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EFFECT OF REPEATED REVERSALS OF STRESS ON DOUBLE-REINFORCED CONCRETE BEAMS

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I. INTRODUCTION

1. GENERAL STATEMENT

In a ship at sea the change from "hogging" to "sagging" may occur 10 to 15 times per minute. This means a large number of reversals of stress during the life of a ship, and it means that both the deck and the bottom of the ship are required to withstand tensile and compressive stresses alternately. The effect of these reversals of stress has a bearing upon the use of reinforced concrete in lieu of wood and steel in the construction of ships, and the investigation of this effect is a matter of importance.

Although earlier tests[1] have been reported showing the effect of repeated loads in one direction on a concrete beam, none are known to have been made in which a concrete member has been subjected alternately to compressive and tensile stresses large enough to crack the concrete. Assuming that the action above described would sometime produce cracks in the structure of a concrete ship, the possibility was foreseen that the repeated opening and closing of the cracks might produce a grinding action on the surface of the fracture which would result ultimately in disintegration. This was one of the important features considered in the tests here reported. This investigation was undertaken by the Bureau of Standards at the request of the concrete ship section of the Emergency Fleet Corporation.

Acknowledgment is made to A. S. Merrill, engineer of the Bureau of Standards, for his editorial work upon this paper and for many valued suggestions and criticisms for its improvement.

2. SCOPE OF TESTS

The scope of this investigation was intended to bring out only the outstanding features of the behavior of reinforced concrete beams subjected to repeated reversal of stress. The original program was modified somewhat after the results of the first tests were obtained.

In the investigation only five beams were tested. One of these five beams had not failed at the time that it became necessary to discontinue the testing operations. However, since this beam had undergone a large number of repetitions of a load which produced approximately the design stresses, it furnishes information of some value.

Although the tests which have been carried out are considerably smaller in number than was planned, the impossibility of completing the program in the near future makes it desirable that the results which have been obtained be presented at the present time.

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[1] J. L. Van Ornum, The Fatigue of Concrete, Trans. Am. Soc. C. E., 58, p. 294, 1907; W. K. Hatt, Notes on the Effect of Time Element in Loading Reinforced Concrete Beams, Proc. Am. Soc. Test. Mat., 7, p. 421, 1907; H. C. Berry, Some Tests of Concrete Beams under oft repeated Loading, Proc. Am. Soc. Test. Mat. 8, p. 454, 1908.

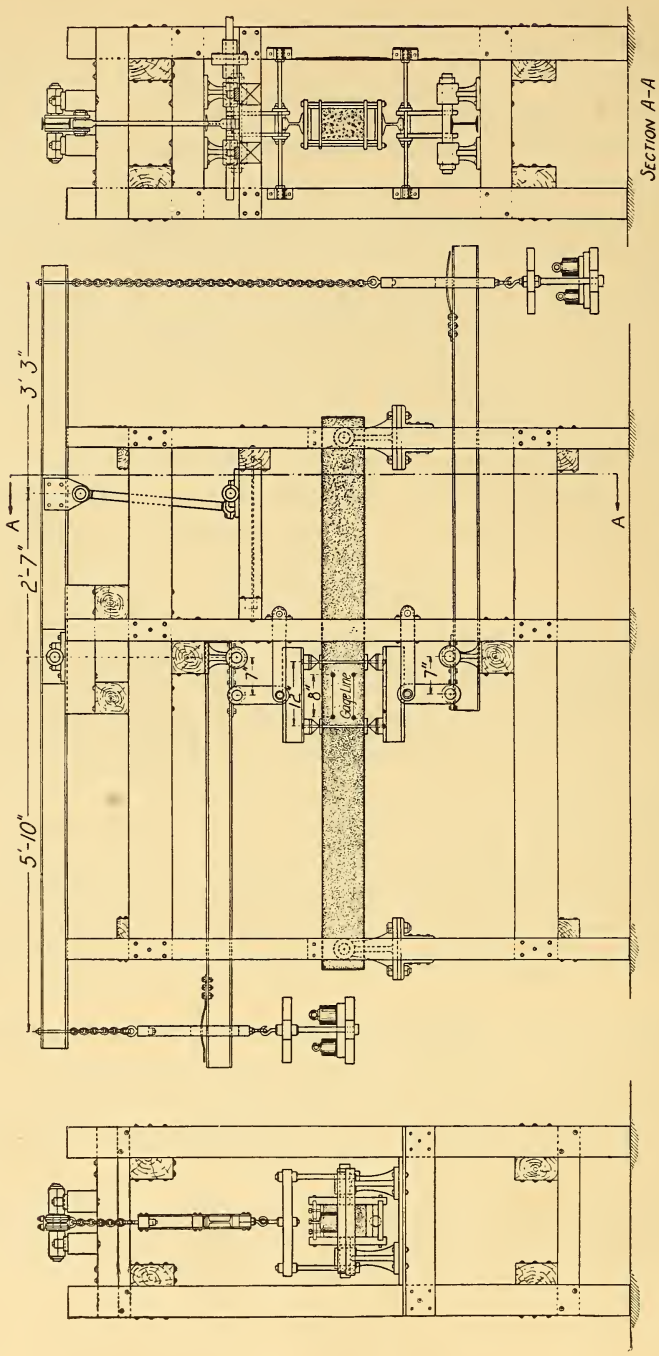

FIG. 1.—*Reversal-of-stress testing machine*

II. TESTING APPARATUS

1. TESTING MACHINE

The machine designed for these tests applied a load alternately downward and upward at a rate of approximately 17 cycles[2] per minute. Three units of the machine were built so that three beams might be under test at the same time.

The testing machine is shown in Fig. 1, and consisted essentially of a wooden frame with a system of levers so arranged and operated that a load applied at the end of one of the main levers produced a load ten times as great on the concrete test beam. One main lever applied the load in the upward direction and the other main lever applied it in the downward direction. When one load was being applied, the load in the opposite direction was being removed. Slightly before one load had been entirely removed the full load in the opposite direction had been applied.

During the test the beam was supported at sections 4 inches from each end by means of steel yokes, shown in Fig. 1. Each yoke was supported at mid height by a shaft which was free to turn as the beam deflected. Since the supporting shaft was approximately at the neutral axis, the change in the distance between the point of support, due to changing the curvature of the beam, was negligible.

The load was transmitted from each main lever through a link to a rail section, as shown in Figs. 1 and 2. By means of the rail section the load was applied to the beam at points usually 6 inches on either side of the center of the span both on the top and on the bottom of the beam, but in testing beam 5L1 the knife-edges were placed 12 inches either side of the center. The knife-edges through which the load came upon the beam were held in place by means of a yoke around the beam at each point of application of load

When tests were being conducted, the units were driven by means of a shunt-wound electric motor developing 3-horsepower at 1700 revolutions per minute. The shaft of the motor is directly connected to a worm-gear reducing unit. An individual shaft, clutch, and pulley arrangement enables each unit to be operated independently. The walking beam, which applies the load to the main levers, is driven by means of a connecting rod from a crank attached to the individual driving shaft of each unit. A

[2] The term "cycle," as used in this report, refers to one complete revolution of the crank shaft of the testing machine. Each cycle involved one application of the load downward and one application of the load upward.

control rheostat regulates the speed of the motor at different loads and is the means of obtaining the same speed whether running with one unit or all units in operation. For a part of the time that the tests were in progress the machines were run continuously day and night.

Fig. 3 shows the position of the three units of the machine relative to each other and to the driving motor. Fig. 4 is a side view of a beam in one of the units of the testing machine.

2. STANDARDIZATION OF TESTING MACHINE.

A standard 6-inch I-beam was used to rate the reversal-of-stress testing machine. The I-beam was first standardized in a 200 000-pound Olsen testing machine, using an 8-foot span and 2-point loading, 6 inches either side of mid span. Loads were applied in increments of 500 pounds, as measured on the scale beam of the Olsen machine, and the corresponding deflections were measured at mid span. Readings of deflection were also noted as the load was removed. The beam was then inverted and loaded again, and it was found that the load-deflection curve agreed closely with that for the beam loaded in the previous position. The extreme fiber stress did not exceed the elastic limit of the steel. The I-beam was then transferred to the reversal-of-stress machine and loaded with the same spacing of load points and supports as that employed in the Olsen testing machine and in the tests of the reinforced concrete beams.

From the deflection curve obtained from the test in the Olsen machine and the deflection curve from the loading in the reversal-of-stress machine, curves were drawn which gave the relation between the applied load and the load on the weight carrier. It was found that the equations of these curves varied slightly for the different units. The equations found were corrected for the weight of the beam and for certain parts of the loading apparatus and were used in determining the loads on the test specimens. The equations are as follows:

Unit 1 upward $W = 2088 + 10.03\ W_1 - \frac{4}{7}\ W_2 - W_3.$
Unit 1 downward $W = 2070 + 9.79\ W_1 + \frac{4}{7}\ W_2 + W_3.$
Unit 2 upward $W = 2078 + 9.88\ W_1 - \frac{4}{7}\ W_2 - W_3.$
Unit 2 downward $W = 1990 + 10.05\ W_1 + \frac{4}{7}\ W_2 + W_3.$
Unit 3 upward $W = 2070 + 9.83\ W_1 - \frac{4}{7}\ W_2 - W_3.$
Unit 3 downward $W = 2000 + 9.41\ W_1 + \frac{4}{7}\ W_2 + W_3.$

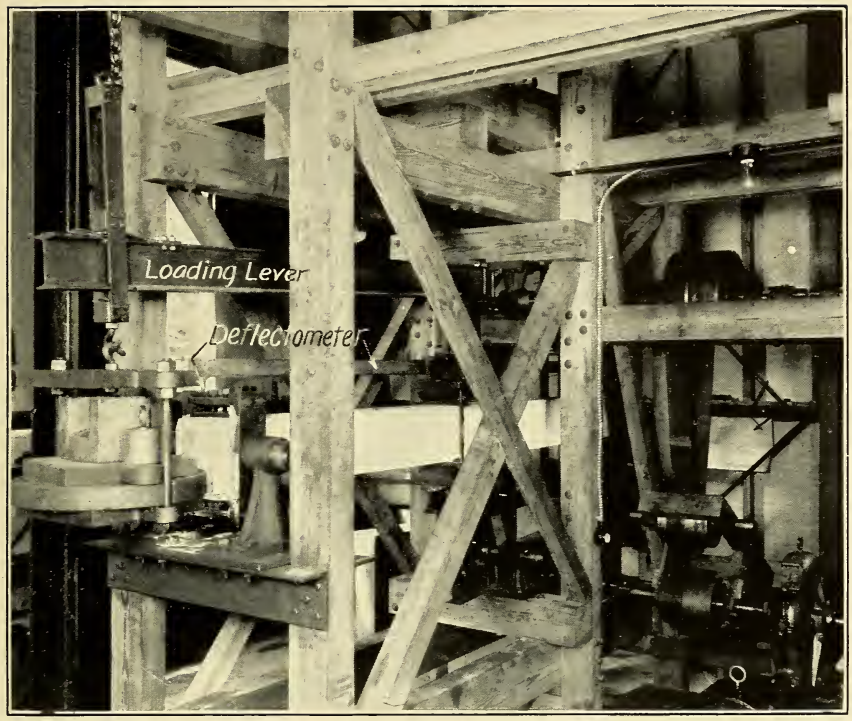

FIG. 2.—*View of unit No. 1 of reversal-of-stress testing machine*

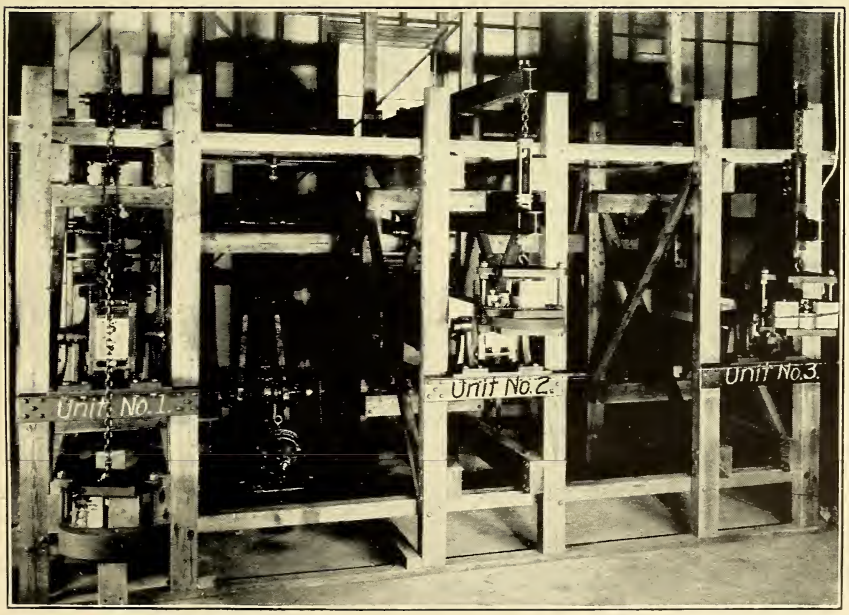

FIG. 3.—*View showing the three units of reversal-of-stress testing machine*

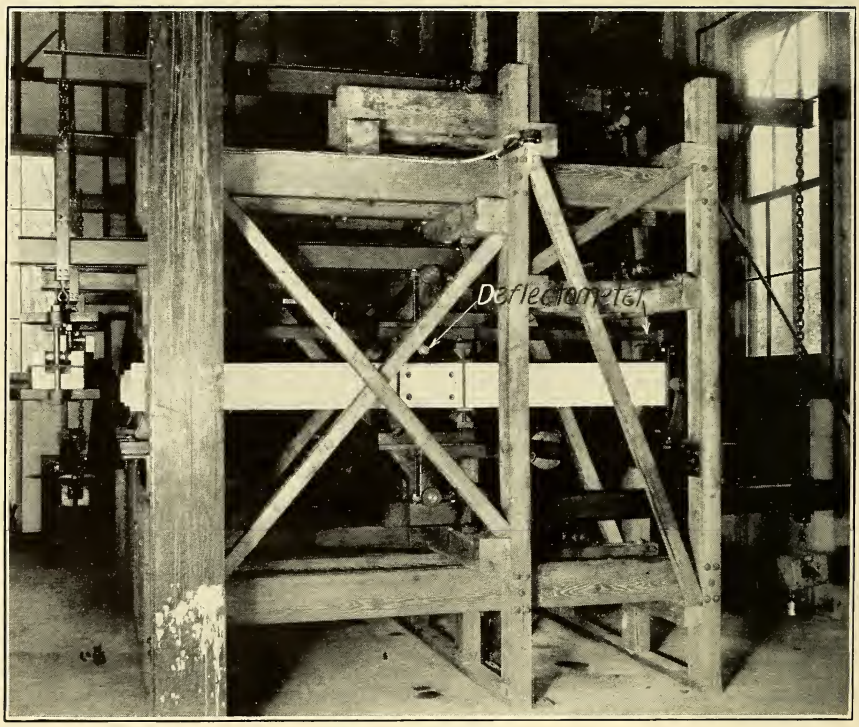

FIG. 4.—*View showing beam 5C1 in unit No. 3 of testing machine with deflectometer in position*

In these equations W is the load upon the test beam, W_1 is the load applied to the weight carrier, W_2 is the weight of the test specimen, and W_3 is the weight of the yokes and T-rails used for applying the load.

It will be seen that for all the units the load without weights being added to the weight carriers was about 2000 pounds. In testing beam 5C1 it was desired to apply only 670 pounds upward. This necessitated removing the weight carrier at one end of unit No. 3 and the attaching of small weights to the main lever. This may be seen at the right of the view in Fig. 4.

