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EFFECT OF CONCRETE SHRINKAGE ON STRESSES IN REINFORCING STEEL

BY

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A

THESIS

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Department **Chairman**

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Major Professor

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The author wishes to express his appreciation to Professor E. W. Carlton, Chairman of the Department of Civil Engineering, who suggested the thesis topic, and to Professor John L. Best, for their encouragement and guidance through the conduct of this investigation.

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INTRODUCTION

Shrinkage is one of four phenomena that are considered as causing volume changes in concrete, the other three being creep, temperature change effects, and possible chemical disintegration. While all four are interrelated, the volume change due to loss of moisture is associated with the term shrinkage. Creep is the time-dependent change in volume resulting from external loads. A rise or fall of temperature will produce an expansion or contraction of concrete but also will affect the rate of shrinkage by increasing or decreasing the rate of moisture evaporation from the surface of the concrete.

In the design of concrete structures, the usual concern with shrinkage is to prevent its magnitude from becoming excessive. Excessive shrinkage would produce cracks of sufficient size to destroy the appearance of the concrete or permit the entrance of water. Control of the amount of shrinkage can be exercised by proper choice of materials, proportioning, and curing. Theoretically, one might eliminate all shrinkage but the requirements for so doing would not be practical. Shrinkage does have a valuable aspect in the case of reinforced concrete in that it causes the concrete to grip the steel tightly thus reducing the possibility of bar slippage.

The size of cracks formed by shrinkage of concrete can be reduced by the use of shrinkage reinforcement. The amount of reinforcement used is not sufficient to greatly reduce the total amount of shrinkage but results in the formation of numerous small cracks rather than a few large ones.

The action of reinforcing steel in resisting the decrease in volume of concrete places the steel in compression. This pre-compression could be useful in the case of tensile steel as the stress in a bar would be that resulting from the dead load and live load minus the stress from shrinkage of the concrete.

Standard concrete design makes no allowance for this pre-compression and assumes that the bars start with zero load. If there does exist a pre-compression of a determinable and consistent amount, the present method of design requires an excess amount of tensile steel.

It is the purpose of this study to see if shrinkage does give a compression stress in the steel of sufficient magnitude to warrant a reduction in the tensile steel requirements of reinforced concrete beams.

A REVIEW OF THE LITERATURE

Experiments on the behaviour of reinforced concrete have been carried on ever since its first use as a structural material more than eighty years ago. For in 1877 Thaddeus Hyatt wrote a book giving "An Account of Some Experiments with Portland Cement Combined with Iron".(1)

The earliest recorded experiments on the effect of reinforcing steel on shrinkage seems to be those conducted by E. Considere in 1899 and by O. Graf and C. Bach in 1909. Both found shrinkage of reinforced mortar and concrete to be about one-third to one-fourth the amount found in similar material without reinforcing.(2)

In 1915 Mr. F. R. McMillan tested three beams identical except for the manner of curing. The results showed little variation in the total shrinkage though there was a fifty percent variation in the compressive strength. Other conclusions were that one-half to two-thirds of the total shrinkage could be expected within forty to sixty days after exposure to dry air, and that moisture content of the air has a decided effect upon the rate of shrinkage.(3)

In 1921 the University of Illinois published results of experiments on the effect of moisture content on concrete that had been performed in 1918. These results pointed to 1.5 percent of reinforcement as a critical

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(1) Hatt, W. K., Researches in Concrete, Bulletin No. 24 Engineering Experiment Station, Purdue University, 1925, p. 8.

(2) Davis, Raymond E., A Summary of the Results of Investigations Having to do with Volumetric Changes in Cements, Mortars and Concretes, Due to Causes Other Than Stress, Proceedings of the American Concrete Institute, Vol. 26, 1930, pp. 431, 432.

(3) McMillan, Franklin R., Shrinkage and Time Effects in Reinforced Concrete, Studies in Engineering, Number 3, University of Minnesota, March 1913, pp. 29, 30.

value. If less than 1.5 percent is used, shrinkage stresses in the steel may reach the usual working stress of steel; if more than 1.5 percent is used, shrinkage stresses in the concrete may reach the ultimate tensile strength of the concrete.(4)

Mr. C. P. Vetter investigated shrinkage and temperature stresses in a continuous reinforced concrete structure and found that a ratio of reinforcement of from 0.60 to 0.75 percent was required to prevent unsightly cracks.(5)

In the discussion of the above article by Mr. Vetter, Professor A. H. Beyer and Mr. A. G. Solakian reported on their determination of shrinkage stresses by photo-elastic methods using a bakelite beam reinforced with an aluminum rod at its geometric axis. Bakelite reinforced with aluminum has about the same relative physical properties as concrete reinforced with steel. The tensile stresses in the bakelite and the compressive stresses in the aluminum were practically constant for the center two-thirds of the beam. Bond stresses were highest at the ends and gradually reduced to zero at about the quarter points. Results were qualitatively comparable to those obtained by Mr. Vetter.(6)

In 1938 Professor Roy W. Carlson reported on a long-range program aimed at giving a better understanding of concrete shrinkage. A large

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(4) Matsumoto, T., A Study of the Effect of Moisture Content Upon the Expansion and Contraction of Plain and Reinforced Concrete, Bulletin 126, University of Illinois Experiment Station, 1921, p. 28.

(5) Vetter, C. P., Stresses in Reinforced Concrete Due to Volume Changes Transactions of the American Society of Civil Engineers, Volume 98, 1933, p. 1051.

(6) Beyer, A. H. and Solakian, A. G., Discussion of Stresses in Reinforced Concrete Due to Volume Changes by C. P. Vetter, Transactions of the American Society of Civil Engineers, Volume 98, 1933, pp. 1064-1070.

number of tests were conducted trying various combinations of materials and methods to determine which factors had an effect on shrinkage. Variation in the amount of mixing water was found to have the greatest effect. Each one percent of added mixing water caused an increase of almost two percent in the shrinkage. Size of aggregate, except in that it would change the water requirement, had little or no effect on shrinkage. Neither was shrinkage affected consistently by deviation of the curing time. An appreciable reduction in shrinkage was obtained by adding one-half percent (by weight of cement) of commercial ground mica of 60-mesh size.(7)

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(7) Carlson, Roy W., Drying Shrinkage of Concrete as Affected by Many Factors, Proceedings American Society of Testing Materials, Volume 38, 1938, pp. 436-437.

In all of the previously reported experiments, measurements of steel stress in reinforced concrete were made by mechanical gages of rather long gage length which gave average rather than localized peak stresses. With the perfection of the bonded wire resistance strain gage (known commonly as the SR-4 electric strain gage) in 1938 a new technique was made available as the gage could be attached directly to the bar. A wide variety of gage sizes are manufactured. Thus by use of a short gage length strains at a point could be measured. After the development of mass production methods reduced the cost of the gages, their popularity grew rapidly. From that time on nearly all investigations of strains in reinforcing steel made use of the SR-4 gage. Usage of the gage, however, presented the problem of proper attachment to the bars and of protection from moisture and pressure.

