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Bond in prestressed concrete, July 1952

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BOND IN PRESTRESSED CONCRETE

BY

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SYNOPSIS

Pretensioned, prestressed concrete relies on bond between the wire and the concrete for the transfer of the prestress from the wire to the concrete.

This research was mainly concerned with the determination of the length of a 0.10" wire required to transfer the total prestress on the wire to the concrete.

Three lengths of embedments were used namely; 1', 3' and 4.5'. Of each length three specimens were made for the tests. The cross-sections of all specimens were substantially the same, 5"x5", with twenty-five wires uniformly spaced across the cross-section.

During the performance of the research some difficulty was encountered in finding an efficient and reliable method for prestressing the wires. This took a large portion of the work and is described later more fully.

I. GENERAL: Prestressed concrete is one of the most useful developments in modern construction. It has many advantages over ordinary reinforced concrete which makes its use on a large scale unavoidable.

There are many problems and points in prestressed concrete that require further study and development without which the practical application of prestressing will not expand as it should.

The two methods of prestressing the concrete are pretensioned and posttensioned. The first of the two, which is the main concern in this work, relies on bond between the wire or strand and the concrete for the transfer of the prestress to the concrete. Actually the high tensile-steel wire is stressed in the forms, to a certain percentage of its ultimate strength. It is held like this until the concrete, which is later cast around it has hardened sufficiently and attained enough compressive strength and bond resistance. Then the tensioning force is released by releasing the wires at the ends. The tensioning force is carried entirely by bond as a result of which the concrete is in compression.

It is seen from the above that bond is the most important factor in pretensioned, prestressed concrete.

Bond is one of the many problems on which the available literature is extremely limited, and further study is of great value.

II. BOND IN PRESTRESSED CONCRETE: The factors that build up bond stress in prestressed concrete are three, namely: (1) adhesion between the concrete and the wire. It is a purely molecular effect and its value varies with various conditions. (2) Friction between the surface of the wire and the concrete. This force of friction is due to pressure imposed on the wire by concrete when it shrinks. The condition of the surface of the wire therefore has an appreciable effect on frictional resistance. (3) The wedge effect at the ends of the beam. It is obvious that when wire is stretched its diameter decreases. The concrete is poured when the wire is in this condition. After it has hardened the wire is released at the ends and thus it tries to attain its previous diameter before it was stressed. This increases the pressure between the surface of the wire and the concrete and in turn increases the second factor which is frictional resistance.

It is very difficult to emphasize on the importance of any one of the above factors over the others. It is obvious that all of them combine to develop the bond stress. Opinions vary in this respect and some engineers give one of the factors more importance than the others.

The following are extracts from some of the opinions of some engineers on the subject of bond.

P.W. Abeles says in his book "The Principles and Practice of Prestressed Concrete": "A wedge is formed when the tensioned wire is severed at the end of the member and regains its original diameter which is greater than that where it has been reduced through the contraction caused by the tension. The higher the tensile stress employed and the smaller the diameter of the wire the more efficient this anchorage will be. Transmission of the force from wire to concrete is effected by bond resistance and friction together with a radial compression".

E. Freyssinet, who conducted tests with preliminary stresses as high as 256,000 psi explained at the joint meeting of the Institution of the Structural Engineers and the Societe' des Ingenieurs Civils de France in 1937, that adhesion is not a question of the concrete sticking to the steel, but that it is a wedging action under the effect of the transversal deformations of the concrete, similar to the gripping of a bar in a wedge clamp. Its intensity and its efficiency depend on the quality of the concrete and the packing of the concrete around the bars".

W.E.I. Armstrong in his paper "Bond in Prestressed Concrete" published in the Journal of the Institution of Civil Engineers says: "Similar factors apply in prestressed concrete construction (he means adhesion and friction). In this case, however, when the ends of the wire are released they expand and increase the pressure between the steel and the concrete which will be considerably reduced by the wear which takes place as the wire moves through the concrete".

From the above it is seen that there is no fixed opinion on bond stress in prestressed concrete which means that further investigation is required.

Because of the great importance of bond stress in pretensioned, prestressed concrete, inclination has been toward the use of many fine wires instead of large diameter wires.

The cross-sectional area of wire varies with the square of the radius, while the circumference varies with the first power of the radius, hence a decrease in diameter reduces the load on each wire by an amount much more than the reduction in bond resistance, and the opposite is true when the diameter is increased. A detailed study to determine the length of any size of wire required to transfer the prestress from the wire to the concrete through bond is very essential.

III. TWO PHASES OF BOND: In prestressed concrete there are two phases of bond stress. The first occurs exactly after the release of the prestress, when the wire at the ends of the member tries to push into the member, and is held from doing so by bond stress. This action in pretensioned, prestressed concrete might be called end anchorage. In posttensioning the cable is held from pushing into the member by using an anchoring device at the end which bears against the end of the members.

End anchorage in pretensioned, prestressed concrete varies from end anchorage in posttensioned, prestressed concrete in the fact that in the first the anchorage is along a certain length at each end of the wire, while in the second it is only at the ends of the member.

The second phase of bond stress occurs after the first phase and when the member acts as a beam.

In a symmetrically loaded beam the bond stress varies gradually from zero at the center to a maximum at the ends. Here the bond stress varies in value on each point as when the external forces vary, while in the first phase the distribution of bond stress pattern along the wire remains constant after the release of the prestress.

The two phases constitute two separate topics in bond stress and should be investigated separately. For this purpose a complete research program was planned and it includes the following:

A. Type of tests.

1. Strain and slip tests.

2. Beam tests.

3. Modified beam tests - jacking plates apart that are located in the center of the beam.

4. Pull-out tests.

B. Variables to be considered.

1. The concrete mix proportions.

2. The strength of concrete.

3. The quality of the wire.

a. proportional limit
b. creep
c. wire coating and surface of wire
d. ultimate strength

4. Length of wire imbediment.

5. Surface of the wire.

6. Effect of wire strands.

7. Diameter of the wire.

8. Admixture effects.

Due to the time limit of this research project which was carried on during the academic year 1951-52, and which is presented in this paper, the program was limited to the first phase of bond stress, and to a small number of tests and variables. Therefore, it is concluded that this work is incomplete and it could be considered as a pilot test for a wider research to be carried on later.

IV. ACTUAL RESEARCH:

A. Purpose: The purpose of this research was to determine the distribution of bond stress along prestressed concrete specimens after the release of the prestress. The length of imbediment required at each end of concrete specimens to transfer all the prestress from the wire to the concrete through bond was the primary interest.

B. Variables Considered:

1. Concrete: The cross-section of all the specimens was nominally 5"x5" = 25 sq.in. The specimens were reinforced by 25 0.10" wires uniformly distributed over the cross-sections. This number was chosen to produce a larger force on the cross-sections and hence larger strains. The prestress on each wire was initially 135,000 psi and it was assumed that this would be reduced to 125,000 psi due to losses in creep, shrinkage, etc.

According to this assumption the final stress on each 0.10" wire was 125,000 x 0.007854 = 982 pounds. Therefore, the stress on the concrete was 982 psi = f_c.

The ultimate strength of concrete was assumed to be three times f_c giving an f_c' of 3 x 982 = 2946 psi. The concrete mix was designed to give an f_c' of 3000 psi at seven days.

Because of the limited time available high early strength cement was used in order to produce the required strength in seven days with a water cement ratio of 6.5 gallons per sack. The maximum size of coarse aggregate used was one-half inch in order to allow placing around the wires. The absolute volume method was used for the design of the mix as follows:

For a three-inch slump water content = 40 gal. per C.Y.

Cement factor $= \frac{40}{6.5} = 6.15$ sacks per cubic yard

Absolute volume of cement $= \frac{94 \times 6.15}{3.15 \times 62.3} = 2.95$ cubic feet.

Volume of water $= \frac{40}{7.48} = 4.34$ cubic feet.

Volume of paste = 7.29 cubic feet.

Absolute volume of aggregate = 27 - 7.29 = 19.71 cu. ft.
Absolute volume of sand = 19.71 x 51% = 10.05 cu. ft.
Absolute volume of gravel = 19.71 - 10.05 = 9.66 cu. ft.
Weight of surface dry sand = 10.05 x 62.3x2.6 = 1630 lb.
Weight of surface dry gravel = 9.66 x 62.3x2.7 = 1630 lb.

<u>Weight per sack of cement</u>:

dry sand = 1630/6.15 = 265 lbs.
dry gravel = 163/6.15 = 265 lbs.

<u>Correction for moisture</u>:

moisture in sand = $\frac{1.5}{100}$ x 265 = 3.98 lbs.

moisture in gravel = 0 lbs.

Total moisture = $\frac{3.98}{8.33}$ = 0.48 gallon.

Weight of moist sand = 265 + 3.98 = 268.98 lbs.

Weight of gravel = 265.00 lbs.

Water to be added = 6.5 - 0.48 = 6.02 gal./sack

<u>Weight per batch</u>:

Proportions: Cement = 1
Gravel = $\frac{265}{94}$ = 2.82
Sand = $\frac{268.98}{94}$ = 2.86

Batch volume = 1.6 cu. ft.

Absolute volume of sand = 10.05 cu.ft.
Absolute volume of gravel = 9.66 cu. ft.
Absolute volume of cement = 2.95 cu.ft.

Sand/batch = $\frac{10.05}{27}$ x 1.6 = 0.595 c.ft. = 0.595 x 2.6x62.3 = <u>96.7#</u>

Gravel/batch = $\frac{9.66\text{x}1.6}{27}$ = 0.572 c.ft.=0.572x2.7 x62.3 = <u>96.5#</u>

Cement/batch = $\frac{2.95}{27}$ x1.6 = 0.175 c.ft.= 1.75x3.15x62.3= <u>34.3#</u>

Water/batch = $\frac{6.02\text{x}34.3}{94}$ = 22 gals. = 2.2 x 8.33 = <u>18.3#</u>

After mixing the first batch it was found that the mix was not workable, hence some water was added holding the water cement ratio constant. The quantity of water added was that which was for an additional 10 lb. of cement.

$\frac{10}{34.3}$ x 18.3 = 5.34 lb.

Adjusted weights per batch:

Sand = 96.7 lb.
Gravel = 96.5 lb.
Cement = 34.3 + 10 = 35.30 lb.
Water = 18.3 + 5.34 = 23.64 lb.

For the last batch the additional quantity of cement left was 7 lb. which made the amount of additional water equal to $\frac{7}{34.3}$ x 18.3 = 3.7 lb.

Adjusted weights for last batch:

Sand = 96.7 lb.
Gravel = 96.5 lb.
Cement = 34.3 + 7 = 41.3 lb.
Water = 18.3 + 3.7 = 22.0 lb.

Four batches of concrete were necessary to provide for the required volume of concrete. From each batch one control cylinder was made which gave a total of four. The cylinders were cured in the same way as the specimens by using wet burlap for six days.

Two of these cylinders were tested in the 300,000# machine in Fritz Engineering Laboratory nine days after pouring in order to determine the strength of concrete in the first specimens which were tested also nine days after pouring. The ultimate strength for the first cylinder was 6020 psi and that of the second 6730 psi. The average value was 6372 psi.

The remaining two cylinders were tested in the same way eleven days after pouring because the remaining specimens were also tested at this time. The ultimate strengths were 6780 psi and 5550 psi respectively, giving an average value of 6170 psi.

The big difference in ultimate strength between the estimated value of 3000 psi in the designed mix and the actual ultimate strength was due to two important reasons. In the first place in order to obtain an f'_c of 3000 psi at seven days a water cement ratio of 7.5 gal/sack should have been used. Actually 6.5 gal/sack were added. In the second place the cylinders were tested at nine and eleven days respectively and not at seven days. This had also a substantial effect in the increase in strength.

Tables (1) and (2) represent the results of tests on the four cylinders. Figure (1) contains the stress-strain curves for the four cylinders and Figure (2) represents the procedure of testing the cylinders in the 300,000 lb. machine in Fritz Engineering Laboratory.

2. Wire: One type of wire was used for all the specimens. It was the 0.10" wire produced by J.A. Roebling's Sons Co. To plot the stress-strain curve and hence determine the modulus of elasticity of the wire, an A-12, SR-4 strain gage was mounted on a piece of this wire, and then tested in the 300,000 lb. machine in Fritz Laboratory. Table (3) represents the results of the test. The wire was loaded up to 1200 lb. and then unloaded. This operation was repeated two more times. In the fourth operation the load was carried up to 1580 lbs. The wire was threaded at the ends and four standard 3-48 nuts were used on each end for gripping. This will be explained later, more fully. Failure occurred at 1580 lbs. when the nuts sheared off.

