST RESULTS

Frictional Resistance

The results of a typical set of measurements for frictional resistance between specimen and sand bed are shown in Figure 6. These curves show the forces required to produce the movements indicated on the abcissae. The direction of motion was toward the jack end for the first movement, 1, and was away from the jack for the last movement, 4. The curves show that the frictional resistance at sliding became fairly steady at 940 lb during the fourth movement. This corresponds to a coefficient of sliding friction of 0.45 for the specimen weight of 2,090 lb. Table 4 shows the results of the eleven sliding friction measurements made.

Typical Behavior Under Load

Curves showing load as a function of preformed crack opening were plotted from the log of each test. Typical examples of such curves are shown in Figures 7, 8, 9, 10, and 11. Each crack is indicated by a number or letter on the curve at the point where it occurred, and the same symbol locates the crack on the sketch on the curve

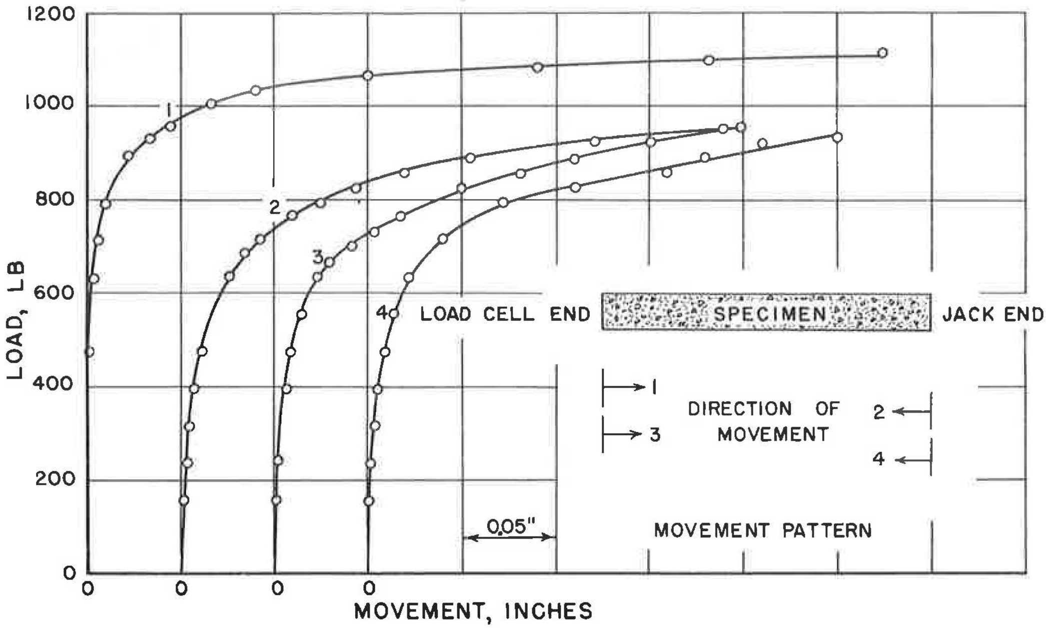
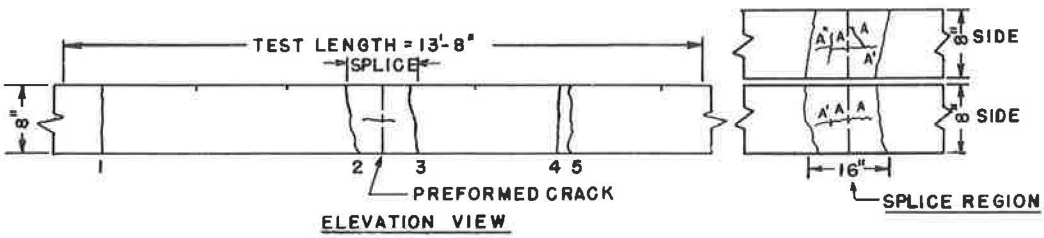


Figure 6. Frictional resistance, specimen D16-14.



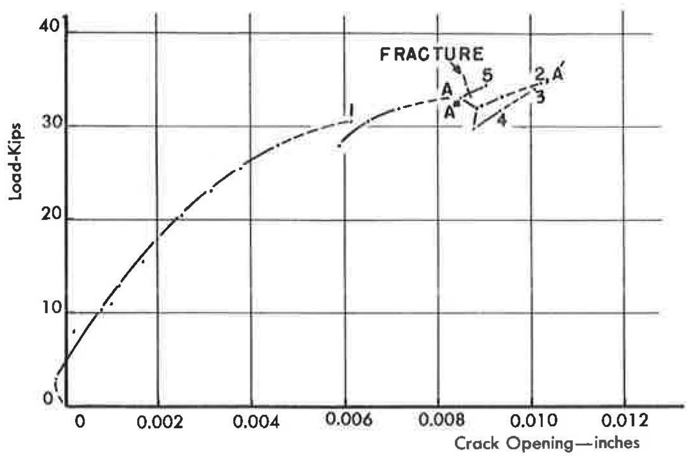


Figure 7. Test record, specimen D16-7.

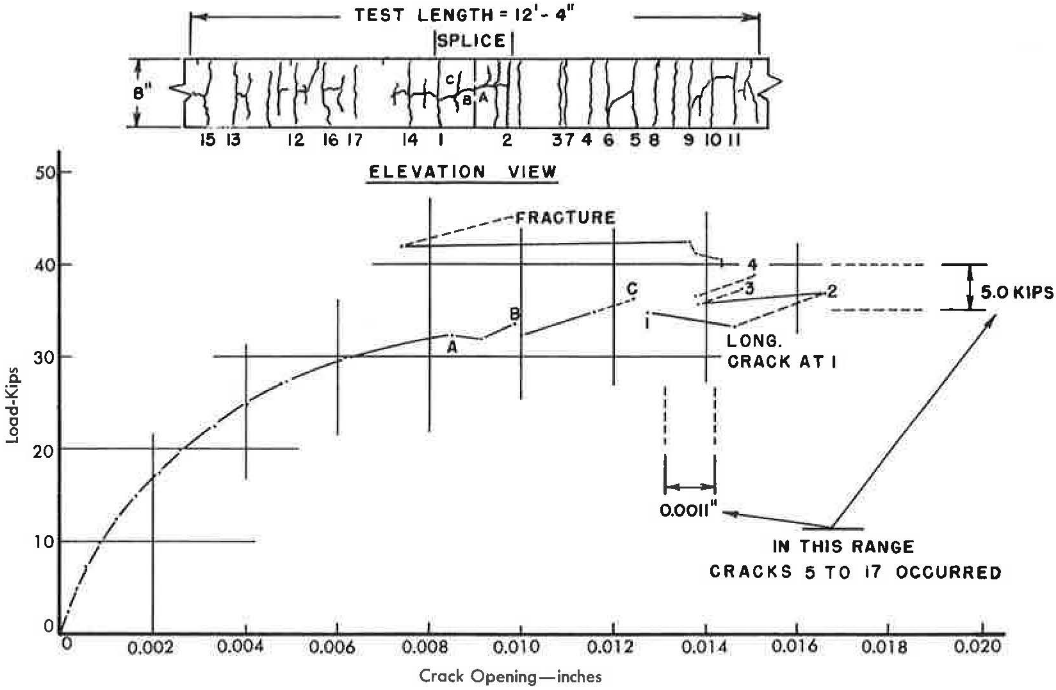


Figure 8. Test record, specimen D20-15.

