Ultimate Shear Tests Of Prestressed Concrete I-Beams Under Concentrated And Uniform Loadings

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SYNOPSIS

This paper presents and discusses the results of thirty-five shear tests on twenty pretensioned prestressed concrete I-beams. The principal variables were the amount of web reinforcement and the shear span to effective depth ratio. Symmetrical and unsymmetrical concentrated loadings and uniform loadings were used. Web crushing, stirrup fracture, and shear compression failures were obtained. Conservative but realistic agreement was found between the tests results and the new ultimate shear strength provisions of Section 2610, ACI 318-63.

INTRODUCTION

When a prestressed concrete beam is subjected to an ultimate strength test, the behavior of the members may be described with reference to the uncracked and cracked, or overload, range. In the uncracked range the response to load is approximately linear. However, at cracking a fundamental change takes place in the way in which the beam resists load. Two cases are important. When flexure predominates, the strain distribution remains linear up to the point of failure. However, when shear is significant, inclined cracks develop, and in the region of inclined cracking the strain distribution becomes non-linear. If shear is critical, the inclined cracking leads to a shear failure.

The shear failure mechanism has been studied extensively, both in reinforced and prestressed concrete. This research work has resulted in the new provisions governing the design of prestressed beams for shear, which are contained in Section 2610 of the ACI Building Code (ACI 318-63).

A study of the overload behavior of pretensioned prestressed I-beams was completed at Lehigh University in 1963. This work led to an investigation of the basic shear strength of I-beams with web reinforcement. Shear failures have been obtained in this investigation on beams tested on shear span to effective depth ratios varying from 2.11 to 7.75 and having percentages of web reinforcement, based on the web width, varying between 0.09 and 0.73. Only the principal results of these tests are presented herein. In addition, the test results are compared to the new provisions of ACI 318-63.

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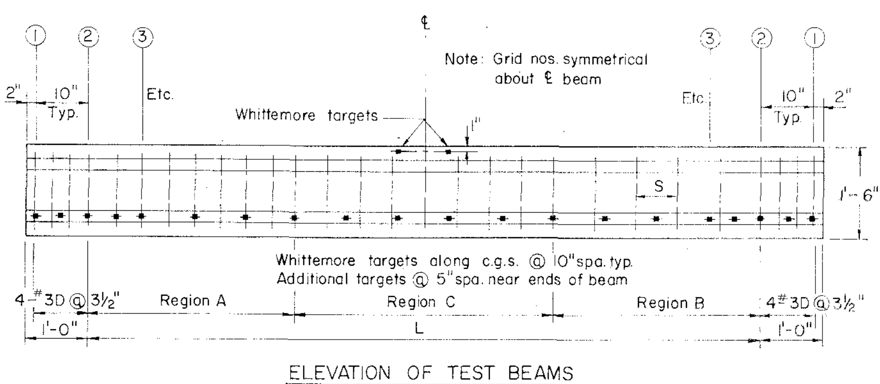
TEST SPECIMENS

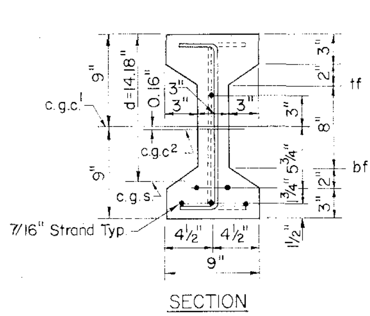
A doubly symmetrical I-shaped cross section with a total depth to flange width ratio (h/b) of 2 and a flange to web width ratio (b/b') of 3 was used for all twenty beam specimens. An elevation and cross section of the test beams, referred to as the F Series, are shown in Fig. 1.

Except for the uniformly loaded test beams, the span length (L) of each beam was divided into three regions, designated as A, B, or C, in which different amounts of web reinforcement were provided, as indicated in Table 1. The web reinforcement was fabricated from hot-rolled No. 3 or No. 2 deformed bars, or from annealed 3/16 in. diam. deformed masonry bars. For the No. 3 bar, the yield stress (f_y) was 52,500 psi and the ultimate stress (f_u) was 78,300 psi, based on an area of 0.11 sq. in. For the No. 2 bar, f_y was 59,500 psi and f_u was 85,700 psi, based on an area of 0.049 sq. in. For the 3/16 in. diam. bar, f_u was 36,600 psi and f_u was 47,500 psi based on an area of 0.0276 sq. in. Each stirrup consisted of either one or two U-shaped bars, referred to as S or D, respectively. The amount of web reinforcement in different regions may be compared by the web reinforcement index ($rf_y/100$), where the percentage of web reinforcement (r) is based on the web width.

Prestress was provided by six 7/16 in. diam. high tensile strength strands which were straight throughout the length of the test beam. Each strand was pretensioned to a nominal initial force of 18.9 kips. A stress-strain curve for the strand is shown in Fig. 2.