Professor R. H. Sherlock and Mr. Adil Belgin used a shield made of plexiglass tubing to protect SR-4 gages placed on reinforcing bars.(8)

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(8) Sherlock, R. H. and Belgin, A., Protection of Electric Strain Gages in Concrete, Proceedings, ACI, Vol. 44, 1947, p. 190.

This method gave protection against pressure as well as moisture but would seem to be difficult and costly. In a test of three beams, strain readings during a 7-day curing period on one of the beams showed a sharp elongation the first day, almost zero change the second and third days, and then continued elongation until the end of the curing period. The other two beams behaved differently showing a small amount of shortening the first two days and then elongation at about the same rate as the first beam. The beams had no external loads applied during the curing period.(9)

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(9) Sherlock, R. H. and Belgin, A., Authors' Closure of Protection of Electric Strain Gages in Concrete, Proceedings, ACI, Vol. 44, 1947, p. 192-3.

A much simpler method of water-proofing a strain gage on a reinforcing bar is to apply several layers of quick-drying rubber cement over the gage and on the steel surface surrounding the gage. Very little of the bond area is destroyed by this method.(10)

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(10) McHenry, D. and Walker, W. T., Laboratory Measurements of Stress Distribution in Reinforcing Steel, Proceedings, ACI, Vol. 44, 1948, p. 1042.

In order to preserve all of the bond area, Mr. R. M. Mains sawed the bar into two unequal parts by a longitudinal cut. A channel was cut into the larger part for the gages and wires. After waterproofing, the bar was held together by tack welds at 2-inch centers.(11)

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(11) Mains, R. M., Measurements of the Distribution of Tensile and Bond Stresses Along Reinforcing Bars, Proceedings, ACI, Vol. 48, 1952, p. 228.

Mr. Frank R. Beyer measured the strain in reinforcing steel due to volume changes with SR-4 bakelite gages protected by a 3/16" layer of Petrosene wax. In one of the tests a 1-inch round rod was centrally located in a 7 x 7 beam with relatively watertight forms. The concrete was poured with the specimen vertical and a glass plate was used to cover the open end. For the first eighteen hours after pouring the bars were in compression with a peak of 1200 psi at 10 hours. A maximum tension of 1400 psi was reached after 50 hours. After four days the bar was in compression and reached a value of 7500 psi after 85 days. He concluded that since these stresses are of appreciable magnitude, some consideration of these stresses in design seems advisable.(12)

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(12) Beyer, Frank R., Stresses in Reinforced Concrete Due to Volume Changes, Proceedings, ACI, Vol. 45, 1949, pp. 718-721.

MATERIALS

Concrete: The concrete was proportioned by weight to give a 28-day strength of 4000 psi. The mix was as follows:

Item	Parts by Volume
Cement	1
Fine Aggregate	3.05
Coarse Aggregate	2.59
Water (gals./sack)	5.5

The cement used was Portland Cement type I.

The sand had a specific gravity of about 2.54.

The coarse aggregate was crushed limestone with a maximum size of 3/4 inch and a specific gravity of about 2.67. It was screened and then combined in the following proportions:

Sieve Size	Percent Retained
3/4	0
1/2	10
3/8	40
#4	45
#8	5
Total	100

A one cubic foot drum mixer was used. The dry materials were placed in the mixer and mixed dry for about one minute. The mixing water was added and mixing continued for two minutes. The mixer was emptied into a large pan and then a small scoop was used to place the concrete into the form. A blunt-nosed rod was used to consolidate the concrete. Three batches were required for each beam. A slump test was taken of each batch averaging about four inches for the first three beams and about seven inches for the fourth beam. Curing was effected by means of wet burlap and was continued for three days for the first beam, four days for the second, and six days for the third and fourth beams.

A standard 6" x 12" test cylinder was taken for each batch. These were cured in the same manner as the beams and tested at 28 days.

The beams were poured and cured in the basement of Harris Hall near the middle of the west wall. All measurements were taken in the same location.

Forms: The forms for the beams were of box construction of 3/4" plywood. The bottom was grooved to receive the sides which were bolted in place to prevent any sagging. Two cross-pieces were used at the top to prevent any outward movement of the sides. Before being used the forms received several coatings of oil. The sizes of beams poured were 6" x 6" and 8" x 8". One form of each size was made.

Steel: Four types of reinforcing bars were used. Beam 1 contained a #3 bar, semi-deformed with 0.017-inch deformations spaced at 0.34 inches. The #3 bar in beam 2 had helical rib deformations 0.023 inches in height and spaced at 0.22 inches. A #5 bar was used in beam 3 and had an x-pattern deformation. The x's were end to end and 0.53 inches long. Height of the deformation was 0.026 inches. A standard deformed #6 bar with transverse lugs 0.044 inches high and spaced at 0.45 inches was used in beam 4. All of the bars were several inches longer than the beam in which they were used and were supported at each end by a hole drilled in the end piece of each form. The #3 bars required a wire chair at the midpoint to maintain its position in the center of the beam. The heavier bars used in the shorter beams 3 and 4 did not require intermediate support. The steel percentages were 0.28 for Beams 1 and 2, 0.48 for Beam 3 and 0.69 for Beam 4.

STRAIN GAGES

Type: A wide variety of SR-4 strain gages is available to meet almost any possible research condition. In the selection of the gages for this experiment, a major requirement was that the gages be small since bar sizes down to #3 would be used. Thus the A-7 gage with a 1/4" gage length and overall dimensions of 7/8 x 11/32 inch was selected. The A-7 is a "wrap-around" paper gage in which the sensitive elements are made of a continuous length of wire wrapped in a tight helix pattern around a thin, flat core paper. This sensitive element is then sandwiched between two cover papers for protection and insulation purposes. Two shipments of gages were used. The first shipment had a resistance in ohms of 120.5 ± 0.3 and a gage factor of 1.99 ± 2%. The second shipment had a resistance in ohms of 120 ± 0.3 and a gage factor of 1.97 ± 2%.

Installation: To present a smooth surface for application of the gage, deformations were removed from the reinforcing bars by grinding and filling. Size 000 sandpaper was used for final finishing. Then the surface was cleaned with a cloth moistened with SR-4 solvent.

A layer of SR-4 cement was applied to the bar and then the gage was immediately placed in position. A thin piece of plastic was wrapped around the bar which held the gage in place while the clamping force was applied. The clamping force was a suspended 1-pound weight applied by means of a heavy piece of plastic through a quarter-inch pad of sponge rubber. The sponge rubber served to distribute the load evenly over the gage surface. After about ten minutes the clamping force was removed. While excess cement coated the top of the gage and adjacent areas, it showed little affinity to the thin plastic. Thus the plastic cover was easily removed without shifting the gage. About 3/4" square pieces of paper were cemented to the bar adjacent to the gage and under the lead wires to prevent the bare wires from contacting the bar.