3. MEASURING INSTRUMENTS

A Berry strain gage, having an 8-inch gage length, was used to measure the deformations in the steel reinforcement. The multiplication ratio of this strain gage was 4.94. Readings on a gage line on an unstressed bar of structural steel were used as a basis for correcting all strain-gage readings on the test specimens.

For measuring deflections a removable deflectometer was used. It consisted of a wooden bar having fixed trammel points 8 feet apart and having an Ames-gage micrometer mounted at its center. The wooden bar was supported on the steel yokes at the ends of the test beam in the same position for consecutive observations. The difference in the deflections at the center of the span was shown by the Ames gage. Readings were made directly to the nearest 0.001 inch. To provide for the exact placing of the deflectometer, one end was held in a gage hole on one supporting collar, while the opposite end was held on the other collar in a groove cut parallel to the axis of the beam. This allowed compensation for the upward and downward movement of the points of support of the deflectometer which took place as the beam deflected. The deflectometer may be seen on the test specimen in Fig. 4.

To obtain the corrections necessary to be applied to the deflectometer readings to compensate for the unavoidable errors caused by vibrations, change in temperature, or other uncontrollable or accidental movement of the gage, standard readings of the deflectometer were taken on the top flange of a 24-inch steel I-beam which was not under load.

Ames-gage micrometers were used to measure the slip of the ends of the bars in beam 5L1. The reinforcement in this beam consisted of two 1¼-inch plain round bars placed one in the top of the beam and the other one in the bottom, as shown in Fig. 5. Holes were drilled and tapped in the ends of these bars and short pieces of steel were screwed in place. The gages were clamped

to these extension rods with the plungers bearings against the ends of the beam. Gage No. 1 was mounted at the east end of the top bar, gage No. 2 at the east end of the bottom bar, gage No. 3 at the west end of the top bar, and gage No. 4 at the west end of the bottom bar.

For each unit the number of cycles of load was shown by a revolution counter connected to the main shaft of the unit.

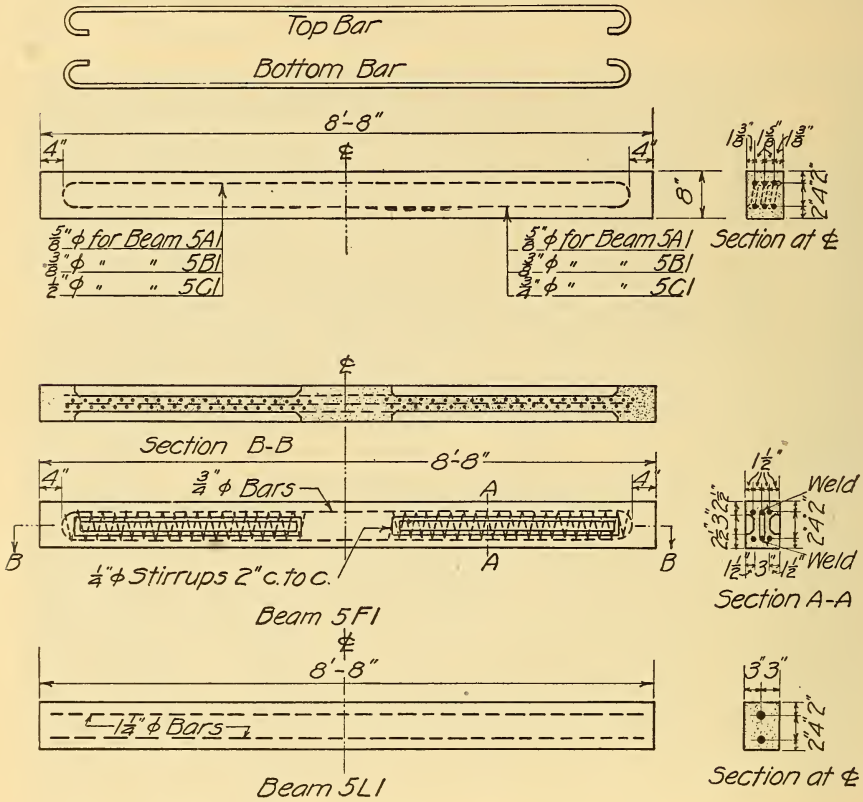

FIG. 5.—*Dimensions and reinforcement of test specimens*

III. TEST SPECIMENS AND TESTING

1. DESCRIPTION OF TEST BEAMS

The beams were 8 feet 8 inches long, 6 inches wide and 8 inches deep, and the test span was 8 feet. The top bars were placed generally 2 inches below the top surface, and the bottom bars 2 inches above the bottom surface. The cross section was rectangular for all of the beams except 5F1. That beam was I-shaped in cross section, both flanges being 6 inches wide and 2½ inches deep; the web was 3 inches thick, and the total depth of the beam was 8 inches. At the ends, where beam 5F1 was supported, and

between the load points the web was filled out to the full 6-inch width of the flange in order to avoid serious secondary stresses due to the concentration of load at these points. Beam 5F1 was made with an I-shaped cross section in order to develop a high shearing stress in the web without affecting appreciably the resistance to tensile and compressive stresses.

The reinforcing bars in all of the beams except 5L1 had semicircular hooks on the ends to furnish anchorage. Beam 5L1 was reinforced with straight bars in order to study the effect of repetition of high bond stresses on the end slip of unanchored bars.

The depth of embedment of the reinforcing bars was designed to be 2 inches in all cases. In general, it was desired to develop high compressive stresses in the concrete, and this could be accomplished in these tests only by placing the bars farther from the compression surface of the beam than otherwise would have been done. Fig. 5 shows the arrangement of the reinforcement in the beams.

Table 1 shows the amount of reinforcement used, the loads applied, and the computed stresses for all of the test specimens.

TABLE 1.—Schedule of Beams for Reversal-of-Stress Tests

Beam No.	Reinforcing bars				Load applied	
	Top		Bottom			
	No.	Diameter	No.	Diameter	Upward	Downward
		Inches		Inches	Pounds	Pounds
5A1	3	⅝	3	⅝	5000	5000
5B1	3	⅜	3	⅜	2380	2380
5C1	3	½	3	¾	670	3630
5F1[a]	3	¾	3	¾	5000	5000
5L1	1	1¼	1	1¼	6000	6000

Beam No.	Computed stresses						Remarks
	Tension in steel		Compression in steel		Compression in concrete		
	Top	Bottom	Top	Bottom	Top	Bottom	
	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²	
5A1	23 590	23 590	4293	4293	2020	2020	
5B1	28 800	28 800	−112	−112	1538	1538	
5C1	4 800	12 050	480	5080	311	1360	
5F1	16 750	16 750	5360	5360	1641	1641	I section; computed shear 175 pounds per square inch.
5L1	19 100	19 100	5900	5900	1835	1835	Computed bond stress 161 pounds per square inch.

[a] Web reinforced with one-fourth-inch wire loops, 2-inch pitch.

2. MATERIALS

A Portland cement was used which passed the tests prescribed in the United States Government Specification for Portland Cement [3] and which appeared to be of good quality in all respects.

Potomac River washed sand and gravel were used. The sand was graded in size, and was all less than one-fourth inch. The gravel was graded in size from one-fourth to one-half inch. All of the aggregate appeared to be clean, and sections sawed from some of the beams showed a good gradation of the materials, as shown in Figs. 7 and 8.

The reinforcing steel used in the test beams was purchased in the open market. Coupons for testing were taken from the steel before the beams were made. After the reversal of stress tests had been completed additional specimens of steel were taken from the broken beams and were subjected to chemical analysis and tests of their physical properties. The results of the physical tests on the individual test specimens are given in Tables 2 to 5, and the chemical analyses are given in Table 6. Eighteen specimens of the steel taken from the tested beams passed the cold bend test by being bent through an angle of 180° without any sign of fracture.

TABLE 2.—Physical Properties of Reinforcing Steel of Beam 5A1

SAMPLES TAKEN BEFORE MAKING THE BEAM

Sample No.	Location in beam	Original diameter	Yield point	Ultimate strength	Elongation in 8 inches	Reduction of area
		Inch	Lbs./in.²	Lbs./in.²	Per cent	Per cent
1		0.632	37 400	51 500	(a)	46.5
2		.629	38 500	52 700	12.5	42.0
3		.635	36 400	50 500	24.0	46.0
Average		.632	37 400	51 600	18.3	44.8
SAMPLES TAKEN FROM BEAM AFTER TEST						
1	Top, north	0.637	35 950	49 600	24.8	50.4
2	Top, middle	.621	39 600	53 850	29.5	55.8
3	Top, south	.632	40 500	51 500	(a)	43.5
4	Bottom, north	.624	43 620	55 650	21.3	52.0
5	Bottom, middle	.631	38 400	52 150	25.8	43.3
6	Bottom, south	.626	39 650	53 950	20.2	57.3
Average		.629	39 620	52 780	24.3	50.4

[a] Broke outside gage length.

[3] Circular of the Bureau of Standards, No. 33; 1917.

TABLE 3.—Physical Properties of Reinforcing Steel of Beam 5B1

SAMPLES TAKEN BEFORE MAKING THE BEAM

Sample No.	Location in beam	Original diameter	Yield point	Ultimate strength	Elongation in 8 inches	Reduction of area
		Inch	Lbs./in.²	Lbs./in.²	Per cent	Per cent
1		0.381	38 830	51 890	22.0	38.0
2		.379	40 160	53 060	17.9	39.0
3		.378	44 120	50 490	13.3	16.6
Average		.379	41 040	51 810	17.7	31.2

SAMPLES TAKEN FROM BEAM AFTER TEST

1	Top, north	0.378	47 500	60 200	12.5	21.0
2	Top, middle	.377	42 350	53 950	16.4	27.5
3	Top, south	.388	40 400	52 400	18.3	34.9
4	Bottom, north	.386	39 300	55 150	18.0	25.1
5	Bottom, middle	.384	38 500	50 950	22.3	28 8
6	Bottom, south	.386	35 600	52 650	16.7	41.6
Average		.383	40 610	54 220	17.4	29.8

TABLE 4.—Physical Properties of Reinforcing Steel of Beam 5F1

SAMPLES TAKEN BEFORE MAKING THE BEAM

Sample No.	Location in beam	Original diameter	Yield point	Ultimate strength	Elongation in 8 inches	Reduction of area
		Inch	Lbs./in.²	Lbs./in.²	Per cent	Per cent
1		0.757	43 000	58 800	(a)	62.0
2		.746	41 100	60 000	28.0	55.0
3		.755	40 600	58 310	28.8	63.5
Average		.753	41 570	59 040	28.4	60.2

SAMPLES TAKEN FROM BEAM AFTER TEST

1	Top, north	0.755	41 500	60 500	28.5	65.9
2	Top, south	.754	42 500	61 300	35.5	62.9
3	Bottom, north	.750	44 100	62 000	24.0	61.5
4	Bottom, south	.755	38 600	60 700	48.0	59.4
Average		.754	41 680	61 130	34.0	62.4

[a] Broke outside gage length.

TABLE 5.—Physical Properties of Reinforcing Steel of Beam 5L1

SAMPLES TAKEN BEFORE MAKING THE BEAM

Sample No.	Location in beam	Original diameter	Yield point	Ultimate strength	Elongation in 8 inches	Reduction of area
		Inches	Lbs./in.²	Lbs./in.²	Per cent	Per cent
1		1.270	37 000	66 200	49.5	49.8
2		1.270	38 600	66 500	48.5	49.8
Average		1.270	37 800	66 350	49.0	49.8

SAMPLES TAKEN FROM BEAM AFTER TEST

1	Top	1.272	38 500	66 600	50.5	52.6
2	Bottom	1.268	39 400	66 800	49.0	50.5
Average		1.270	38 950	66 700	49.8	51.6

TABLE 6.—Comparison of Representative Physical and Chemical Tests of Reinforcing Steel Used in Concrete Ships and Reversal-of-Stress Beams

SAMPLES TAKEN FROM REVERSAL-OF-STRESS BEAMS AFTER TEST

Sample taken from—	Physical tests					Chemical contents				Grade
	Diameter	Yield point	Ultimate strength	Elongation in 8 inches	Reduction of area	Carbon	Manganese	Phosphorus	Sulphur	
	Inches	Lbs./in.²	Lbs./in.²	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	
Beam 5A1	0.629	39 620	52 780	24.3	50.4	0.023	0.20	0.130	0.064	
Beam 5B1	.383	40 610	54 220	17.4	29.8	.052	.22	.095	.052	
Beam 5F1	.754	41 680	61 130	34.0	62.4	.085	.38	.120	.095	
Beam 5L1	1.270	38 950	66 700	49.8	51.6	.31	.59	.011	.030	
Beam 5C1	.752	41 566	59 036	28.4	60.2	.085	.38	.120	.095	
Beam 5C1	.502	38 450	54 220	23.5	38.0	.....	.....	.....	.....	

SAMPLES TAKEN FROM REPRESENTATIVE TESTS OF REINFORCING STEEL USED IN CONCRETE SHIPS

Mobile	1.125	52 130	98 050	15.0	22.7	0.47	0.70	0.04	0.04	Shell discard.
Jacksonville	.625	68 420	99 130	20.5	43.0	.44	.67	.035	.035	Do.
San Francisco	1.250	37 940	60 810	24.3	.....	.21	.44	.031	.037	Structural.
San Diego	.750	36 070	61 920	25.7	.....	.22	.44	.014	.037	Do.
Wilmington	.750	45 840	63 690	25.6	54.4	.16	.38	.046	.058	Do.
Barges	[a] .50	55 760	93 130	14.0	.....	.41	.50	.02	.04	Do.

[a] Square bars.

Samples of the steel taken from beams 5A1 and 5B1 for microscopic examination showed the microstructure of wrought iron which was contaminated more or less with prominent steel streaks. They had the appearance of an inferior grade of wrought iron.

The chemical tests showed that the phosphorous content in the reinforcement generally exceeded the limit for reinforcing bars,[4] and the percentages of manganese and carbon were much lower than those ordinarily found in structural steel. It seems evident that some of the steel obtained for these tests was of an inferior grade, although it was purchased as a good grade of structural reinforcement. Representative tests which were made in the inspection of reinforcing bars used in concrete ships and in concrete barge construction for the Inland Waterways Commission gave the results shown in Table 6. A comparison of the chemical analyses given in this table shows wide variations and indicates the importance of a careful inspection of all steel which is supplied for use in reinforced concrete construction.

3. MAKING AND STORAGE OF TEST SPECIMENS

The beams for these tests were made at the Bureau of Standards, Washington, D. C. The concrete was mixed in the proportion of 1 part of Portland cement, two-thirds parts of sand, and 1⅓ parts of gravel, by weight, for all of the beams except 5C1, in which the mix was 1 part of Portland cement, three-fourths parts of sand, and 1½ parts of gravel, by weight. A rich mix was chosen in order to make the conditions closely similar in this respect to those in concrete ship construction.

The water used was 12 per cent, by weight, of the total dry materials. Calcium chloride was added to the water to accelerate the hardening of the concrete. Four pounds of calcium chloride were used with each 96 pounds of the mixing water.

A Snell mixer was used for mixing the concrete. Each batch was mixed for five minutes at a speed of 18 revolutions per minute, and the material was moved in wheelbarrows to the forms and shoveled into place. The forms used were made of wood. Beams 5A1 and 5B1 were puddled by means of one-half by 2 inch wooden paddles, while in the remaining beams the forms were rapped with a hand hammer during the period of placing the concrete. The top face of each test beam was troweled and then covered with a 6-inch board. The wet burlap, which was spread over all, was sprinkled daily until the forms were removed. The forms were removed after three days, and the beams were stored in moist sand at the normal temperature of the laboratory and kept moist during the period of storage.

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[4] Standard Specifications for Billet-Steel Concrete Reinforcement Bars, A. S. T. M., Standards, p. 148; 1918.