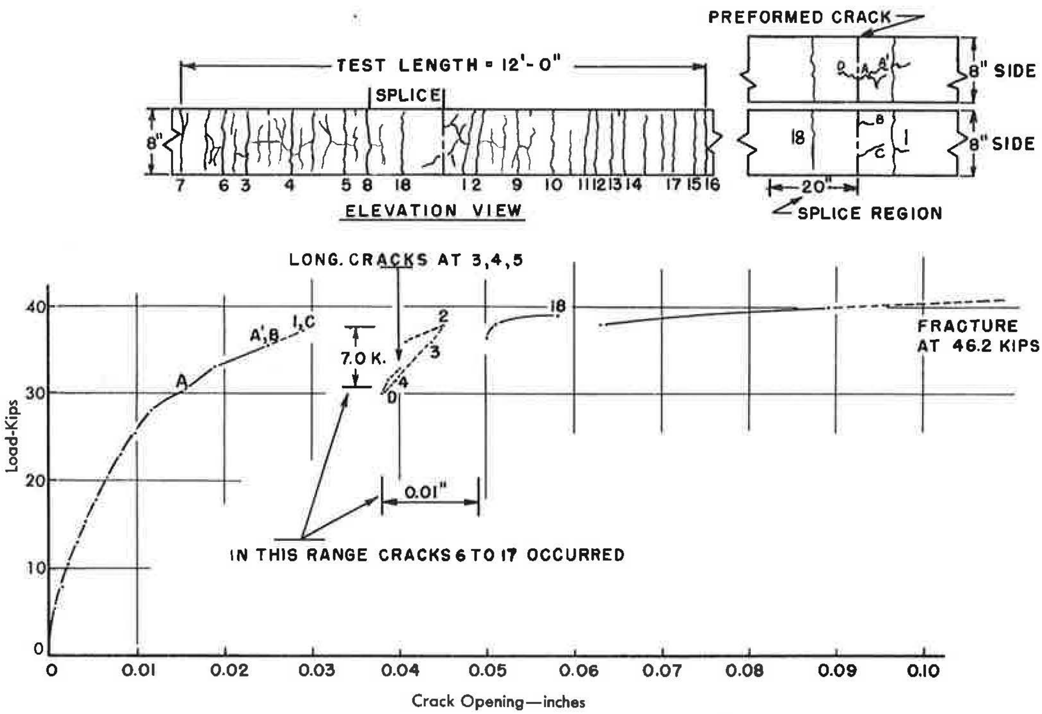


Figure 9. Test record, specimen D20E-14.

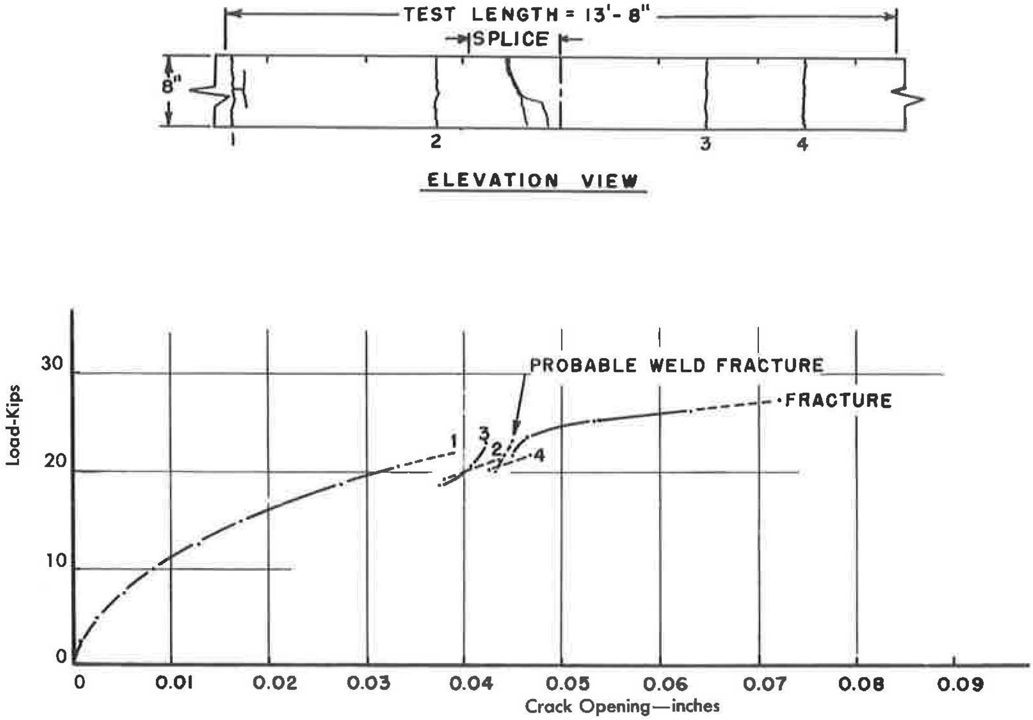


Figure 10. Test record, specimen WWF18E-1.

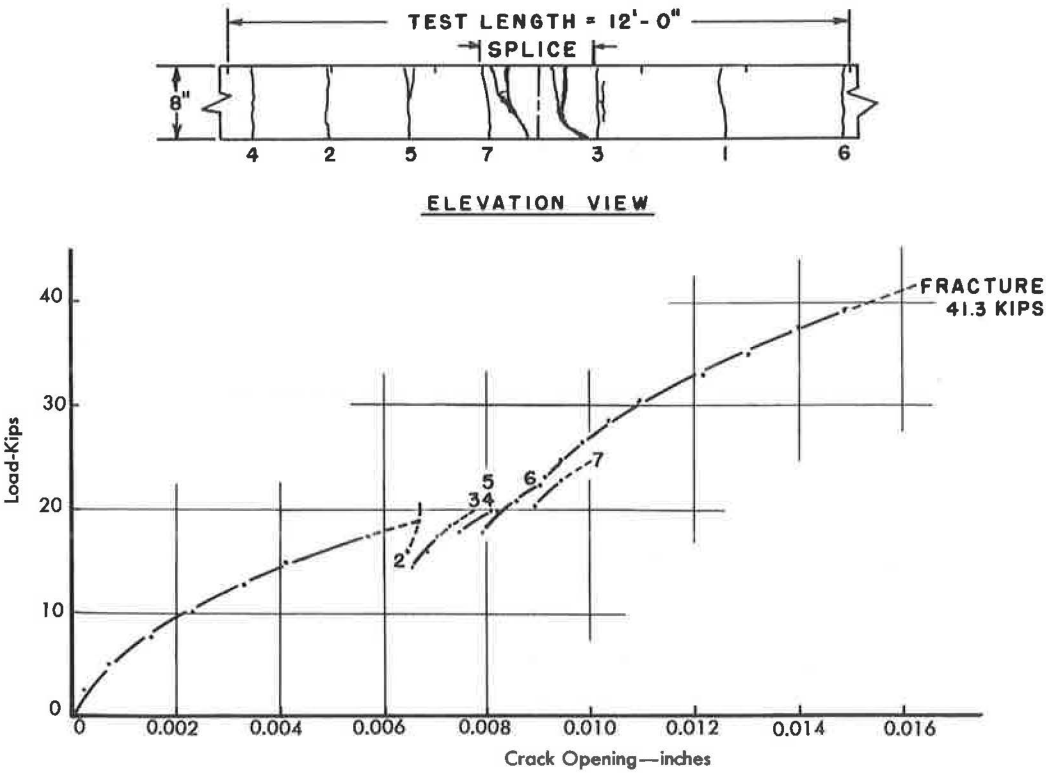


Figure 11. Test record, specimen WWF26-1.

sheet. Numbers represent transverse cracks in the order of appearance, and letters denote longitudinal horizontal cracks. Primes indicate extension of existing cracks.

Specimen D16-7, 16-in. lap, 7-day concrete (Fig. 7), is representative of a relatively weak deformed-bar splice. Some initial adjustment in the dials at early stages of loading accounts for the small (0.0005 in.) zero error. The preformed crack opened at increasing rate until the first transverse crack (1) occurred 6 ft from the preformed crack at 30.2 kips and 0.006-in. opening of the preformed crack. Load dropped slightly and the preformed crack closed a little because the transverse crack released some of the strain on the specimen.