The test beams were cast in steel forms using ready-mixed concrete with a cement to sand to coarse aggregate ratio of approximately 1 to 2 to 2.2. The mix contained 7.5 bags of Type III portland cement per cubic yard and the slump varied be-





SECTION PROPERTIES		
Property	Concrete Section¹	Transformed Section²
A	102.0 in.²	105.3 in.²
I	3854 in⁴	3986 in⁴
Z^{top}	428.2 in³	435.2 in³
Z^{bot}	428.2 in³	450.9 in³
Q^{tf}	262.5 in³	270.9 in³
Q^{cg}	286.5 in³	298.5 in³
Q^{bf}	262.5 in³	276.3 in³

Fig. 1—F Series Test Beams.

tween 1.5 and 4 in. Maximum size of the coarse aggregate was ¾ in. With each test beam were cast 21 or more standard concrete cylinders and three modulus of rupture beam specimens. The test beams and modulus of rupture specimens were vibrated; the cylinders were rodded. The concrete was cured by covering with wet burlap and plastic sheeting for four days. Instrumentation in the form of Whittemore Strain Gage targets was positioned on the test beams after the surface of the test beams had dried. Prestress was slowly transferred to the test beams on the fifth day after casting, after which the specimens were stored in the laboratory until the time of testing.

PROCEDURE AND RESULTS

Concrete and Prestressing Data

Compression tests were conducted on standard concrete cylinders to determine the ultimate compressive strength (f'_c) of the concrete associated with the test beams at the time

Table 1. Test Beam Details

Beam No.	Region	Length (in.)	Web Reinf.	$\frac{rf_y}{100}$ (psi)	Beam No.	Region	Length (in.)	Web Reinf.	$\frac{rf_y}{100}$ (psi)
	A	48	#2S@8″	117		A	70	3/16S@3.5″	96
F-X1	B	48	#2S@8″	117	F-10	B	70	3/16S@7″	48
	C	50	#3D@6.25″	612		C	50	#3D@5″	766
	A	30	#3S@5″	383		A	70	#2S@8.75″	107
F-1	B	30	#2S@5″	188	F-11	B	70	3/16S@5″	67
	C	50	#3D@5″	766		C	70	#3S@7″	274
	A	40	#2S@5″	188		A	80	3/16S@4″	84
F-2	B	40	#2S@8″	117	F-12	B	80	3/16S@8″	42
	C	50	#3D@6.25″	612		C	50	#3D@8.33″	460
	A	40	#3S@6.67″	287		A	80	3/16S@3.2″	105
F-3	B	40	3/16S@4″	84	F-13	B	80	3/16S@5.72″	59
	C	60	#3D@6″	638		C	50	# 3S@6.25″	306
	A	50	#2S@6.25″	150		A	90	3/16S@4.5″	75
F-4	B	50	#2S@8.33″	113	F-14	B	90	3/16S@9″	38
	C	50	#3D@6.25″	612		C	36	#3D@6″	638
	A	50	#2S@5″	188		A	100	3/16S@5″	67
F-5	B	50	3/16S@4.16″	81	F-15	B	100	3/16S@10″	34
	C	60	#3D@7.5″	511		C	16	#3D@4″	957
	A	100*	—	—		A	100	3/16S@3.33″	101
F-6	B	100	3/16S@7.15″	47	F-16	B	110	3/16S@7.33″	46
	C	16	#2D@4″	468		C	0	—	—
	A	60	#2S@7.5″	125		A			
F-7	B	60	#2S@10″	94	F-17	B	150	3/16S@6″	56
	C	50	#3D@6.25″	612		C			
	A	60	#2S@6″	156		A			
F-8	B	60	3/16S@6″	56	F-18	B	210	3/16S@6″	56
	C	60	#3S@6″	319		C			
	A	90	3/16S@3.33″	101		A	50	#2S@5″	188
F-9	B	90	3/16S@6″	56	F-19	B	50	#2S@6.25″	150
	C	36	#3D@6″	638		C	100	#2S@5″	188

** 3/16 S @ 10″ ($rf_y/100 = 34$) were used beginning at the reaction for 50″ of the shear span; #2S @ 6.25″ ($rf_y/100 = 150$) were used in the remaining 50″.*

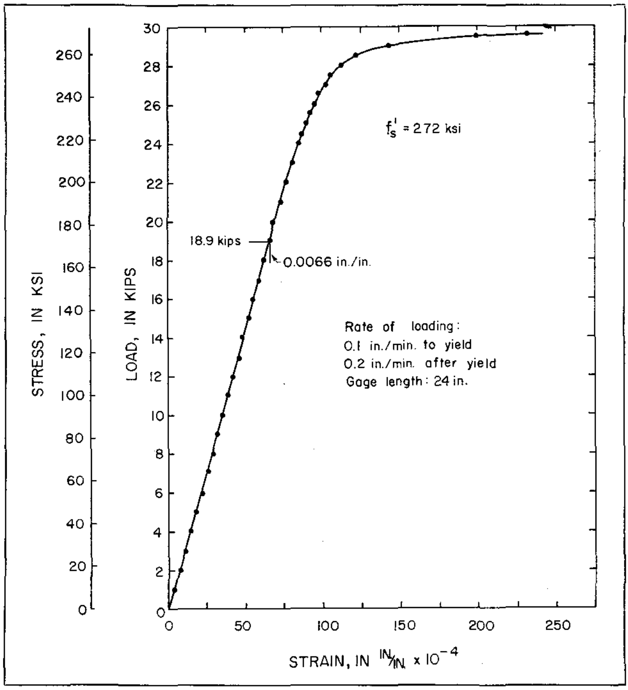


Fig. 2—Stress-Strain Curve for Prestressing Strand.