4. CONTROL SPECIMENS

Four 6 by 12 inch cylinders, made with each beam and stored under the same conditions as the beams, were used as control specimens and were tested in compression. Results of these tests may be found in Table 7. A density calculation was made for three of the beams and is recorded in the table.

TABLE 7.—Test Results for Control Cylinders

Beam No.	Proportions of mix (by weight)	Density	Date of molding, 1918	Age of beam at start of test	Control cylinders	
					Age when tested	Average compressive strength
				Days	Days	Lbs./in.²
5A1	1:⅔:1⅓	0.745	Apr. 24	63	163	5596
5B1	1:⅔:1⅓	.745	do	147	163	5563
5C1	1:¾:1½	.752	May 18	155	139	6235
5F1	1:⅔:1⅓	.....	June 28	124	98	4205
5L1	1:⅔:1⅓	.....	Sept. 9	71	.....	.....

5. GAGE LINES

In beams 5A1, 5B1, 5C1, and 5F1 two horizontal gage lines, 8 inches long, were located on each side of the beam at the center. These gage lines were placed in the outside bars in both top and bottom reinforcement and are designated in Figs. 17 to 26 as north top, north bottom, south top, and south bottom.

The gage holes in the reinforcing bars were generally drilled with a No. 50 drill (0.07 inch) to a depth of about $\frac{3}{32}$ inch. They were countersunk slightly with a $\frac{3}{32}$-inch drill in all cases except for beam 5B1, the only beam which had bars as small as three-eighths inch in diameter.

In beam 5L1, which had only one bar in the top and one in the bottom, the gage lines were located only on the south side at the center of the span.

6. METHOD OF TESTING

The surfaces of the beams were whitewashed in order to facilitate the detection of cracks in the concrete during the tests. After a beam had been properly placed in the testing machine, a complete set of initial readings was taken as a basis for determination of deflections and deformations. In the case of beam 5L1 initial readings were also taken of the four Ames-gage micrometers which

were attached to the ends of the reinforcing bars for measuring the slip.

After the initial readings had been taken, the predetermined total load was applied statically in the downward direction and a new set of readings of deformation, deflection, and crack widths was taken. The cracks were traced on the beam with a pencil. The same operation was repeated with the upward load applied statically and the downward load released.

The machine was then started running and the test proceeded. In the conduct of the tests it was not possible to keep the machine running all of the time, but, when circumstances permitted, the machine was operated continuously day and night. For beams 5A1, 5F1, and 5L1 the continuity of the tests is shown in Fig. 25. For beam 5B1 the continuity is shown in Fig. 13. The vertical lines in these graphs indicate periods of rest.

At periodic intervals two readings of the strain gage were taken on each gage line, first with the upward load on the beam and then with the downward load. It was not possible to take these readings for upward and for downward load on consecutive reversals of load, but they were taken as close together as possible. Strain-gage readings were also taken at intervals with the machine not running and with no load on the test beam. When beam 5L1 was tested the slip readings for the upward load and then for the downward load were taken while the machine was in operation and as nearly simultaneously as possible.

Deflection readings were taken at intervals when the machine was in operation for the load upward and then for the load downward and generally preceding each series of steel deformation readings. Deflection readings were also taken with the machine not running and with no load on the test beam. Readings were taken on the reference beam before and after each set of deflectometer readings.

Crack widths were measured by estimation to the nearest 0.001 inch by means of a steel scale graduated to 0.01 inch and read through a glass magnifying about 4½ diameters. The crack widths were observed with the machine stopped and with the full static load on the beam. This was done for both the upward and the downward loads. Careful observations of the beam were made during the progress of the test and the cycle number at which each crack appeared was recorded on the beam just opposite the crack. As the crack increased in length the number of cycles

was recorded for various stages of the crack. Figs. 9 and 11 are views taken after completing some of the tests and show the progress of the cracks for the beams which were tested to failure.

The cracks were all outlined by means of a heavy pencil in order to make them visible in the photographs. The test of beam 5C1 was discontinued before failure occurred, and the cracks which had developed up to the time of stopping the test are sketched in Fig. 10. Each value of crack width plotted in Figs. 12 to 16 is one-half of the sum of all of the crack widths on both sides of the beam, as measured about one-fourth inch below the top or above the bottom of the beam. Each value represents approximately the total extension either in the upper or the lower surface of the beam due to the opening of cracks.

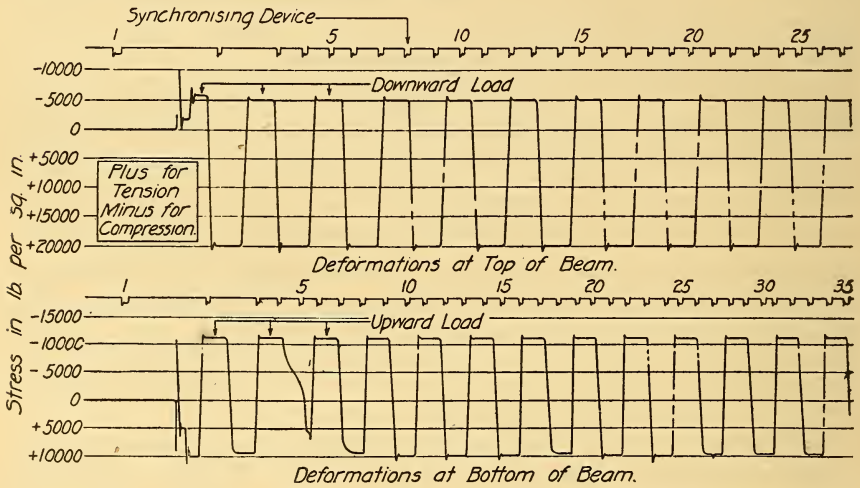

FIG. 6.—*Strainagraph record showing characteristic behavior of beams during test*

A strainagraph record,[5] taken during a portion of the test of one of the specimens, is shown in Fig. 6. This brings out some of the characteristics of the action of the testing machine.

It is found that the full load was in position about 80 per cent of the time and that about 10 per cent of the time of each cycle was required for the application of the load and 10 per cent for its removal. Assuming 17 cycles per minute as the ordinary rate of operation, it is found that the application of each load required about three-fourths of a second, and that for each 24 hours in which the machine operated the specimen was under full load about 20 hours.

[5] F. R. McMillan, The Strainagraph and its Application to Concrete Ships, Proc. Amer. Concrete Inst., 15, p. 108; 1919.

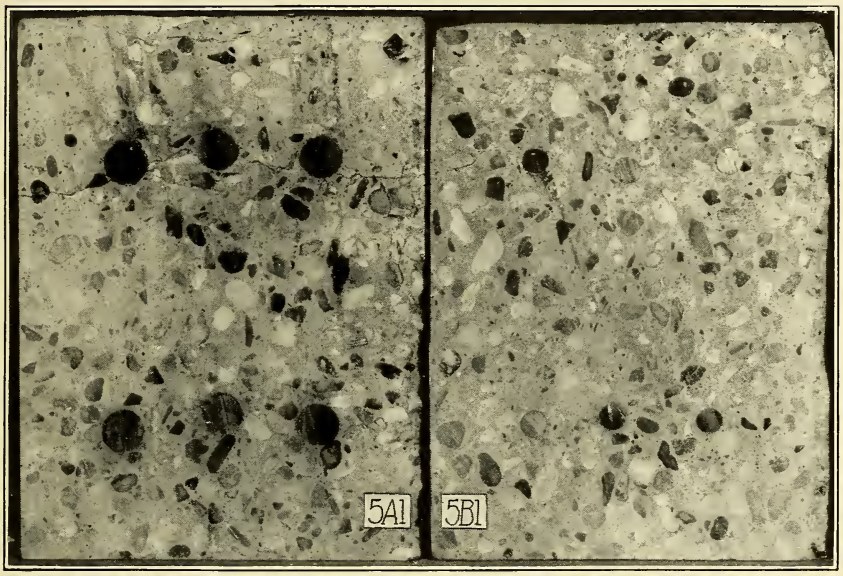

FIG. 7.—*View of cross sections through beams 5A1 and 5B1 after test*

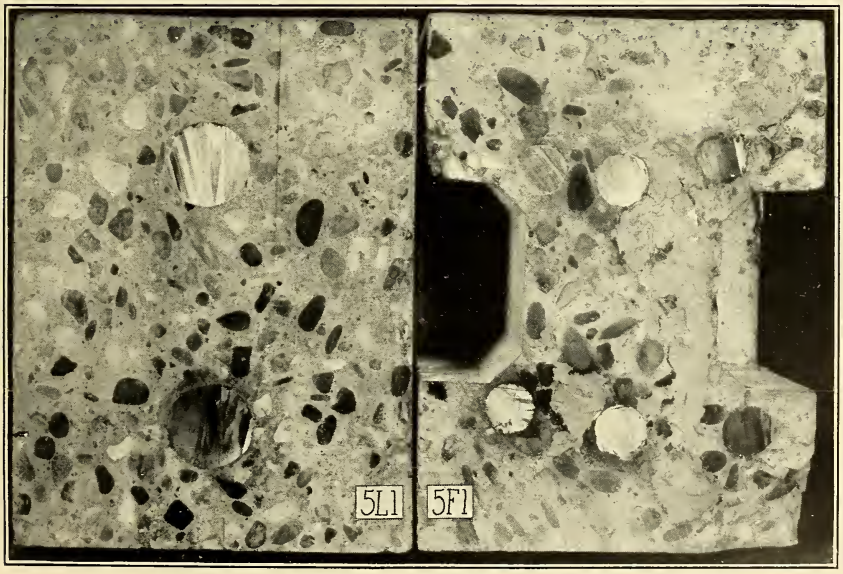

FIG. 8.—*View of cross sections through beams 5L1 and 5F1 after test*

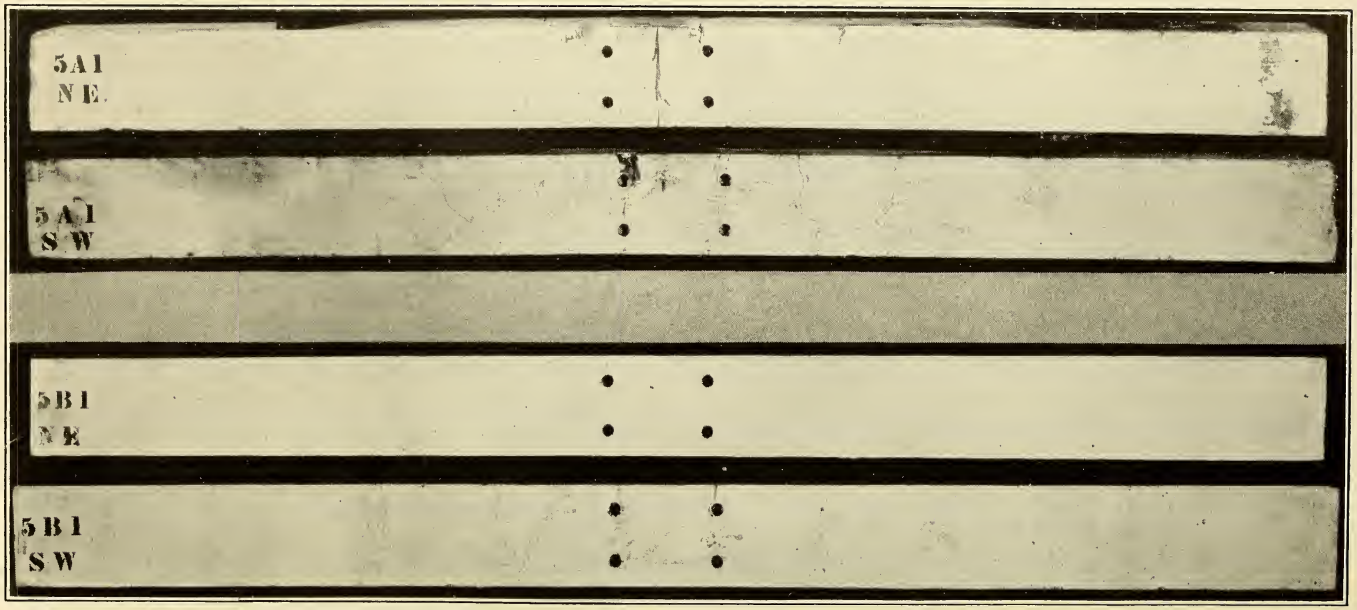

FIG. 9.—*Side view of beams 5A1 and 5B1 after test*

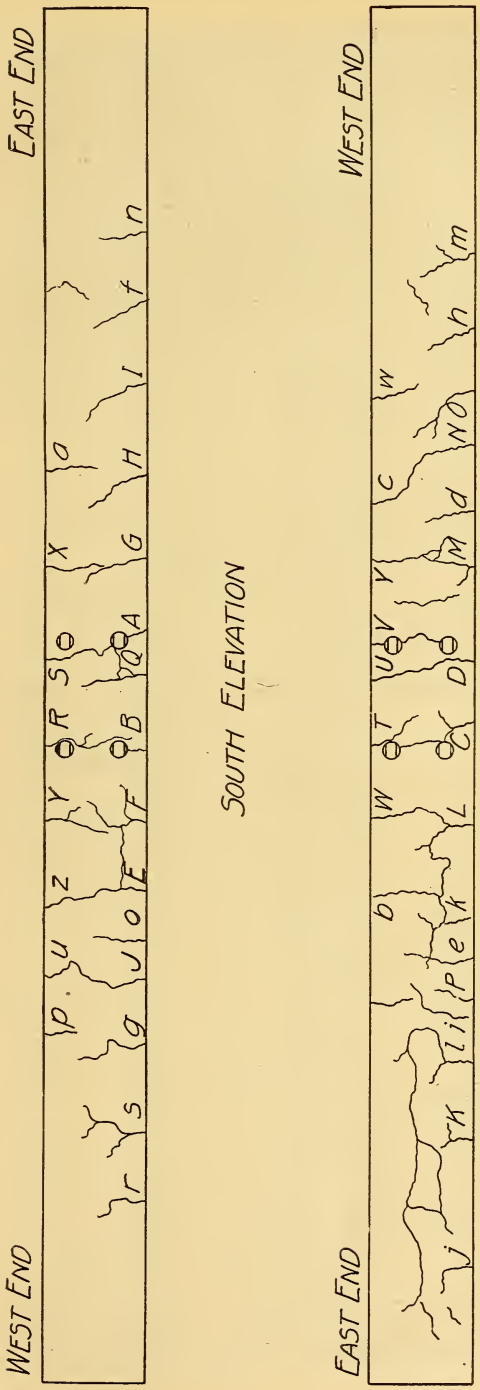

FIG. 10.—*Sketch showing location of cracks on beam 5C1 after test*

That the stress due to impact was small is shown by the form of the graph. The only portion of the graph in which anything like an effect of impact appears is the peak which occurs with each application of the load. The height of this peak above the horizontal portion of the graph is about 4 per cent of the total height of the graph. Assuming that the peak is caused entirely by impact on the beam, the stress due to impact would be about 4 per cent of the sum of the tensile and compressive stresses due to static load. Since the inertia of the mechanism of the strainagraph may have been partly responsible for the occurrence of the peak, it is possible that the impact may have been smaller than the amount stated, but it does not seem that it can have been larger than that.

IV. TEST DATA AND DISCUSSION

1. TABLES AND DIAGRAMS

The measured dimensions and computed properties of the test beams are given in Table 8.