The purpose of the last loading cycle was to show the shearing resistance of four 3-48 nuts which proved to be safe enough for this research. The results of the strains from the various loading cycles were very close as it is seen from Table (3) and while plotting the curves the different points nearly coincided. Hence an average value of the last three cycles

Kips	Cylinder #1 (slump = 3 1/4) June 30, 1952 — First Cycle	Δ	Second Cycle	Δ	Third Cycle	Δ	Fourth Cycle	Δ
0	6 953		6 940		6 937		6 938	
5	6 920	33	6 910	30	6 907	30	6 905	33
10	6 890	63	6 876	64	6 870	63	6 871	67
15	6 853	100	6 839	101	6 838	95	6 840	98
20	6 822	131	6 808	132	6 800	133	6 800	138
25	6 782	171	6 771	169	6 768	165	6 763	175
30	6 748	205	6 738	202	6 732	201	6 730	208
35	6 710	243	6 701	239	6 700	233	6 693	245
40	6 670	283	6 666	274	6 663	270	6 660	278
45	6 633	320	6 630	301	6 628	305	6 622	316
50							6 588	350
55							6 552	386
60							6 517	421
65							6 478	460
70							6 435	503
75							6 397	541
80							6 357	581
85							6 315	623
90							6 271	667
95							6 228	710
100							6 187	751
105							6 142	796
110							6 98	840
115							6 51	887
120							5 1030	908
125							5 950	988
130							5 908	1030
135							5 853	1085
140							5 800	1138
145							5 740	1198
150							5 700	1238
155							5 610	1328
160							5 532	1406
165							5 437	1501
170							5 281	
175								
180								
185								
190								
195								
200								

Kips	Cylinder #2 (slump = 2 1/4) June 30, 52 — First Cycle	Δ	Second Cycle	Δ	Third Cycle	Δ	Fourth Cycle	Δ
0	5 409		4 1379		4 1373		4 1369	
5	398	11	1345	34	1345	28	1340	29
10	345	64	1316	63	1310	63	1303	66
15	310	99	1279	100	1273	100	1270	99
20	275	134	1240	139	1245	128	1232	137
25	240	169	1202	177	1203	170	1203	166
30	203	226	1165	214	1168	205	1168	201
35	168	261	1136	243	1130	243	1124	245
40	129	300	1100	279	1095	278	1090	279
45	90	339	1060	319	1058	315	1052	317
50	5 52	377	1030	349	1022	351	1018	351
55	4 1010	419	998	381	988	385	982	387
60	960	469	953	426	951	422	948	421
65	932	497	915	464	915	458	910	459
70	4 892	537	4 883	496	4 881	492	4 870	499
75							840	529
80							800	569
85							760	609
90							720	649
95							675	694
100							635	734
105							590	779
110							548	821
115							501	868
120							458	911
125							410	959
130							360	1009
135							310	1059
140							260	1109
145							211	1158
150							152	1217
155							100	1269
160							4 040	1329
165							3 973	1396
170							905	1464
175							831	1538
180							750	1619
185							648	1721
190							3 503	
195								
200								

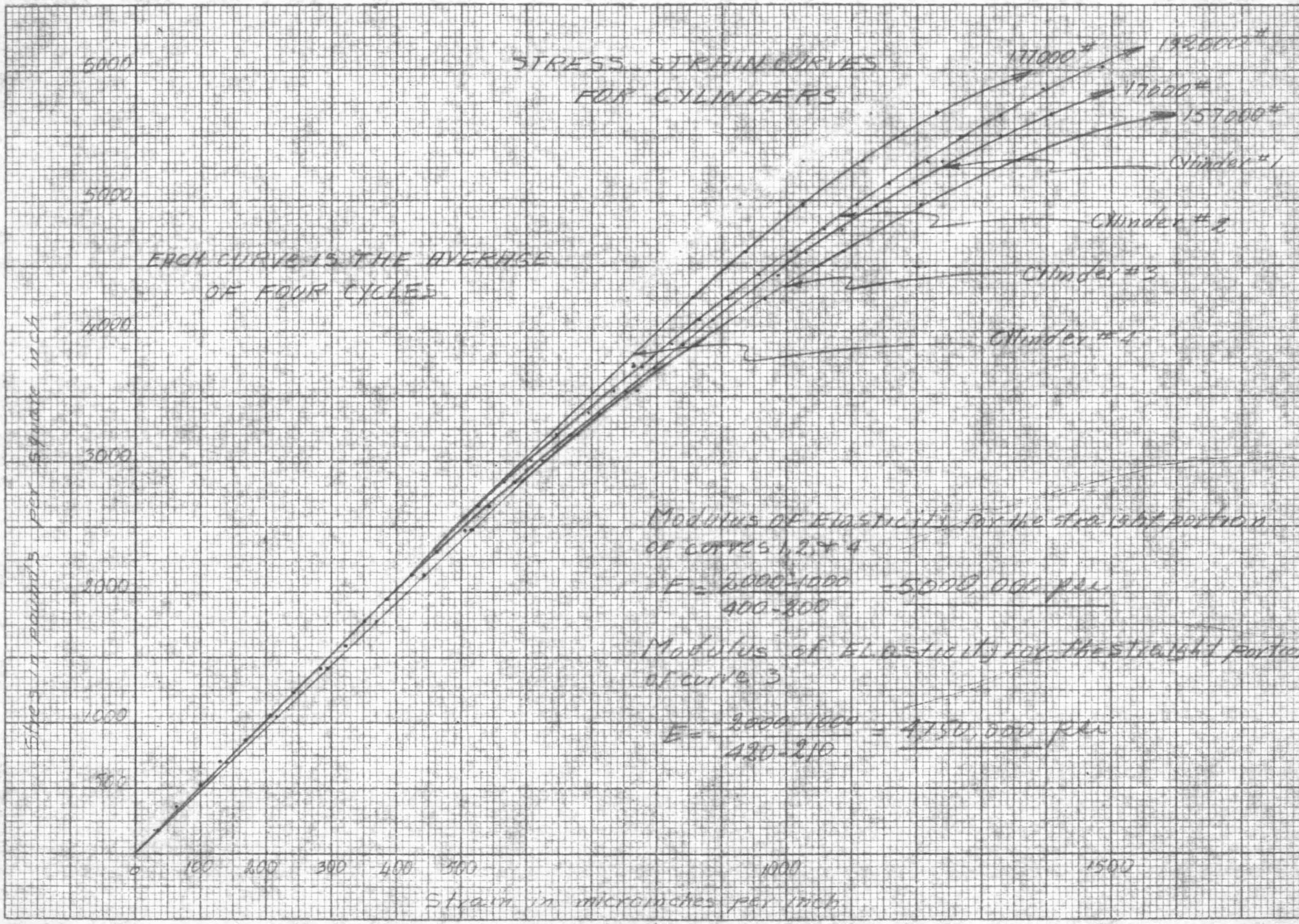
COMPRESSION TESTS ON CYLINDER 1+2

TABLE (1)

	Cylinder No. 3 (slump = 4") July 2, 1952								Cylinder No. 4 (slump = 1 1/4) July 2, 1952							
Kips	First Cycle	Δ	Second Cycle	Δ	Third Cycle	Δ	Fourth Cycle	Δ	First Cycle	Δ	Second Cycle	Δ	Third Cycle	Δ	Fourth Cycle	Δ
0	5 1042		5 1003		5 1005		5 1001		5 1301		5 1272		5 1268		5 1263	
10	970	72	940	63	938	67	932	69	1238	63	1203	69	1200	68	1200	63
20	898	144	860	143	864	141	860	141	1163	138	1138	134	1135	133	1130	133
30	825	217	800	203	788	217	782	219	1092	209	1070	202	1068	200	1060	203
40	744	298	712	291	710	295	708	293	1020	281	1000	272	1000	268	994	269
50	668	374	650	353	635	370	630	371	948	353	930	342	930	338	923	330
60	585	457	568	435	558	447	558	443	872	429	864	408	862	406	860	393
70	5 501	581	5 493	510	5 490	515	485	516	5 800	501	5 800	472	5 798	470	792	461
80							408	593							720	533
90							320	681							648	605
100							230	770							570	683
110							138	862							490	763
120							5 30	970							400	853
130							4 910	1090							320	933
140							792	1208							230	1023
150							641	1359							130	1123
160							4 403	1597							5 24	1229
170															4 873	1480
180																

COMPRESSION TEST S ON
CYLINDERS 3 + 4

TABLE (2)



STRESS STRAIN CURVES FOR CYLINDERS
EACH CURVE IS THE AVERAGE OF FOUR CYCLES
177000#
192000#
147000#
157000#
Cylinder #1
Cylinder #2
Cylinder #3
Cylinder #4
Modulus of Elasticity for the straight portion of curves 1, 2, + 4
E = 2000-1000 / 400-200 = 5000 000 psi
Modulus of Elasticity for the straight portion of curve 3
E = 2000-1000 / 420-210 = 4750 000 psi
Stres in pounds per square inch
6000
5000
4000
3000
2000
1000
500
0
100
200
300
400
500
1000
1500
Strain in microinches per inch

FIG.(1)

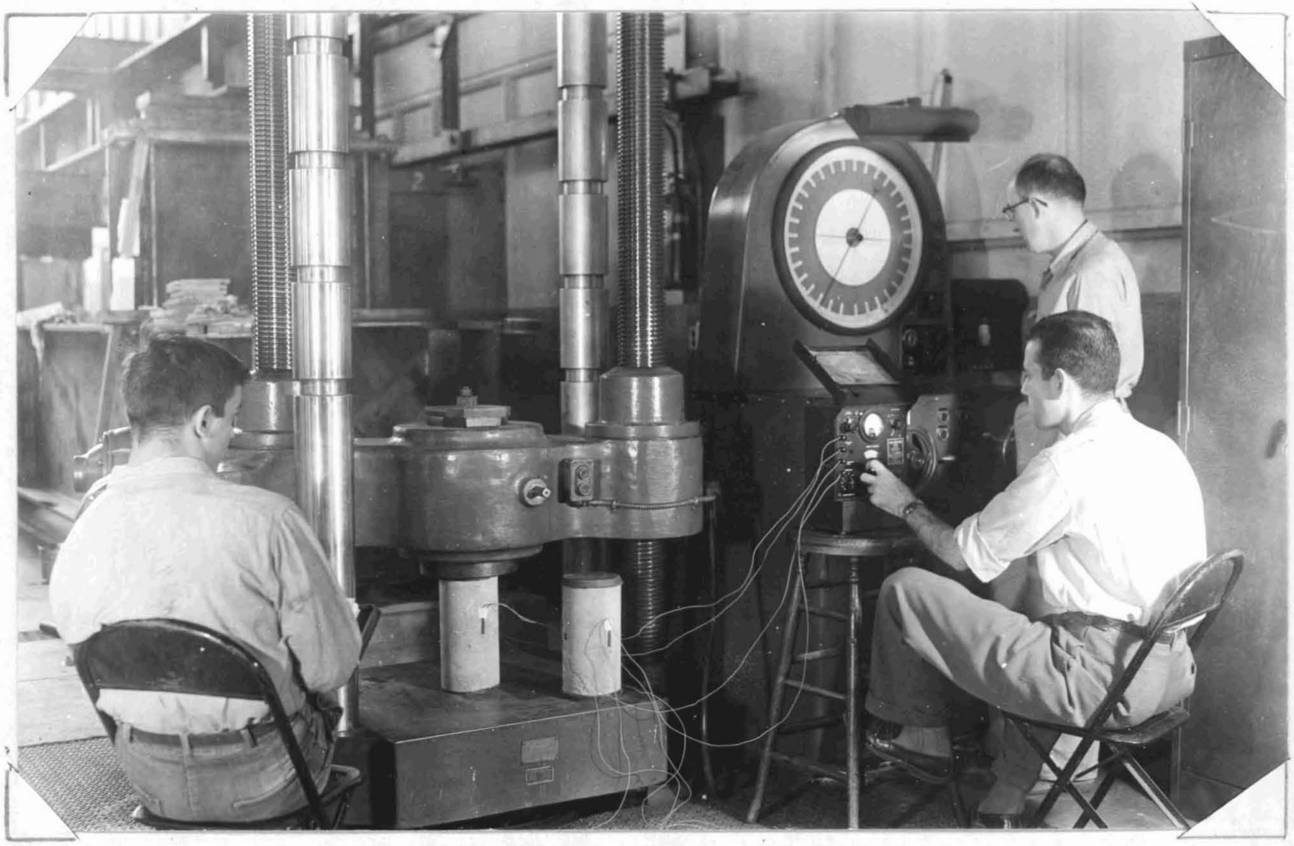


Figure (2)
The Process of Testing Concrete Cylinders
on 300,000 lb. Machine

TENSION TEST ON 1/10" WIRE

Load	Reading ↑		Δ	Reading ↓		Δ	Reading ↑		Δ	Reading ↓		Δ	Reading ↑		Δ	Reading ↓		Δ	Reading ↑		Δ
0	09	1115	778																		
200	09	1893	917																		
260							A1	628	565				A1	624	579				A1	621	595
400	010	1810	714	A2	128		A1	1193	810	A1	1149		A1	1203	797	A2	126		A1	1216	794
600	A2	1064	854				A2	1003	847				A2	1000	820				A2	1008	813
800	A2	1918	872	A3	820		A3	850	824	A3	770		A2	1820	845	A3	748		A2	1821	841
1000	A4	790	813				A3	1674	871				A3	1665	845				A3	1662	850
1200	A4	1603					A4	1545					A4	1510					A4	1512	840
1400																			A5	1352	448
1500																			A6	800	418
1580																			A6	1218	

Area of cross section of 1/10" wire = 0.007854 sq.in

200# = 25465 p.s.i 1000# = 127325 p.s.i

260# = 33105 p.s.i 1200# = 152790 p.s.i from 0-A = + 9460

400# = 50930 p.s.i 1400# = 178255 p.s.i

600# = 76395 p.s.i 1500# = 190987 p.s.i

800# = 101860 p.s.i

TABLE (3)