Gages on the first three beams were left to air dry for at least 48 hours in a steam heated room. Humidity was low and temperature average was at least 80° F. When gages for the fourth beam were installed, the season no longer required the building to be heated. About two and one-half days were allowed before waterproofing the gages and heat was applied to the gages for about six hours.

Plastic covered lead wires were securely tied to the bar and then soldered to the gage wires. Loops were placed in the lead wires to diminish the possibility of tension on the wires affecting the gages.

Waterproofing: Since the gages were to be cast in concrete, it was necessary to use a protective coating to prevent any moisture from reaching the gages. About a quarter inch thick coating of Petrosene-A wax was used for this purpose. The bar was heated to the melting point of the wax--about 175°F--and then the wax was applied in thin layers by means of a small paint brush. To prevent any physical damage to the wax, it was wrapped with several layers of rubber tape or splicing compound. Rubber tape was used in Beams 1 and 2, Pittsburg splicing compound manufactured by Westinghouse Electric was used in Beams 3 and 4.

TESTING PROCEDURE

To measure the change in resistance of the strain gages an SR-4 strain indicator, consisting of a battery-powered Wheatstone bridge balancing unit, was used. This unit is manufactured by the Baldwin-Lima-Hamilton Corporation of Eddystone, Pennsylvania. The dial of the indicator is graduated to read the change in resistance as microinches per inch of strain.

Initial readings were taken shortly after each beam was poured. These served as zero points for any particular gage. Thus the difference between the initial reading and any subsequent reading would give the strain in microinches per inch that had occurred during that time provided there were no effects of temperature or zero drift.

A change in temperature will change the length of the gage wires and thus their resistance. To remove the effects of temperature, a second gage, besides the one measuring the strain being recorded, must be connected to the strain indicator. This is known as compensating gage. The compensating gage can be a "dummy" gage, i.e., unstressed, or it can also be measuring strain. Both types were used in this experiment.

The dummy gage consisted of an A-7 gage placed on a short length of #3 bar. It was covered with Petrosene wax and then stored near the beams so that it would have approximately the same temperature as the gages in the beams. As long as the temperature of the active gage and dummy gage were the same, any change in their temperature would not cause any change in the strain readings. To minimize temperature differences, the dummy gage was stored in a container of coarse aggregate near the beams. Thus it would not be affected by a change in room temperature as rapidly as an exposed gage. Frequent temperature checks of the aggregate and the inside of the beams indicated a maximum variation of one to two degrees Fahrenheit.

For ideal temperature compensation, the compensating gage should be placed on the same material near the active gage. Thus both gages will be subjected to the same temperature variations. In the case of material undergoing pure tension or compression, this can be accomplished only by a "Poisson" arrangement of the gages. The active gage is placed longitudinally with respect to the bar and the compensating, or "Poisson" gage, is placed perpendicular to it. Under this arrangement the compensating gage will be subject to a strain due to the Poisson effect and the strain indicator reading will be greater by the amount of Poisson's ratio than if a dummy gage had been used for temperature compensation.

To keep usage of the batteries to a minimum, the dial was always set to approximately the correct reading before switching on the strain indicator. The bridge was balanced quickly and immediately the set was turned off. This procedure is advisable as discharge of the batteries is the principal cause of zero drift. A check on the magnitude of zero drift in the instrument can be made by taking two readings of a pair of gages, one with the active and dummy gages in their normal positions on the indicator and one with their positions reversed. This would reverse the apparent sign of the strain when read from the indicator dial. A plot of these readings would be symmetrical about the initial zero-strain reference point if there had been no drift in the instrument. This method was followed with a pair of gages in Beam 2 and in Beam 3. These readings are tabulated in the data sheets and show only small variations. This indicates that zero drift of the instrument was not significant.

Strain Readings: Initial readings were taken within thirty minutes after the beams were poured, except for Beam 1 when the first reading was taken about two hours after pouring. Readings were taken frequently the day of the pour, several times a day for the next few days, at least daily up until thirty days, and then about once a week. Since the location of the gages and the readings taken varied with each beam, an individual description of each will be given.

To identify the gages, a three part serial number is used. Part one is the number of the beam. Part two is either the letter L or P. L indicates a longitudinal gage; P indicates a Poisson gage, that is, one placed perpendicular to the length of the bar. The last part indicates the set number in which the gage is located. A set consists of a single longitudinal gage or a longitudinal gage and a Poisson gage. Sets were numbered from one on each beam. Thus on Beam 2 the serial number of the Poisson gage in set one is 2-P-1. Since only one dummy gage was used, it will be referred to by that name.

In Beam 1 three gages were placed longitudinally on the #3 bar, one at the center line and one about twenty-four inches each side of the center line. A reading was taken of each gage with the dummy gage as a compensator.

In Beam 2 a longitudinal gage and a Poisson gage were placed about twelve inches on one side of the center line. Another longitudinal gage was placed about twelve inches on the other side of the center line but it failed to function properly and no readings could be taken with it. Four sets of strain readings were taken:

Active Gage	Compensator Gage
2-L-1	2-P-1
2-L-1	Dummy
2-P-1	Dummy
Dummy	2-P-1

In Beam 3 a longitudinal and a Poisson gage was placed about 6" on each side of the center line. Readings taken were:

Active Gage	Compensator Gage
3-L-1	3-P-1
3-L-1	Dummy
3-P-1	Dummy
Dummy	3-P-1
3-L-2	3-P-2
3-L-2	Dummy
3-P-2	Dummy

In Beam 4 the same gage arrangement was used as on Beam 3; that is, a longitudinal and a Poisson gage six inches each side of the center. Initially only two sets of readings were taken consisting of each longitudinal gage with its adjacent Poisson gage. However, after several weeks it was noticed that the strains were far from agreeing so on the twenty-first day four additional sets of readings were started using the dummy gage as compensator with longitudinal and Poisson gages as the active gage. Shortly after the forty-fourth day it was noted that a part of one of the lead wires in set one had been broken or cut off. As this would have an effect on the strain readings, no additional readings were taken.

Active Gage	Compensator Gage
4-L-1	4-P-1
4-L-2	4-P-2

After the twenty-first day the following readings were added:

4-L-1	Dummy
4-L-2	Dummy
4-P-1	Dummy
4-P-2	Dummy

Other Measurements: Two brass gage plugs were cast into Beam 2 so that changes in length of the beam could be checked mechanically. The length change gage was a 50-inch invar steel, self compensating gage, designed by Mr. Bengt F. Fribert, Consulting Engineering of St. Louis, Missouri, and made by Mr. A. V. Kilpatrick of the Missouri School of Mines.(13) Measurements of length could be read to the one-thousandth of an inch and interpolated to the one ten-thousandth. The initial reading was taken six hours after pouring and all changes in length were based on the length at that time. Four readings were taken each time and the average value was used.