TABLE 8.—Measured Dimensions and Computed Properties of the Test Beams

Dimension	Notation	Beam numbers				
		5A1	5B1	5C1	5F1	5L1
Nominal cross section	.....	6 x 8 in.	6 x 8 in.	6 x 8 in.	I section	6 x 8 in.
Width of beam, inches	b	6.03	6.00	6.00	.....	6.00
Distance, compression face to center of tension steel, inches	d	6.00	5.93	6.00	6.00	6.00
Distance compression face to center of compression steel, inches	d′	2.05	2.07	2.00	2.00	2.00
Sectional area bottom steel, square inches	A_s	.9204	.3312	1.325	1.325	1.227
Sectional area top steel, square inches	A'_s	.9204	.3312	.588	1.325	1.227
Ratio A_s/bd	p	.0254	.0093	.0368	.....	.0341
Ratio A'_s/bd	p′	.0254	.0093	.0163	.....	.0341
Ratio of depth of neutral axis to distance compression face to center of tension steel	k	.461	.348	[a] .530 [b] .393	.495	.490
Ratio moment arm of resisting couple to depth *d*	j	.808	.884	[a] .794 [b] .823	.....	.784
Distance between center of compression area and center of tension steel, inches	jd	4.848	5.242	[a] 4.764 [b] 4.938	4.76	4.704

[a] Downward. [b] Upward.

NOTE.—In these computations *n* is taken as 10.

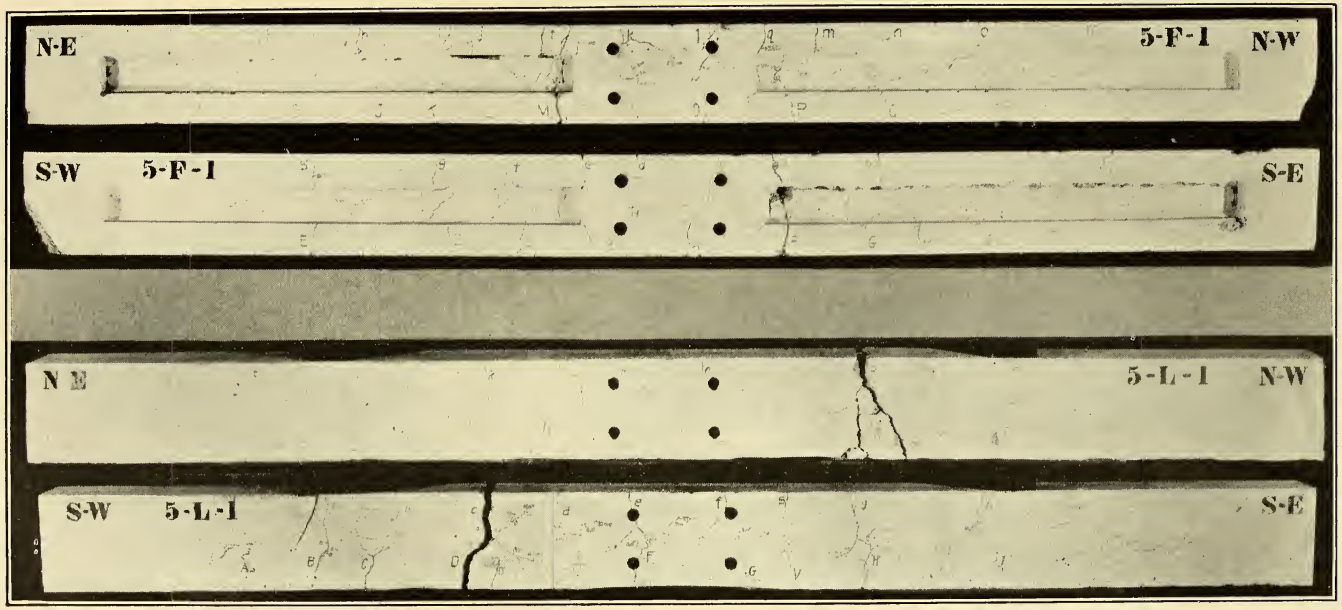

FIG. 11.—*Side view of beams 5F1 and 5L1 after test*

General results for the beams tested are given in Table 9. The values of the measured tension and measured compression in the reinforcement given in this table are determined directly from the unit deformations given in Figs. 17 to 23. These values for each beam represent the stresses at a time when the beam had reached approximately a stationary condition of stress. The compressive stresses given were based on the assumption that the total compressive stress in the concrete was equal to the numerical difference between the total tension and the total compression in the reinforcement of the beam. The stresses were assumed to be dis-

TABLE 9.—Results of Reversal-of-Stress Tests

Beam No.	Reinforcement					Measured tension in steel f'_s		Measured compression in steel f'_s	
	Top		Bottom		Bar ends				
	Number of bars	Diameter	Number of bars	Diameter		Top, load upward	Bottom, load downward	Top, load downward	Bottom, load upward
		Ins.		Ins.		Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²
5A1	3	5/8	3	5/8	Hooked	21 600	19 500	5400	7000
5B1	3	3/8	3	3/8	...do	21 900	22 800	.....	.....
5C1	3	1/2	3	3/4	...do	1 500	11 000	7500	.....
5F1[a]	3	3/4	3	3/4	...do	11 400	11 700	6900	7000
5L1	1	1 1/4	1	1 1/4	Straight	18 000	17 400	4000	4800

Beam No.	Computed compression in concrete f_c		Range of stress in steel from tension to compression		Number of cycles at failure	Remarks
	Top, load downward	Bottom, load upward	Top	Bottom		
	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²		
5A1	1565	1555	27 000	26 500	709 041	Three top bars failed in tension at east gage point.
5B1	1210	1160	21 900	22 800	59 377	Three top bars and one bottom bar failed in tension at east gage point.
5C1	157	1435	9 000	11 000	.....	Test discontinued at 2 008 000 cycles without sign of failure.
5F1	.....	.....	18 300	18 700	544 448	Top middle bar, all bottom bars, and the web steel failed in tension.
5L1	2080	2020	22 000	22 200	431 821	Both bars failed in tension 16 inches west of center.

[a] Web reinforced with one-quarter inch wire loops, 2-inch pitch: I section.

tributed according to a straight-line relation. The equation which gives these stresses is

$$f_c = \frac{2\,(f_s A_s - f'_s A_c)}{b\,(xy + d') - A_c}, \text{ in which}$$

f_c = extreme fiber compressive stress in concrete,
f_s = observed tensile stress in reinforcement,
f'_s = observed compressive stress in reinforcement,
A_s = area of reinforcement in tension,
A_c = area of reinforcement in compression,
b = breadth of beam,
y = depth from center of compression reinforcement to center of tension reinforcement,
d' = distance from compression surface to center of compression reinforcement,
$x = \frac{f'_s}{f'_s + f_s}$ = ratio of distance between neutral axis and compression reinforcement to distance between tension and compression reinforcement.

The summations of the crack widths which were measured at intervals during the tests, at levels one-fourth inch above the bottom and one-fourth inch below the top of the beams, are shown in Figs. 12 to 16. These figures show also the measured deflections. Letters were used in alphabetical order to identify the cracks as soon as they were discovered. These letters may be distinguished in Figs. 9 to 11. Figs. 17 to 23 show the number of cycles plotted as abscissas and the unit deformations as ordinates.

2. BEHAVIOR OF BEAMS DURING TESTS

In the following paragraphs are given the more important phenomena of the tests.

(*a*) Beam 5A1 had three ⅝-inch plain round bars in the top and three in the bottom. The applied load was 5000 pounds both upward and downward. This beam was tested to show the effect of repeating a compressive stress in the concrete of about 2000 pounds per square inch, combined with a relatively large range of stress from tension to compression in the steel. A stress of 1500 pounds per square inch was used in the design of the concrete ships.

Fig. 12 shows the relation between the deflection either upward or downward and the total crack widths in the top and in the bottom of the beam throughout the test. Figs. 17 and 18 show

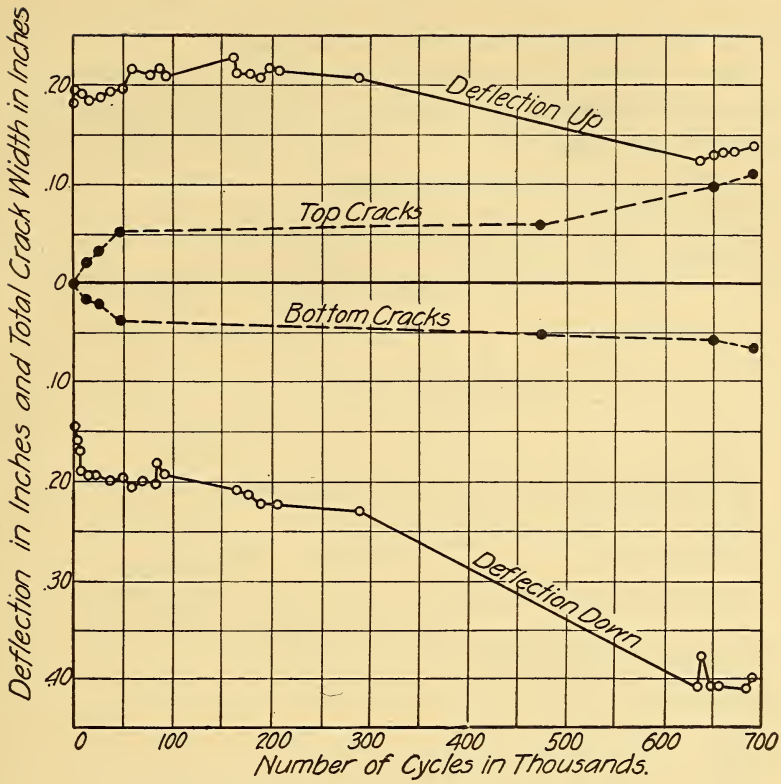

FIG. 12.—*Deflection and total crack widths for beam 5A1*

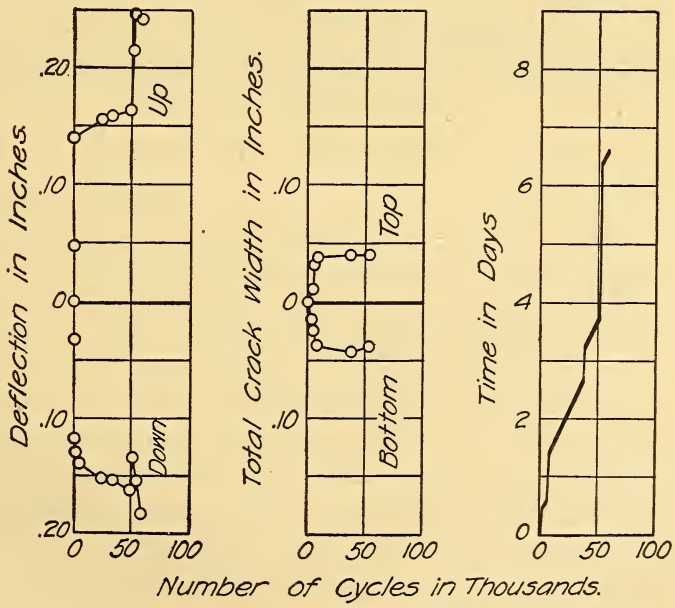

FIG. 13.—*Deflection crack widths and continuity of test for beam 5B1*

the unit deformations in the reinforcing steel as ordinates and the number of cycles of the machine as abscissas.

During the first 1000 cycles[6] the widths of the tension cracks increased to a total of 0.025 inch in the top and 0.020 inch in the bottom of the beam (Fig. 12). As the tension cracks increased in number and size the steel deformations changed slightly with a marked increase in deflection of the beam both upward and downward. After the first 1000 cycles the crack widths, deflections, and deformations remained almost constant through about

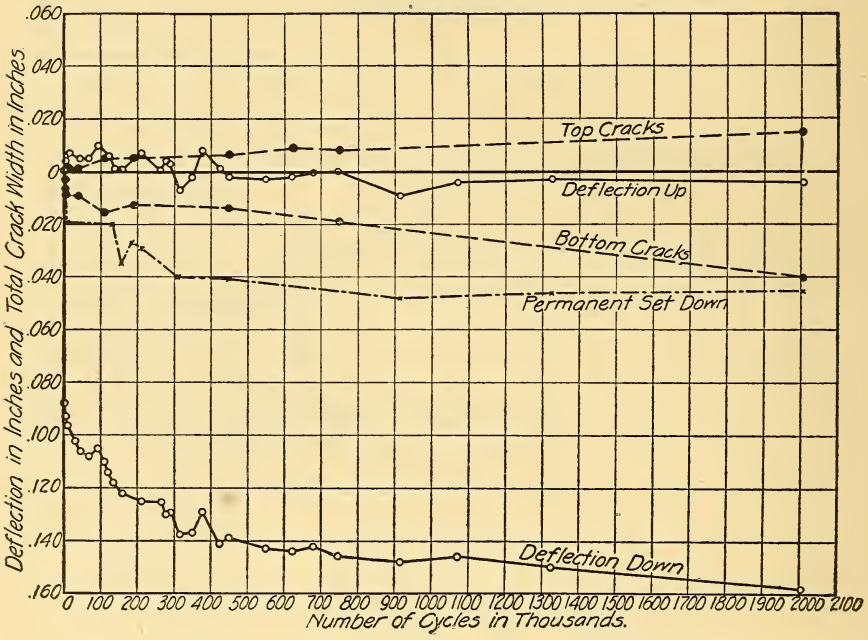

FIG. 14.—*Deflection and crack widths for beam 5C1*

one-half the duration of the test, when the deflection downward and the crack widths increased gradually until the beam failed.

The cracks increased in length, and toward the end of the test many of them extended from the top of the beam to the bottom. The cracks in the top of the beam did not close entirely with downward load, due, apparently, to some small particles of concrete chipping off and falling into the cracks. As a result the cracks in the top of the beam appeared somewhat ragged, but in the bottom of the beam they were still clean cut. The top steel failed in tension at 709 041 cycles at the west gage point, which was 4 inches west of the center of the span.

[6] An error has been found in Fig. 12. For all plotted points in this figure showing crack widths the number of cycles should be reduced by 13 500.

(*b*) Beam 5B1 had three ⅜-inch plain round bars in the top and three in the bottom. This beam was designed so that when the load was applied the computed tensile stress in the steel would be high (28 800 pounds per square inch), and the computed

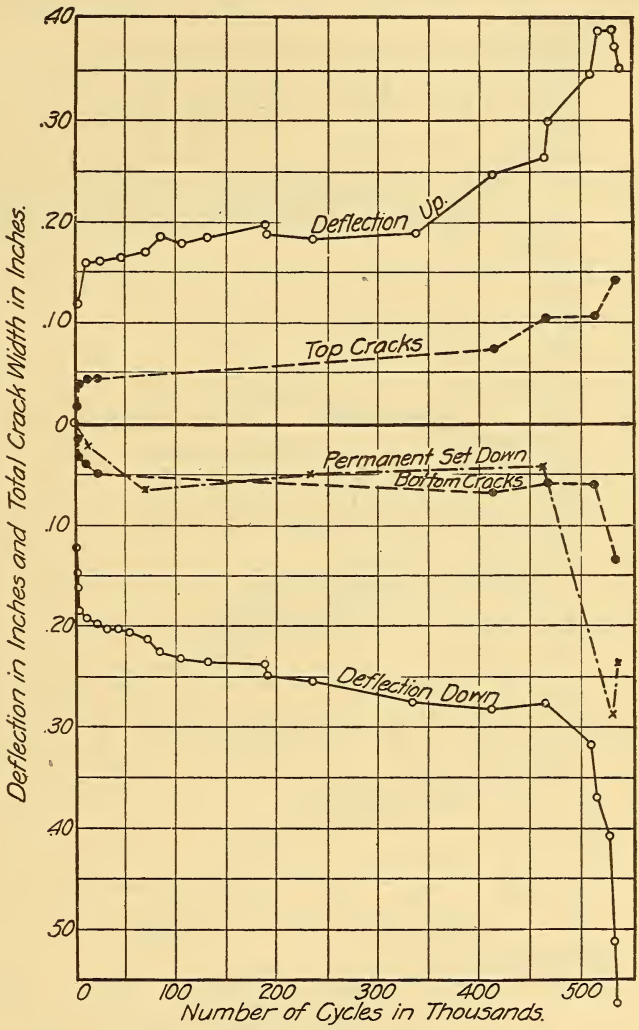

FIG. 15.—*Deflection and crack widths for beam 5F1*

compressive stress in the concrete would be about equal to the working stress used in the design of the concrete ships. The applied load was 2380 pounds both upward and downward. The deflections, crack widths, and the continuity of the test are shown in Fig. 13. The deformations are shown in Fig. 19.