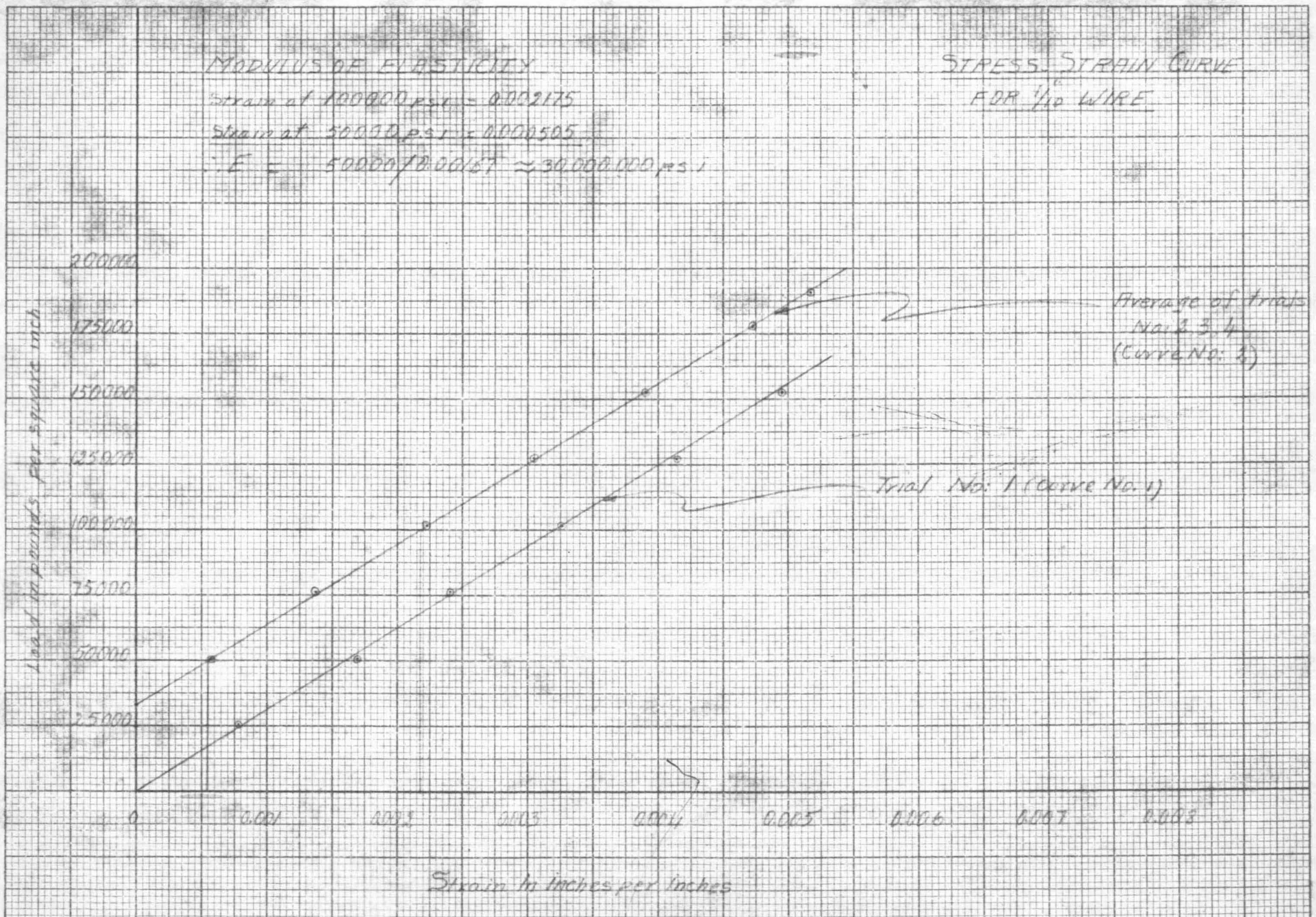

MODULUS OF ELASTICITY
Strain at 100000 psi = 0.002175
Strain at 50000 psi = 0.000505
∴ E = 50000/0.00167 ≈ 30,000,000 psi
STRESS STRAIN CURVE
FOR 1/10 WIRE
Average of trials No. 2, 3, 4 (Curve No. 2)
Trial No. 1 (Curve No. 1)
Load in pounds per square inch
200000
175000
150000
125000
100000
75000
50000
25000
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
Strain in inches per inches

FIGURE (3)

was taken to draw curve number (2) shown on Figure (3). In the last three cycles the zero reading was taken as 260 lbs. on the wire or 33,100 psi. The modulus of elasticity of the wire as calculated on Figure (3) was very close to 30,000,000 psi.

The above experiment proved the efficiency of an A-12, SR-4 strain gage when used on the 0.10" wire because the modulus of elasticity obtained was very close to that reported by manufacturers obtained by other methods involving much larger gage lengths.

3. Lengths of Embedments: Three lengths of embedment were considered in the research, namely; 1, 3, and 4.5 feet. In turn, three specimens of each of the afore-mentioned lengths were cast. All the specimens were reinforced with 25 wires uniformly distributed across the cross-section.

C. PROCEDURE OF RESEARCH

1. Forms: The forms used in this work were previously used by other personnel in Fritz Engineering Laboratory, to pour certain perstressed concrete specimens for pull-out tests. They were made of two side channels and a bottom plate, and were five inches wide and six inches deep and 56 inches long. Three new forms 5"x6"x112" were made by welding certain of the above forms together. For each of the three forms a pair of end plates 6"x10"x1/2" was made with thirty holes, 0.12" in diameter. The purpose of these end plates was to furnish a surface on which the prestressing devices could bear. The end plates carried the whole prestress in the wires before it was transferred into the concrete. These plates rested against the ends of the forms and were held in place by seat clamps.

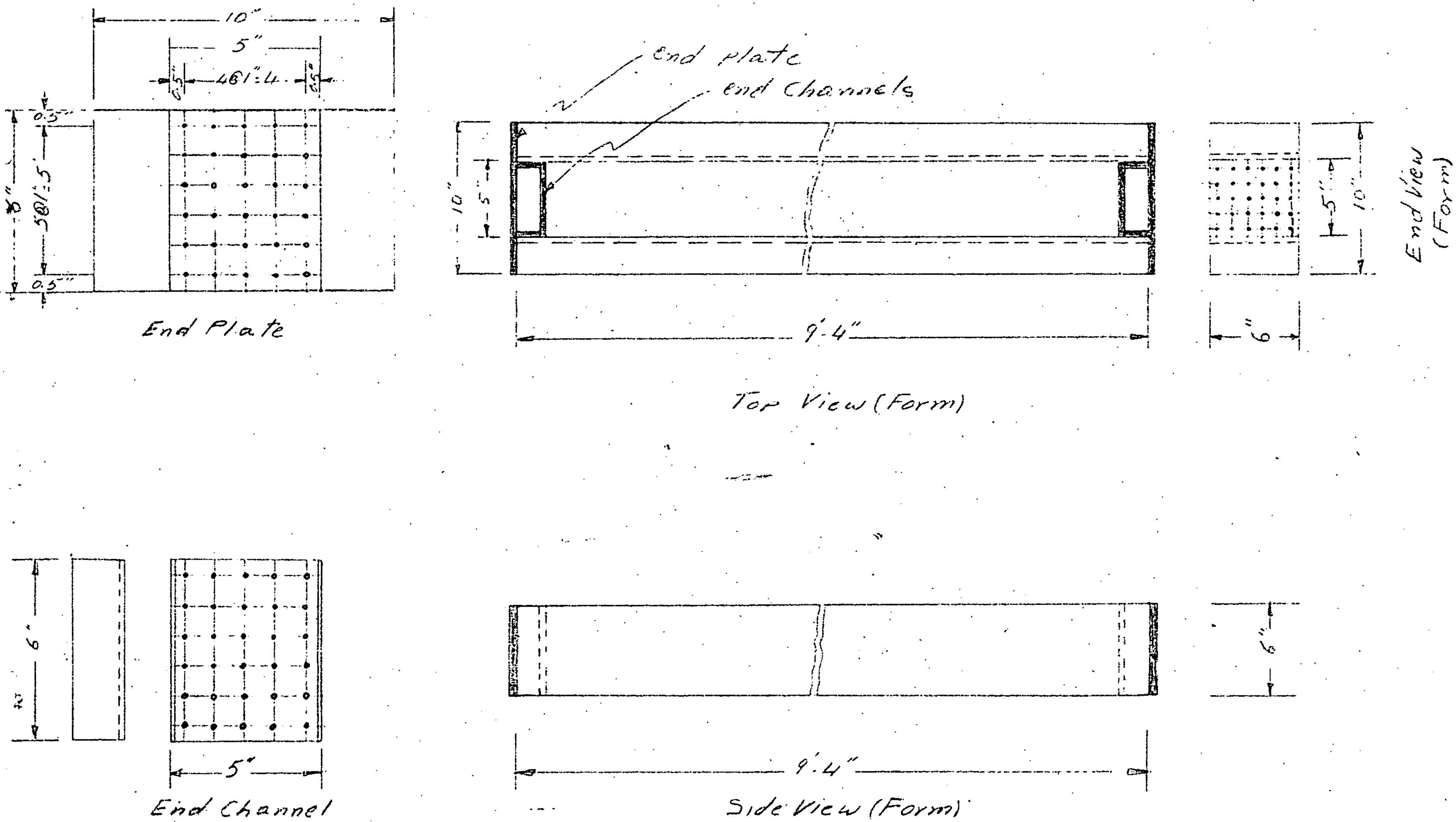
In order to keep the wires in alignment and for the protection of symmetry, two end channels were especially constructed with the same pattern of holes as in the end plates. They were 5"x6" and were placed in the forms between the sides. These secured perfect alignment and prevented the end plates from moving. Figure (4) shows the end plates, the end channels and the forms.

2. <u>The Prestressing Device</u>: The basic idea of the prestressing device was taken from the unit which was used by Mr. Melville at the University of Virginia.

This unit was made of a bolt, a number of nuts, and an allen set screen with a bearing ball as shown in Figure (5). A hole was drilled through the entire length of the bolt. Then the wire was inserted into this hole and was anchored by the Allen set screw which forced the bearing ball against the wire. To stress the wire the nut adjecent to the bearing plate is unscrewed, which pushes the bolt out, thus causing an elongation in the wire. In case one nut is not enough to produce the required elongation the second one bearing against the first is unscrewed. This process is continued using as many nuts as necessary to develop the required elongation in the wire.

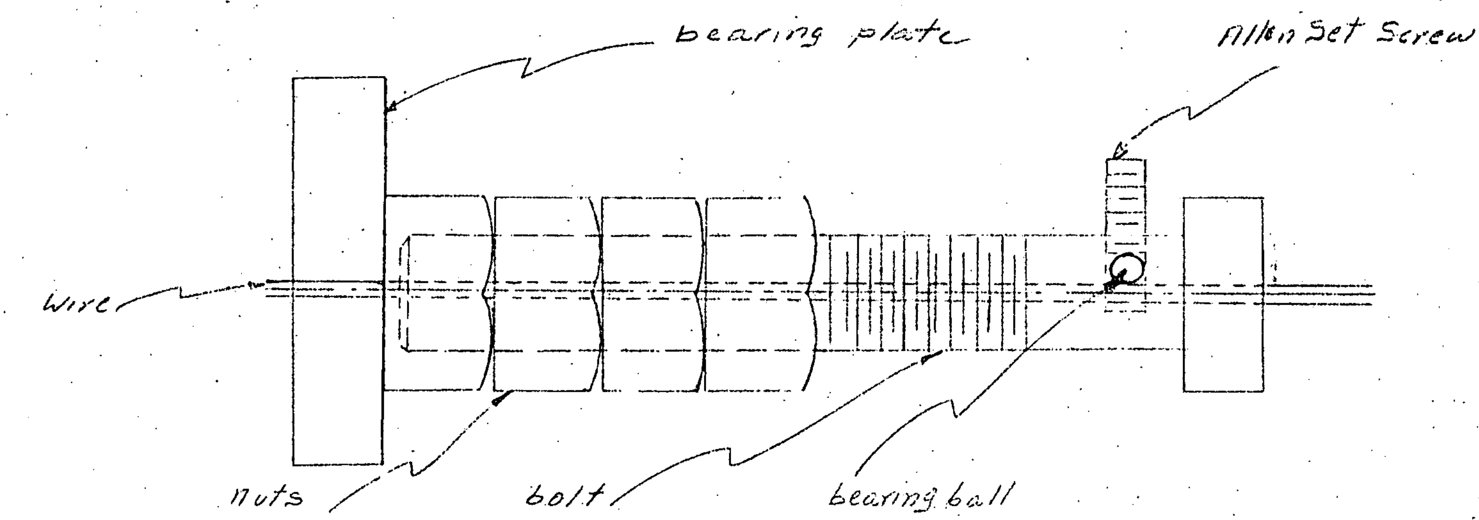
Mr. Melville used in his research a wire of a smaller diameter than the wire used here and hence the prestress on each wire was less than one-half the stress on the 0.10" wire applied in this research.