of prestress transfer and at the time of test. In addition, modulus of rupture tests on 6 in. sq. beam specimens of plain concrete and splitting tests on standard concrete cylinders were conducted to determine the tensile strength (f'_r and f'_{sp}, respectively) of the concrete. Strips of plywood 1/8 in. thick and 1 in. wide were used between the cylinders and the testing machine in conducting the splitting tests. The results of these tests are presented in Table 2. The values of f'_c at transfer and f'_r at test are an average of three tests; all other values are an average of six or more tests.

The initial prestress force (F_i) was measured by means of load cells placed on each strand, and is given in Table 3. Whittemore readings on the surface of the test beams were used to determine the losses in the prestress force after transfer and to the time of test. Based on these losses, the prestress force in each test beam at the time of test (F) was determined and is given in Table 3. The Whittemore readings were also used to determine the distance from the ends of the beam along the center of gravity of the prestressing strand to the point at which 85% of the prestress force was effective. These values are given as the transfer distances in Table 3.

Concentrated Load Tests

Concentrated loads were applied to all of the test beams except F-17 and F-18. The typical procedure was to first load the test beams as shown in Fig. 3a. Shear failures were obtained in Region B in every case except for F-9, in which case the shear failure occurred in Region A. After completion of the first test, the physical appearance of the part of the beam away from the failure region indicated a high degree of recovery.

Flexure and shear cracks were closed, and noticeable camber remained. Measurements of the prestress force by means of the Whittemore targets on the c.g.s. indicated little or no change in the magnitude of the prestress force. Consequently it was possible, on all of the test beams except F-6, F-15, and F-16, to conduct a second test, loading the beams as shown in Fig. 3b.

In general, loads were applied in increasing shear increments of approximately 2 kips, except when approaching loads at which cracking was expected, in which case the

Table 2. Properties of the Concrete

Beam No.	At Transfer Age (days)	At Transfer f'_c (psi)	At Test Age (days)	At Test f'_c (psi)	At Test f'_r (psi)	At Test f'_{sp} (psi)
F-X1	5	4920	40	6650	640	650
F-1	5	5250	32	6820	560	570
F-2	5	4680	78	6550	660	540
F-3	5	5530	32	6840	520	620
F-4	5	4870	33	6340	730	580
F-5	5	5040	36	6410	560	540
F-6	5	4790	34	6230	470	580
F-7	5	5390	27	6620	690	600
F-8	5	5440	27	6880	510	600
F-9	5	5010	29	6660	450	600
F-10	5	5560	27	7050	510	600
F-11	5	4660	34	6030	510	580
F-12	5	5110	32	6500	510	570
F-13	5	4890	36	6450	490	540
F-14	5	5670	27	6760	510	580
F-15	5	4800	41	5790	520	480
F-16	5	5030	29	6700	510	610
F-17	5	5130	42	6950	560	630
F-18	5	5440	30	6900	520	580
F-19	5	6150	35	7410	560	570
Ave.	5	5170	35	6630	550	580

Table 3. Prestress Data

Beam No.	F_i (kips)	Percent Losses Transfer	Percent Losses Test	F (kips)	Transfer Distance End A	Transfer Distance End B
F-X1	113.6	7.7	19.2	91.7	16	16
F-1	113.7	7.7	18.8	92.3	19	19
F-2	113.6	8.2	24.0	86.3	—	12
F-3	113.7	8.5	22.9	87.7	16	16
F-4	113.5	7.7	16.6	94.6	13	15
F-5	113.7	8.8	23.5	87.0	19	16
F-6	113.4	8.3	22.2	88.1	15	16
F-7	113.5	8.2	17.5	93.7	15	14
F-8	113.5	8.2	19.4	91.5	15	15
F-9	113.4	8.5	20.8	89.7	11	12
F-10	113.4	8.6	19.4	91.3	16	13
F-11	113.5	8.6	22.9	87.5	13	13
F-12	113.7	9.1	22.1	88.6	15	14
F-13	113.3	8.3	26.5	83.2	17	16
F-14	113.6	8.8	19.4	91.5	17	17
F-15	113.6	9.4	30.8	78.7	22	20
F-16	113.7	8.2	21.6	89.2	12	12
F-17	113.8	8.9	21.1	89.8	13	14
F-18	113.6	8.2	21.4	89.3	15	18
F-19	113.6	8.0	20.9	89.8	11	11
Ave.	113.6	8.4	21.6	89.1	15	15