No cracks appeared when a static load of 2380 pounds was first applied, but cracks *A* to *P*, Fig. 9, occurred on the first repetition of the load. During the first 300 cycles the deflections increased rapidly, while the crack widths increased rapidly during the first 7000 cycles. Both deflections and crack widths then remained

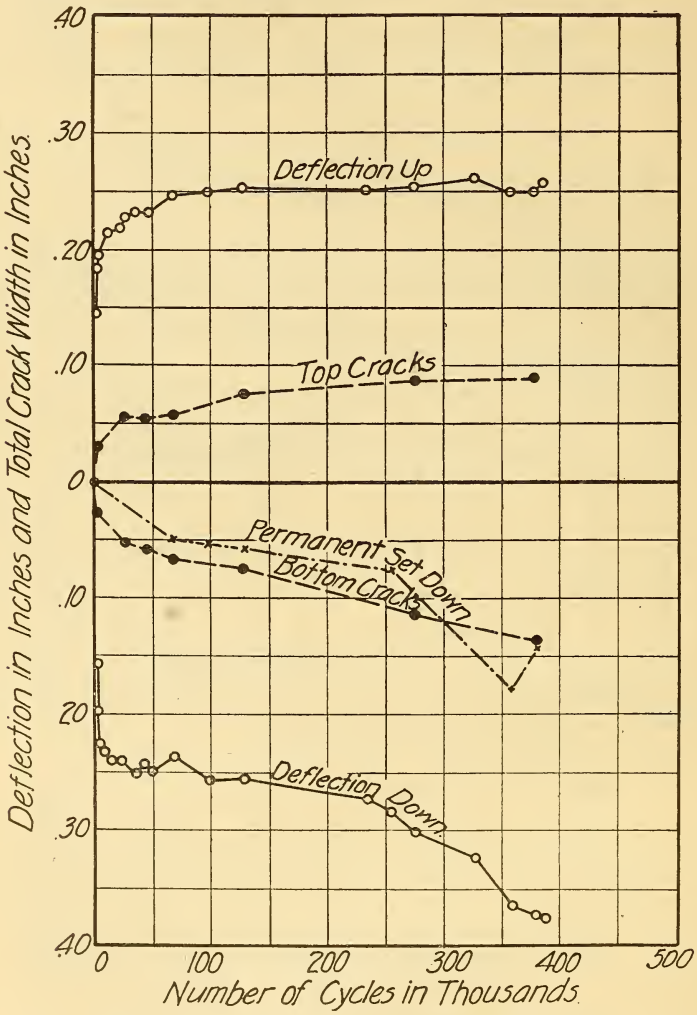

FIG. 16.—*Deflection and crack widths for beam 5L1*

almost stationary until the beam was close to failure. The deformations show less regularity than the deflections and crack widths throughout this portion of the test. In the last measurements taken before failure the deflections and deformations generally showed a great increase, but the crack widths did not.

At 59 377 cycles all three of the top bars broke without any necking which could be detected by visual observation. The south bar broke in the east gage hole, the north bar in the west gage hole, and the middle bar at a point opposite the west gage hole.

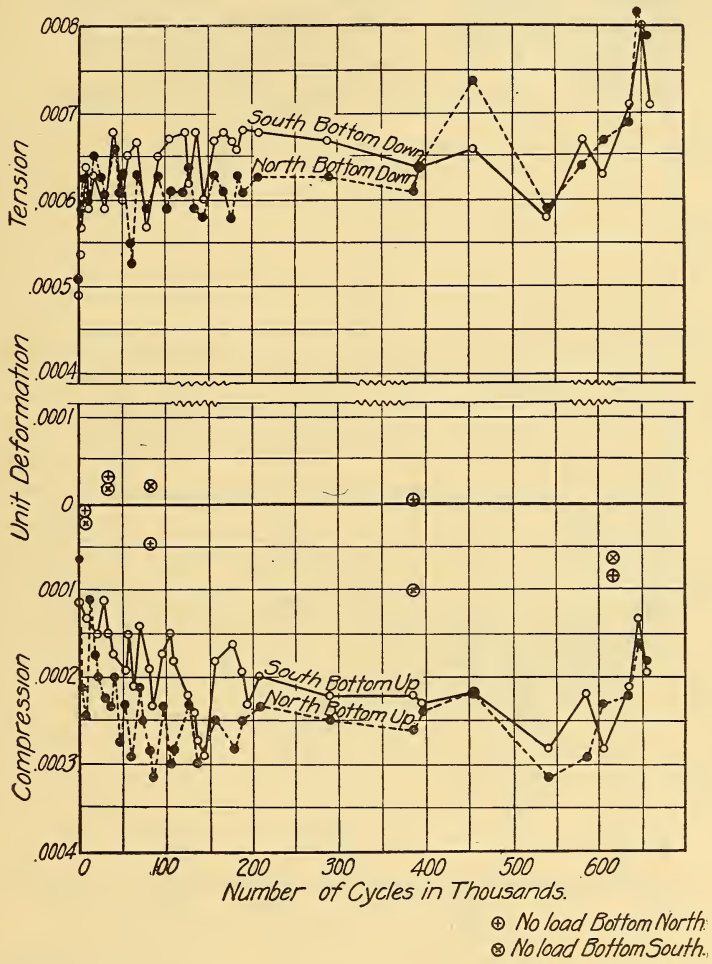

FIG. 17.—*Unit deformations in bottom of beam 5A1*

(*c*) Beam 5C1 had three ¾-inch plain round bars in the bottom of the beam and three ½-inch plain round bars in the top. This beam was designed so that the test load would produce stresses not greater either in tension or compression than the working stresses used in the concrete ship design. The applied load was 3630 pounds in the downward direction and 670 pounds in the

upward direction. Fig. 14 shows the crack widths and deflections throughout the test. Fig. 20 shows the unit deformations as the test progressed.

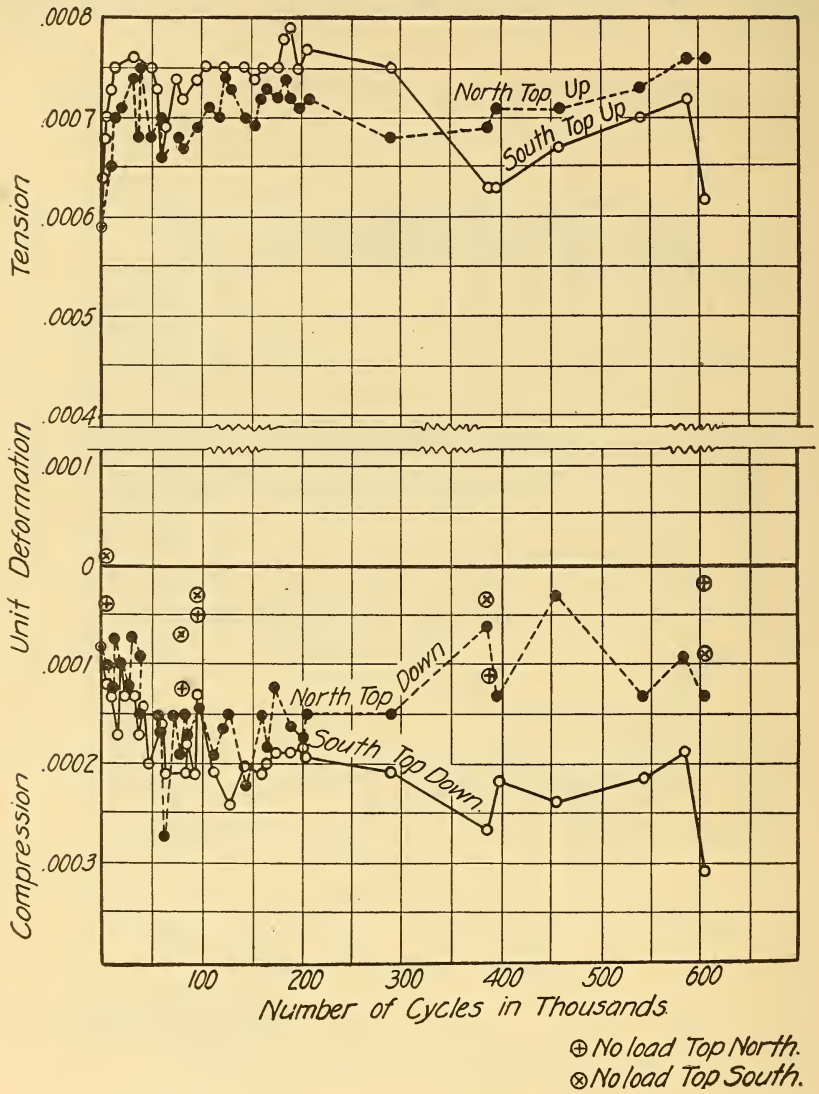

FIG. 18.—*Unit deformations in top of beam 5A1*

The upward deflections and the crack widths in the top of the beam increased slightly at the start but remained almost constant throughout the remainder of the test. The downward deflection, the downward permanent set, and the crack widths at the bottom of the beam increased gradually through about 400 000 cycles

of load. The test was discontinued at 2 008 000 cycles of load and had shown very little change after passing 400 000 cycles. The cracks were very small and extended only a short distance from the top and bottom surfaces of the beam. No serious

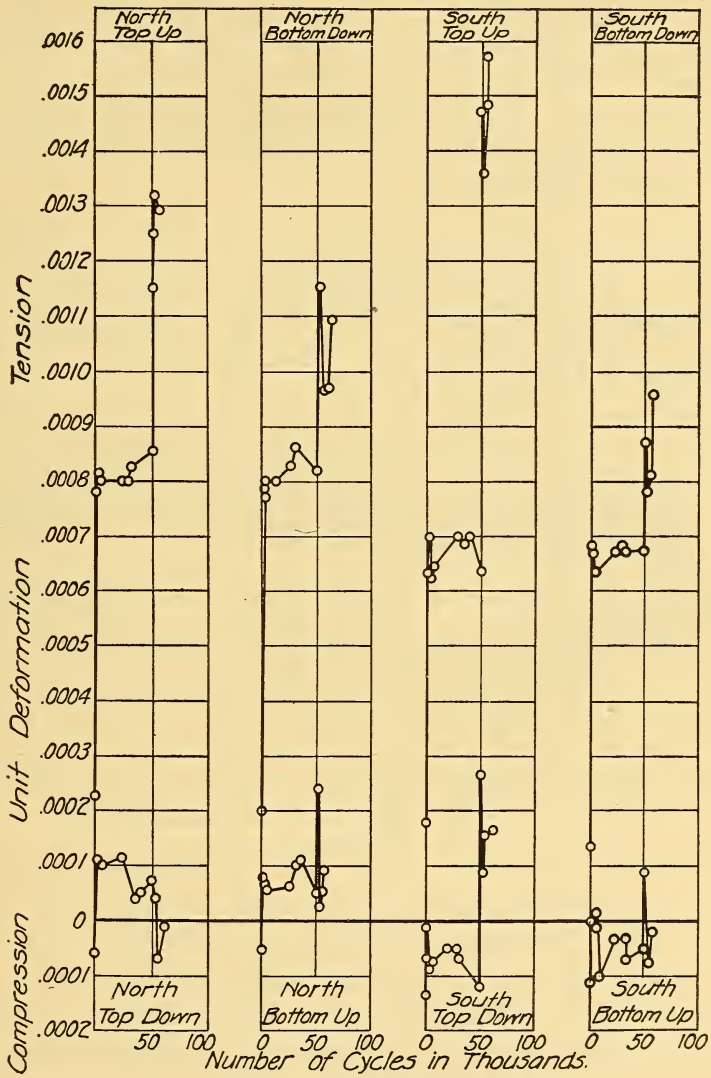

FIG. 19.—*Unit deformations in beam 5B1*

developments of any kind showed indications of approaching failure.

(*d*) Beam 5F1 was made with an I-shaped cross section with three ¾-inch plain round bars in the top flange and three in the

bottom flange, with web reinforcement consisting of a ¼-inch plain round bar wound around and welded to the top and bottom central bars with a pitch of 2 inches. This test was designed to develop high shearing stresses in the web without affecting appreciably the resistance to tensile and compressive stresses. The applied load was 5000 pounds both upward and downward. This gave a computed shearing stress of 175 pounds per square inch. Fig. 15 shows the deflections, crack widths, and permanent set downward as the test progressed. Figs. 21 and 22 show the unit deformations.

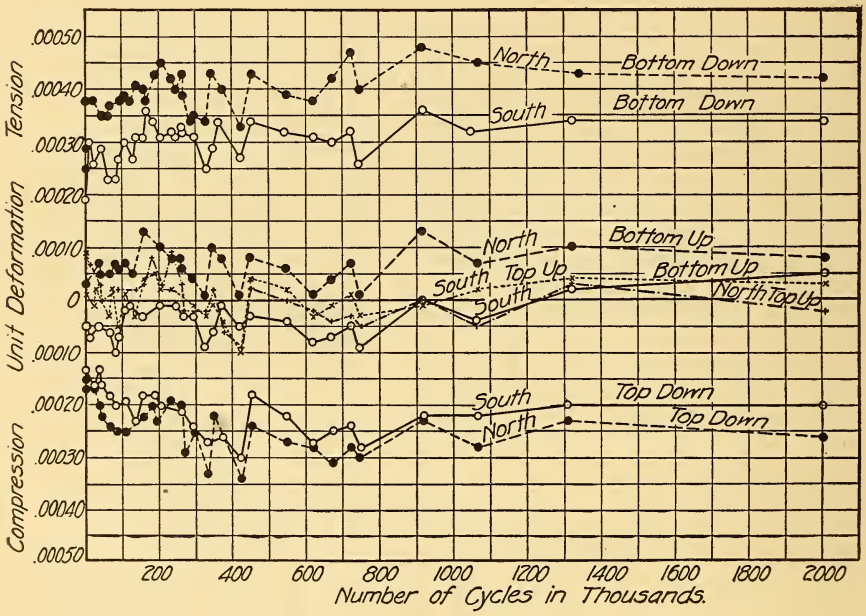

FIG. 20.—*Unit deformations in beam 5C1*

The deflections in both directions of loading increased rapidly with a gradual increase in crack widths during the early stages of the test. At 3600 cycles a horizontal crack appeared at the top of the web extending the whole length of the I-shaped portion east of the center of the beam. From the horizontal crack small diagonal cracks extended downward toward the center of the web as the test continued. Similar cracks appeared later at the junction of the web with the lower flange. From 3600 cycles until the test was about three-fourths completed, the crack widths and deflections remained almost constant but the unit deformations varied considerably.