Continued straining led to the development of longitudinal horizontal cracks (A), on both sides of the preformed crack at 32.8 kips (steel stress 55.6 ksi). Load dropped to 31.7 kips but the preformed crack opened to 0.0089 in. At 34.5 kips a transverse crack (2) developed at the end of the splice, together with extension of the longitudinal cracks. Further straining, but at loads less than 34.5 kips, caused a crack at the other end of the splice (3) and two additional transverse cracks, as indicated by isolated points (4, 5) on the curve. During this stage, it was apparent that the concrete had broken out on one side of the preformed crack and all load transfer was through the remaining half of the splice on the other side. Because the concrete between the preformed crack and crack (2) had broken free, the dials indicate a partial closing of the preformed crack. This occurred in many cases of splice failure. Fracture occurred at 35.3 kips (steel stress 59.8 ksi) with a sudden complete longitudinal crack on the previously unbroken side of the splice. Figure 12a shows a fracture at the splice that is typical of the shorter splices in deformed bars.

Specimen D20-15 is typical of a stronger deformed-bar splice (Fig. 8). When the load reached 32.5 kips, longitudinal splitting (A) occurred in the splice, extending 3 in. on one side of the preformed crack. At the same time, the preformed crack opened another 0.0006 in. At 34.0 kips, crack (A) lengthened and a longitudinal crack (B) started on the other side of the splice. Vertical cracks (C) developed from the ends of these longitudinal cracks, about 4 in. from the preformed crack, at 36.5 kips. Load decreased, and with straining a transverse crack (1) formed at one end of the splice at 35.1 kips. The second transverse crack (2) developed at 37.1 kips (opening 0.0167 in.) accompanied by secondary cracking shown on the sketch. Following this crack the preformed crack opening decreased to 0.014 in.

Fifteen additional transverse cracks formed at loads between 35.0 and 40.1 kips (67.8 ksi steel stress) and preformed crack opening between 0.0131 and 0.0142 in. Some of these natural cracks opened as much as 0.04 in., and longitudinal cracks developed in several locations between closely spaced transverse cracks (Fig. 12b). The steel was stressed to the yield range at the higher loads in this stage. Further straining caused increased opening of all cracks, the widest attaining 0.132 in., with load rising to 43.0 kips. Because of the cracks in the splice region, the dials indicated a closing of the preformed crack. Fracture occurred at 45.3 kips, with large separation at the splice (Fig. 12c).

Specimen D20E-14 (Fig. 9) represents the deformed-bar specimens that exhibited large preformed crack openings (DC and D20-E). Longitudinal crack, (A), developed at 30.3 kips on the unspliced side of the preformed crack, extending 2 in. from the crack. At 35.3 kips the crack, (A) extended further both vertically and longitudinally, (A′), and a longitudinal crack (B) occurred 2 in. below top surface in the opposite side of the specimen. With further increase of load to 37.1 kips (steel stress 62.9 ksi), a transverse crack (1), formed and another longitudinal crack (C) extending 4 in., occurred 3 ½ in. below the crack (B). At this stage, no longitudinal cracks were observed on the spliced side of the preformed crack. The load decreased to 35.8 kips, and the preformed crack opened another 0.012 in. After forming additional transverse cracks (2) at 37.7 kips, (3) at 35.9 kips and (4) at 31.9 kips a longitudinal crack, (D), developed on the spliced side, extending 3 in. from the preformed crack.

Fourteen additional transverse cracks formed at loads between 30.0 and 38.9 kips and at preformed crack openings between 0.0378 and 0.0631 in. Longitudinal cracks developed at some of the transverse cracks, but cracks (A), (B), and (D) did not extend further in this stage. As the load was further increased, no additional cracks formed

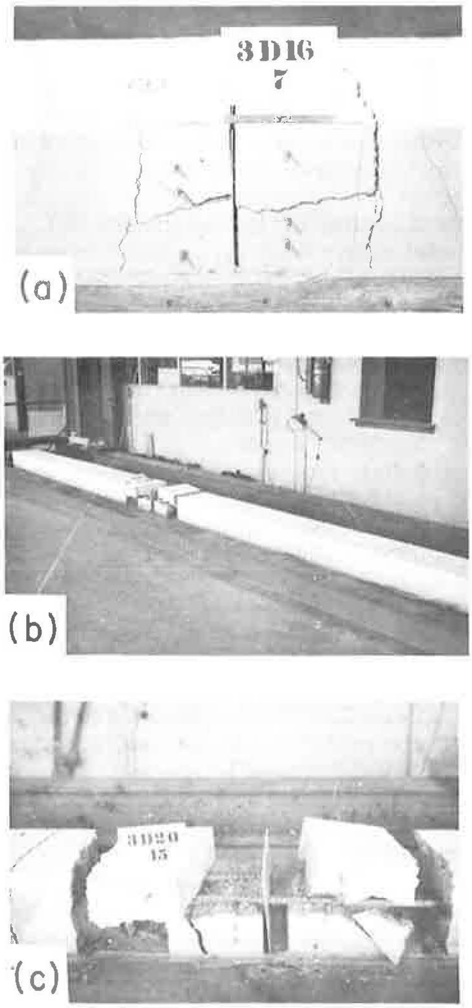


Figure 12. Fracture patterns: (a) specimen D16-7, (b) D20-15, and (c) D20-15.

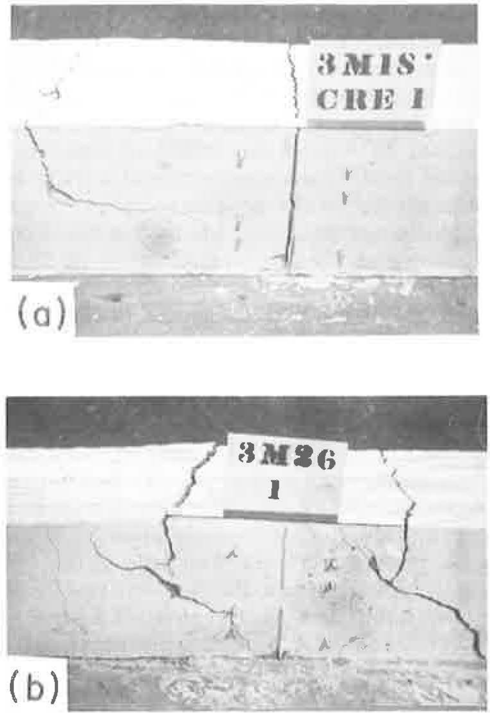


Figure 13. Fracture patterns: (a) specimen WWF18E-1 and (b) WWF26-1.

but the transverse cracks as well as the preformed kept opening with extension of the longitudinal cracks until sudden fracture of the splice at 46.2 kips (steel stress 78.2 ksi). Some transverse cracks opened as much as 0.2 in. just prior to fracture.

Specimen WWF18E-1 (Fig. 10) represents a relatively weak welded-wire fabric splice. At 21.6 kips (steel stress 36.7 ksi) a transverse crack, (1), formed. The load dropped to 19.0 kips and the preformed crack closed a little. Three additional transverse cracks formed between 18.6 and 22.8 kips and preformed crack openings of 0.0375 to 0.0470 in. At 22.9 kips, a noise was heard, probably indicating failure of one weld at the second transverse wire from the preformed crack. With further increase of load, the transverse and preformed cracks continued to open until fracture occurred at the splice at 27.2 kips (steel stress 46.2 ksi). Cracks appeared at the second transverse wire from the preformed crack (Fig. 13a). Just prior to the fracture, some transverse cracks opened 0.06 in.

Specimen WWF26-1 (Fig. 11) is typical of stronger welded-wire fabric splices. The first transverse crack (1) formed at 18.5 kips (steel stress 31.4 ksi). As the load dropped to 15.7 kips and the preformed crack closed a little, a second transverse crack (2) formed. Five additional transverse cracks formed at loads between 14.1 to 24.4 kips and preformed crack openings 0.0065 to 0.01 in. Beyond this stage, both preformed and transverse cracks continued to open but no additional cracks occurred prior to fracture of the splice at 41.25 kips (steel stress 70.0 ksi). The fracture was accompanied by cracks at sections between the first and second transverse wires on both sides of the preformed crack (Fig. 13b). The maximum transverse crack opening was 0.12 in.