The same device was constructed and tested on the 60,000# machine in Fritz Engineering Laboratory. When the stress on the 0.10" wire reached a value of above 200#, that is to say, 25,000 psi, slip occurred which proved the inefficiency of one

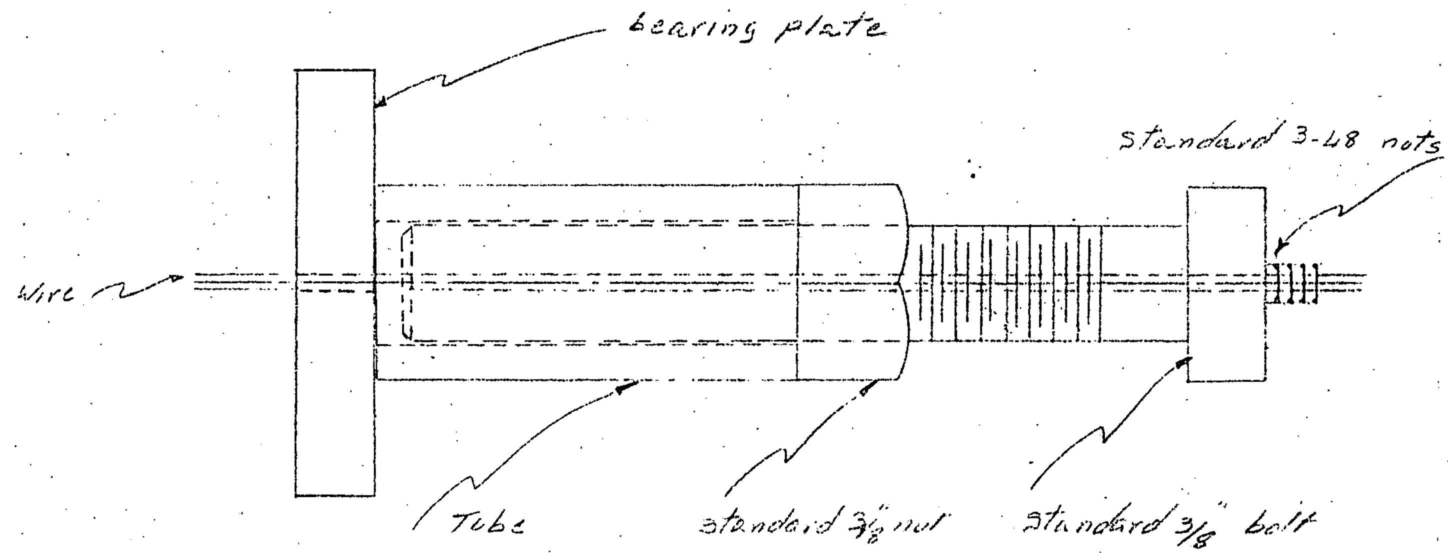


DETAILS OF FORMS WITH END PLATES AND CHANNELS

FIGURE (4)



Mr. Mellville's Unit



Unit used in this work.

FIGURE (5)

allen set screw to hold the wire. Then another allen set screw with a bearing ball was provided on the side of the bolt opposite to that where the first allen set screw was and about 1/2" below. This new device was again tested and it was found that the highest stress obtainable before slip occurred was about 40,000 psi.

The foregoing tests proved the inefficiency of this method of anchorage for a 0.10" wire, and thus a new method was used. This was to thread the ends of the wire. A number of 3-48 - standard nuts were screwed onto the wire so that they rested against the end of the bolt as shown in Figure (5). The basic idea of the threading of the wire adopted was developed and reported by Professors' W.J. Eney and A.C. Loewer, Jr. at the First U.S. Conference on Prestressed Concrete at M.I.T. in August, 1951. This will be later discussed in detail.

Another modification to Mr. Melville's unit was made. Instead of using a number of nuts to produce the required elongation a tube one inch in length was devised. First, a standard nut was screwed onto the bolt and then the bolt was fitted into the tube until the nut was bearing against the tube. By unscrewing the nut the tube was pushed out and eventually the bolt was pushed in the opposite direction thus stretching the wire, Figure (5).

This tube has four advantages over the system of nuts devised by Mr. Melville. In the first place it is much easier to handle because one nut is used only until the required elongation is developed. In the second place, when the stress is a little high and the nut in Mr. Melville's unit is threaded all the way out, there might not be sufficient area on the root of the threads to hold the stress, therefore the threads on the bolt or nut might shear off. This is completely avoided in the unit used here, because the nut is never threaded all the way out of the bolt. In the third place when the first nut in Mr. Melville's unit is threaded all the way out, and before the second nut is used, the bolt tends to lean from the perpendicular to the plate and thus a source of error is encountered. This is also completely avoided in the new unit used here. In the fourth place, when the second nut which is bearing against the first is unscrewed, the first tends to move around the wire thus becoming eccentric. In this case the second nut is partly bearing against the first nut hence the load becomes eccentric. This might cause some inclination of the bolt. This source of error is not possible in the new unit.

Figure (5) represents a diagram of the unit used in this research and also Figure (6) is a photograph of the same unit and various parts.

3. Threading the Wires: The threading of the wires was tried when the method of gripping the wire by the allen set screw failed. In the beginning an ordinary 3-48 die was used to chase a thread on the ends of a short piece of wire. The die was completely ruined after one end of the wire was threaded for a distance of about one-half inch. This was because of the extreme hardness of the wire. After this unfortunate result the attention towards other possible methods for gripping the wire were considered.

One method which was tried and which proved to be a failure was to give a few blows to the end of the wire in order to flatten it thus increasing its one dimension. This was done and then the wire was fitted into a piece of steel

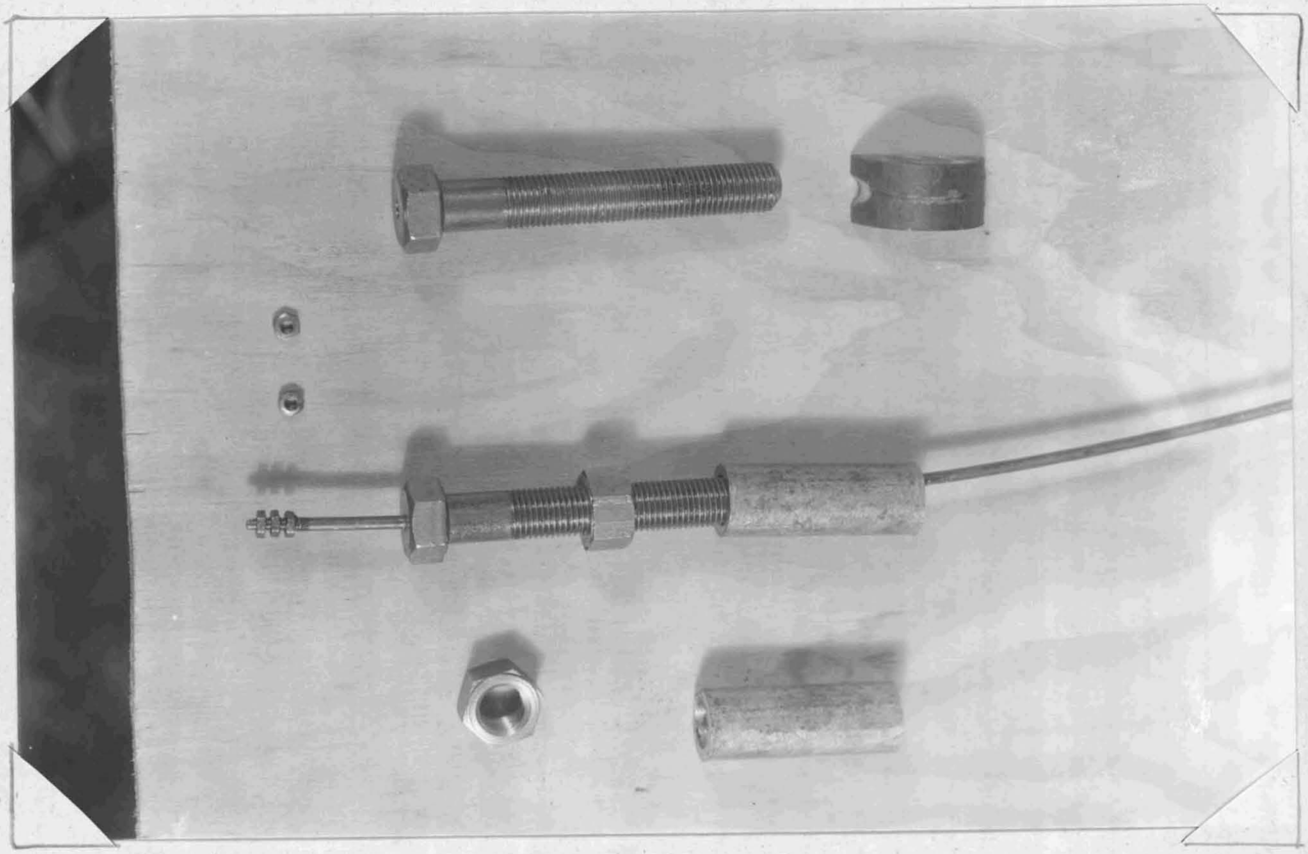


Figure (6)
Various Parts of Prestressing Unit, End
Anchorage, and Half Rod Piece

with a hole 1/10" diameter. Then it was tested in the machine by gripping the other end. When the load went to about 35,000 psi slip occurred and then the wire started making a groove in the hole in the piece of metal in order to find its way out.

Another method was to bend the end of the wire at right angles and then to fit it in the hole of the piece of metal. When this was tested at a load of about 50,000 psi the end of the wire straightened itself and slipped out.

All the above facts switched the attention back to threading, which proved to be a reliable method of gripping as presented in the report by Professors' W.J. Eney and A.C. Loewer, Jr.

The number of wires whose ends were to be threaded for a length of about half an inch was 75. To use ordinary dies was a very expensive method, because as mentioned before a one-half inch of thread was enough to ruin the die, hence adjustable high speed dies were tried. They proved to be much better than the ordinary ones.

Several ways for handling these dies were tried and the most effective was to begin the pattern of threads with one die which was adjusted by increasing its diameter slightly. This first pattern of thread was not deep enough to fit into a 3-48 standard nut, thus a second die was used whose diameter was increased by a little less than the first one. Still the depth of thread was not enough and a third unadjusted die did the final job perfectly.

This method reduced tremendously the number of dies which would have been necessary had ordinary low-speed dies been used. It was concluded that even the high-speed dies were not of sufficient hardness for threading the wire.

To thread the ends of the wire was a very good method for gripping especially because three standard 3-48 nuts were enough to hold the stress. It was also very reliable because it avoided practically all possible losses due to slip at the anchored end, but this method of threading would be very impractical for large jobs because of the long time it requires.

If certain special dies lined with diamond particles, or made of the same hard steel could be produced then the process of threading becomes very simple and quick. This is very possible, and then this method would be recommended, otherwise, the development of another method for gripping would be advisable.

4. The Dead End: The number of prestressed wires used in the work was 75. If both ends of the wire were to be gripped for anchorage then 150 threaded ends would have been required . This would have been a very laborious and expensive job and a method was devised which cut the labor and expenses tremendously. The required threaded ends were cut in half by having the wires in pairs, each pair made of one length of wire and U-turned around a piece of half-rod at the end plate. Figures (7)A and (7)B represents the end plates showing the wire turned around the half-rod, the end of the threaded wire, and the prestressing devices. The piece of half-rod was cut from a rod one inch in diameter and notched at both ends so as to reduce its diameter to 9/10 of an inch, the distance between inner faces of each pair of wire. After turning the wire around the half-rod it was given a few blows at this

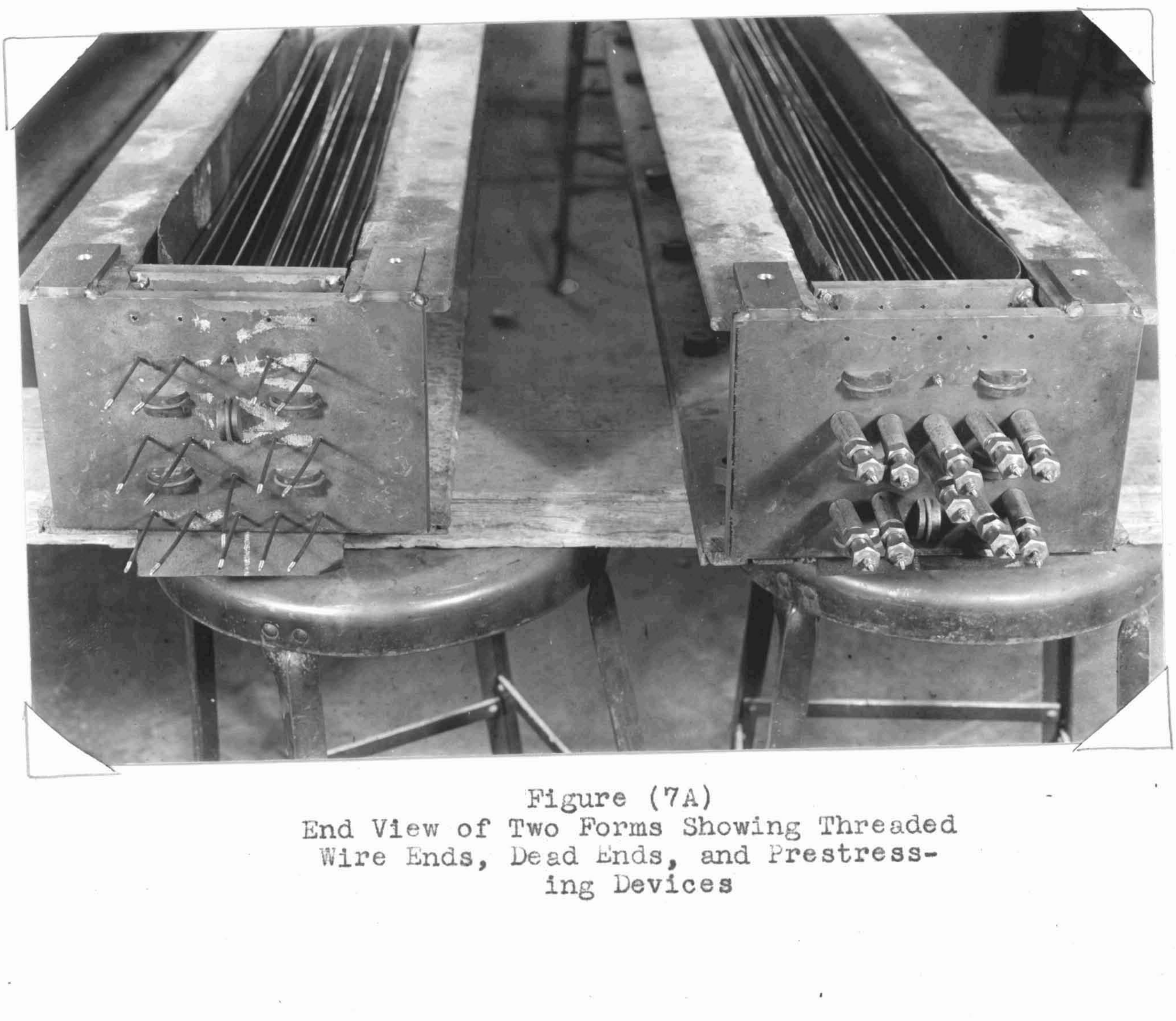


Figure (7A)
End View of Two Forms Showing Threaded Wire Ends, Dead Ends, and Prestressing Devices

Figure (7B)
End View of Forms With Prestressing
Devices and Dead Ends

dead end until it nested exactly on the half-rod. Approximately no clearance was left between the wire and the half-rod. Had clearance occurred here, the wire might have been pulled to an erroneous stress by misinterpretation of elongation at the loading bolt.