Temperature and relative humidity were determined frequently though not as often as strain readings were made. A sling psychrometer was used to determine relative humidity. Room temperature was measured by placing the sling psychrometer on the surface of one of the beams and reading the dry bulb thermometer. A Weston dial type thermometer ranging from 50° F. to 300° F. was placed in a temperature well at one end of each beam to determine the beam temperature. Temperature of the coarse aggregate that surrounded the dummy gage was also checked but was found to agree closely with the beam temperature. Variations in temperature and in relative humidity are shown in Figures 16 and 17 respectively. Also, values taken at the time of strain readings for Beam 2 are shown in Table 3.

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(13) Best, John L., Length Changes in Prestressed Concrete Slabs with Outside Exposure. Thesis, Mo. School of Mines, Rolla, Missouri, p. 27.

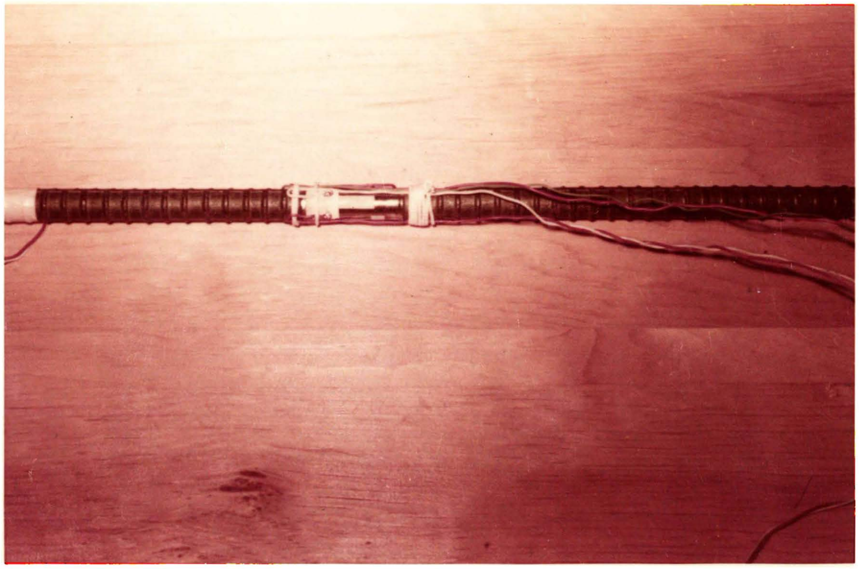

FIGURE 1

STRAIN GAGES ON #6 BAR OF BEAM 4

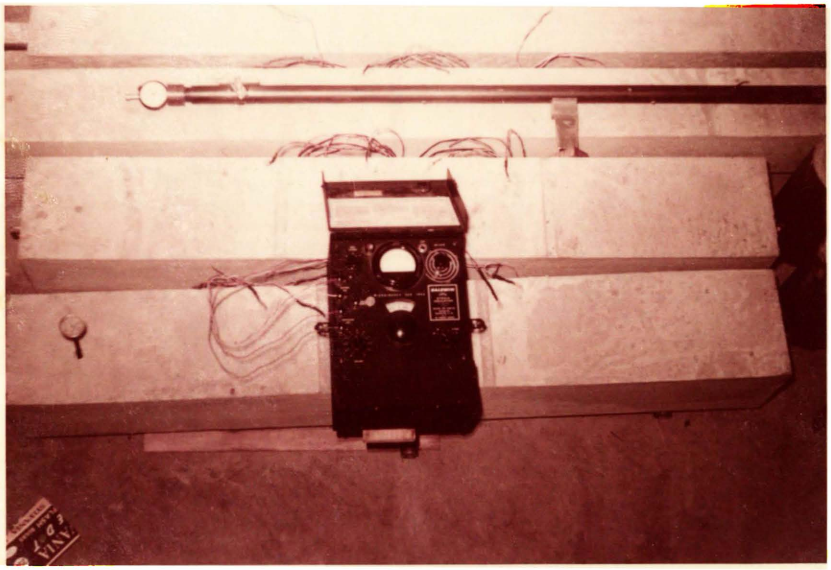

FIGURE 2

VIEW OF BEAMS WITH 50" LENGTH GAGE AND STRAIN INDICATOR

FIGURES 3 THROUGH 6

DRAWINGS OF BEAMS

EXPLANATION OF FIGURES 3 THROUGH 6

The drawings give the overall dimensions, location of the gages, serial numbers of the gages, bar size, and length along the bar required by the Petrosene-A wax used for waterproofing. The drawings are not to any scale.