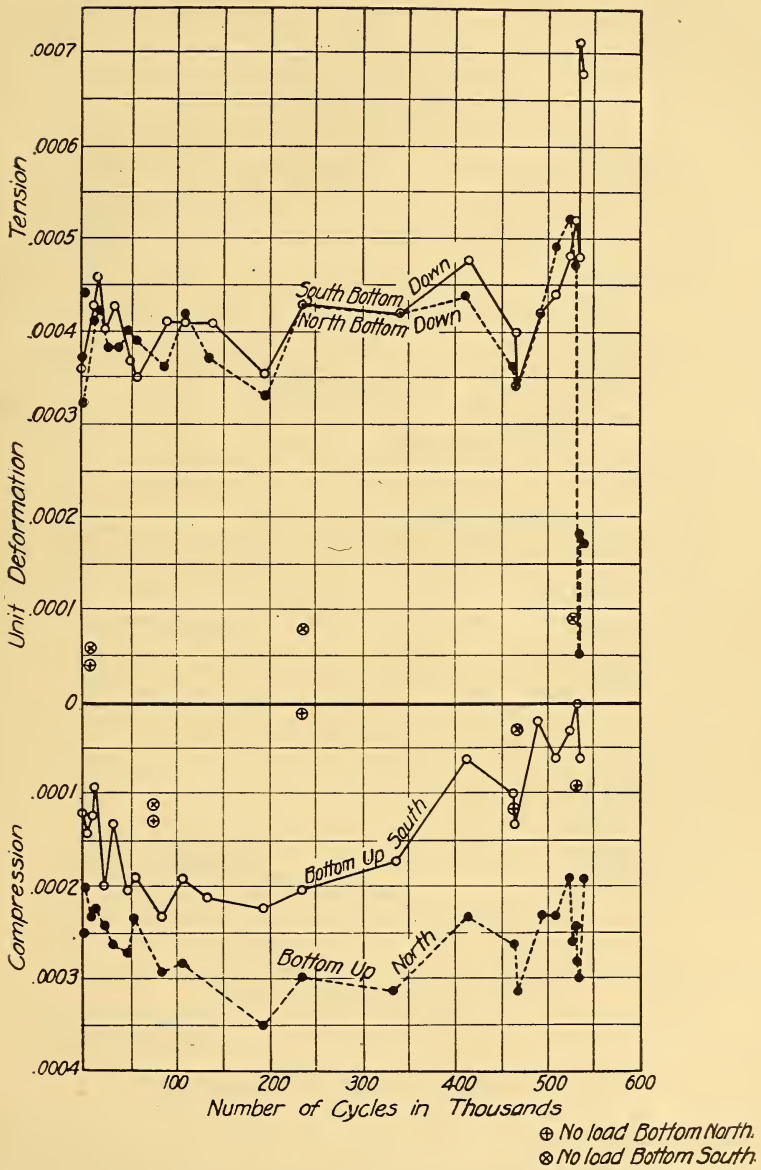

FIG. 21.—*Unit deformations in bottom of beam 5F1*

At 467 000 cycles the cracks in the top and bottom flanges and the vertical web cracks just east of the east load point, at the section where the web thickness was reduced, showed a marked increase in size and failure seemed imminent at this point. Rust and pulverized concrete were working out of the cracks at this

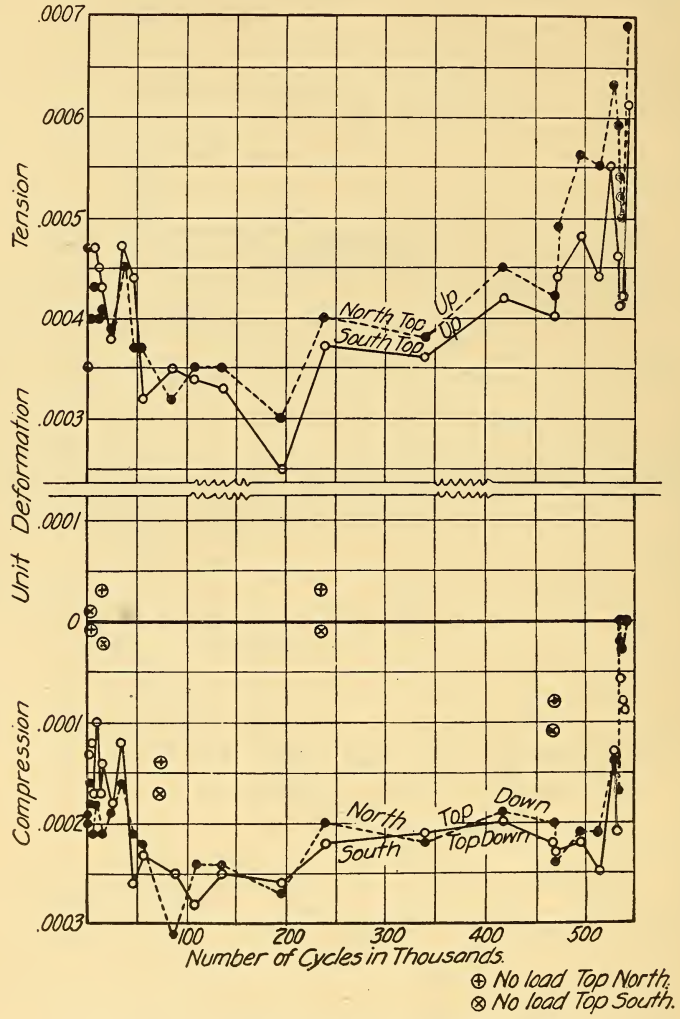

FIG. 22.—*Unit deformations in top of beam 5F1*

point and along the horizontal crack under the top flange of the beam. Apparently the horizontal crack passed under the horizontal bars and separated the top flange from the web in the east portion of the beam. A horizontal movement of the flange longitudinally with reference to the web was observed. This

movement was 0.015 inch when first measured. As the separation of flange and web became more nearly complete the movement increased, until shortly before failure it was as much as 0.07 inch.

The total crack width just before failure was 0.141 inch at the top surface and 0.133 inch at the bottom surface of the beam. The steel bars became visible in several places where the concrete was chipping off and considerable slipping of the bars in the top was noticeable with the sliding of the top flange. There was little cracking of the concrete in the west portion of the beam.

During the last 100 000 cycles of the test the deflections and permanent set downward increased very rapidly, with an increase in the deformations in the reinforcing steel. At 544 000 cycles the top and bottom middle bars and both outside bars in the bottom failed in tension at points about 5 inches east of a section through the east gage holes. The web reinforcement in that section also failed in tension at the point where it was welded to the top bar. Although the end of the test was brought about by complete tension failure in the reinforcement, the separation of the flanges from the web was so extensive that, toward the end of the test, the beam sagged greatly and some of the load probably was carried by the lever which was not applying the load.

(*e*) Beam 5L1 had one 1¼-inch plain, round, straight bar in the top and another in the bottom. The beam was designed for the purpose of studying the effect on the end slip caused by repeated application of high bond stresses. The applied load was 6000 pounds both upward and downward. This gave a computed bond stress of 161 pounds per square inch. The permanent set downward, the crack widths and the deflections are shown in Fig. 16. The deformations in the steel are shown in Fig. 23. Fig. 24 shows the end slip of the bars.

A gradual increase in deflections, crack widths, and permanent set downward took place until 70 000 cycles were recorded. The top crack widths and upward deflection remained almost constant until the completion of the test. The permanent set downward, the downward deflection, and the bottom crack widths increased gradually throughout the remainder of the test.

Up to 7200 cycles very gradual movements of the ends of the bars from their initial positions were detected by the gages which were used to measure slip, but no reversal in direction of movement with the reversal of load could be detected. From this time on

throughout the test there was a rapid increase in the amount of slip at the west end of the bottom bar and a reversal in the direction of the movement of the end of the bar with the reversal in the direction of load. It was expected that failure would occur on account of this slip, but it actually occurred after 431 821 cycles of load by tension in both reinforcing bars at a section 16 inches from the center of the span.

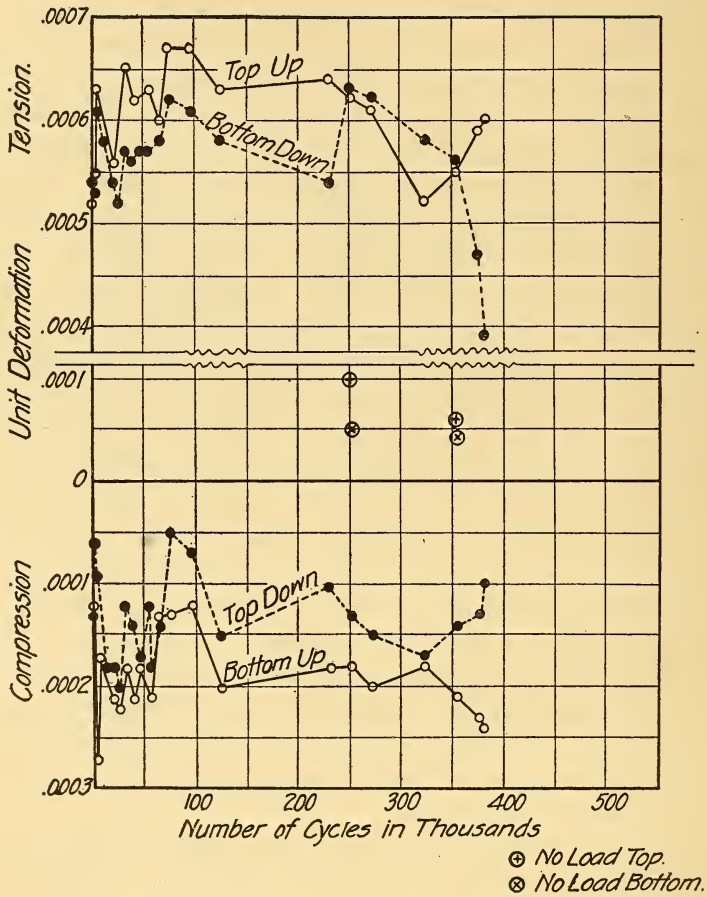

FIG. 23.—*Unit deformations in beam 5L1*

3. SIGNIFICANCE OF TENSION FAILURES

The failures of all of the beams tested have been by tension in the steel. The failures generally occurred with fewer repetitions of load than would be expected if the results of previous tests [7]

[7] Moore and Seely, The Failure of Materials under Repeated Stress, Proc. Am. Soc. Test. Mats., **15**, p. 437, 1915; also Constants and Diagrams for Repeated Stress Calculations, **16**, p. 471, 1916.

be taken as a guide. It seems probable that the use of defective steel as reinforcement was partly responsible for this result. Yet it should be noted that the steel was purchased as a commercial grade of reinforcement and probably was no worse than steel that is frequently used on small jobs where little or no inspection is exercised. All of the tension failures of the steel occurred without necking of the bars. This is characteristic of failure under repeated tensile stress and, whatever may have been the grade of the steel used, the effect of the repetition of loads seems clearly to have been present.

Besides the tension failures in the steel, other effects of the loading were apparent, and if a better grade of steel had been used, it seems probable that in some cases failure would have been due to other causes than tension in the reinforcement. Thus, in beam 5A1 a ragged appearance at the edges of the cracks was noted, and if the steel had not failed when it did, critical conditions in the concrete might have developed. However, the indications at the time of failure were that the concrete was still carrying its full proportion of the compression.

In beam 5F1 the web was badly cracked before the tension failure occurred. The flanges of the beam had been almost detached from the web at one end and the deflections had become excessive. It is possible that the tension failure may have been hastened by a repeated bending of one of the reinforcing bars. At any rate, it seems likely that a failure would have developed in the web before a great length of time, if failure of the steel in tension had not intervened.

In beam 5L1 the end slip of one of the bars had increased to 0.06 inch before tension failure took place. This is well beyond the amount of slip which, in the analysis of test data,[8] has previously been recognized as critical, and it seems certain that a complete failure in bond was impending and would have been the primary cause of failure if the tension failure in the steel could have been delayed for a short time.

4. END SLIP OF BARS

Slip of bars was measured in beam 5L1 only. In all other beams the bars were hooked to prevent end slip. Fig. 24 shows the movement of the ends of the bars plotted as ordinates, and the number of cycles of load as abscissas. Movement toward the

[8] D. A. Abrams, Tests of bond Between Concrete and Steel, Bull. No. 71, Eng. Exp. Sta., Univ., of Ill., 1913.

center of the span is plotted upward and movement away from the center is plotted downward.

Most of the slip occurred at the west end of the bottom bar. Up to 7200 cycles of load a movement of 0.0009 inch at this point

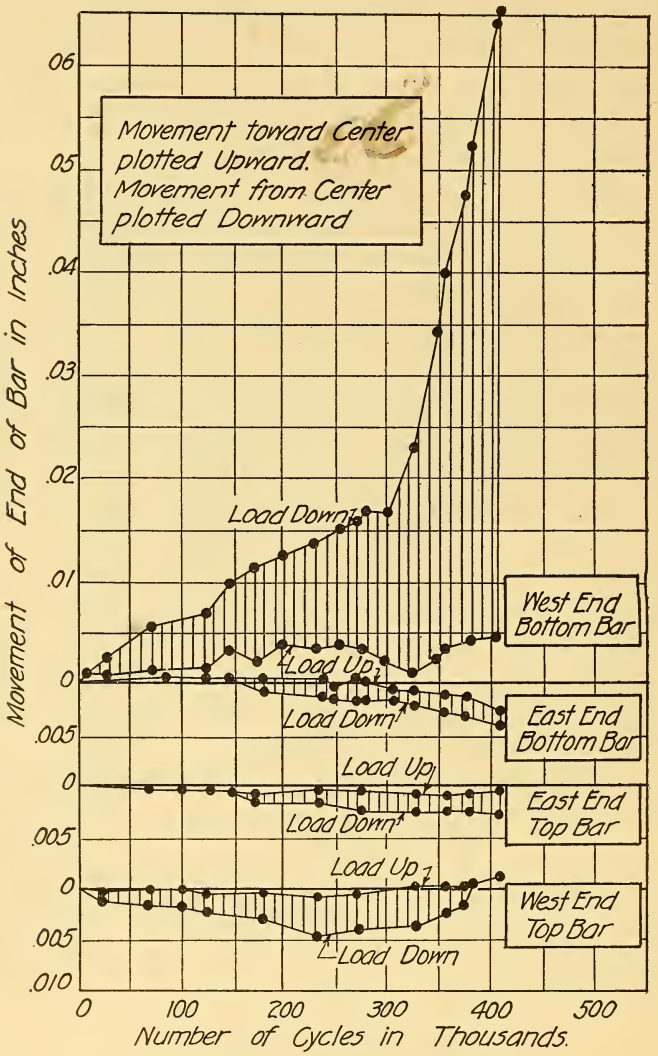

FIG. 24.—*End slip of reinforcing bars for beam 5L1*

was detected. This may have represented an actual movement of the bar with reference to its initial position, but up to this stage of the test no movement of the pointer of the Ames dial could be detected between successive applications of the load. From this time on, however, there was an instantaneous movement of the west end

of the bar toward the center of the span when the load was applied downward, and a return to approximately the original position when the load was applied upward. This cycle of slip was traversed with each cycle of load, and as the bar reached the end of its slip the suddenness of its stopping was marked by a sharp sound as of the impact of steel against concrete. The movement toward the center of the span increased with an increase in the number of applications of load, but as the test progressed the end of the bar fell short more and more of coming back to its original position with the application of upward load.

It is a matter of interest to note that the data indicate a simultaneous movement of one end of the bottom bar toward the center of the span and of the other end away from it; that is, the entire bar would appear to have been moving through the beam from west to east. The total movement of the bottom bar was slight, however, and it is doubtful if the data afford any satisfactory explanation of this phenomenon. It is just as inexplicable that both ends of the top bar appear to have been moving away from the center of the beam as that the bottom bar, as a whole, was moving through the beam from west to east. However, the movements observed at the ends of the top bar were so small that they are unimportant in comparison with the large amount of slip which occurred at the west end of the bottom bar.

The sharp increase of slip which occurred at the west end of the bottom bar at 300 000 cycles of load seemed to forecast that failure would be due to the slipping at that position; but, after 431 821 cycles of load, failure occurred by tension in both of the reinforcing bars at a section 16 inches west of the center of the span. When the beam was broken up an examination showed that the adhesion between the lower bar and the concrete in the west portion of the beam had been entirely destroyed. Near the section of tension failure scratches on the reinforcing bar were present, which indicated an abrading action of the aggregate on the bar, due to its movement back and forth through the concrete.