TABLE 4

FRICTIONAL RESISTANCE

Specimen	Age (day)	Maximum Frictional Resistance in the Fourth Movement (lb)	Frictional Coefficient
D16	1	1,030	0.49
D16	3	910	0.44
D16	7	950	0.45
D16	14	940	0.45
D12	1	1,070	0.51
D12	3	810	0.39
D12	7	870	0.42
D12	14	760	0.36
WWF14	1	950	0.48
WWF14	4	860	0.43
WWF14	7	830	0.42
Avg.		907	0.44

Summary of Tests

The principal results of the tests are summarized for deformed-bar reinforcement (Table 5) and for welded-wire fabric reinforcement (Table 6). Load and preformed crack opening at the formation of the first natural transverse crack within the test length are given, and cases in which the first transverse crack formed at the end of the splice are indicated.

Load and preformed crack opening at first observation of a longitudinal crack are also given in Table 5. Most of the longitudinal cracks were first observed at the preformed cracks as previously described; those observed first at natural transverse cracks are indicated.

The number of transverse cracks before fracture is given in both Tables 5 and 6. Fracture data (Table 6) include load, maximum preformed and natural transverse

TABLE 5

TEST RESULTS DEFORMED-BAR REINFORCEMENT

Specimen	Age (day)	First Trans. Crack: Load (kip)	First Trans. Crack: Preform. Crack Open. (in.)	First Long. Crack: Load (kip)	First Long. Crack: Preform. Crack Open. (in.)	No. of Transverse Cracks Before Fracture	Fracture: Load (kip)	Fracture: Maximum Crack Opening Observed: Preformed (in.)	Fracture: Maximum Crack Opening Observed: Transverse (in.)	Fracture: Type
DC	1	21.3[a]	0.0115	28.8[b]	0.0181	15	45.0	0.1356	0.2080	Test terminated with no fracture
DC	3	31.9[a]	0.0183	34.8[b]	0.0200	20	46.3	0.1066	0.1360	
DC	7	27.4[a]	0.0120	31.3	0.0191	21	46.8	0.1338	0.2180	
DC	14	35.0	0.0300	30.0	0.0150	23	46.9	0.1325	0.1940	
D24	1	18.8	0.0047	30.8[b]	0.0083	12	42.1	0.0116	0.0880	Longitudinal crack in splice
D24	3	30.0	0.0077	30.0	0.0076	17	44.2	0.0137	0.0560	
D24	7	36.3	0.0093	31.3	0.0067	17	48.2	0.0132	0.1000	
D24	14	36.4	0.0093	36.4	0.0092	25	48.9	0.0153	0.1840	
D20	1	18.3	0.0020	29.5[b]	0.0056	14	42.3	0.0120	0.1320	Longitudinal crack in splice
D20	3	31.0	0.0094	27.0	0.0062	16	45.2	0.0130	0.1600	
D20	7	35.0[c]	0.0130	26.1	0.0056	6	37.9	0.0218	0.0360	
D20	15	36.5[c]	0.0131	32.5	0.0085	22	45.3	0.0166	0.1520	
D20E	1	28.6	0.0157	31.2[b]	0.0170	14	41.3	0.0980	0.1080	Longitudinal crack in splice
D20E	3	20.4	0.0084	29.1	0.0157	23	42.0	0.1150	0.1200	
D20E	7	35.0	0.0267	30.1	0.0144	31	44.4	0.1200	0.1200	
D20E	14	37.1	0.0290	30.3	0.0154	23	46.2	0.1700	0.1680	
D18	1	22.5[a]	0.0064	29.9	0.0124	13	33.5	0.0184	0.0260	Longitudinal crack in splice
D18	4	31.5	0.0091	31.5	0.0126	6	35.2	0.0223	0.0360	
D18	7	35.0[c]	0.0175	33.4	0.0104	20	40.0	0.0184	0.0900	
D18	14	34.4[c]	0.0105	34.4	0.0105	25	50.0	0.0149	0.1140	
D16	1	23.4	0.0104	27.1	0.0130	8	27.2	0.0130	0.0200	Longitudinal crack in splice
D16	3	27.8	0.0073	29.0	0.0093	1	29.4	0.0146	0.0300	
D16	7	30.2	0.0061	32.8	0.0080	5	35.3	0.0103	0.0220	
D16	14	32.9[c]	0.0149	32.9	0.0150	4	36.6	0.0168	0.0260	
D12	1	18.8	0.0128	23.1	0.0186	3	23.1	0.0186	0.0118	Longitudinal crack in splice
D12	3	22.5[c]	0.0098	23.3	0.0320	1	23.3	0.0322	—	
D12	7	25.3[c]	0.0129	26.3	0.0129	1	27.4	0.0165	—	
D12	14	28.9[c]	0.0095	28.9	0.0114	1	29.2	0.0125	—	

[a]Located at the end of yoke.
[b]Located at natural transverse crack.
[c]Located at end of splice.

TABLE 6

TEST RESULTS WELDED-WIRE FABRIC REINFORCEMENT

Specimen	Age (day)	First Trans. Crack: Load (kip)	First Trans. Crack: Preform. Crack Open. (in.)	No. of Transverse Cracks Before Fracture	Fracture: Load (kip)	Fracture: Maximum Crack Opening Observed: Preformed (in.)	Fracture: Maximum Crack Opening Observed: Transverse (in.)	Type[a]
WWFC	1	17.5[b]	0.0158	7	50.7	0.2400	0.176	A
WWFC	3	35.0	0.0436	6	53.3	0.1510	0.256	A
WWFC	7	41.3	0.0435	6	51.3	0.0740	0.100	A
WWFC	14	39.5	0.0475	7	50.0	0.1150	0.160	A
WWF27E	1	20.5	0.0185	9	35.5	0.0700	0.046	B
WWF27E	3	30.5	0.0281	7	52.5	0.1150	0.224	A
WWF27E	7	32.9	0.0288	5	51.5	0.0625	0.140	A
WWF27E	14	32.9	0.0267	7	54.5	0.0650	0.126	B
WWF26	1	18.5	0.0067	9	41.3	0.0162	0.124	C
WWF26	3	27.5	0.0078	7	47.7	0.0198	0.096	B
WWF26	7	37.5[b]	0.0132	7	48.5	0.0155	0.174	D
WWF26	14	35.0	0.0101	8	52.3	0.0186	0.108	B
WWF18E	1	21.6[b]	0.0360	4	27.2	0.0720	0.060	B
WWF18E	3	25.1	0.0394	6	31.0	0.2318	0.080	B
WWF18E	7	27.5	0.0395	3	33.5	0.2512	0.076	B
WWF18E	14	39.4	0.0450	8	47.9	0.0825	0.200	B
WWF18	1	20.7	0.0070	7	23.9	0.0230	0.136	B
WWF18	3	24.9	0.0058	10	41.2	0.0109	0.084	B
WWF18	7	28.2	0.0087	6	37.2	0.0140	0.280	B
WWF18	14	31.1	0.0078	10	38.8	0.0230	0.100	B
WWF14	1	-	-	-	14.6	0.0453	-	C
WWF14	4	-	-	-	20.6	0.0309	-	C
WWF14	7	-	-	-	23.4	0.0100	-	C
WWF14	14	-	-	-	29.9	0.0100	-	C

[a]Failure types:
(a) Longitudinal wire tension,
(b) Weld and concrete at splice,
(c) Concrete at splice, and
(d) Weld and longitudinal wire tension.
[b]Located at end of yoke.

crack openings, and type of failure. The maximum crack openings were measured at the last load increment prior to fracture. "Weld and concrete at splice" (footnote a under fracture type in Table 6) indicates fracture by cracking of concrete in the vicinity of the transverse wires of the spliced region accompanying the weld failures (Fig. 13b).

DISCUSSION OF RESULTS

First Transverse Crack

First transverse cracks occurred in the uniformly reinforced test length between the yokes and the ends of the splice in 33 out of 52 cases. In 8 of the 28 deformed-bar specimens the first crack developed at one end of the splice. In 7 other cases in both series D and WWF, it developed at the end of the yoke bars. No transverse cracks developed in specimens WWF14. In all cases, the load required to cause the second crack was but little greater than at first crack. Apparently there is no significant stress concentration in the concrete at the end of a reinforcing bar to cause early cracking at this place.