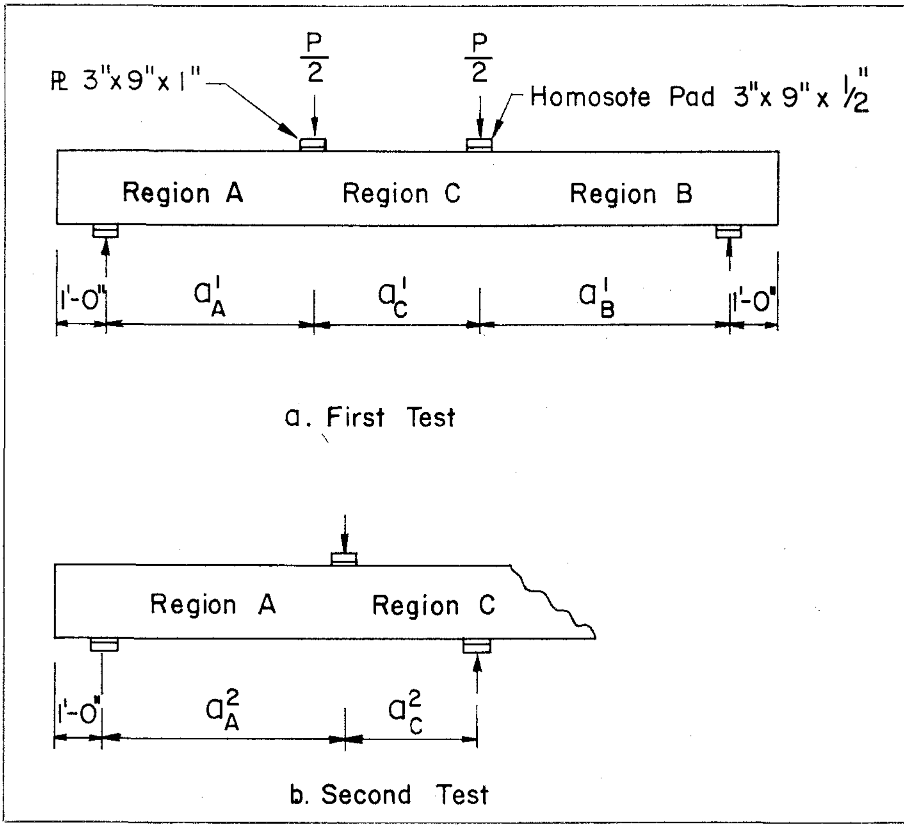


Fig. 3—Concentrated Load Tests. Shear failures occured in Region B in all First Tests except for F-9, in which case the failure occured in Region A. Therefore the Second Test for F-9 is similar to that shown above except that Region A is actually Region B.

shear increment was reduced to approximately 1 kip. The loads at which flexural and inclined cracking, and failure, took place were noted and crack patterns were marked on the test beams after the application of each load increment. Photographs were taken during and after testing.

The lengths of the shear spans and the results of the first test conducted on the beams subjected to concentrated loads are presented in Table 4. The maximum applied load moment in the test beams at the time that flexural cracking was first observed is given as M_{cr}, i.e. the net flexural cracking moment. The values of V_c indicate the shear at which critical inclined cracking occurred. V_u is the ultimate shear in the shear span in which the failure occurred, which was Region B in every case except F-9, in which case failure occurred in Region A.

The inclined cracking shears, V_c, are for inclined cracks which ultimately were associated with failure. For the test beams with the shorter shear spans, i.e. 50 in. or less, inclined diagonal tension cracking appeared suddenly in regions of the test beam which were as yet uncracked. In some instances only a single diagonal tension crack would form; however, more often two or more cracks would form almost simultaneously. These diagonal tension cracks were randomly located throughout the shear span, although tending to form in the region of higher moment. The first inclined cracking to appear in the test beams with shear spans of greater than 50 in. was flexure shear cracking, i.e. cracking which began as a flexure crack but, because of the presence of shearing forces, turned and became inclined in the direction of increasing moment. For most of the test beams with shear spans between 60 and 90 in., however, the inclined cracking which finally was associated with failure was diagonal tension cracking which appeared to be precipitated by the initial formation of a flexure crack. The diagonal tension cracking would first appear directly above the initiating flexure crack, and would quite often be followed by the development of ad-

Table 4. Results of the First Test on Beams Subject to Concentrated Loads

Beam No.	a_A^1 (in.)	a_B^1 (in.)	a_C^1 (in.)	M_{cr} (ft.-kips)	Region A V_c (kips)	Region B V_c (kips)	V_u (kips)	Failure
F-X1	48	48	50	95.2	30.0	28.4	32.0	WC
F-1	30	30	50	94.5	32.8	33.7	60.0	WC
F-2	40	40	50	98.5	34.0	30.0	40.0	WC
F-3	40	40	60	90.0	31.0	28.0	40.0	WC
F-4	50	50	50	104.0	33.4	32.0	38.0	SF
F-5	50	50	60	95.0	27.9	27.9	32.2	WC
F-6	100	100	16	95.7	17.0	19.0	19.1	WC
F-7	60	60	50	100.0	29.1	28.0	29.1	WC
F-8	60	60	60	90.0	27.0	27.0	27.0	SF
F-9	80	90	46	90.2	22.0	19.0	25.3	SF
F-10	70	70	50	81.6	27.0*	24.8	24.8	WC
F-11	60	70	80	87.5	27.0	26.0	26.0	SF
F-12	80	80	50	96.7	25.0*	23.0	23.0	SF
F-13	70	80	60	93.5	25.3	21.8	24.3	SF
F-14	90	90	36	90.0	20.9	20.0	22.2	SF
F-15	100	100	16	91.7	16.0	16.0	17.0	SF
F-16	100	110	0	100.9	18.7	17.0	19.2	SF
F-19	40	50	110	103.0	29.9	32.2	39.6	SF