5. <u>Prestressing the Wire</u>: The Modulus of Elasticity of the wire was found to be 30,000,000 psi and the length of one wire was 9.75'. Hence the elongation of each wire required to develop a stress of 135,000 psi was determined as follows:

$$\epsilon = \frac{f_s}{E} = \frac{135000}{30,000,000} = 0.0045 \text{ in/in.; total elong.} = 0.0045 \times 9.75 \times 12 = 0.5265''$$

In order to check whether this elongation produced the required stress, A-12, SR-4 strain gages were set on three pairs of wire, one pair in each form. (Figures 8 and 9).

As seen from above, 0.0045 in/in were required to produce a stress of 135,000 psi or 4500 micro inches. Therefore, the wires on which the gages were set were stressed until an elongation of 4500 micro inches was indicated in the strain indicater and also the elongation of the wire was measured by measuring the distances the bolt moved away from the nut. In the first pair it was more than the estimated value of 0.5265 by 0.083", in the second pair by 0.088 inches and in the third by 0.0735".

These results proved that the calculated elongation was not enough to produce the required stress because parts of it were lost in the dead ends in deformation in the prestressing device, in the end plate, in bending, which was seen by the naked eye and in shortening of jacking frame itself.

It was assumed that an increase of 0.0735 inches in the

Figure (8)
A-12, SR-4 Strain Gages On Wires
For Checking On Prestress

Figure (9)
The Process of Prestressing The Wires On
Which A-12, SR-4 Strain Gages
Are Set

elongation was necessary to produce the required elongation and each wire was elongated by this distance.

After stressing all the wires in the three forms, another check was considered. The three pairs of wires on which the SR-4 gages were set, were again released from their stress. The same process of stressing them was followed as previously described and it was found that the actual elongation in the first pair was 0.023 inches more than the estimated figure of 0.5265", in the second, it was 0.052 inches more; and in the third 0.048 inches more. The average value was 0.041 inches.

The actual increase in each wire was 0.0735 inches, and the final check proved that part of it was lost in the deformation caused by the initial setting of the test frame. The estimated prestress is within 5% of the actual and thus was satisfactory for the purpose of this work.

D. DESCRIPTION OF TESTS:

It was previously mentioned that very little has been reported concerning bond stress in pretensioned, prestressed concrete. Opinions varied as to the length of each end of the wire necessary for end anchorage. Actually this length varies for various wires, and the range of this length which was given in the available literature was very large beginning with (50-90) diameters for fine wire, 0.08" in diameter, up to (150-400), diameters for larger diameter wires, 0.2".*

In this work three lengths of embedment were chosen to determine the length required for end anchorage of a 0.10" wire. They were 1'-0" (A series) 3'-0" (B series) and

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* Magazine of Concrete Research - Dec. 1949, p. 121

4'-6" (C series). Three specimens for each length were made with a nominal cross-section of 5"x5". All the specimens were reinforced with 25 - 1/10" wires, uniformly distributed across the cross-section and equally prestressed. Hence a uniform unit load was assumed to develop across any section in any specimen. This assumption holds true only if the stresses in all the wires were equal and if the distribution of bond stress along the lengths of all the wires were the same. As to the first criterion it was previously concluded that the stress in all the wires was within 5% of the estimated value which was quite satisfactory for the purpose of this work. The second assumption depends on how well the concrete was poured in all the specimens and upon the surface condition of all the wires. Thus it was assumed that all the wires had the same condition of surface and that concrete was poured in the same way in all specimens. Of course this assumption was not exactly true because the surface condition of all the wire was not exactly the same and hence another source of error was created.

According to the above assumptions, the strain across any cross-section in any specimen was assumed to be the same. The idea behind this work was to determine the distribution of bond stress along the length of wire in each specimen by determining the strains produced in the concrete along the length of each specimen after the release of the prestress. The strains were assumed to vary from zero at the end to a maximum value somewhere near the center.

The length from the end of each specimen to the point where the strain is maximum should determine the length of wire required to transfer the prestress from the wire to the concrete by bond.

For this purpose it was decided to mount a certain number of A-11, SR-4 strain gages along the centerline of the exposed surface of each specimen. Because of the fact that there was no clear idea about the pattern of the distribution of bond along the length of the wire, a pilot test was conducted on specimen #1C (4'-6" long) and specimens #1A, 2A and 3A (1'-0" long). All these specimens were poured in one of the forms as shown in Figure (10). The gages were set in the pattern shown on Tables (4), (5), and (6). This test was conducted when the concrete was nine days old. An initial set of readings was taken before the release of the wire, Tables (4) and (5) and Figure (11). Then the wire was released.

Figure (10A) represents the position of the specimens in the form, and the side views show how the wires were stressed. The dots are the prestressing devices and the lines joining pairs of dots represent the dead ends. The wires were released at each end in such a way as to avoid concentration of stress on one part of the section.

In the beginning the inclination was toward having all the prestressing devices at one end of the form and the dead ends at another end. This would have rendered the process of prestressing very difficult because of the small clearances between the prestressing devices and hence it was decided to have the distribution shown in Figure (10). This facilitated extremely the prestressing process but at the same time it created an unpredicted result.

During the process of releasing the stress the specimens in the form were held from moving freely by the force of friction between them and the form. This is obvious from a comparison

POSITION OF SPECIMENS IN FORMS

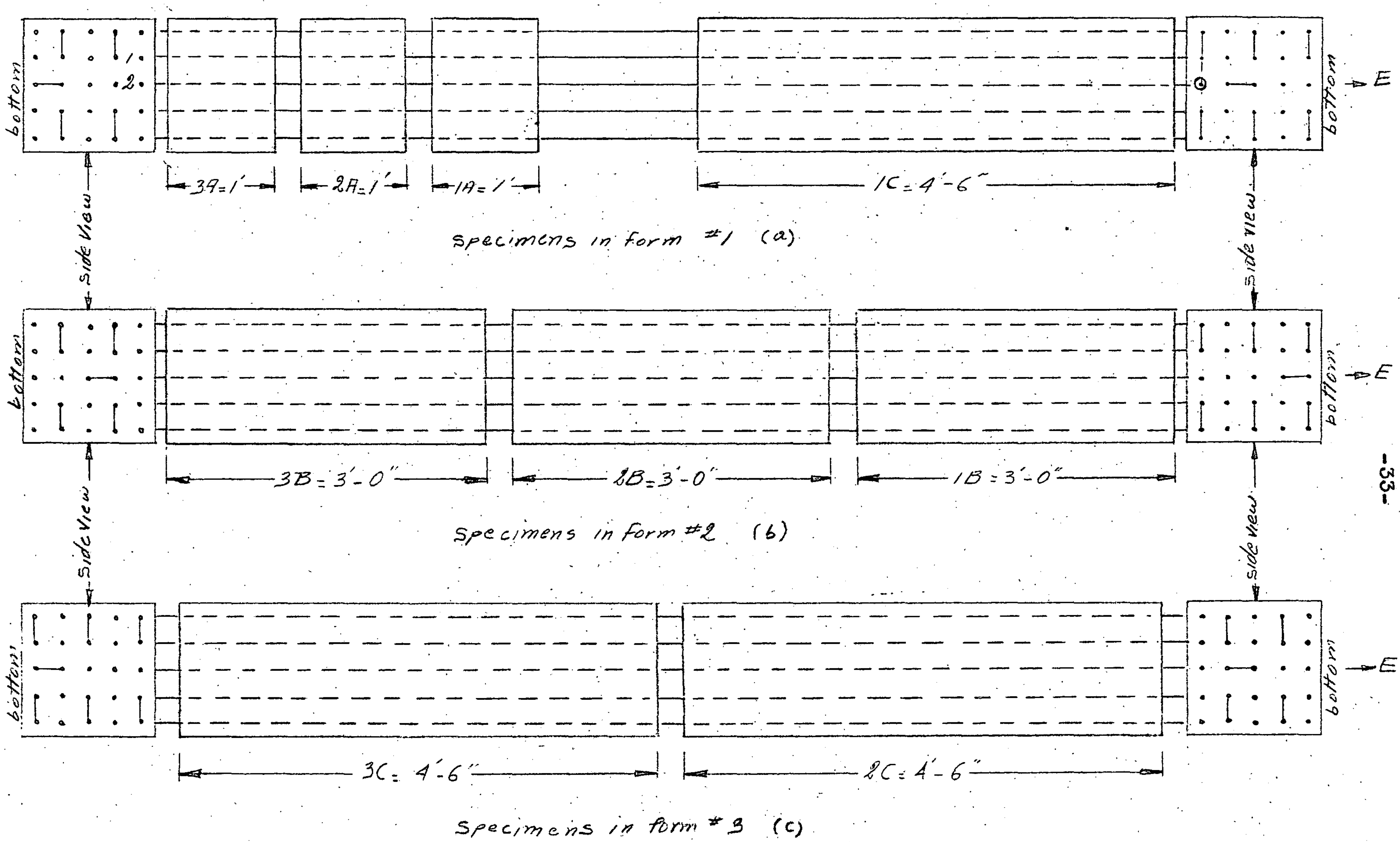
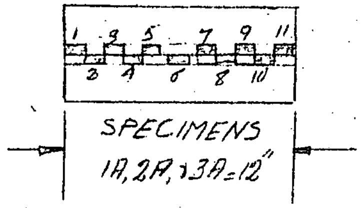


FIG. (10)



LOCATION OF SR-4 STRAIN GAGES ON SURFACE OF 1' SPECIMENS.

TEST RESULTS ON 1' SPECIMENS

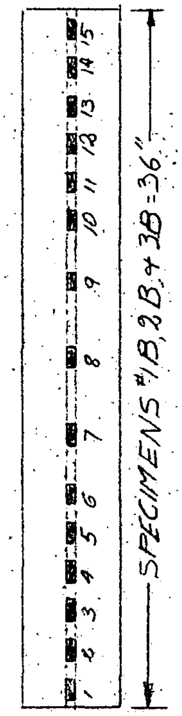
Gage	before release		after release June 30, 1:35pm		Δ	Form removed June 30, 2:16pm		Δ	July 2, 10:30am		Δ	July 7, 9:50am		Δ	July 14, 3:45pm		Δ	
1	6	600	6	600	0	6	600	0	6	590	-10	6	595	-5	6	613	+13	Specimen #1A=1 ft
2	7	053	7	040	-13	7	43	-10	7	38	-15	7	29	-24	7	22	-31	
3	9	100	9	078	-22	9	90	-10	9	105	+5	9	130	+30	9	131	+31	
4	7	330	7	300	-30	7	312	-18	7	303	-27	7	323	-7	7	352	+22	
5	7	970	7	938	-32	7	950	-20	7	930	-40	7	949	-21	7	980	+10	
6	8	976	8	942	-34	8	953	-23	8	956	-20	8	971	-5	8	985	+9	
7	8	1000	8	972	-28	8	980	-20	8	988	-12	8	1019	+19	8	1041	+41	
8	7	1705	7	1675	-30	7	1680	-25	7	1665	-40	7	1683	-22	7	1720	+15	
9	6	1235	6	1215	-20	6	1220	-15	6	1221	-14	6	1250	+15	6	1270	+35	
10	8	539	8	522	-19	8	523	-16	8	503	-36	8	528	-11	8	570	+31	
11	6	1241	6	1230	-11	6	1227	-14	6	1200	-41	6	1250	+9	6	1328	+87	
1	8	1073	8	1070	-3	8	1070	-3	8	1041	-32	8	1070	-3	8	1130	+57	Specimen #2A=1 ft
2	8	645	8	640	-5	8	648	+3	8	631	-14	8	640	-5	8	662	+17	
3	7	808	7	800	-8	7	810	+2	7	813	+5	7	850	+42	7	890	+82	
4	6	1425	6	1410	-15	6	1425	0	6	1410	-15	6	1420	-5	6	1440	+15	
5	8	1068	8	1050	-18	8	1072	+4	8	1060	-8	8	1073	+5	8	1091	+23	
6	7	599	7	581	-18	7	600	+1	7	595	-4	7	616	+17	7	653	+54	
7	7	553	7	540	-13	7	550	-3	7	532	-21	7	532	-21	7	540	-13	
8	8	419	8	398	-21	8	405	-14	8	376	-43	8	368	-51	8	385	-34	
9	7	1005	7	994	-11	7	1000	-5	7	982	-23	7	990	-15	7	1000	-5	
10	7	843	7	823	-20	7	830	-13	7	800	-43	7	797	-46	7	835	-8	
11	7	752	7	740	-12	7	740	-12	7	713	-39	7	752	0	7	832	+80	
1	9	217	9	210	-7	9	200	-17	9	200	-17	9	235	+18	9	300	+83	Specimen #3A=1 ft
2	8	1024	8	1020	-4	8	1021	-3	8	1009	-15	8	1018	-6	8	1031	+7	
3	7	1450	7	1452	+2	7	1450	0	7	1443	-7	7	1445	-5	7	1454	+4	
4	8	790	8	793	+3	8	800	+10	8	783	-7	8	793	+3	8	818	+28	
5	9	100	9	110	+10	9	118	+18	9	121	+21	9	159	+59	9	185	+85	
6	7	960	7	960	0	7	975	+15	7	948	-12	7	938	-22	7	955	-5	
7	8	203	8	203	0	8	215	+8	8	211	+8	8	239	+36	8	260	+57	
8	6	992	6	990	-2	6	1000	+8	6	991	-1	6	995	+3	6	1008	+16	
9	8	493	8	490	-3	8	503	+10	8	503	+20	8	509	+16	8	510	+17	
10	6	1429	6	1413	-16	6	1425	-4	6	1416	-13	6	1430	+1	6	1432	+3	
11	6	542	6	538	-4	6	540	-2	6	553	+11	6	588	+46	6	640	+98	

TABLE (4)

TEST RESULTS ON 3' SPECIMENS.