Test results for series D (Fig. 14) are grouped by age, because cracking is a function of concrete strength. At 1-day age, load at first crack varied from 18.3 to 28.6 kips, whereas at 14 days the range was between 28.9 and 37.1 kips. The preformed crack opening when the first transverse crack occurred was between 0.0020 and 0.0157 in. at 1-day age, and between 0.0093 and 0.0300 in. at 14-day test age. Larger preformed crack openings appeared in DC and D20E, in which only two reinforcing bars cross the preformed crack.

All splice lengths of 16 in. or greater in deformed-bar reinforcement were capable of resisting loads great enough to break the concrete in tension in unspliced regions at

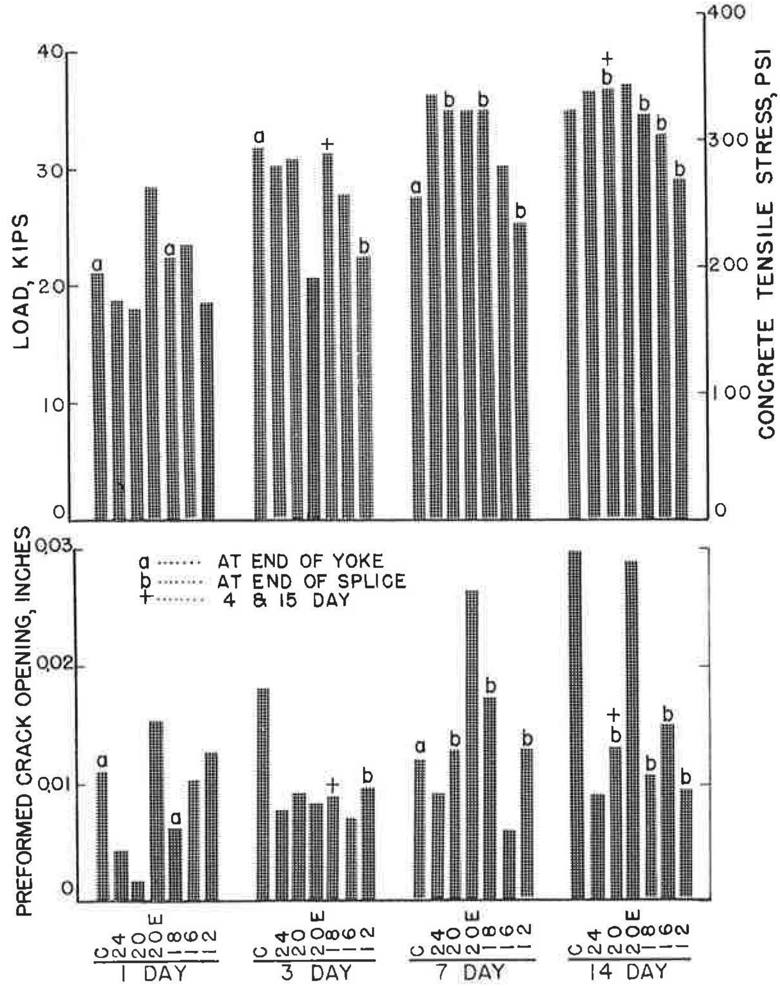


Figure 14. First transverse cracks, series D.

all ages. Preformed crack openings within or at the end of these splices were held to small values as the additional transverse cracks developed.

In specimens D12-3, -7, and -14, the only transverse cracks occurred at the end of the splice, and load at fracture was but little greater than load at first crack. Although these were transverse cracks, they appear to be part of the breakdown of the splice and not independent cracks as occurred with longer splices.

First transverse crack data for welded-wire fabric are given in Table 6 and Figure 15. At 1-day age, load at first crack varied from 17. 5 to 21. 6 kips, and from 31. 1 to 39. 5 kips at 14-day test age. Preformed crack openings were 0. 0067 to 0. 0360 in. at 1-day and 0. 0071 to 0. 0475 in at 14-day age. The openings were greater for WWFC and WWF27E because four longitudinal wires from one fabric only were effective across the preformed crack. All lap lengths tested except 14 in. were strong enough to hold preformed cracks within the splice from opening excessively prior to the formation of additional transverse cracks.

The average values of the first transverse crack openings measured immediately after the cracks formed were 0. 0159 in. for deformed-bar and 0. 0292 in. for welded-wire fabric specimens. These measurements were made on all specimens.

Concrete strength varied somewhat from batch to batch (Table 1) and increased with age. A comparison was made, therefore, between concrete tensile stress at formation

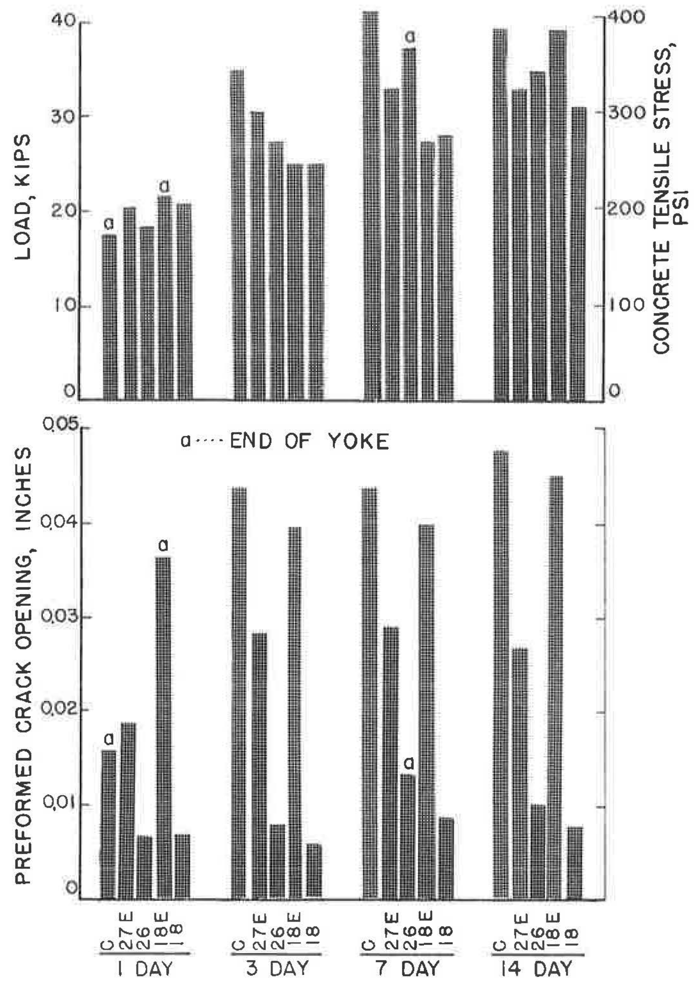


Figure 15. First transverse cracks, series WWF.

of the first transverse crack and strength measurements from the control samples. Concrete tensile stresses were calculated by dividing the test loads by the transformed area of cross-section. Modulus of elasticity of concrete was measured on nine compression test cylinders from different batches and an average value of 4,130,000 psi for all ages was used to transform steel to equivalent concrete area.