**Critical inclined cracking occurred in the second test.*

Table 5. Results of the Second Test on Beams Subjected to Concentrated Loads

Beam No.	a_A^2 (in.)	a_C^2 (in.)	V_u (kips)	Failure
F-X1	48	50	37.6	WC
F-1	30	50	64.4	WC
F-2	40	50	48.0	SF
F-3	40	60	50.4	WC
F-4	50	50	39.8	WC
F-5	50	60	40.3	SC
F-7	60	50	34.6	WC
F-8	60	60	37.0	SC
F-9	90*	36	22.7	SC
F-10	70	50	29.0	SF
F-11	70	70	28.9	SF
F-12	80	50	25.0	SC
F-13	80	50	23.0	SF
F-14	90	36	23.0	SC
F-19	50	100	40.0	WC

* *This distance is a_B^2. See Fig. 3 for explanation.*

jacent diagonal tension cracking while still at the same shear. Inclined cracking in the test beams with 100 and 110 in. shear spans was confined to the region adjacent to the load point, and in most instances the failure developed from a flexure shear crack initially forming at a horizontal distance from the load point greater than twice the total depth of the test beam.

Dimensions and results of the second test on the beams subjected to concentrated loads are presented in Table 5. V_u is the ultimate shear in the shear span in which the failure occurred, which was Region A in every case except F-9, in which case the failure occurred in Region B. The failure in F-10 occurred in the more heavily reinforced region of the web.

The test beams all failed in shear, either by crushing of the concrete in the web, fracture of the web reinforcement, or shear compression, indicated respectively by WC, SF, and SC in Tables 4 and 5. The WC failures generally appeared to start near the intersection of an inclined crack in the web and the top flange of the beam, as shown in Fig. 4 for F-3. Tension cracks in the top flange were evident in every case after failure. Failures were in some cases gradual and in other cases sudden, but never catastrophic or resulting in complete collapse. In contrast, the SF failures occurred suddenly, were catastrophic, and often resulted in complete collapse, as shown in Fig. 5 for F-13. SC failures occurred only in the second tests on beam specimens, and while occurring suddenly, did not result in collapse, as shown in Fig. 6 for F-9. In the picture in Figs. 4, 5, and 6, the heavy vertical lines drawn on the web show the location of the stirrups. Also, the crack patterns were marked during the first test so as to indicate extent of cracking for the value of shear shown on the beam.

Uniform Load Tests

Uniform load was applied to F-17 and F-18 by the method shown in Fig. 7. The testing procedure was similar to that described for the concentrated load tests.

Flexural cracking was observed in F-17 and F-18 at loads of 5.1 and 2.7 kips per ft., respectively. Inclined cracking appeared in both test beams initially as flexure shear cracking, and subsequently at higher loads as diagonal tension cracking precipitated by the formation of a flexural crack. Diagonal tension cracking also appeared in the maximum shear region adjacent to the reactions of F-17 at loads of 7.4 kips per ft. at one end and 7.7 kips per ft. at the other end.

A shear compression failure occurred in F-17 at an ultimate load of 8.6 kips per ft. The failure, shown in Fig. 8, occurred suddenly after F-17 had sustained the ultimate load for several minutes. None of the stirrups were fractured. Spalling of the top concrete fibers near midspan occurred just prior to failure.

Test beam F-18 collapsed suddenly when several stirrups fractured at a load of 4.7 kips per ft. However, F-18 had previously sustained a load of 4.8 kips when it became necessary to un-load and adjust the equipment. The failure, shown in Fig. 9, occurred in a region where inclined flexure shear cracking had formed at approximately the third point of the span.

DISCUSSION

Comparison of Test Results with ACI 318-63

According to the provisions of

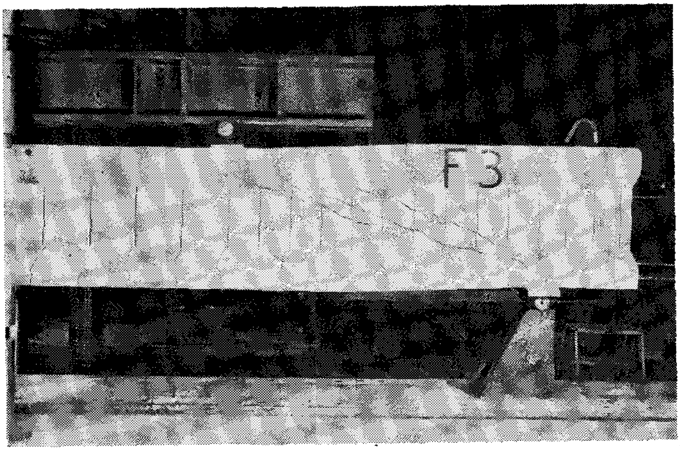


Fig. 4—Web Crushing Failure in F-3.