It is of importance that, although up to 7200 cycles of load there was no measurable slip between successive applications of load, a continuation of the test finally produced a slip of 0.06 inch. The slip probably would have progressed to the point of causing failure of the beam if tension failure in the reinforcement had not occurred before that stage was reached.

5. EFFECT OF GAGE HOLES ON LOCATION OF POINT OF FAILURE

As noted in Part III, article 5, the gage holes in the reinforcing bars were 0.07 inch in diameter and about three thirty-seconds inch deep. In most cases also the holes were countersunk slightly. The proportional reduction of area of the cross section of the bar due to the presence of the gage holes was comparatively small, even in the case of the smallest bars used, which were three-eighths inch round, but the effect of the gage holes in hastening failure may have been important. It has been pointed out [9] that "a sudden change of section is a great source of weakness in withstanding repeated stresses." The presence of gage holes furnished a sudden though slight change in section.

The smallest bars used would be expected to show the largest effect from the presence of gage holes. In beams 5A1 and 5B1, having five-eighths and three-eighths inch bars, respectively, failure occurred through the gage holes. In these beams the middle bars had no gage holes, but in each case failure of the middle bar occurred at a point just opposite a gage hole in the outer bar.

In all of the beams there seemed to have been a tendency for failure to occur in all of the bars at the same section through the beam. For the beams having three-eighths and five-eighths inch bars, the location of the section of failure appeared to be influenced by the location of gage holes. For the beams having three-fourths and 1¼ inch bars, the location of the section of failure was not determined by the location of the gage holes.

The number of repetitions required to cause failure was smallest for the beam 5B1, in which the proportional effect of the gage holes was largest. This seems to be in keeping with the discussion in the previous paragraphs, but the tensile stresses developed in this beam, as shown by the deformations in Fig. 19, were enough larger than those in the other beams to raise some doubt as to the correctness of the conclusion that the gage holes had an important effect in hastening failure or determining where it should occur.

If the gage holes in the five-eighths-inch bars were important in causing failure, beam 5A1 should have been expected to fail under a smaller number of applications of load than beams 5L1 and 5F1, in which failure did not occur through the gage holes. On the contrary, beam 5A1 withstood a larger number of repetitions than either 5L1 or 5F1, although the stresses developed in beam 5A1 were higher than the stresses in either of the other beams.

[9] Johnson's "Materials of Construction," fifth ed., p. 776.

Although there are indications that the gage holes in the bars had some influence in determining the location of the section of failure, it does not seem that they had much effect upon the ultimate strength of the steel under repeated loading.

6. EFFECT OF CRACK DEVELOPMENT ON LOCATION OF POINT OF FAILURE

Even where gage holes in the bars appeared to determine the location of the section of failure, there was also a marked development of cracks at the same section. In fact, in all cases tension failure of the reinforcing bars occurred at sections where large cracks extended entirely through the section of the beam.

At the sections where tension failure occurred the maximum widths of the cracks just before failure were as given in Table 10. These were the largest cracks in the beams. In beams 5A1 and 5L1 it was noted that the cracks did not seem to close entirely with each reversal of load. If the fractured surfaces were abraded to such an extent as to render ineffective some of the concrete, the reinforcement would have been forced to take more than its share of the compressive stresses and that would have increased the range of stress in the steel, traversed in each cycle, above that given in computations of stress (Table 1) based upon the unity of the entire section. On the contrary, the data taken as the test progressed do not show any more rapid increase in compressive stress than in the tensile stress, and this would discredit an explanation of failure based upon an assumed increase in compression in the steel as the test progressed.

TABLE 10.—Width of Cracks at Points of Failure

Beam No.	Designation of crack measured	Measured width of crack	Number of cycles at time of measurement	Number of cycles at failure
		Inch		
5A1	B	0.012	648 241	660 000
	F	.025		
	H	.023		
5B1	A	.000	57 387	59 377
	F	.000		
	J	.013		
	N	.002		
5F1	u	.025	532 490	544 448
	F	.012		
	M	.023		
5L1	D	.070	377 450	431 821
	R	.008		
	Z	.070		
	c	.040		
	p	.040		

If the reinforcement had taken all of the compression, the stresses in tension and in compression should have been equal. The fact that the tensile stresses were much larger than the compressive stresses indicates that the concrete must have assisted greatly in resisting the compressive stresses. Although the cracks seemed not to be entirely closed, this must have been merely a surface condition.

At the sections where failure finally occurred there developed, toward the end of the tests, a change in slope of the beams so sharp that it could be observed by visual inspection without instruments. This phenomenon, whatever be its cause, would be expected to introduce a sharper curvature of the bar at this point than the elastic curvature of the beam as a whole. Bending stresses in the reinforcing bars independent of those in the beam as a unit would result, and this may assist in explaining the early failure of some of the beams.

7. EFFECT OF REPETITION OF BENDING STRESSES ON PHYSICAL PROPERTIES OF STEEL REINFORCEMENT

The physical tests indicated very little change in the properties of the steel due to the repetition of load on the beam. Table 11 shows a comparison of yield point, ultimate strength, ultimate elongation, and reduction of area for specimens of the steel taken before making the beams and for specimens taken from the beams after failure. Each value is derived from the tests of four to nine specimens. This table shows that the original values were slightly smaller than those obtained from specimens cut from three of the beams after the reversal-of-stress tests, but the original values were somewhat greater for the specimens applying to beam 5B1 than the average values obtained from specimens cut from the beam after failure. In most cases the difference is so slight that it is probably accidental.

TABLE 11.—Comparison of Properties of Reinforcing Steel after Repeated Loading with Properties before Repeated Loading

[Values are stated in percentage in corresponding values obtained before use in beam tests]

Beam No.	Yield point	Ultimate strength	Ultimate elongation	Reduction of area
	Per cent	Per cent	Per cent	Per cent
5A1	106.0	102.3	132.9	112.3
5B1	99.0	104.8	98.3	95.5
5F1	100.0	103.4	119.8	103.6
5L1	103.0	100.6	101.7	103.6

In the failures under repeated stress, no necking of the bars could be detected, and this is characteristic of fatigue tests of steel. Almost the same ultimate elongation was shown in the tension tests of the steel specimens taken from the bars before molding of the test beams and from the bars which had been subjected to repeated stress in the beams. This indicates that the general structure of the steel was not affected by the repeated reversal of stress.

8. CHEMICAL COMPOSITION OF STEEL REINFORCEMENT

Table 6 shows the chemical composition of the steel used as reinforcing for the test beams and also for some of the concrete ships and barges built by the Emergency Fleet Corporation. This table shows that the steel used in the test beams was generally much lower in carbon and much higher in phosphorus than that used in the ships and barges. It is generally believed that low carbon content reduces the resistance of the steel to fatigue, and that high phosphorus content reduces its resistance to shock. It has been stated that "in normal steels the strength against fatigue increases with the carbon content up to about 0.09 carbon,"[10] and that "Phosphorus is especially dangerous in railroad rails which are exposed to severe shocks in service, * * *. For most purposes not more than 0.05 per cent of phosphorus is allowable in steel, except for thin rolled plates, etc."[11]

Beam 5L1 was the only one in which the chemical analysis of the steel approached that ordinarily expected in a good grade of reinforcing steel. Yet that beam failed under an unexpectedly small number of repetitions of reversed stress. This fact indicates that the poor grade of reinforcing used in the other beams is not in itself sufficient to account for the early failure of those beams.

9. EFFECT OF REST PERIODS ON NUMBER OF CYCLES THAT CAUSED FAILURE

Reference to Fig. 25 shows when rest periods occurred in the tests. There is no indication in Figs. 17 to 23 that these rest periods affected in any way the amount of the deformation. This result might be expected, but Fig. 26 seems to indicate that an increase in the proportion of the time during which the machine was not in operation caused a marked increase in the number of cycles which was required to cause failure. It is believed that the arrangement of the plotted points must be largely accidental,

[10] J. B. Johnson, Materials of Construction, fifth ed., p. 776.
[11] H. F. Moore, Materials of Engineering, p. 96.

since there were inequalities in the stresses developed which would be expected to destroy the regularity of the curves.

It is not to be expected that a given period of rest will have equal value in prolonging the life of a beam, regardless of the stage of the test at which the rest period occurs.

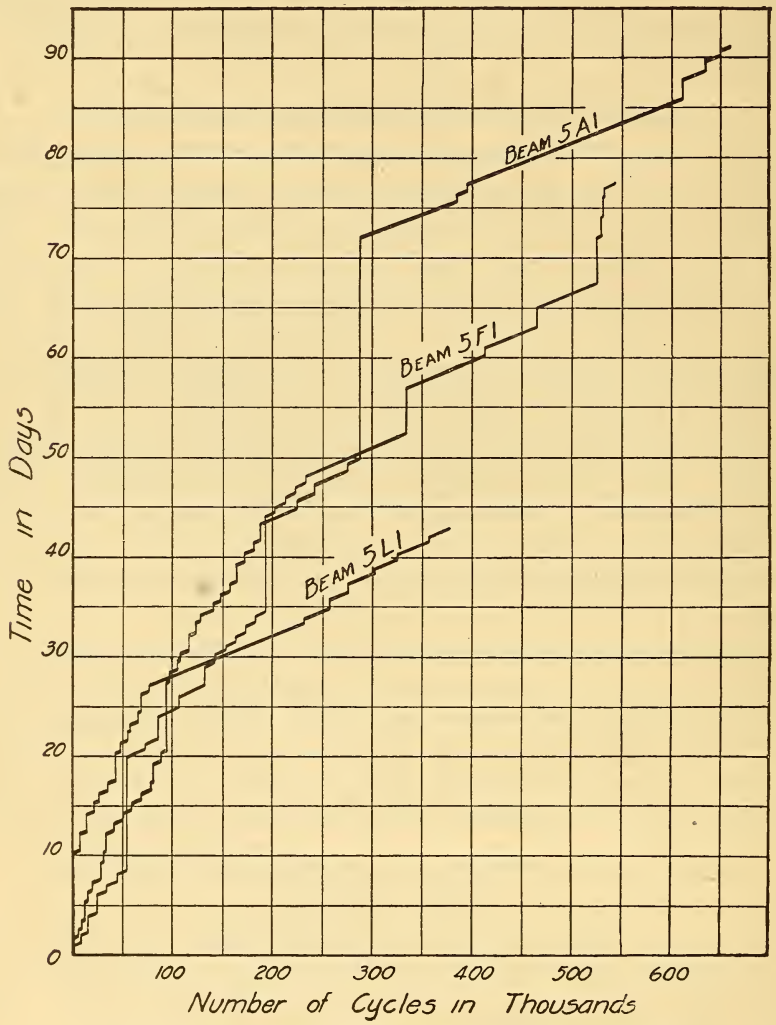

FIG. 25.—*Continuity of tests for beams 5A1, 5F1, and 5L1*

The rest periods also varied greatly in length and were irregular in their frequency.

When these facts are taken into consideration, it seems that less importance should be attached to the curves in Fig. 26 than their regularity would indicate.

10. RELATION BETWEEN MAGNITUDE OF BENDING STRESSES AND NUMBER OF CYCLES THAT CAUSED FAILURE

In Fig. 27 the abscissas represent the number of cycles of load which caused failure in all beams except 5C1 and the ordinates

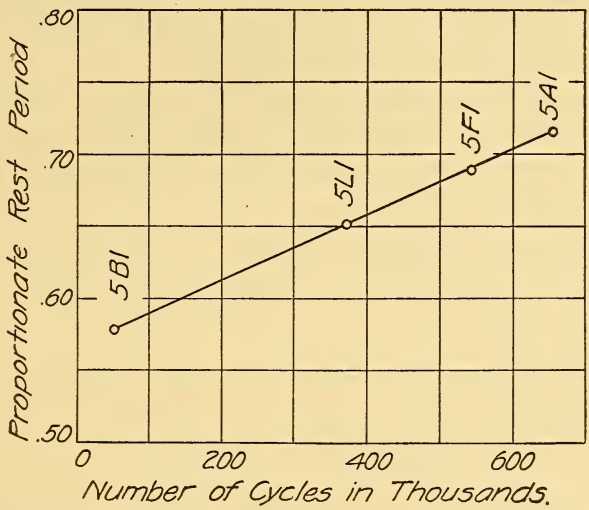

FIG. 26.—*Ratio of rest periods to total time of test*

represent the tensile stress in the reinforcing bars corresponding to the measured deformations at the same load. Fig. 28 is similar except that the ordinates represent the arithmetical sum

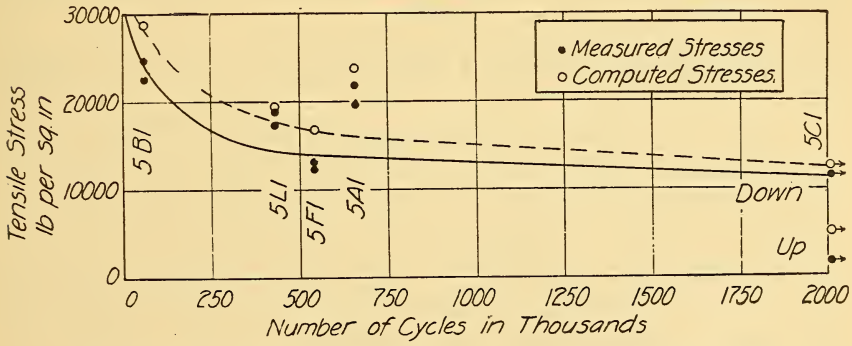

FIG. 27.—*Relation between tensile stress and number of cycles at failure*

of the tensile and compressive stresses instead of the tensile stresses alone.

The data of beam 5C1 are included in these figures although the test of that beam was not carried to the point of failure. They are used to indicate the trend of the curve although it is

recognized that the inclusion of these data is not fully justified. In Fig. 27 the stresses for beam 5C1 for the upward load are given no weight in determining the positions of the curves. The upward load was much less than the downward load, and the stresses were correspondingly smaller. Therefore it is not likely that the time of failure would depend to any extent upon the number of repetitions of the upward load.

Although the discussion in Part IV, article 7, indicates that the tension failure of the steel in these beams can not have been due directly to the large number of repetitions of the tensile stress, nevertheless Figs. 27 and 28 indicate that there is some relation between the number of cycles of load required to cause failure and the tensile stress developed. The number of cycles

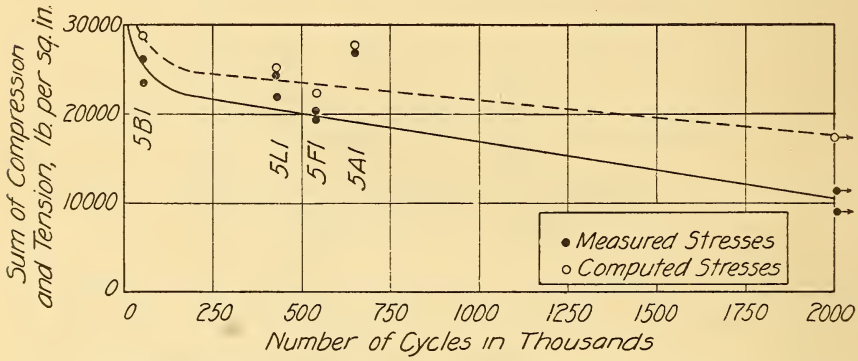

FIG. 28.—*Relation between sum of compressive and tensile stresses and number of cycles at failure*

decreased with the increase of stress, except in the case of beam 5A1.

In Part IV, article 3, it was suggested that the formation of the pronounced crack in the top flange of beam 5F1, and the consequent bending of the bar at this crack, may have been an important element in bringing about tension failure of the bar. If this explanation applied to all similar cases, bending would be likely to be more severe in beams where the tensile stresses are high than in those where they are low. This would help to account for the results shown in Figs. 27 and 28.