Concrete tensile stresses at formation of the first transverse crack are given in Table 7. These values varied with age, as would be expected. The ratio of concrete tensile stress to modulus of rupture and the ratio of concrete tensile stress to the square root of compressive strength at the same age were calculated. Average values of these ratios are

$$\sigma_c = 0.57 \, M_r \text{ and } \sigma_c = 5.20 \sqrt{f_c}$$

Number of Transverse Cracks Before Fracture

The ability of a splice to withstand loads sufficient to produce transverse cracks at unspliced sections is important to the satisfactory functioning of reinforcement in continuous pavement. The number of transverse cracks formed before fracture (Tables

TABLE 7

CONCRETE TENSILE STRESS AT FIRST TRANSVERSE CRACK

Deformed Bar					Welded Wire Fabric				
Specimen	Age (day)	Concrete Tensile Stress σ_c (psi)	$\frac{\sigma_c}{M_r}$	$\frac{\sigma_c}{\sqrt{f_c'}}$	Specimen	Age (day)	Concrete Tensile Stress σ_c (psi)	$\frac{\sigma_c}{M_r}$	$\frac{\sigma_c}{\sqrt{f_c'}}$
DC	1	198[a]	0.58	4.78					
D24	1	174	0.74	5.37	C	1	172[a]	0.60	4.84
D20	1	170	0.45	4.01	27E	1	201	0.60	4.93
D20E	1	265	0.70	6.53	26	1	182	0.67	5.75
D18	1	209[a]	0.44	4.80	18E	1	212[a]	0.65	5.53
D16	1	217	0.80	6.99	18	1	203	0.62	5.21
D12	1	174	0.55	4.63	14	1	-	-	-
Avg.		201	0.61	5.30	Avg.		194	0.63	5.25
DC	3	296[a]	0.56	5.14					
D24	3	278	0.62	5.73	C	3	343	0.69	6.47
D20	3	288	0.58	5.60	27E	3	299	0.59	5.45
D20E	3	189	0.40	3.68	26	3	270	0.56	5.11
D18	4	292	0.51	5.28	18E	3	246	0.55	4.18
D16	3	258	0.53	5.19	18	3	244	0.54	4.87
D12	3	209[b]	0.46	4.18	14	4	-	-	-
Avg.		259	0.52	4.97	Avg.		280	0.59	5.22
DC	7	254[a]	0.37	3.84					
D24	7	337	0.65	5.63	C	7	405	0.67	6.72
D20	7	325[b]	0.62	5.58	27E	7	323	0.56	5.44
D20E	7	325	0.61	5.74	26	7	368[a]	0.64	6.14
D18	7	325[b]	0.55	5.28	18E	7	270	0.47	4.29
D16	7	280	0.50	4.79	18	7	277	0.52	4.64
D12	7	235[b]	0.46	4.04	14	7	-	-	-
Avg.		297	0.54	4.99	Avg.		329	0.57	5.45
DC	14	325	0.47	4.56					
D24	14	338	0.62	5.09	C	14	388	0.60	6.10
D20	15	339[b]	0.60	5.19	27E	14	323	0.50	5.13
D20E	14	344	0.55	5.44	26	14	343	0.61	5.40
D18	14	319[b]	0.52	4.96	18E	14	387	0.68	6.08
D16	14	305[b]	0.50	4.90	18	14	305	0.55	4.72
D12	14	268[b]	0.48	4.32	14	14	-	-	-
Avg.		320	0.53	4.92	Avg.		349	0.59	5.49
Grand Avg.			0.55	5.05	Grand Avg.			0.59	5.35

[a]Crack at end of yoke.
[b]Crack at end of splice.

5 and 6) indicates the ability of the splice to produce transverse cracks. Eighteen-inch or longer splices in both deformed-bar and welded-wire fabric specimens produced numbers of cracks comparable with the unspliced specimens (DC and WWFC).

First Longitudinal Cracks—Series D

Longitudinal cracks appearing in the 8-in. faces in the plane of reinforcement are evidence of bond failures in the deformed-bar test specimens. They are caused by tensile splitting forces in the concrete acting perpendicular to the reinforcement. Beyond the adhesion stage, the bond strength depends chiefly on bearing of reinforcement deformations against the concrete, and the tensile splitting forces are thus induced.

In more than half of these tests, the first transverse cracks were observed before the formation of the longitudinal crack (Table 5). The 12 cases in which the first longitudinal cracks formed before, or at the same time as, the first transverse cracks involved later-age test specimens. It seems that the occurrence of the first longitudinal crack is a function of the preformed or transverse crack opening as well as concrete strength, whereas the first transverse crack depends on concrete strength alone. While these longitudinal cracks extended gradually, many additional transverse cracks developed before complete longitudinal splitting at the splice took place at fracture.

In most cases, the first longitudinal crack occurred at preformed cracks. The 5 cases in which the first longitudinal cracks developed elsewhere were early-age test specimens either unspliced or having relatively longer splices. The openings of the preformed cracks, except DC and D20E, never exceeded 0. 015 in. unless the splice was in final process of fracture. The preformed cracks opened as much as 0. 02 in before the first longitudinal cracks were observed in DC and D20E.

The steel stresses at which longitudinal cracks occurred in unspliced portions of the test length are given in Table 8. These cracks were in the plane of the steel and developed from previously formed transverse cracks or from the preformed crack in DC and D20E. These longitudinal cracks are apparently associated with steel stresses of about 50 ksi or greater, and are somewhat dependent on concrete age.

The occurrence of longitudinal cracks within the splice at the preformed crack is more significant than splitting at other transverse cracks. Crack opening, steel stress (based on 0. 6 percent steel) and bond stress are given in Table 9.

Splitting within the splice occurred at preformed crack openings between 0. 0052 and 0. 0150 in. in all cases (except D12) having four bars across the crack. Openings for specimens DC and D20E are larger, since there is but half as much steel stiffening the crack.

Steel stresses of about 40 ksi or higher were required to start splitting in the splice. There is some tendency toward higher stresses for longer splices and later ages. Sixteen-inch or longer splices were capable of developing steel stresses of 44 ksi or more at all test ages before the first longitudinal cracks were observed. These steel stresses are comparable to the steel stresses developed by unspliced specimens, DC. The 12- and 16-in. splices developed longitudinal cracks only within the splice, at loads near fracture (Fig. 16).

Bond stress is computed as the average unit bond stress on the total embedded bar surface area at the splice. Bond stresses increase with age in general. The bond stresses are lower for the longer splices. It is recognized that the bond stress distribution along the splice is not uniform; rather, splitting begins at a higher than average bond stress adjacent to the preformed crack. The higher values of average bond stress for the shorter splices (Table 9c) are probably near the unit bond stress attained locally along the splice when a longitudinal crack forms. However, the average bond stresses for the initiation of longitudinal cracks in the longer splices may be of use in estimating the likelihood of such occurrences in other splices of these proportions made with similar materials.

TABLE 8

LONGITUDINAL CRACKS IN UNSPLICED REGIONS (Series D)

Specimen	Steel Stress at Trasverse Crack			
	1-Day	3-Day	7-Day	14-Day
DC	48.8	59.0	53.1	50.8
D24	51.7	57.3	63.6	65.9
D20	50.0	55.1[a]	60.2[a]	62.9[a,b]
D20E	51.9	49.3	51.0[a]	59.8[a]
D18	-	55.9[a,c]	59.3[a]	61.7[a]
D16	-	-	-	-
D12	-	-	-	-
Avg.	50.5	55.3	57.4	60.3

[a]Crack at end of splice.
[b]Fifteen-day age.
[c]Four-day age.

TABLE 9

CONDITIONS AT LONGITUDINAL CRACK FORMATION AT THE PREFORMED CRACK (Series D)

Specimen	Age at Test			
	1-Day	3-Day	7-Day	14-Day
(a) Preformed Crack Opening (in.)				
DC	0.0242	0.0286	0.0191	0.0150
D24	0.0112	0.0076	0.0067	0.0092
D20	0.0063	0.0062	0.0052	0.0085[a]
D20E	0.0269	0.0157	0.0144	0.0154
D18	0.0124	0.0126[b]	0.0104	0.0105
D16	0.0130	0.0093	0.0080	0.0150
D12	0.0186[c]	0.0320[c]	0.0129	0.0114
(b) Stress in Steel (ksi)				
DC	55.1	61.5	53.1	50.8
D24	67.8	50.8	53.1	61.7
D20	51.7	45.8	44.2	55.1[a]
D20E	60.3	49.3	51.0	51.3
D18	50.7	53.4[b]	56.6	58.5
D16	45.9	49.2	55.6	55.7
D12	39.2[c]	39.5[c]	44.6	48.9
(c) Bond Stress (psi)				
DC	-	-	-	-
D24	432	324	338	393
D20	395	350	338	421[a]
D20E	461	377	390	393
D18	430	453[b]	481	495
D16	439	470	531	533
D12	499[c]	503[c]	568	624

[a]Fifteen-day age.
[b]Four-day age.
[c]At fracture.