Gage	before release		after release July 2, 1:35 pm		Δ	form removed July 2, 3:00 pm		Δ	July 3, 1:35 pm		Δ	July 7, 9:25 am		Δ	July 14, 3:20 pm		Δ	
1	7	770	7	753	-17	7	753	-17	7	800	+30	7	790	+20	7	820	+50	Specimen #1B = 3.00 ft
2	8	710	8	710	0	8	695	-15	8	720	+10	8	692	-18	8	648	-62	
3	5	1533	5	1535	+2	5	1543	+10	5	1574	+41	5	1563	+30	5	1582	+49	
4	6	1330	6	1329	-1	6	1335	+5	6	1349	+19	6	1340	+10	6	1300	-30	
5	6	1119	6	1113	-6	6	1113	-6	6	1133	+14	6	1089	-30	6	1075	-44	
6	6	619	6	599	-20	6	600	-19	6	620	+1	6	590	-29	6	595	-24	
7	6	140	6	059	-81	6	070	-70	6	100	-40	6	070	-70	6	079	-61	
8	6	1324	6	1260	-64	6	1222	-102	6	1291	-33	6	1263	-61	6	1263	-61	
9	5	951	5	885	-66	5	910	-41	5	913	-38	5	890	-61	5	900	-51	
10	7	632	7	763	+131	7	675	+43	7	442	-190	7	400	-232	7	439	-193	
11	6	933	6	910	-23	6	935	+2	6	940	+7	6	923	-10	6	932	-1	
12	6	1231	6	1226	-5	6	1248	+17	6	1255	+24	6	1244	+13	6	1254	+23	
13	5	993	5	994	+1	5	1005	+12	5	1000	+7	5	993	0	5	998	+5	
14	7	143	7	135	-8	7	139	-4	7	140	-3	7	148	+5	7	175	+32	
15	7	409	7	390	-19	7	400	-9	7	460	+51	7	478	+69	7	500	+91	
1	6	685	6	670	-15	6	670	-15	6	703	+18	6	704	+19	6	650	-35	Specimen #2B = 3.00 ft
2	6	653	6	678	+25	6	663	+10	6	670	+17	6	660	+7	6	655	+2	
3	6	1290	6	1330	+40	6	1328	+38	6	1353	+63	6	1449	+59	6	1491	+201	
4	6	1055	6	1083	+28	6	1090	+35	6	1089	+34	6	1078	+23	6	1090	+35	
5	6	1693	6	1703	+10	6	—	—	6	—	—	6	—	—	6	—	—	
6	6	503	6	510	+7	6	513	+10	6	490	-13	6	484	-19	6	500	-3	
7	7	083	7	079	-4	7	080	-3	7	72	-11	7	29	-54	7	53	-30	
8	7	560	7	549	-11	7	530	-30	7	508	-72	7	472	-88	7	492	-68	
9	6	850	6	820	-30	6	805	-45	6	781	-69	6	760	-90	6	756	-94	
10	6	1414	6	1395	-19	6	1401	-13	6	1400	-14	6	1390	-24	6	1403	-11	
11	5	880	5	891	+11	5	872	-8	5	790	-90	5	759	-121	5	762	-118	
12	6	318	6	325	+7	6	320	+2	6	325	+7	6	325	+7	6	351	+33	
13	6	082	6	90	+8	6	100	+18	6	089	+7	6	069	-13	6	70	-12	
14	7	111	7	109	-2	7	110	-1	7	118	+7	7	125	+14	7	140	+29	
15	6	582	6	561	-21	6	—	—	6	—	—	6	—	—	6	—	—	
1	A5	1000	A5	—	—	A5	1029	+029	A5	165	+2165	A4	29	-1971	A3	209	-2791	Specimen #3B = 3.00 ft
2	6	220	6	226	+6	6	223	+3	6	255	+35	6	252	+32	6	262	+42	
3	6	313	6	323	+10	6	340	+27	6	348	+35	6	355	+32	6	372	+59	
4	6	509	6	520	+11	6	519	+10	6	532	+23	6	538	+29	6	550	+41	
5	7	719	7	723	+4	7	722	+3	7	733	+14	7	728	+9	7	730	+11	
6	7	668	7	683	+15	7	683	+15	7	813	+145	7	896	+228	7	1188	+520	
7	7	1113	7	1120	+7	7	1128	+15	7	1132	+19	7	1175	+62	7	1210	+97	
8	6	1320	6	1318	-2	6	1325	+5	6	1339	+19	6	1340	+20	6	1371	+51	
9	6	410	6	395	-15	6	410	0	6	419	+9	6	435	+25	6	478	+68	
10	6	960	6	958	-2	6	972	+12	6	983	+23	6	1000	+40	6	1022	+62	
11	6	1280	6	1278	-2	6	1300	+20	6	1305	+25	6	1295	+15	6	1300	+20	
12	6	810	6	819	+9	6	839	+29	6	833	+23	6	825	+15	6	850	+40	
13	7	603	7	610	+7	7	623	+20	7	611	+8	7	630	+27	7	625	+22	
14	6	160	6	153	-7	6	160	0	6	168	+8	6	179	+17	6	200	+40	
15	6	900	6	889	-11	6	890	-10	6	949	+49	6	950	+50	6	928	+28	

TABLE (5)



LOCATION OF SR-4 STRAIN GAGES ON SURFACE OF 3' SPECIMENS

TEST RESULTS ON 4.5' SPECIMENS.

Gage #	Before release		After release June 30, 1:25 Pm		Δ	Form removed June 30, 2:16 Pm		Δ	July 2, 10:30 Am		Δ	July 7, 9:50 am		Δ	July 14, 3:45 pm		Δ
1	6	818	6	805	-13	6	810	-8	6	785	-33	6	835	+17	6	893	+75
2	5	943	5	930	-13	5	943	0	5	960	+17	5	980	+37	5	980	+37
3	5	847	5	825	-22	5	830	-17	5	841	-6	5	883	+36	5	952	+105
4	6	290	6	270	-20	6	283	-7	6	290	0	6	348	+58	6	410	+120
5	7	210	7	200	-10	7	210	0	7	211	+1	6	134	-76	7	252	+42
6	6	643	6	626	-17	6	623	-20	6	602	-41	6	625	-18	6	652	+9
7	8	899	8	868	-31	8	850	-49	8	816	-83	8	820	-79	8	833	-66
8	7	1078	7	1042	-36	7	983	-95	7	938	-140	7	941	-137	7	960	-118
9	5	1035	5	985	-50	5	905	-130	5	820	-215	5	791	-244	5	792	-243
10	7	465	7	420	-45	7	330	-135	7	272	-193	7	263	-203	7	270	-195
11	7	863	7	803	-60	7	705	-158	7	641	-222	7	621	-242	7	620	-243
12	8	250	8	186	-64	8	130	-120	8	110	-140	8	123	-127	8	160	-90
13	7	319	7	253	-66	7	245	-74	7	230	-89	6	138	-181	7	251	-68
14	7	530	7	473	-57	7	493	-37	7	465	-65	7	458	-72	7	475	-55
15	8	672	8	632	-40	8	663	-9	8	659	-13	8	675	+3	8	700	+28
16	6	1369	6	1338	-31	6	1369	0	6	1313	-56	6	1378	+9	6	1398	+29
17	7	960	7	932	-28	7	960	0	7	965	+5	7	985	+25	7	1000	+40
18	7	778	7	760	-18	7	775	-3	7	788	+10	7	803	+25	7	830	+52
19	7	840	7	834	-6	7	833	-7	7	805	-35	7	840	0	7	910	+70

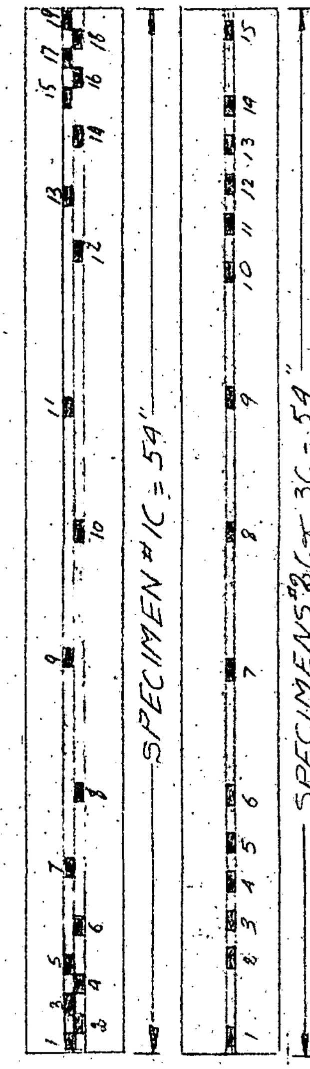
Specimen #1C = 4.5 feet

	Before release		After release July 2, 1:35 Pm		Δ	Form removed July 2, 3:00 Pm		Δ	July 3, 1:35 Pm		Δ	July 7, 9:25 am		Δ	July 14, 3:20 Pm		Δ
1	9	692	9	660	-32	9	683	-9	9	720	-72	9	730	+38	9	784	+92
2	8	1421	8	1368	-53	8	1372	-49	8	1385	-36	8	1358	-63	8	1362	-59
3	6	820	6	758	-62	6	760	-60	6	779	-41	6	775	-45	6	798	-22
4	6	909	6	823	-86	6	840	-69	6	841	-68	6	834	-75	6	861	-48
5	7	825	7	715	-110	7	725	-100	7	733	-92	7	711	-114	7	740	-85
6	6	1016	6	911	-105	6	916	-100	6	929	-87	6	891	-125	6	921	-95
7	6	540	6	404	-136	6	390	-150	6	373	-167	6	320	-220	6	348	-192
8	6	505	6	332	-173	6	300	-205	6	265	-240	6	213	-292	6	200	-305
9	6	772	6	591	-181	6	548	-224	6	510	-262	6	470	-302	6	468	-304
10	6	733	6	578	-155	6	575	-158	6	583	-150	6	568	-165	6	592	-141
11	6	983	6	839	-144	6	860	-123	6	879	-104	6	881	-102	6	908	-75
12	6	1218	6	1095	-123	6	1150	-68	6	1160	-58	6	1150	-68	6	1172	-46
13	5	1241	5	1129	-112	5	1185	-56	5	1198	-43	5	1180	-68	5	1198	-43
14	6	1488	6	1399	-99	6	1440	-48	6	1430	-58	6	1432	-56	6	1442	-46
15	5	753	5	721	-32	5	732	-21	5	750	-3	5	780	+27	5	792	+39

Specimen #2C = 4.5 feet

1	7	131	7	99	-32	7	115	-16	7	161	+30	7	150	+19	7	160	+29
2	7	151	7	80	-71	7	90	-61	7	108	-43	7	84	-67	7	88	-63
3	8	090	8	03	-87	8	05	-85	8	19	-71	8	00	-90	7	992	-98
4	7	420	7	335	-85	7	381	-59	7	372	-48	7	348	-72	7	405	-15
5	6	1043	6	960	-83	6	952	-91	6	952	-91	6	940	-103	6	938	-105
6	7	410	7	326	-84	7	322	-88	7	325	-85	7	318	-92	7	330	-80
7	6	1105	6	950	-155	6	941	-164	6	930	-175	6	908	-197	6	908	-197
8	6	1150	6	989	-161	6	983	-167	6	970	-180	6	930	-220	6	920	-230
9	6	1019	6	830	-189	6	839	-180	6	822	-197	6	800	-219	6	802	-217
10	6	567	6	410	-157	6	456	-111	6	466	-101	6	443	-124	6	460	-107
11	6	793	6	661	-132	6	719	-74	6	728	-65	6	714	-79	6	718	-75
12	5	805	5	690	-115	5	753	-52	5	760	-45	5	745	-60	5	750	-55
13	6	408	6	320	-88	6	373	-35	6	380	-28	6	389	-19	6	400	-8
14	6	619	6	549	-70	6	589	-30	6	586	-33	6	573	-46	6	583	-26
15	6	760	6	741	-19	6	750	-10	6	778	+17	6	809	+49	6	788	+28

Specimen #3C = 4.5 feet



LOCATION OF SR-4 STRAIN GAGES ON SURFACE OF 4.5' SPECIMENS.

TABLE (6)

Figure (11)
Actual Test Before Release of Prestress

of the strains in the specimens exactly after release and those after the removal of the forms and shaking of the specimens, Tables (4), (5), and (6).