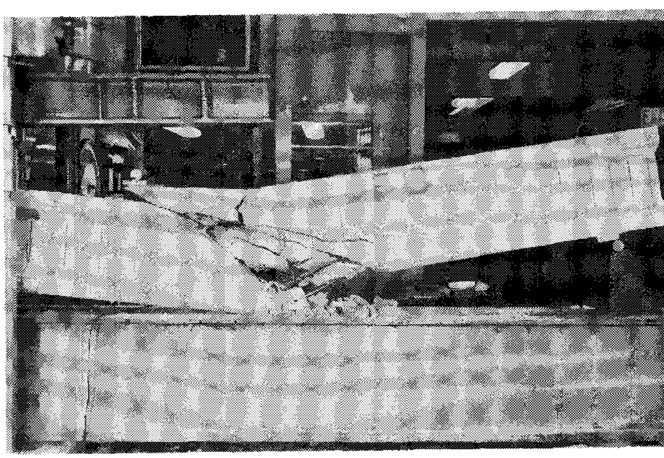


Fig. 5—Stirrup Fracture Failure in F-13.

Fig. 6—Shear Compression Failure in F-9.

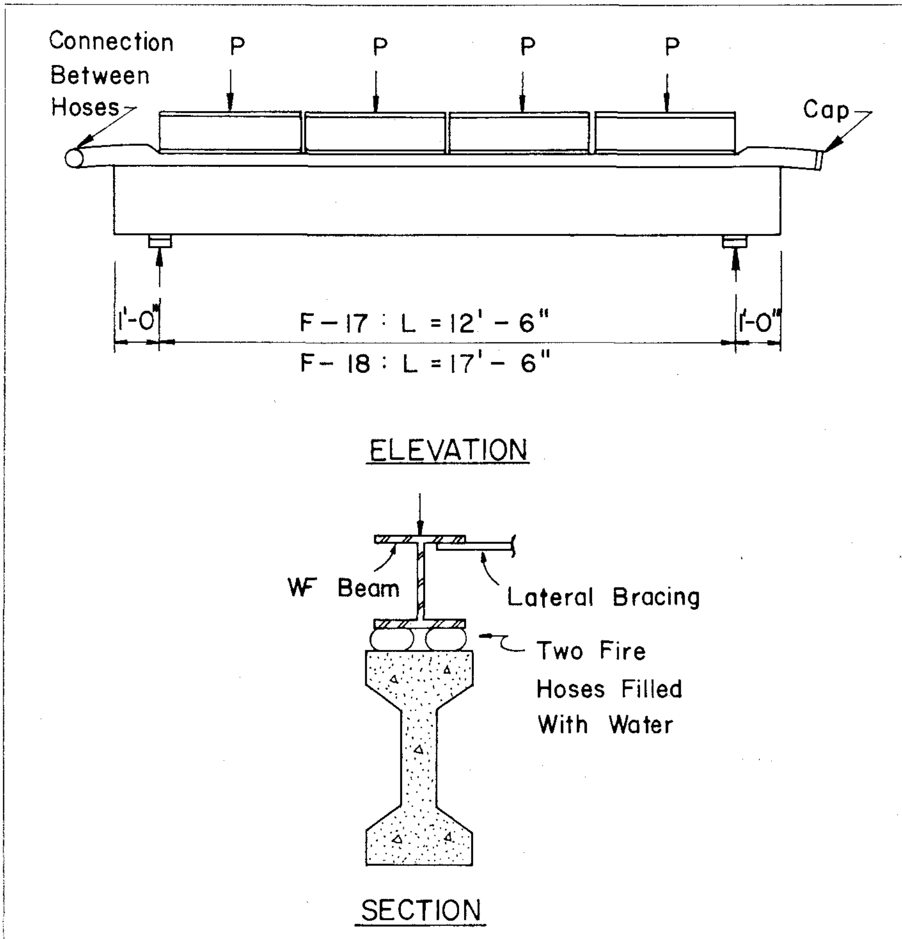


Fig.—7 Uniform Load Tests.

Section 2610 of ACI 318-63, vertical web reinforcement shall be proportioned according to the equation

$$A_v = \frac{(V_u - \phi V_c)s}{\phi\, d\, f_y}$$

Since ϕ is an arbitrary capacity reduction factor, the predicted value of ultimate shear according to the above equation becomes

$$V_u^{pred} = \frac{V_u}{\phi} = \frac{r f_y}{100} b' d + V_c \quad (1)$$

where A_v has been expressed in terms of r *by*

$$r = \frac{A_v}{b's}(100)$$

Equation (1) was recommended for design by Hernandez, Sozen, and Siess[2], and therefore evaluates ultimate shear strength as the sum of the vertical forces in the web reinforcement crossed by an inclined crack, assuming that the web reinforcement has yielded and that the horizontal projection of the inclined crack is equal to the effective depth of the beam, and the shear carried by the concrete, assumed to be equal to the shear at inclined cracking.