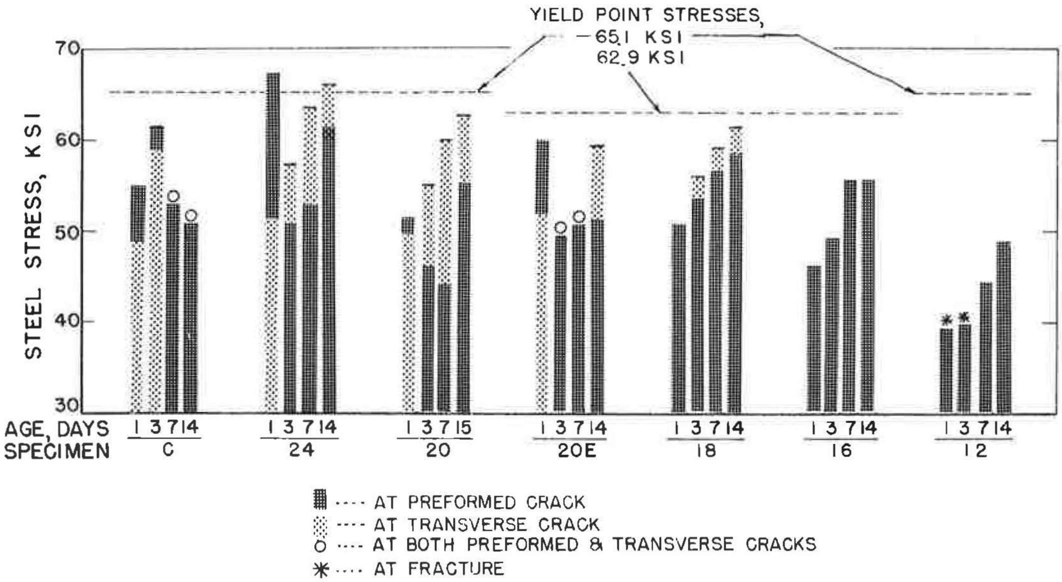


Figure 16. First longitudinal cracks, series D.

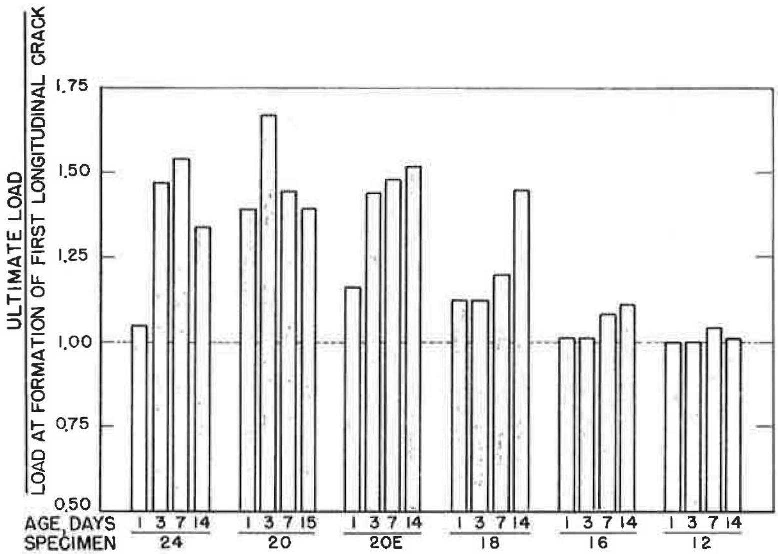


Figure 17. First longitudinal crack at the preformed crack, series D.

The ratios of fracture load to load at the formation of the first longitudinal cracks at the preformed crack are shown in Figure 17. These ratios indicate the reserve strength of a splice after the formation of the first longitudinal cracks. The first longitudinal cracks that developed at the preformed crack continued to extend with further straining of the specimen, and eventually contributed to the complete splitting of the splice at fracture. In the meantime, additional transverse cracks developed and existing ones continued to open. The ability of a splice to resist increased load after starting a longitudinal crack is important. Eighteen-inch or shorter splices are definitely inferior to 20-in. or greater splices in this respect.

TABLE 10

STEEL STRESS FOR 0.05- AND 0.10-IN. CRACK OPENINGS (Series D)

Specimen	Test Age (day)	Crack Opening 0.05 In. Steel Stress (ksi)	0.05 In. No. of Transverse Cracks Formed	0.10 In. Steel Stress (ksi)	0.10 In. No. of Transverse Cracks Formed
DC	1	63.6	10	72.2	10
DC	3	59.0	6	77.1	14
DC	7	62.5	8	72.2	15
DC	14	62.5	5	72.9	20
D24	1	56.2	9	67.8	9
D24	3	67.8	13	-	-
D24	7	63.6	5	72.0	14
D24	14	63.8	2	72.0	14
D20	1	50.0	8	69.8	10
D20	3	59.3	10	72.3	15
D20	7	-	-	-	-
D20	15	70.0	19	72.9	19
D20E	1	53.3	11	65.2	13
D20E	3	50.3	2	63.2	11
D20E	7	59.3	1	62.2	6
D20E	14	64.0	3	66.0	17
D18	1	-	-	-	-
D18	4	-	-	-	-
D18	7	59.3	4	64.4	14
D18	14	61.7	3	72.7	21

TABLE 11

STEEL STRESS FOR 0.05- AND 0.10-IN. CRACK OPENINGS (Series WWF)

Specimen	Test Age (day)	Crack Opening 0.05 In. Steel Stress (ksi)	0.05 In. No. of Transverse Cracks Formed	0.10 In. Steel Stress (ksi)	0.10 In. No. of Transverse Cracks Formed
WWFC	1	38.2	5	57.3	6
WWFC	3	59.5	1	63.7	3
WWFC	7	70.2	2	81.0	7
WWFC	14	67.2	4	68.0	4
WWF27E	1	57.5	7	-	-
WWF27E	3	56.2	2	84.8	8
WWF27E	7	68.5	2	68.5	3
WWF27E	14	60.2	3	68.8	6
WWF26	1	37.2	6	58.5	7
WWF26	3	56.2	2	73.3	7
WWF26	7	63.8	2	65.2	6
WWF26	14	66.5	5	75.8	7
WWF18E	1	37.8	2	-	-
WWF18E	3	47.8[a]	1	50.0[a]	5
WWF18E	7	46.8	2	53.5[a]	2
WWF18E	14	47.0	2	67.0	3
WWF18	1	37.4	2	37.8	4
WWF18	3	44.7	1	63.6	7
WWF18	7	49.0	2	63.3	6
WWF18	14	59.5	6	59.5	7

[a]At preformed crack.

Longitudinal cracks were not observed in the specimens reinforced with welded-wire fabric, except at fracture. In WWF14, 18, and 18E, the concrete above the reinforcement and between the transverse wires in the splice region split apart at fracture (Fig. 13a).

Large Crack Openings

In addition to the ability of a splice to produce transverse cracks in the region away from the splice, the splice should also be capable of opening these transverse cracks in the unspliced region amounts comparable with the crack openings in the unspliced control specimens. A splice is considered satisfactory when it withstands loads at an arbitrary 0.10-in. opening of any transverse crack without opening the preformed crack such amounts. The highest steel stresses (based on 0.6 percent steel) attained and number of transverse cracks formed prior to 0.05- and 0.10-in. openings of any crack are given in Tables 10 and 11. The cases in which the preformed cracks opened 0.05 and 0.10 in. before any other transverse crack opened these amounts are indicated in Table 11. Test specimens WWF14, D12 and D16 fractured before any transverse crack opened 0.05 in. (Tables 5 and 6).

Exclusive of splices at imminent fracture, 0.10-in. cracks did not occur until the stresses exceeded about 60 ksi for both kinds of reinforcement. Steel stresses of 50 ksi or greater in the deformed-bar series and 40 ksi or greater in welded-wire fabric caused 0.05-in. cracks.

Twenty-inch or longer splices in deformed bar and 18-in. or longer in welded-wire fabric were capable of opening some of the transverse cracks to 0.10 in. The number and opening of transverse cracks in the test lengths of specimens having these splices were comparable to the cracking in the control specimens.