Because of the above fact the wires in the one-foot specimens did not move towards the center of each specimen but had to move from the end which was released towards the fixed end (dead end) on the other side. This was obvious and it was detected by the naked eye. As an example, while releasing wires No. (1) and (2) at the west end, Figure (10A) they started slipping through specimens (3A), (2A), and (1A), and the slip was seen as a polished length of wire in the clearance between the specimens. A somewhat similar action took place when the wires were being released from the east end, but to a lesser extent because there were not as many unbonded strain lengths of wire between the specimens and the east end as were at the west end. This no doubt produced a very complicated cross-strain phenomena in all specimens. This result was not satisfactory but it was concluded that the one-foot specimen was not sufficient to hold the prestress by bond when subjected to a condition resembling a pull-out test.

While releasing the wires at the west end, or the end adjacent to the one-foot specimens, the nuts in the prestressing device were turned many times, but this process at the east end towards the 4'-6" specimen required one or two turns to release the prestress. This indicated that the prestress was transferred to the concrete by bond in the 4'-6" specimen, while it was not in the one-foot specimen.

When the prestress was released and when the side of the form was removed, the specimens were shaken and another set of readings was taken.

It is seen from Table (4) and Figure (12) that the strains developed in the one-foot specimens were erratic and very small compared to the strains that should have actually been produced if the whole prestress were held by bond. This will be discussed more fully later.

The strains obtained in the 4.5' specimen No. 1C were more or less satisfactory as shown in the curve Figure (14). This result proved that the strains varied almost from zero around the ends of the specimens to a maximum value around the center. As a result of this first test it was decided to change the pattern of the distribution of the gages along the lengths of the remaining specimens as shown on Tables (5) and (6).

The gages were set for the second part of the test on the three 3.0' feet specimens and on the remaining two 4.5 ft. specimens. An initial set of readings was taken and the wires were then released. Before the removal of the forms and after the release a set of readings was taken, and another also after the removal of the forms. The difference in strains obtained between these two sets of readings as seen from Tables (5) and (6) showed the effect of friction between the concrete and the forms.

During the process of releasing the wire on the three-feet specimens a very important observation was made which interprets the unsatisfactory results obtained as seen from Figure (13). It was found that some of the wires required many turns of the nut on the prestressing device in order to release the stress and others required fewer turns. This meant that the prestress in some of the wires was held by bond while in the others, where many turns were necessary, slip occurred. This seems to substantiate the positive and negative strains shown

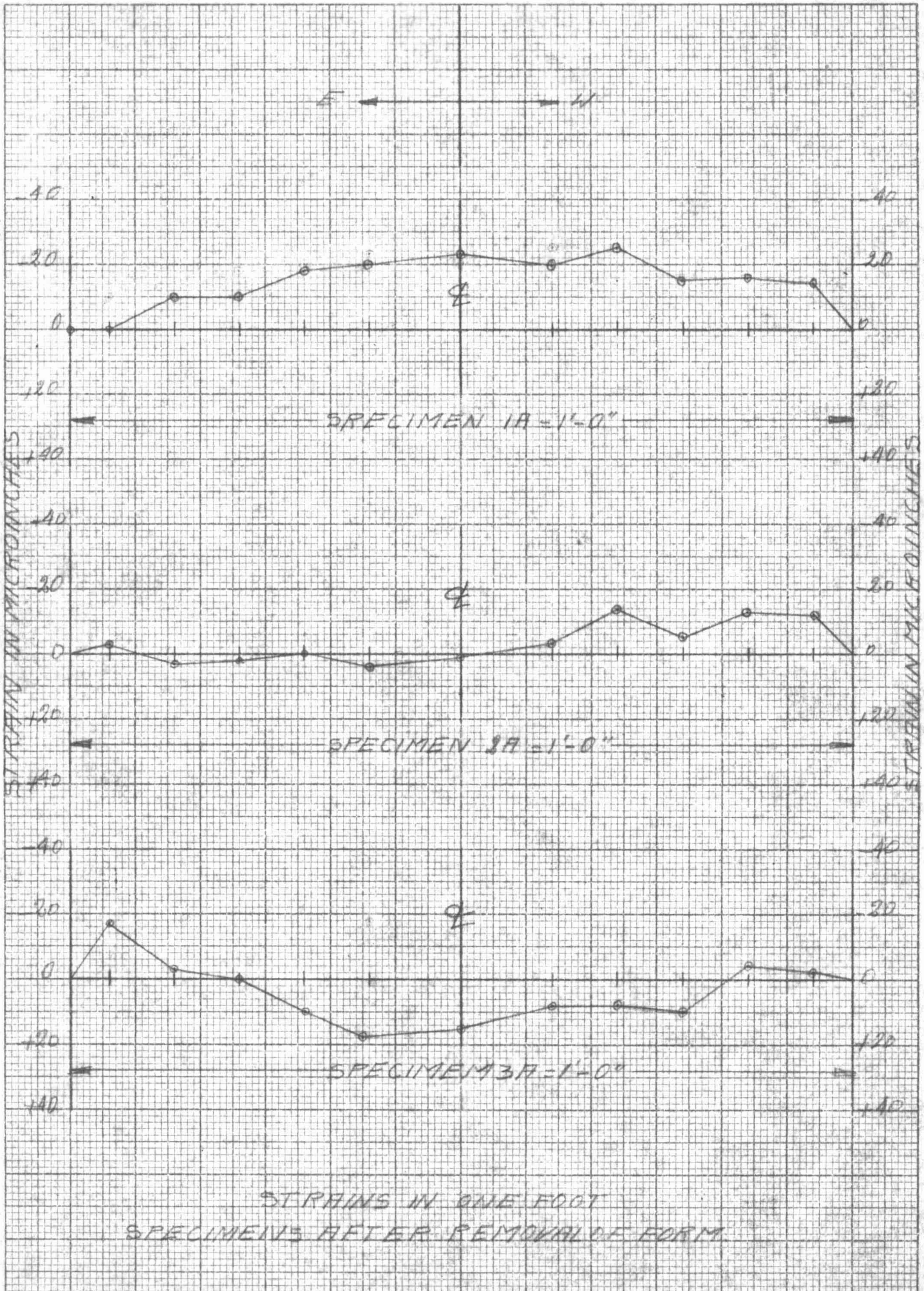

E
W
40
20
0
20
40
SPECIMEN 1A = 1'-0"
SPECIMEN 2A = 1'-0"
SPECIMEN 3A = 1'-0"
STRAIN IN MICROINCHES
STRAINS IN ONE FOOT
SPECIMENS AFTER REMOVAL OF FORM

FIG. (12)

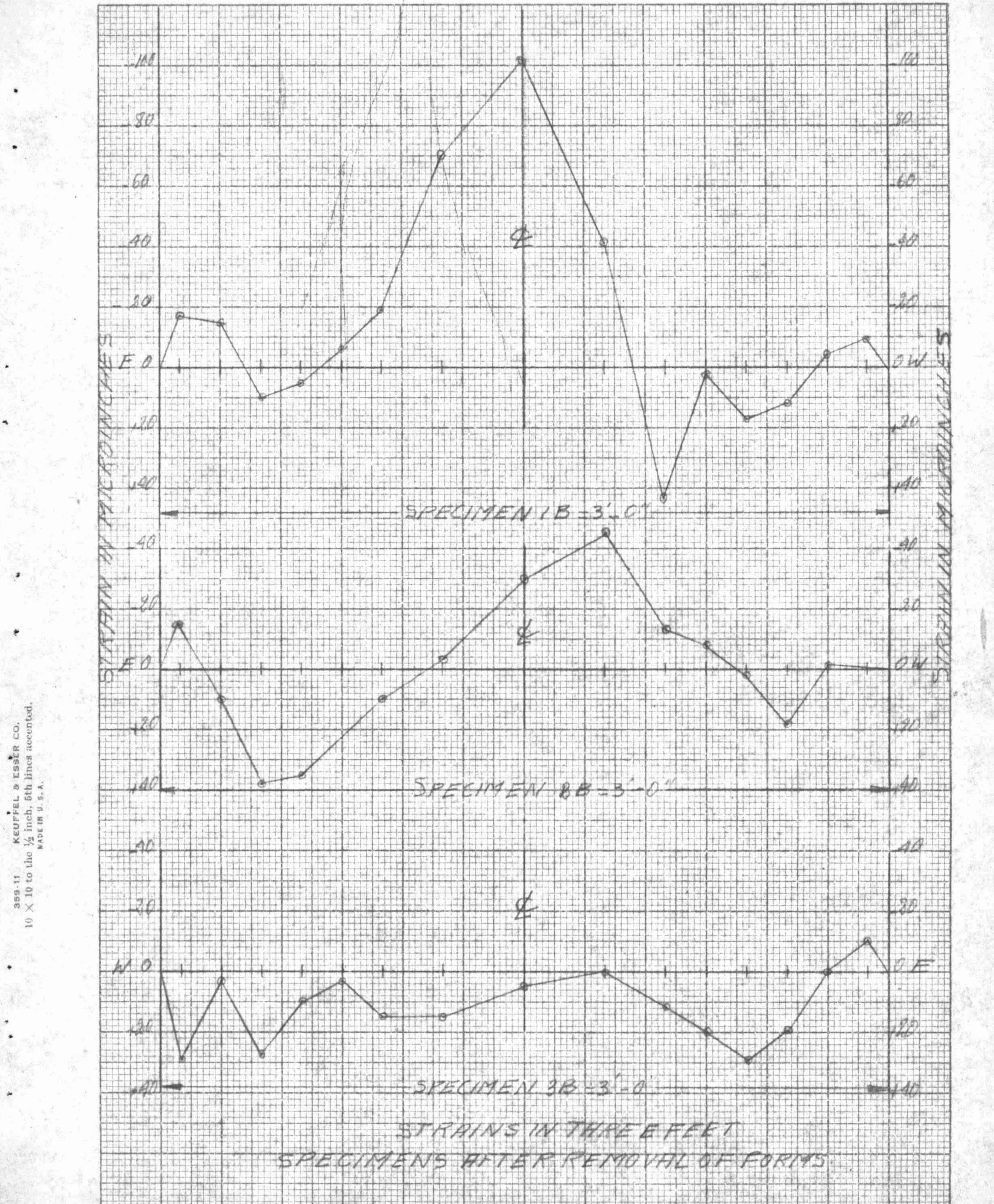

STRAIN IN MICROINCHES
STRAIN IN MICROINCHES
SPECIMEN 1B - 3'-0"
SPECIMEN 2B - 3'-0"
SPECIMEN 3B - 3'-0"
STRAINS IN THREE FEET
SPECIMENS AFTER REMOVAL OF FORMS
KEUFFEL & ESSER CO.
359-11 10 × 10 to the ½ inch, 5th lines accented.
MADE IN U. S. A.

FIG. (13)