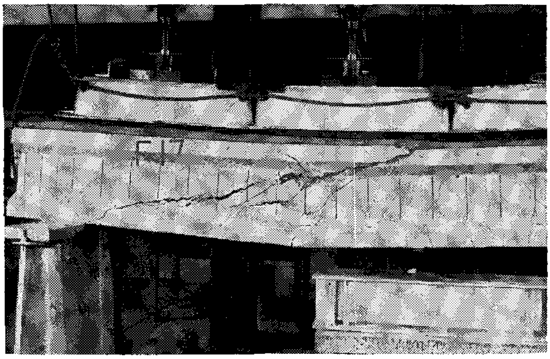


Fig. 8—Shear Compression Failure in F-17.

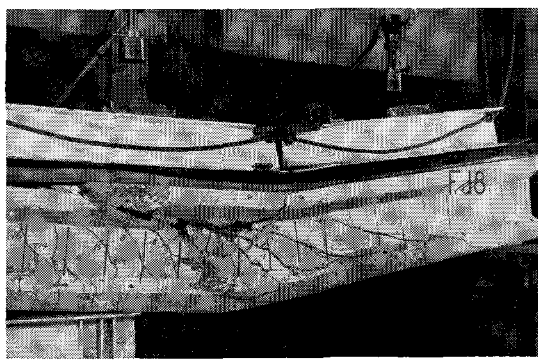


Fig. 9—Stirrup Fracture Failure in F-18.

Table 6. Comparison of Test Results with Eq. (1).

Beam No.	First Test V_u^{pred} (kips)	First Test $\frac{V_u^{test}}{V_u^{pred}}$	Second Test V_u^{pred} (kips)	Second Test $\frac{V_u^{test}}{V_u^{pred}}$
F-X1	28.3	1.13	28.3	1.33
F-1	31.5	1.90	39.8	1.62
F-2	27.5	1.45	30.5	1.57
F-3	26.6	1.50	35.2	1.43
F-4	28.1	1.35	29.7	1.34
F-5	25.9	1.24	30.5	1.32
F-6	15.1	1.26	—	—
F-7	26.7	1.09	28.0	1.24
F-8	24.8	1.09	29.0	1.28
F-9	20.9	1.21	19.1	1.32
F-10	21.2	1.17	23.3	1.25
F-11	21.2	1.22	22.8	1.27
F-12	18.2	1.26	20.1	1.24
F-13	18.1	1.34	20.1	1.15
F-14	16.7	1.33	18.3	1.26
F-15	13.4	1.27	—	—
F-16	14.3	1.34	—	—
F-19	30.2	1.31	31.8	1.26

Values of V_u^{pred} for the concentrated load tests were determined using Eq. (1), in which V_c was calculated according to the recommendations of Section 2610. These values of V_n^{pred} are given in Table 6, along with the ratios of the observed ultimate test shear to predicted ultimate shear. The ratios are plotted in Fig. 10 against the shear span to effective depth ratio on which the test was conducted. The dead load of the test beams was neglected in these calculations. Fig. 10 indicates that the recommendations of Section 2610 give conservative but realistic results for the concentrated load tests reported herein. The higher ratios of V_u^{test} to V_u^{pred} for the smaller a/d ratios indicate the increased strength as the action in the beam begins to change from shear to compression. However, over the range of a/d values from 3.52, for which tests the inclined cracking was of the diagonal tension type, to 7.75, for which tests the inclined cracking was of the flexure shear type, the ratios are very consistent; the average value of V_u^{test} to V_u^{pred} is 1.26.

In Fig. 10, the results have been plotted so as to distinguish between the first and second tests on the beam specimens. Again considering the a/d ratios from 3.52 to 7.75, the average ratio of V_u^{test} to V_u^{pred} for the first tests was 1.25 compared to 1.27 for the second tests. The negligible differences between these values indicates that the results of the second tests are valid, assuming that Eq. (1) may be regarded as an