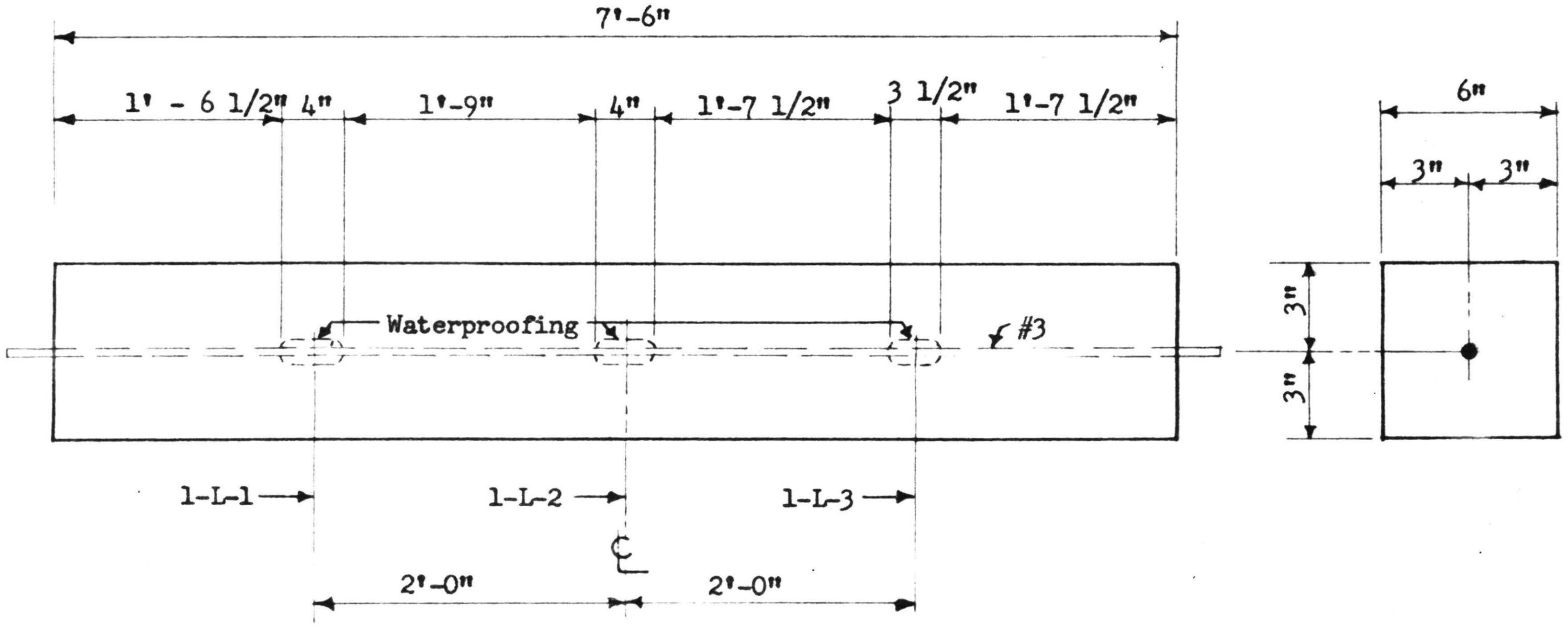

Figure 3

Beam #1

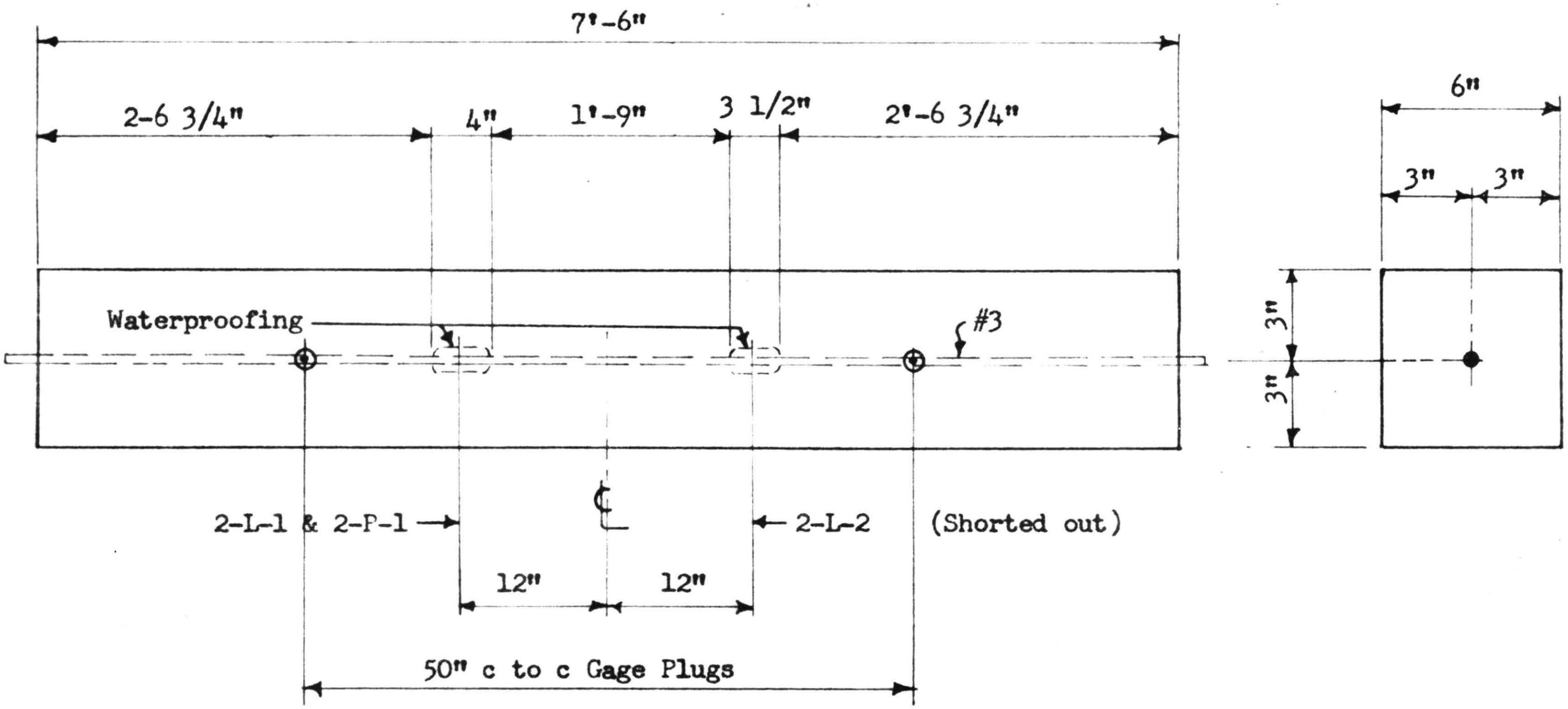

Figure 4

Beam #2

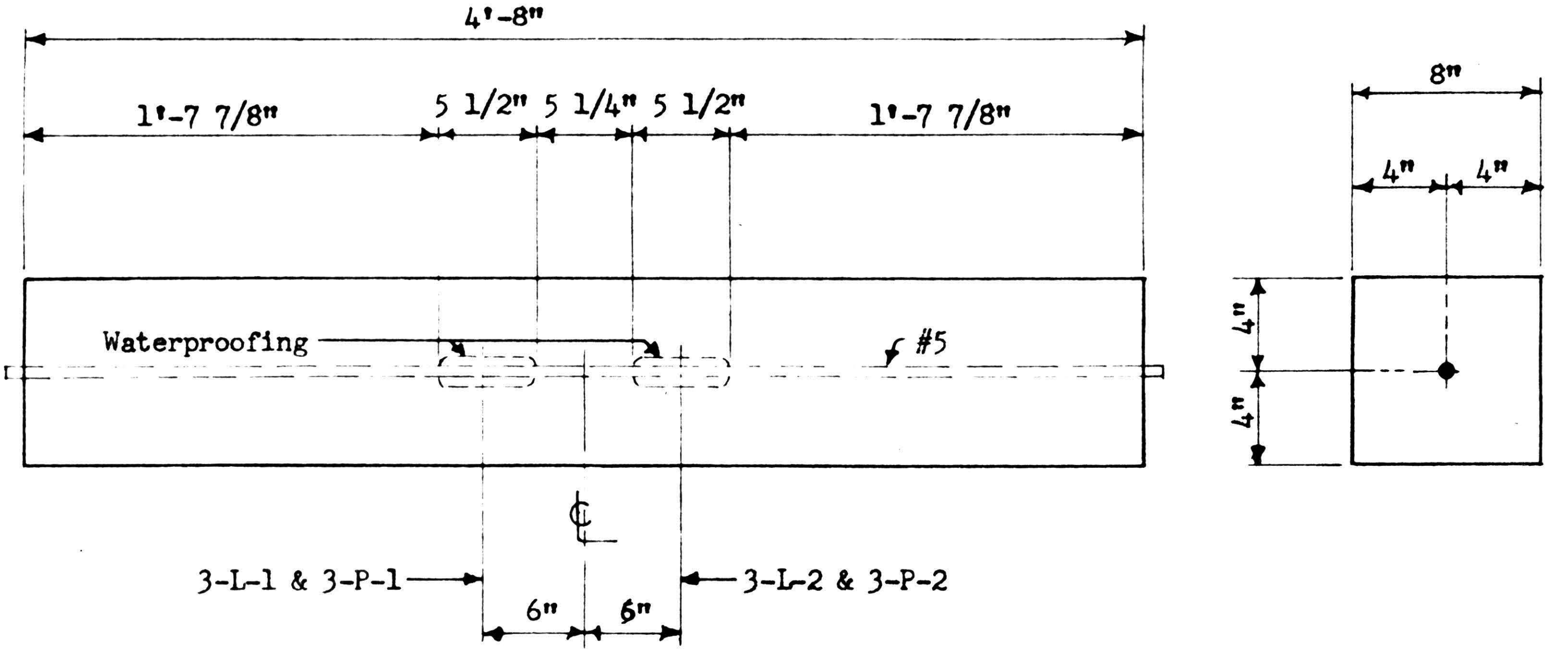

Figure 5

Beam #3

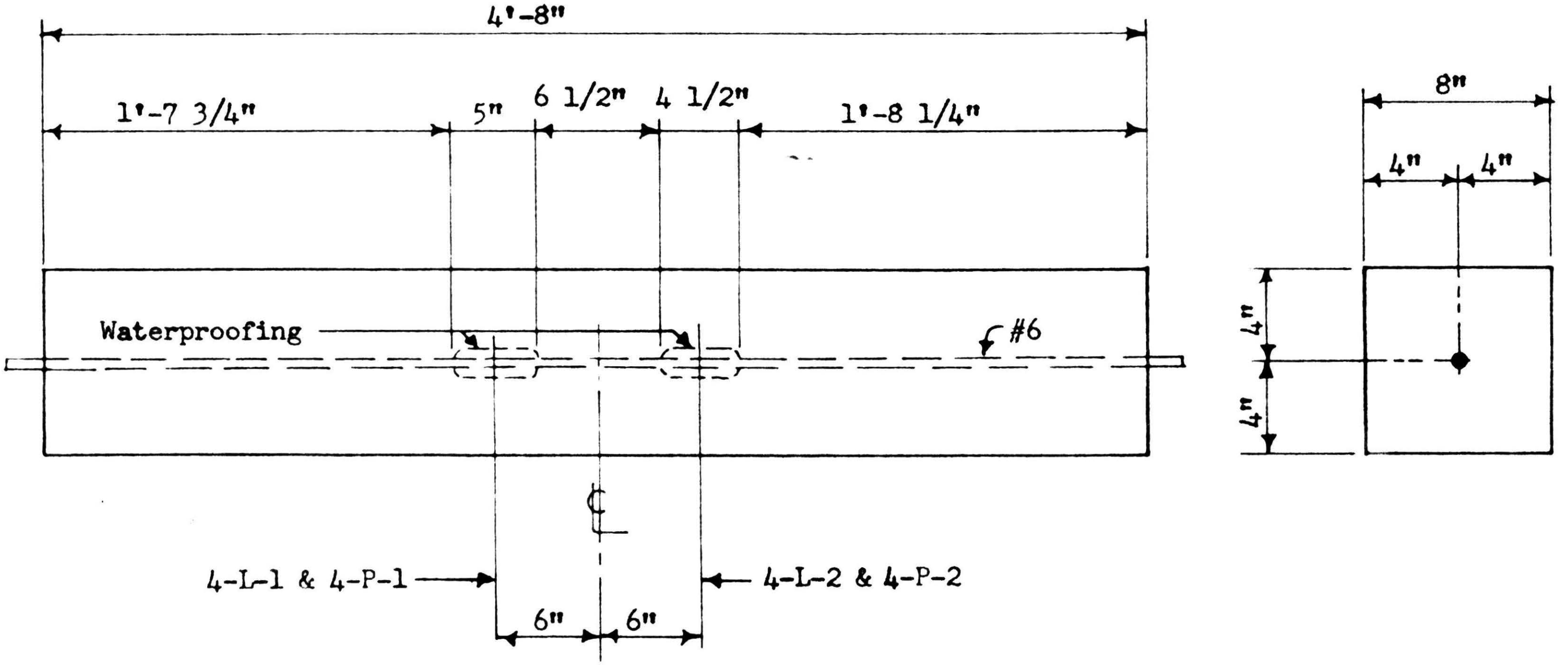

Figure 6

Beam #4

TABLE 1 - GENERAL DATA

Beam Number	1	2	3	4
Date Poured	3-1-58	3-22-58	4-12-58	5-10-58
Length	7'-6"	7'-6"	4'-8"	4'-8"
Dimensions	6" x 6"	6" x 6"	8" x 8"	8" x 8"
Cross Sectional Area	36 sq.in.	36 sq.in.	64 sq.in.	64 sq.in.
Bar Size	#3	#3	#5	#6
Bar Area-Nominal	0.11 sq. in.	0.11 sq. in.	0.31 sq. in.	0.44 sq. in.
Steel Percentage	0.28	0.28	0.48	0.69
Ave. Bar Diameter at Gages	0.368"	0.362"	0.590"	0.731"
Ave. Bar Area at Gages	0.106 sq. in.	0.103 sq. in.	0.27 sq. in.	0.42 sq. in.
Height of Deformations	0.017"	0.023"	0.026"	0.044"
Spacing of Deformations	0.34"	0.22"	0.53"	0.45"
Ave. Concrete Slump	4"	4"	4"	7"
Ave. 28 Day Strength	4350 psi	4880 psi	4650 psi	4450 psi
Curing Time, Days	3	4	6	6
Days Side Forms in place	9	11	10	10
Days on Bottom Form	19	16	12	19

TABLES 2 THROUGH 5

STRAIN DATA

EXPLANATION OF TABLES 2 THROUGH 5

Tables 2 through 5 consist of the strain data obtained from the gages attached to the reinforcing bars. Table 3 also includes the readings of the 50-inch length gage on Beam 2 as well as room temperature, beam temperature, and relative humidity, since these values were pertinent to the surface length changes.

All strain values were referenced to the unloaded condition of the gage except for values on Page 40 of Table 5 which were referenced to the condition that exists on the twenty-first day after pouring. All time intervals were referenced to immediately after pouring the beam.

Plus signs (+) indicate tension and minus signs (-) indicate compression for the strain.