Ultimate Strength

In specimens with the preformed cracks located at center of the splices, the preformed cracks opened less than 0.03 in. for deformed-bar and 0.045 in. for welded-wire

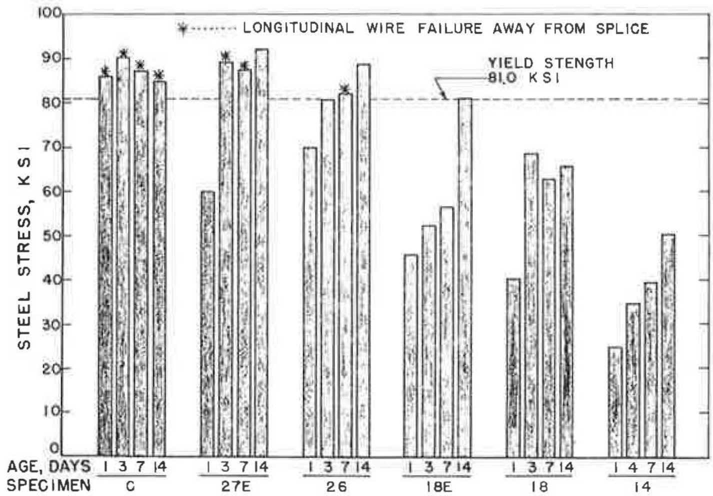


Figure 18. Ultimate strengths, series D.

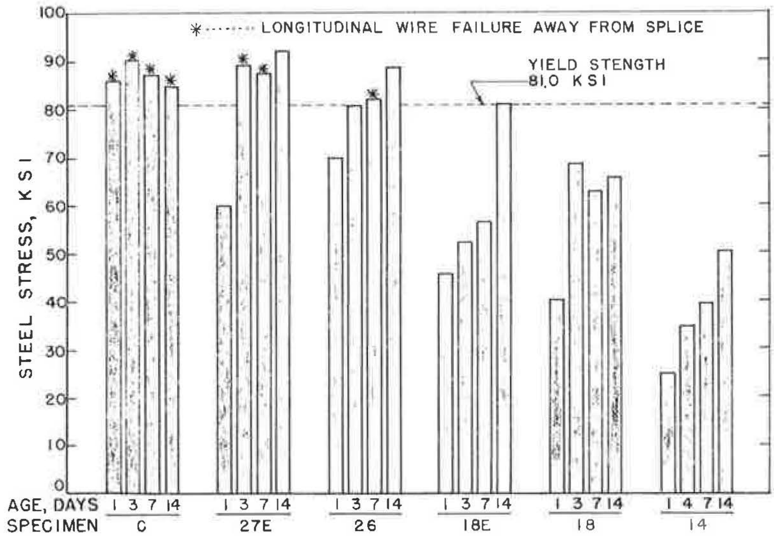


Figure 19. Ultimate strengths, series WWF.

fabric reinforcement. For preformed cracks at the end of the splice and unspliced controls, some preformed cracks opened as much as 0.17 in. for deformed-bar (DC and D20E) and 0.24 in. for welded-wire fabric (WWFC and WWF27E) reinforcement (see Tables 5 and 6). In all specimens reinforced with deformed bars, the preformed crack within the splice opened less than natural transverse cracks until fracure occurred. This was true also of specimens WWF18 and WWF26. Preformed cracks at the ends of the splices in both series behaved like transverse cracks in unspliced reinforcement.

Steel stresses at cracked sections in unspliced regions, series D, were computed from the fracture loads (Fig. 18). Splices 20 in. or longer in deformed bars developed the yield strength of the reinforcement before fracture. Eighteen-inch splices developed

TABLE 12

UNIT BOND STRESS AT ULTIMATE LOAD
(Series D)

Specimen	Age at Test			
	1-Day	3-Day	7-Day	14-Day
D24	454	477	520	528
D20	548	586	491	587[a]
D20E	535	544	575	598
D18	482	507[b]	576	720
D16	440	476	572	593
D12	499	503	592	630
Avg.	493	516	554	609

[a]Fifteen-day age.
[b]Four-day age.

slightly less than the yield strength at one and three days. Ultimate loads for all series D specimens except DC (unspliced) occurred upon fracture of the splice. Transverse crack openings greater than 0.1 in. were obtained for all but three cases of the 20- and 24-in. splices. Tests of specimens DC were terminated at crack openings of 0.1 in. or greater. Thus, only the second part of the third criterion was used in evaluating these splices.

Specimens WWFC, WWF27E-3 and -7, and WWF26-7 failed by tensile fracture of the longitudinal wires in the unspliced region (Fig. 19). WWF26-7 failed at the welds in the splice region on two longitudinal wires and the other two of the same fabric failed in tension at a transverse crack away from the splice. WWF14 and WWF26-1 (Fig. 13b) failed by concrete cracking at the transverse wires in the splice. Fractures in the rest of the WWF specimens occurred by cracking of the concrete at the transverse wires in the splice accompanying the weld shear failures at the transverse wires. The weld failures were observed by removing broken concrete from the splice area after test. The first part of criterion three (develop ultimate strength of reinforcement) applied only to some of the WWF specimens.

Except at 1-day age, 26- and 27-in. splices developed the yield strength of the reinforcement. The shorter splices were unable to attain the yield strength (Fig. 19).

Average unit bond stresses at ultimate load in series D are given in Table 12. These bond stresses were less sensitive to splice length than the bond stresses at the formation of the first longitudinal cracks at the preformed crack. The average values of the ultimate bond stresses for all splice lengths were 493 psi at 1 day, 516 at 3 days, 554 at 7 days, and 609 at 14 days.

SUMMARY OF RESULTS

Tensile cracking strength of the reinforced concrete slab can be estimated by $0.57M_r$ or by $5.20\sqrt{f_c}$ in pounds per square inch, where M_r and f_c are modulus of rupture and compressive strength of the concrete at the time of interest, respectively. Stresses are calculated for the transformed area of the reinforced section.

Horizontal longitudinal cracks occurred in the plane of the reinforcement in specimens reinforced with deformed bars. Such cracking originated at transverse cracks in the unspliced portions of the test specimens when steel stresses reached 50 ksi or greater with crack openings of 0.015 to 0.029 in. These longitudinal cracks are indications of bond failure in regions where the tensile stress in the steel decreases sharply in the longitudinal direction from the high values at the transverse crack. The high tensile stress gradient requires high bond stresses in these regions. When bond failure occurs, the tensile stress gradient must decrease, and the strain in a greater length of steel contributes to marked increases in transverse crack opening.

Longitudinal cracking from the preformed crack in the splice appeared at about the same loads as the first natural transverse crack. In the longer splices, however, these longitudinal cracks were short and did not progress further until many additional transverse cracks had formed.

Ultimate average bond strength in deformed-bar splices between 12 and 24 in. in length varied from 493 psi at 1-day age to 609 psi at 14-day age. These values were obtained with average concrete compressive strengths of 1,470 psi at 1-day age to 4,100 psi at 14-day age.

Large openings of transverse cracks, except at fracture of shorter splices, did not occur until the reinforcement yielded. Such large openings were preceded by the development of many transverse cracks.

Cracks at splices do not open as wide as cracks at the end of splices or in unspliced reinforcement because there is twice as much steel in the splice area.

CONCLUSIONS

On the basis of the three stated criteria, the 20-in. splice length (D20 and D20E) in No. 5 deformed-bar reinforcement was adequate in all respects at all concrete ages. This is a 32-diameter lap. The 18-in. splice (D18), 29-diameter lap, was also adequate based on the first criterion but was on the borderline by the second criterion and did not meet the third at 1- and 3-day ages.

In welded-wire fabric of the size tested, the 26-in. splices (WWF26 and WWF27E) were adequate by all three criteria. The 18-in. splice (WWF18) met only the first criterion.

These experiments, in which loading was continued to failure at early concrete ages, constitute a most severe test of splice strength. Splices adequate by all three criteria will perform as well as the unspliced reinforcement when high stresses occur in the pavement.

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