On the other hand, it seems that the arrangement shown in Figs. 27 and 28 may be largely accidental. In beam 5L1 large bars, 1¼ inches in diameter, were used and a slip of 0.06 inch at one end of one of the bars took place before failure occurred. Both of these facts would cause one to expect more severe stresses

at the crack due to the bending of the bars than would be expected with small bars and with no end slip of the bars. It may be this action, rather than the severity of the tensile stress plotted in Fig. 27, which accounts for the early failure of this beam.

Beam 5B1 failed under the smallest number of applications of load, and both the calculated and measured stresses were higher in this beam than in any other. However, it has been pointed out in Part IV, article 5, that the early failure of this beam may have been due as much to the reduction in area caused by the gage holes in the small bars used as to the intensity of the tensile stress.

With the possibility of explaining the failures of beams 5B1 and 5L1 on other grounds than the tensile stress produced in the steel reinforcement, and with beam 5A1 not conforming to the suggested relation between intensity of stress and number of cycles which caused failure, it seems possible that the arrangement of plotted points shown in Figs. 27 and 28 may be accidental.

11. POSITION OF NEUTRAL AXIS

The positions of the neutral axis for the beams tested are shown in Figs. 29 to 33.

Fig. 19 gives the deformations in the reinforcing bars on the south side of beam 5B1 at the top and at the bottom of the beam. A study of this figure shows that up to about 50 000 cycles of load the amount of tension was nearly the same on the top with the load acting upward as that on the bottom with the load acting downward, and that the amount of compression was nearly the same on the top with the load acting downward as that on the bottom with the load acting upward. A similar statement may be made regarding the bars on the north side, Fig. 19. These relations are as should be expected when the upward loads and the downward loads are equal and when the reinforcing bars in the top and in the bottom of the beam are at equal distances from the neutral axis. The equality of stress in top and bottom bars under conditions of tension and compression, respectively, was not preserved, in general, after the number of load cycles had exceeded 50 000.

It would also be expected that the deformations at the top and at the bottom of the beam would be the same at any instant on the north side as those on the south side, but a study of Fig. 19 shows that they were not equal for beam 5B1. The differences, however, are such as to make the range in deformation from

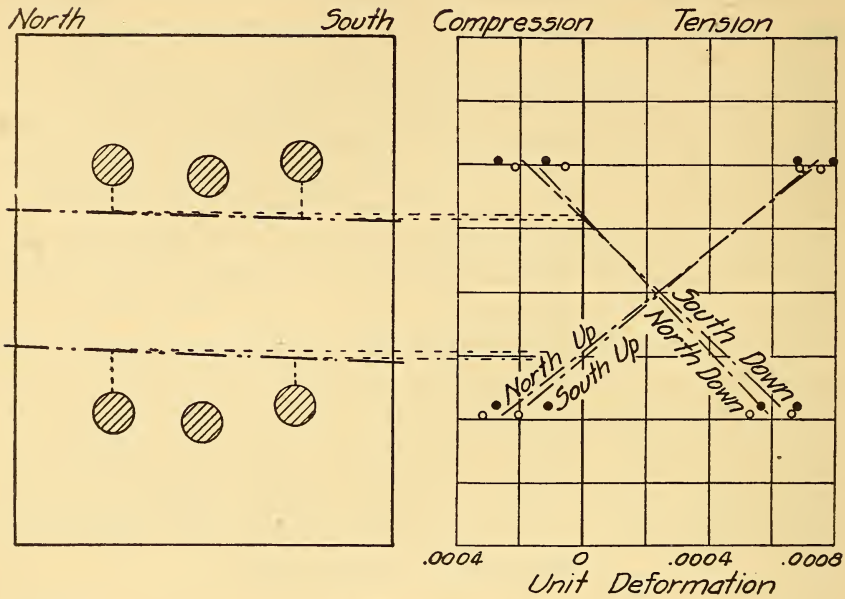

FIG. 29.—*Strain distribution and positions of neutral axis for beam 5A1*

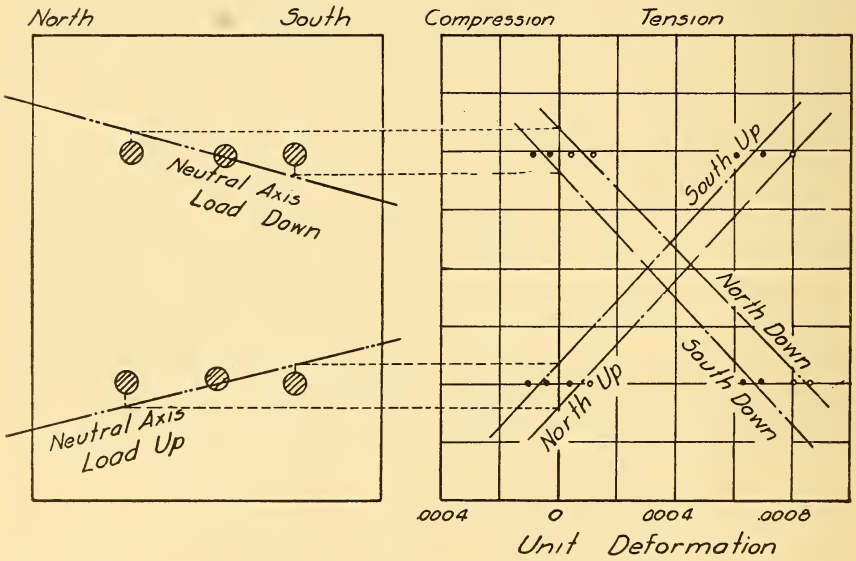

FIG. 30.—*Strain distribution and positions of neutral axis for beam 5B1*

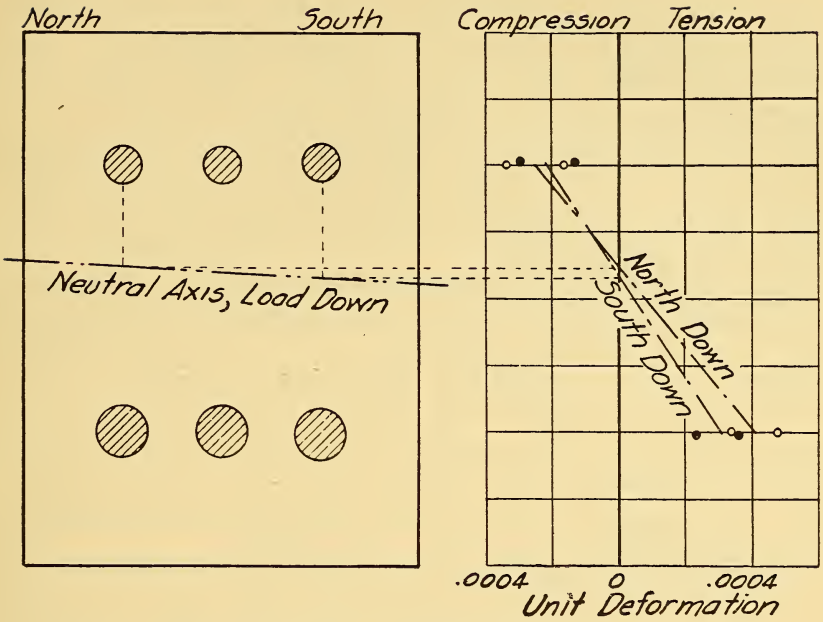

FIG. 31.—*Strain distribution and position of neutral axis for beam 5C1*

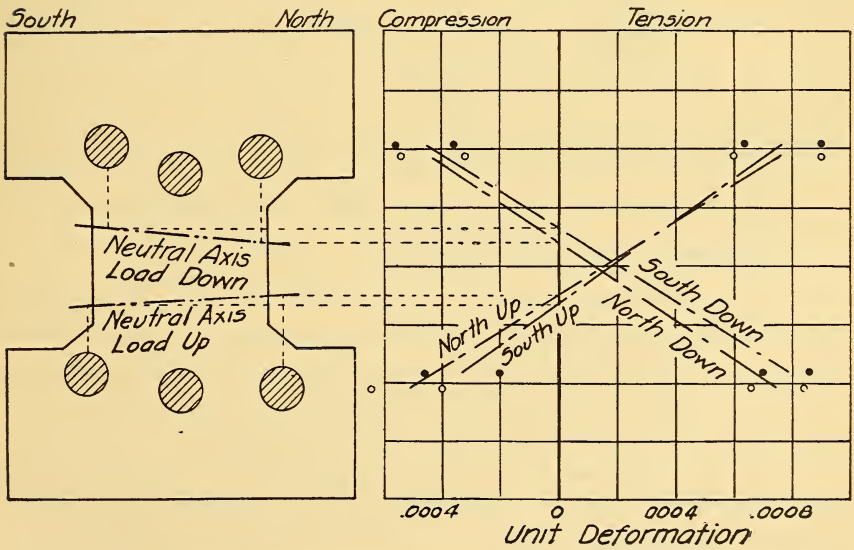

FIG. 32.—*Strain distribution and positions of neutral axis for beam 5F1*

tension to compression at any one gage line, either on the top or on the bottom, the same as the total difference in deformations between a gage line on a top bar and one on a bottom bar. These relations are made much more clear by a study of the strain distributions for beam 5B1 that are shown in Fig. 30. The individual points plotted show the extreme range of deformations corresponding to load cycles above about 10 000 and below about 50 000. The lines are drawn through the mean values represented by the points.

From these strain distributions the approximate positions of the neutral axis for the upward loads and for the downward

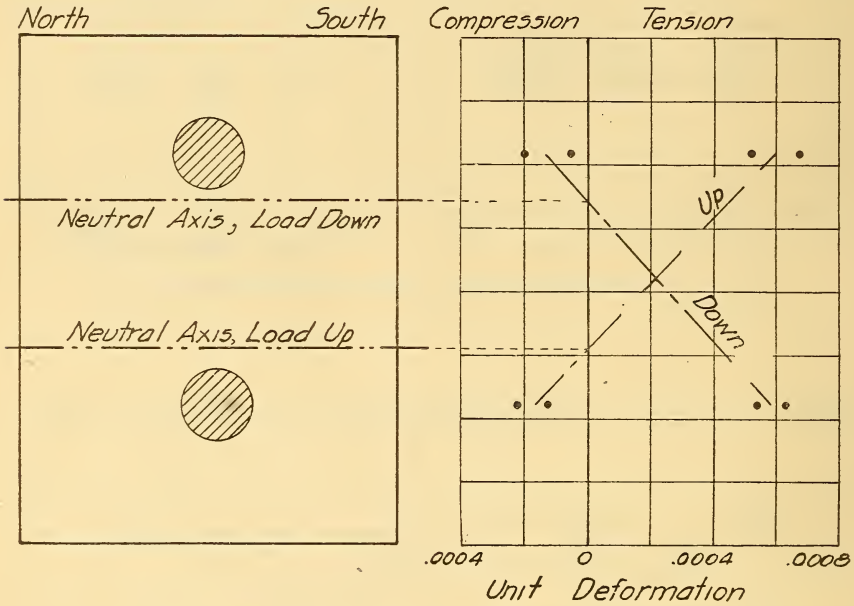

Fig. 33.—*Strain distribution and positions of neutral axis for beam 5L1*

loads have been determined and are shown in the same figure. The neutral axes under the conditions of upward and downward loading do not coincide, nor are they parallel, but the symmetry of the two neutral axes about the horizontal center line of the beam may be of some interest. The convergence of these axes could be accounted for by a curvature in the horizontal projection of the beam, but there is no evidence that any appreciable amount of warping sideways existed. However, a certain looseness in the bearings of the testing machine was observed, and it is possible that this introduced a slight inclination of the beam in one direction when the load was acting downward and in the opposite

direction when the load was acting upward. This would bring about the conditions which were observed. Another possible explanation of the convergence of the neutral axes may be found in the lack of homogeneity in the concrete, which might have considerable effect on the elasticity of opposite sides of a beam of small cross section.

Similar diagrams are shown for beams 5A1, 5C1, 5F1, and 5L1. It should be noted that the strain readings in all of these cases were taken with the machine in operation, and it is not possible to show the instantaneous position of the neutral axis because readings could not be taken on all of the gage lines simultaneously. However, the deformation curves of Figs. 17 to 23 maintain nearly enough the same positions in relation to each other to indicate that by plotting the extreme range of deformations for a small number of cycles the average would represent with reasonable accuracy the conditions which existed at a given time. This procedure has been followed in preparing the diagrams shown in Figs. 29 to 33. The deformation measurements were taken on the side of a bar at the level of its center line.

The positions shown for the reinforcing bars in Figs. 29 to 33 were determined by measurements on the sections after the beams had been tested and sawed in two, except for beam 5C1. This beam has not been sawed in two, and the positions shown are those indicated in the design of the beam.

Any error of observation is likely to show itself in an apparent inclination of the neutral axis. In Figs. 29 and 31, representing beams 5A1 and 5C1, all of the inclination present may be due to errors of observation. Figs. 30 and 32, for beams 5B1 and 5F1, show marked inclination of the neutral axis, and it is likely that these diagrams represent approximately actual conditions in the beams.

For beam 5L1 the neutral axis, as shown in Fig. 33, is horizontal. In this beam there was only one bar in the top and one in the bottom and the measurements were taken on only one side of the beam; consequently, the data furnish no basis for determining the inclination of the neutral axis, if such existed.

The data for beam 5C1 for upward load seem inconsistent and have not been plotted in Fig. 31. The peculiar showing in Fig. 20, in which compression is sometimes found where tension should be expected, is not understood. The smallness of the upward load in relation to the downward load, the consequent importance

of any residual deformations, and the importance, relatively, of small errors of observation were factors which probably contributed to the inconsistencies in the data.

12. SUMMARY

(*a*) For all of the beams tested failure was by tension in the steel. Generally the beams in which the highest stresses were developed in the test withstood a smaller number of repetitions of load than those in which the measured stresses were smaller. However, even the largest number of repetitions was so small that failure in the steel would not have been expected at the time at which it did occur considering that the observed stresses were so low. Other factors than the intensity of the tensile and compressive stresses seem to have had a part in bringing about the early tension failure.

(*b*) All of the tension failures in the reinforcing bars occurred at sections where large cracks extended entirely across the section of the beam. It is possible that in some cases the bending at these cracks was sufficient to make the bending of the bar an important factor in causing failure. The slipping of bars at the ends, such as happened in beam 5L1, would permit the opening of wide cracks and accentuate this tendency.

(*c*) The presence of the gage holes in the bars seems to have had some influence in hastening tension failure, but this influence is not very distinct.

(*d*) The quality of steel used for most of the reinforcement was poor, and this would contribute to bringing about early failure. However, this alone would not account for the small number of repetitions of stress generally required to produce failure.

(*e*) The effect of the repeated loading on the physical properties of the steel reinforcement was slight, at most; the indications of the presence of any effect probably is accidental.

(*f*) Although there appears to exist a marked effect of the rest periods on the life of the beam, it seems unreasonable to believe that the apparent effects are anything more than accidental.

(*g*) After 7000 repetitions of a bond stress of 161 pounds per square inch the slip at the end of the bar in beam 5L1 was less than 0.001 inch; that is to say, less than the amount which has been taken as the criterion of safe conditions based on tests of the bond resistance between concrete and steel. Yet, after 400 000 cycles of load, the amount of slip had increased so much that

failure by slipping of the bars seemed imminent. It seems that the intervention of tension failure at an unexpectedly small number of repetitions of load prevented the bond failure of this specimen.

(*h*) Generally the neutral axes of the beams were inclined, suggesting a slight eccentricity in the application of the load. It is not apparent that the conditions causing this inclination of the neutral axis should have anything to do with shortening the life of beams under reversal of stress.

The tests reported herein indicate the importance of conducting further research upon the effect of repeated reversals of stress in reinforced beams.

WASHINGTON, July 9, 1920.