TABLE 2 - STRAIN DATA - BEAM 1

Active Gage		1-L-1	1-L-2	1-L-3
Compensator Gage		Dummy	Dummy	Dummy
Elapsed Time		Strain	Strain	Strain
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in
0	2	0	0	0
	3	+10	+10	+10
	4	0	0	0
	5	0	+10	+10
	6	0	+20	+15
	7	+10	+20	+20
	8	+10	+25	+25
	9	+10	+30	+35
	19	+55	+80	+60
	23	+65	+90	+70
1	0	+80	+95	+70
	1	+85	+100	+85
	2	+85	+100	+85
	3	+85	+105	+85
	4	+85	+110	+90
	5	+90	+110	+90
	6	+90	+115	+95
	20	+115	+140	+120
	22	+120	+145	+130
2	0	+130	+150	+140
	2	+130	+150	+140
	4	+130	+150	+140
	6	+140	+145	+140
	20	+140	+160	+155
	22	+140	+120	+160
3	2	+160	+170	+165
	4	+170	+180	+170
	7	+160	+170	+160
	9	+160	+160	+150
	20	+155	+155	+140
4	22	+135	+110	+120
5	5	+120	+110	+110
	20	+120	+110	+110
6	4	+120	+115	+110
	20	+115	+105	+100
7	5	+115	+105	+100
8	0	+110	+100	+95
	5	+110	+100	+95

TABLE 2 - STRAIN DATA - BEAM 1

Active Gage		1-L-1	1-L-2	1-L-3
Compensator Gage		Dummy	Dummy	Dummy
Elapsed Time		Strain	Strain	Strain
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in
9		+105	+95	+85
10		+110	+95	+80
11		+100	+85	+75
12		+90	+80	+65
13		+80	+70	+60
14		+80	+70	+55
15		+75	+60	+50
16		+70	+50	+40
17		+60	+50	+35
18		+55	+40	+30
19		+55	+40	+25
20		+50	+35	+20
21		+50	+30	+15
22		+55	+35	+15
23		+45	+25	+10
24		+40	+25	+5
25		+30	+15	0
26		+30	+10	-5
27		+30	+5	-10
28		+25	0	-20
29		+25	-5	-20
30		+20	-10	-25
31		+20	-15	-30
32		+15	-20	-35
33		+20	-20	-40
34		+20	-20	-40
35		+10	-30	-40
36		+10	-20	-50
37		+10	-15	-55
38		+15	-10	-50
39		+15	-10	-55
40		+25	-10	-55
41		+30	0	-55
42		+25	+5	-55
49		+60	+45	-60
56		+95	+70	-15
63		+45	+115	-50

TABLE 2 - STRAIN DATA - BEAM 1

Active Gage		1-L-1	1-L-2	1-L-3
Compensator Gage		Dummy	Dummy	Dummy
Elapsed Time		Strain	Strain	Strain
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in
71		+160	+135	-50
85		+190	+160	-55
92		+200	+170	-50
100		+240	+170	-30
110		+250	+220	-30
115		+235	+245	-35

TABLE 3 - STRAIN DATA - BEAM 2

Active Gage		2-L-1	2-L-1	2-P-1	Dummy	50" Gage	Room Temp.	Beam Temp.	Relative Humidity
Compensator Gage		2-P-1	Dummy	Dummy	2-P-1	Reading			
Elapsed Time		Strain $\times 10^6$ in/in	Strain $\times 10^6$ in/in	Strain $\times 10^6$ in/in	Strain $\times 10^6$ in/in	$\times 10^3$ in.	°F	°F	%
Days	Hours								
0	0	0	0	0	0	0			
	1	+5	-5	0	0				
	2	+15	0	-5	+5				
	3	+30	+15	-10	0				
	4	+30	+5	-15	+15				
	5	+30	+5	-20	+20				
	6	+30	+5	-20	+15	0	74		32
	10	+30	-10	-30	+30				
	19	+105	+60	-40	+30				
1	0	+145	+110	-45	+40				
	2	+155	+110	-50	+45				
	5	+175	+130	-55	+50	+1.1	76.5	73	
	20	+210	+140	-65	+60				
2	0	+210	+140	-60	+50				
	5	+210	+150	-55	+50	+1.3	74		35
	20	+220	+155	-50	+50				
3	1	+225	+160	-50	+50	+0.8	74	70	35
	4	+220	+155	-50	+45				
	20	+225	+170	-50	+45				
4	2	+230	+175	-45	+40	+0.8	77	70	31
	5	+210	+165	-35	+30				
	20	+180	+140	-30	+30				

TABLE 3 - STRAIN DATA - BEAM 2

Active Gage		2-L-1	2-L-1	2-P-1	Dummy	50" Gage	Room Temp.	Beam Temp.	Relative Humidity
Compensator Gage		2-P-1	Dummy	Dummy	2-P-1	Reading			
Elapsed Time		Strain	Strain	Strain	Strain				
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^3 in.	°F	°F	%
5	5	+155	+120	-25	+20	+1.7	76.5	73	33
	20	+135	+110	-20	+20				
6	6	+115	+100	-10	+5		79		
	20	+115	+90	-5	0				
7	5	+95	+95	0	-5	+1.7	78		33
	22	+85	+95	+10	-10				
8	5	+80	+95	+15	-20	+0.7	78		
	20	+65	+90	+20	-30				
9	5	+50	+85	+35	-40	+0.7	80	80	22
	20	+40	+80	+45	-50				
10	5	+25	+80	+50	-60	+0.5	83		32
	20	+15	+75	+60	-65				
11	5	+15	+85	+75	-80	-0.4	83		
	20	-5	+70	+80	-85				
12		-10	+70	+85	-90	-1.3	82		40
13		-35	+70	+105	-110	-1.6	85		
14		-65	+55	+120	-130	-1.9	86	86	13
15		-60	+65	+125	-130	-2.7	83		
16		-60	+75	+140	-145	-2.5	82		

TABLE 3 - STRAIN DATA - BEAM 2

Active Gage		2-L-1	2-L-1	2-P-1	Dummy	50" Gage	Room Temp.	Beam Temp.	Relative Humidity
Compensator Gage		2-P-1	Dummy	Dummy	2-P-1	Reading			
Elapsed Time		Strain	Strain	Strain	Strain				
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^3 in.	°F	°F	%
17		-80	+70	+150	-155	-2.8	84	80	16
18		-100	+60	+160	-170	-2.9	84		
19		-80	+80	+160	-170	-3.5	82	78	23
20		-100	+85	+170	-180	-3.7	83		
21		-105	+80	+190	-195	-4.4	84	81	18
22		-120	+75	+200	-210	-4.3	86	81	27
23		-125	+80	+210	-220	-4.1	85	82	33
24		-125	+90	+220	-230	-4.3	84	80	33
25		-135	+95	+230	-240	-5.1	84	81	30
26		-160	+90	+245	-260	-5.0	86	82	23
27		-150	+100	+255	-265	-5.8	82	80	26
28		-170	+90	+260	-275	-6.0	80	79	38
29		-170	+100	+270	-275	-6.4	79	78	34
30		-190	+90	+280	-290	-6.5	79	79	
32		-265	+55	+320	-335	-4.9	88	84	48
34		-280	+55	+330	-340	-7.1	81	80	22
36		-285	+60	+350	-355	-6.8	81.5	80	34
38		-260	+90	+350	-355	-8.3	76.5	77	22
40		-260	+100	+360	-365	-8.5	76	76	38
42		-255	+115	+370	-375	-8.1	76	76	67
44		-220	+140	+360	-365	-9.6	70	70	47
46		-250	+125	+375	-385	-9.6	70.5	71	31