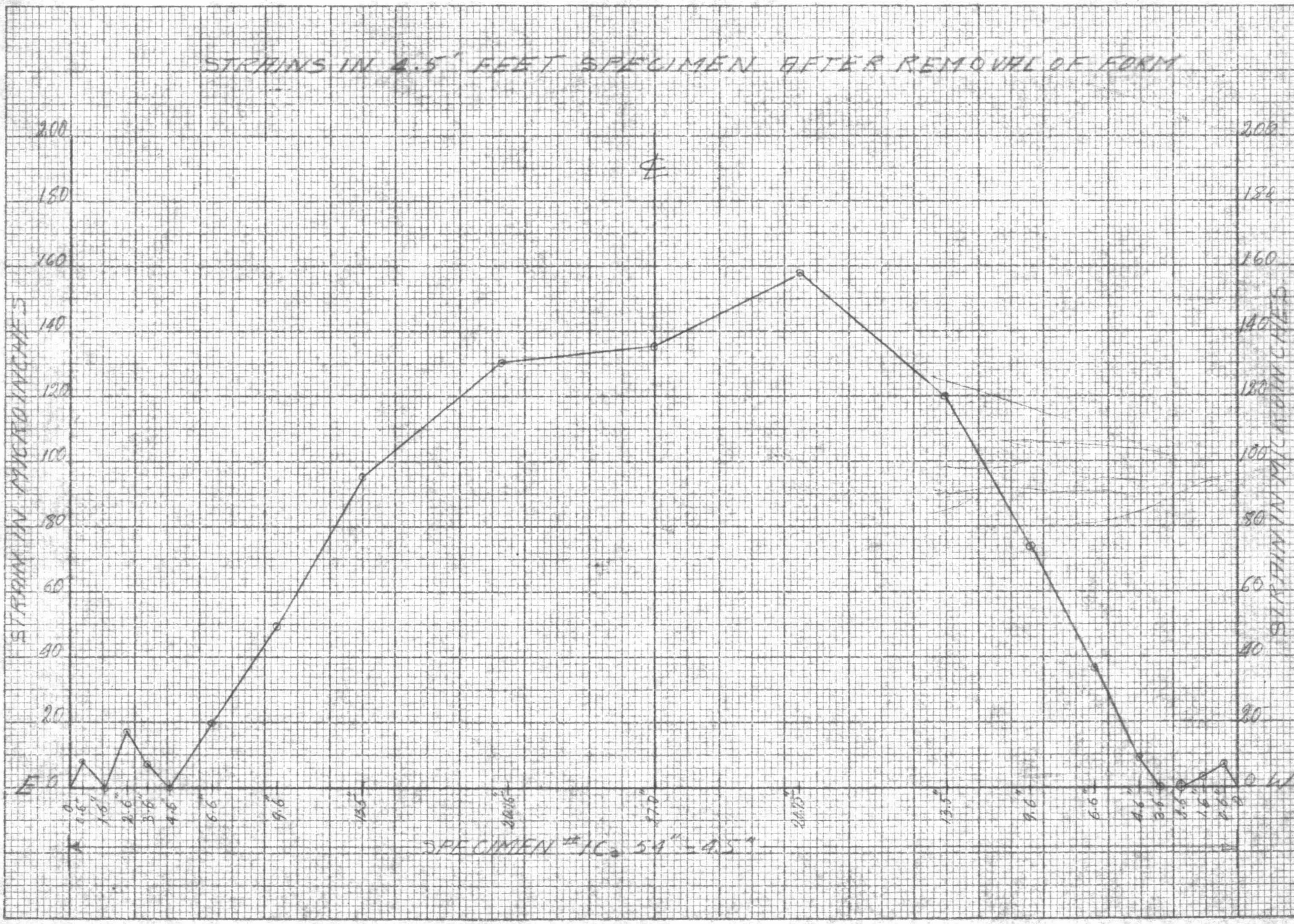
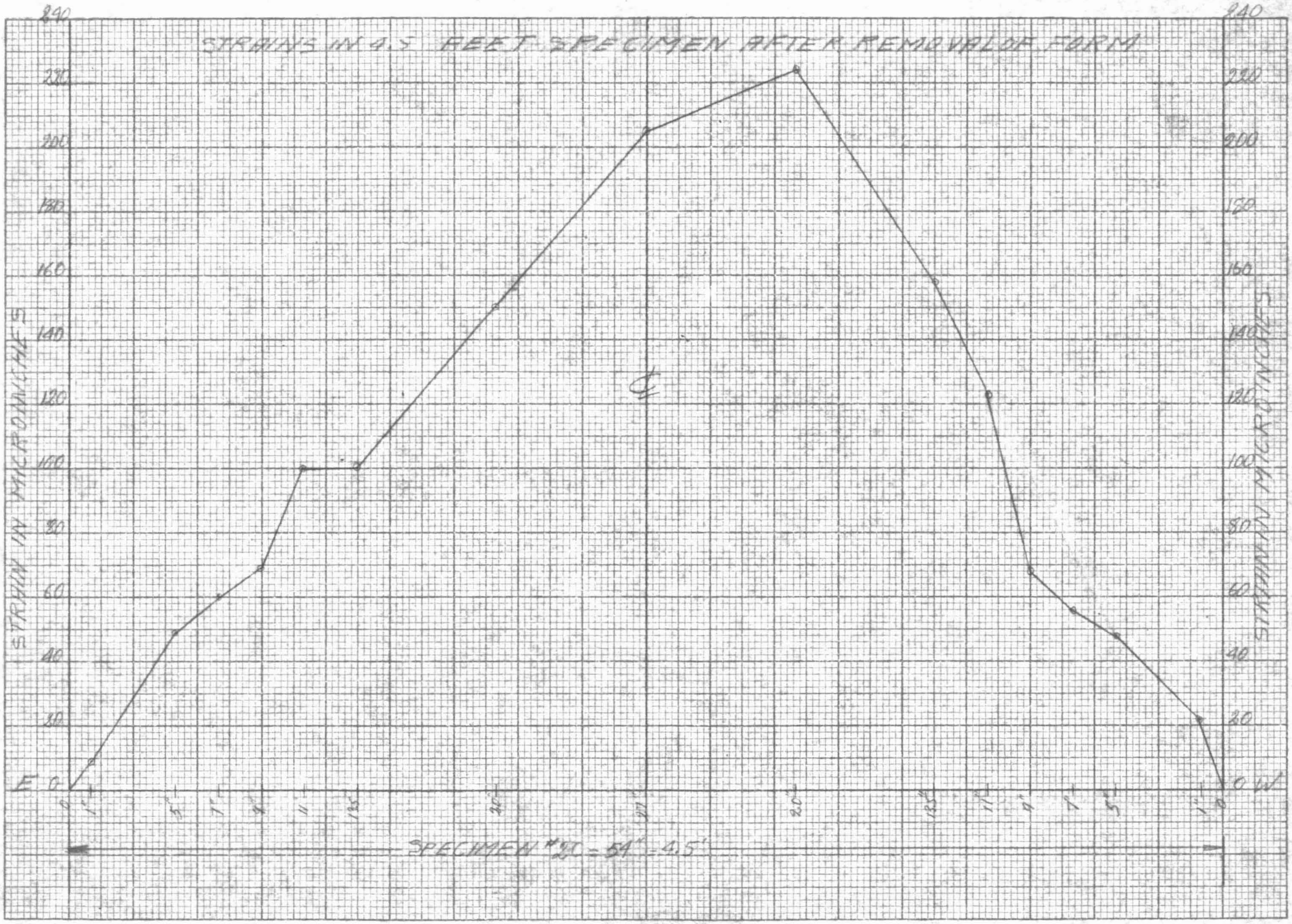

STRAINS IN 4.5' FEET SPECIMEN AFTER REMOVAL OF FORM
STRAIN IN MICROINCHES
200
180
160
140
120
100
80
60
40
20
0
E
W
℄
SPECIMEN # 1C. 54" = 4.5'

FIG. (14)



STRAINS IN 4.5 FEET SPECIMEN AFTER REMOVAL OF FORM
STRAIN IN MICROINCHES
240
220
200
180
160
140
120
100
80
60
40
20
E 0
0 W
℄
SPECIMEN #2C = 54" = 4.5'

FIG(15)

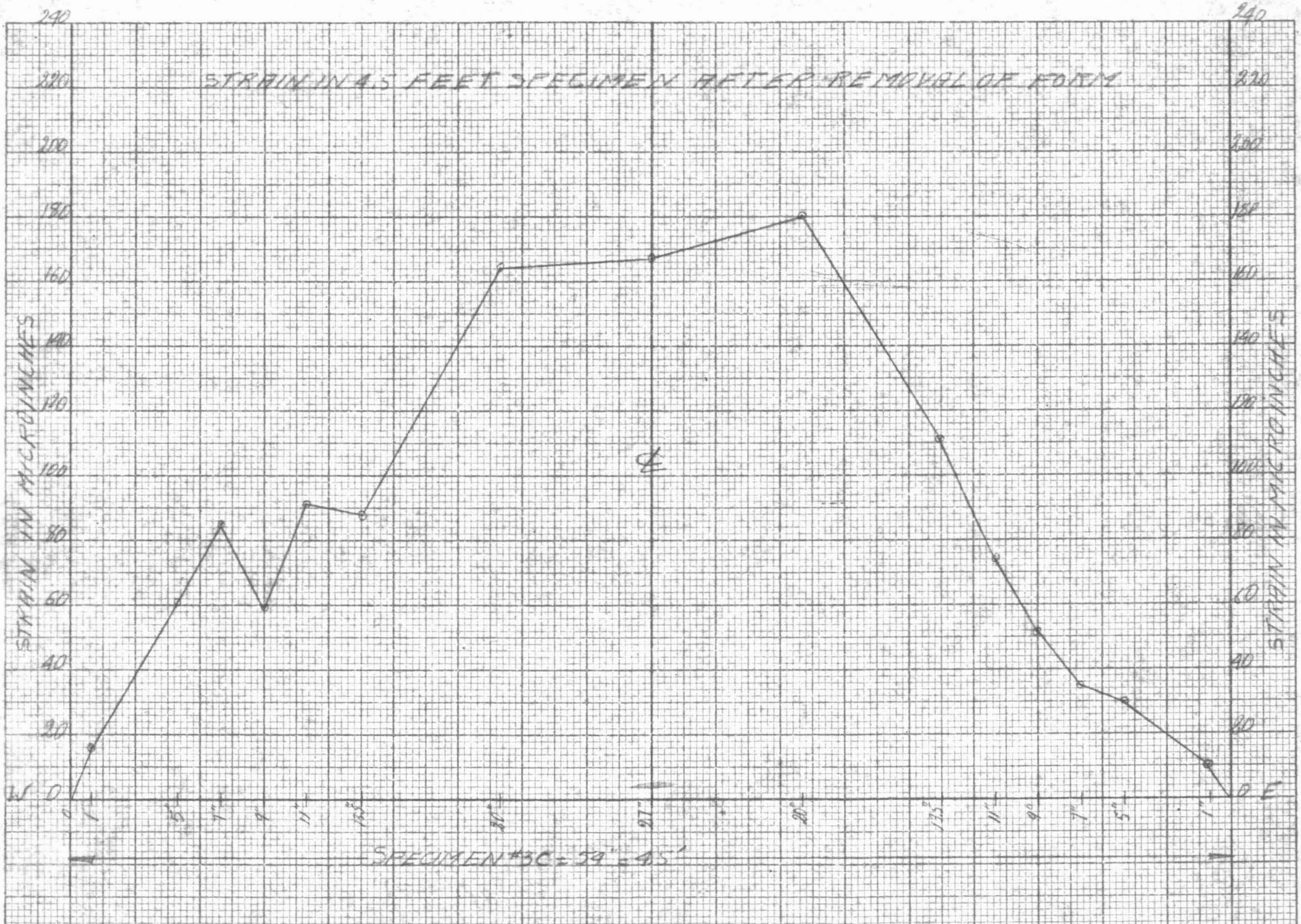

STRAIN IN 4.5 FEET SPECIMEN AFTER REMOVAL OF FORM
STRAIN IN MICROINCHES
STRAIN IN MICROINCHES
240
220
200
180
160
140
120
100
80
60
40
20
0
W
E
℄
0
1"
5"
7"
9"
11"
13.5"
20"
27"
20"
13.5"
11"
9"
7"
5"
1"
SPECIMEN #3C = 54" = 4.5'

FIG. (16)

on Figure (13). The curve for 3B shows that most of the top wires slipped while the bottom ones were partly held by bond causing expansion of the top surface of the specimen and hence the positive strains. The strains obtained for specimens No. 2C and 3C were quite satisfactory and this is shown in Figures (15) and (16).

1. Calculations: The prestress on each wire was assumed to be 135,000 psi. Each wire was elongated by 4500 micro inches/inch in order to develop this stress. Immediately after the release of the wire part of this stress was lost due to the strains developed in the concrete the calculations for which are shown below:

(a) Specimen No. 1C

Maximum strain in the specimen = 158 micro inches.

At this point the stress in the wire becomes:

$$135,000 \times \frac{4500-158}{4500} \simeq 130,000 \text{ psi.}$$

Load on each wire - 130,000 x 0.007854 = 1020 lbs. and hence unit load on concrete = 1020 psi. This unit load should have produced a maximum strain in the specimen of:

$$\epsilon = \frac{1020}{5,000,000} = 0.000204 \text{ inches/inch or 204 micro inches.}$$

The fact that this strain was not fully developed might be partly attributed to losses in prestress due to (1) plastic flow and shrinkage, (2) to the uneven section of the specimen being a little more than five inches because the side of the form was warped after welding it at the bottom, (3) the longitudinal clearance between the specimens was not enough for the stress to relax completely. While pouring, the concrete went through these clearances and caused a stress concentration, as a result of which the specimens were slightly lifted at the ends making an angle with the bottom of the form when the initial tension was released, (4) due to drift in the strain indicator.

(b) Specimen No. 2C:

Maximum strain in specimen = 224 micro inches.

Stress in wire becomes $135,000 \times \frac{4500-224}{9500} = 128,200$ psi.

Load/wire = $128,200 \times 0.007854 \approx 1000$ lbs. and unit load on concrete = 1000 psi. Maximum strain that should have been developed is:

$$\epsilon = \frac{1000}{4,750,000} = 0.00021 \text{ inches} = 210 \text{ micro inches.}$$

This is much closer to the actual value obtained = 224 micro inches.

(c) Specimen No. 3C:

Maximum strain in specimen = 180 micro inches.

Stress in wire becomes $135,000 \times \frac{4500-180}{4500} \approx 130,000$ microinches

Load/wire = $130,000 \times 0.007854 = 1020$ lbs. and unit load on concrete = 1020 psi. Maximum strain that should have been developed is:

$$\epsilon = \frac{1020}{4,750,000} = 245 \text{ micro inches.}$$

The difference between the actual value and the calculated value might be attributed to the same factors mentioned for specimen No. 1C.

As it is seen from Tables (4), (5) and (6) three sets of readings were taken for all the specimens during the two weeks following the initial readings. The recorded strains must have been erroneous, and this can definitely be attributed to the drift in the strain indicator and gages over time. This conclusion was derived from the fact that while the one-foot specimens showed negligible strains in the first readings the indicated strains changed tremendously in the later readings. This strain change was not constant for all gages observed. Tables (4), (5), and (6) show that the readings on July 3, 7, and 14 , 1952 are completely unreliable. These results proved that the gages used will not give good results except immediately after taking the zero readings.

CONCLUSIONS

The time allotted for this work was very limited, and hence many sources of erros which were mentioned previously and which will be mentioned again could have been avoided.

For similar future work the following should be considered:

(1) The jacking frame should be separate from the pouring forms.

(2) Before the release of the prestress, and in order to provide complete freedom for the specimens to move the sides and bottom of the pouring forms should be removed and some bearing rollers set between the bottom of the specimens and the floor.

(3) The tar paper which was used as an inner lining of the forms should be avoided and oiling the forms from the inside substituted therefore.

(4) The longitudinal clearance between specimens should be at least two inches.

(5) The jacking of the wires should be from one side of the jacking frame only to eliminate cross-strains in the specimens.

(6) Some good method for mechanical vibrations should be provided.

It was concluded from the results of the tests that a length of at least 30 inches from each end of any member is necessary to transfer the prestress from the 0.10" wire to the concrete by bond. Any length which is less than this is not advisable.

The method of pouring the concrete affects this length substantially. On large construction projects it is very difficult to achieve high quality concrete at all times as is possible in controlled laboratory research. Hence a length greater than 30 inches from each end might be desirable from the viewpoint of sufficient factor of safety.

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