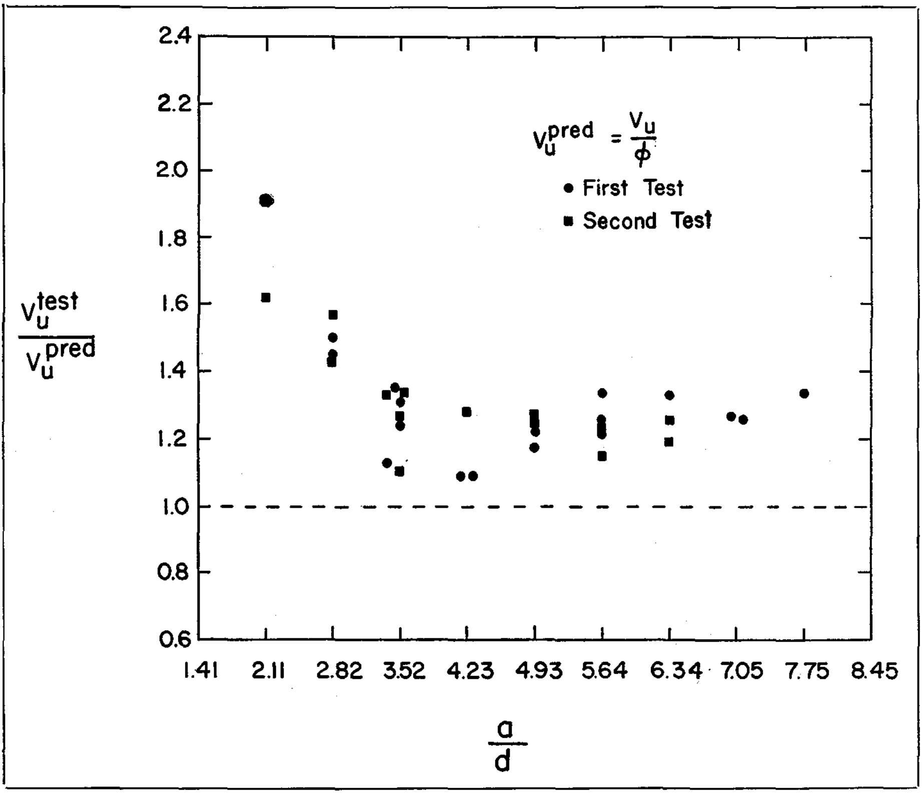


Fig. 10—Comparison of Eq. (1) with Test Results.

acceptable basis for comparison.

A comparison of the uniform load test results with the Code is difficult to make because the shear varies, and the failure section is not closely defined. The failure section will be considered at the intersection of the inclined crack most clearly associated with the failure mechanism and the top flange. Working from the picture of the failure section in Fig. 8 and Fig. 9, the failure section for both F-17 and F-18 is seen to be located at approximately the third point of the span. Therefore V_u^{test} at the failure section equals 17.9 kips for F-17 and 14.0 kips for F-18. V_u^{pred}, calculated from Eq. (1) where V_c has been determined from Eq. (26-12) in the Code, is 15.9 kips for F-17 and 12.4 kips for F-18. The ratio of V_u^{test} to V_u^{pred} is therefore 1.13 for both tests.

Failure Mechanisms

All three of the modes of failure commonly referred to in the literature—web crushing, stirrup fracture, and shear compression—were observed in these tests. The predominant mode of failure for the tests with an a/d of 3.52 or less was web crushing. Between a/d ratios of 3.52 and 4.93 all three types of failures were observed. Tests having an a/d ratio greater than 4.93 failed either by fracture of the web reinforcement or shear compression.

The web crushing failures could be described as gradual and noncatastrophic. This type of failure generally seemed to begin at the junction of the web and top flange and close to an inclined crack. In contrast, the stirrup fracture or shear compression failures were sudden and often catastrophic, i.e., resulting in collapse of the member. The desirability of the former type of failure over the latter two suggests that a greater degree of safety should be provided against the stirrup fracture or shear compression failures. However, from Fig. 10 it is apparent that Eq. (1) affords a greater degree of safety to the web crushing failures.

Of further significance is the observation that on beams subjected to concentrated loads, all of the first test failures which were not due to web crushing were stirrup fracture failures, whereas the second test failures which were not web crushing were nearly equally divided between stirrup fracture and shear compression. This indicates that a greater part of the total shear was carried by the concrete in the second, or re-load, test than in the first test. The difference, however, as far as Eq. (1) is concerned is apparently not too important in view of the fact that the average of the ratios of V_u^{test} to V_u^{pred} for the first and second tests were nearly equal, as noted before.

It should be noted that the majority of the test beams have less than the minimum amount of web reinforcement required according to Eq. (26-11) of the Code, i.e. $rf_y/100$ equal to 114. However, only the results of the first test on F-8, F-10, F-11, and F-12 and the second test on F-12 appear to be influenced by the small amount of web reinforcement provided ($rf_y/100 = 56, 48, 67, 42$, and 84 respectively). For these five cases, as may be seen from Table 4 and Table 5, the inclined cracking shear and the ultimate shear were equal. In effect, this indicates that there was not enough web reinforcement in the beam to effect the re-distribution of shear required at inclined cracking.

A shear failure at the inclined cracking load, even though it may not be sudden or catastrophic, is still undesirable because there is no advance indication of distress in the region in which failure occurs. Based on the tests reported herein, the minimum web reinforcement provision of the Code is 25% higher than needed to prevent simultaneous inclined cracking and ultimate shear failures.

CONCLUDING REMARKS

1. The ultimate shear strength provisions contained in Section 2610 of the ACI Building Code (ACI 318-63) gave conservative but realistic results for the concentrated and uniform load tests reported herein.

2. Web crushing, stirrup failure, and shear compression failures were observed. The web crushing failures were predominant for the concentrated load tests conducted on a/d ratios less than approximately 3.5. Tests on a/d ratios greater than approximately 5 failed by stirrup fracture or shear compression.

3. Both uniformly loaded test beams, which had stirrups at a constant spacing, failed at approximately the third point of the span.

4. The minimum web reinforcement provision of the code was 25% higher than the tests reported herein indicated necessary.

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