TABLE 3 - STRAIN DATA - BEAM 2

Active Gage		2-L-1	2-L-1	2-P-1	Dummy	50" Gage	Room Temp.	Beam Temp.	Relative Humidity
Compensator Gage		2-P-1	Dummy	Dummy	2-P-1	Reading			
Elapsed Time		Strain	Strain	Strain	Strain				
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^3 in.	^{o}F	^{o}F	%
48		-250	+130	+380	-390	-9.9	70	71	48
56		-290	+130	+420	-425	-9.0	76	75	43
63		-315	+130	+440	-450	-9.7	75	76	60
72		-380	+130	+495	-505		78	77	57
74		-415	+125	+520	-540	-9.5	78	78	57
80		-530	+140	+670	-675	-8.9	82	81	81
86		-580	+290	+855	-870	-9.7	78	78	58
88		-620	+320	+930		-10.0	77	78	68
90		-620	+410	+990	-970	-9.4	79	78	54
96		-665	+570	+1220	-1230	-12.1	74	74	43
97		-685	+595	+1260	-1280	-11.9	75	75	50
98		-700	+615	+1295	-1320	-11.7	75	75	54
99		-710	+645	+1335	-1355	-12.1	76	76	56
100		-720	+680	+1380	-1395	-11.1	77	78	58
101		-730	+700	+1410	-1425	-10.9	79	78	68
102		-715	+740	+1430	-1455	-10.8	80	80	63
103		-710	+780	+1475	-1490	-9.3	81	81	56
104		-700	+815	+1510	-1525	-9.8	80	80	72
105		-680	+890	+1550	-1570	-10.8	81	80	69
106		-655	+940	+1600	-1580	-10.3	80	80	67

TABLE 4 - STRAIN DATA - BEAM 3

Active Gage		3-L-1	3-L-1	3-P-1	Dummy	3-L-2	3-L-2	3-P-2
Compensator Gage		3-P-1	Dummy	Dummy	3-P-1	3-P-2	Dummy	Dummy
Elapsed Time		Strain x 10^6 in/in	Strain x 10^6 in/in	Strain x 10^6 in/in	Strain x 10^6 in/in	Strain x 10^6 in/in	Strain x 10^6 in/in	Strain x 10^6 in/in
Days	Hours							
0	0	0	0	0	0	0	0	0
	1	+10	-5	0	0	0	+10	0
	3	-5	-10	0	-10	-5	-5	-10
	8	-70	-60	0	-10	-30	-60	-30
	21	+5	-20	-30	+20	+20	-30	-50
1	7	+60	+30	-30	+20	+60	+25	-35
	21	+100	+60	-45	+35	+90	+60	-35
2	7	+125	+75	-50	+40	+105	+70	-35
	22	+135	+80	-55	+40	+115	+80	-40
3	7	+140	+85	-55	+40	+120	+90	-60
	21	+160	+95	-65	+55	+125	+95	-55
4	7	+160	+100	-65	+50	+130	+95	-65
	21	+160	+95	-70	+55	+125	+90	-70
5	7	+170	+105	-70	+55	+130	+95	-70
	21	+180	+110	-70	+60	+140	+110	-50
6	7	+185	+105	-80	+70	+145	+105	-65
7	7	+160	+75	-85	+70	+125	+75	-90
8	7	+170	+70	-95	+90	+130	+70	-95
9	7	+160	+65	-100	+90	+125	+60	-65
10		+155	+65	-90	+80	+120	+60	-65
11		+110	+40	-70	+60	+90	+40	-60

TABLE 4 - STRAIN DATA - BEAM 3

Active Gage		3-L-1	3-L-1	3-P-1	Dummy	3-L-2	3-L-2	3 - P-2
Compensator Gage		3-P-1	Dummy	Dummy	3-P-1	3-P2	Dummy	Dummy
Elapsed Time		Strain	Strain	Strain	Strain	Strain	Strain	Strain
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in
12		+165	+60	-105	+100	+125	+60	-70
13		+120	+30	-95	+80	+90	+25	-70
14		+135	+35	-100	+90	+100	+30	-75
15		+120	+25	-95	+80	+90	+25	-70
16		+100	+15	-90	+80	+80	+10	-70
17		+145	+30	-110	+105	+105	+25	-80
18		+150	+35	-110	+110	+110	+30	-80
19		+140	+30	-110	+110	+105	+25	-80
20		+135	+25	-115	+105	+100	+15	-85
21		+140	+25	-110	+105	+100	+20	-80
22		+135	+20	-120	+105	+95	+15	-85
23		+165	+25	-140	+130	+115	+15	-100
24		+155	+20	-135	+125	+110	+15	-100
25		+150	+20	-130	+120	+105	+10	-95
26		+145	+15	-130	+120	+100	+10	-95
27		+145	+15	-130	+120	+105	+10	-100
35		+85	-10	-100	+85	+65	-20	-90
43		+50	-35	-85	+70	+45	-40	-90
50		+25	-45	-70	+60	+30	-50	-85
60		0	-55	-50	+40	+10	-60	-80

TABLE 4 - STRAIN DATA - BEAM 3

Active Gage		3-L-1	3-L-1	3-P-1	Dummy	3-L-2	3-L-2	3-P-2
Compensator Gage		3-P-1	Dummy	Dummy	3-P-1	3-P-2	Dummy	Dummy
Elapsed Time		Strain	Strain	Strain	Strain	Strain	Strain	Strain
Days	Hours	$x10^6$ in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in
61		-10	-55	-50	+35	+10	-60	-75
64		-10	-55	-45		+5	-65	-75
70		-15	-75	-60	+45	0	-80	-80
76		-10	-75	-60	+55	+5	-80	-90
80		-40	-80	-40	+30	-10	-85	-80
89		-40	-85	-40	+30	-10	-85	-80

TABLE 5 - STRAIN DATA - BEAM 4

Active Gage		4-L-1	4-L-2
Compensator Gage		4-P-1	4-P-2
Elapsed Time		Strain x 10^6 in/in	Strain x 10^6 in/in
Days	Hours		
0	0	0	0
	1	+5	0
	2	0	0
	4	0	-5
	5	-5	-5
	6	-5	-10
	8	-10	-10
	21	-5	0
1	2	+5	+10
	3	+10	+15
	4	+15	+20
	5	+20	+20
	7	+30	+30
	21	+65	+65
2	7	+70	+75
	22	+90	+90
3	7	+85	+90
	23	+100	+100
4	7	+100	+100
5	7	+90	+100
6	7	+85	+90
7	7	+60	+85
8	7	+45	+75
9	7	+30	+70
10		+25	+65
12		-15	+45
13		-30	+40
14		-35	+45
15		-30	+40
16		-60	+30
17		-75	+25
18		-80	+25
19		-95	+20
20		-105	+15
21		-115	+10
22		-130	0

TABLE 5 - STRAIN DATA - BEAM 4

Active Gage		4-L-1	4-L-2
Compensator Gage		4-P-1	4-P-2
Elapsed Time		Strain	Strain
Days	Hours	x 10^6 in/in	x 10^6 in/in
23		-150	-10
24		-160	-15
25		-175	-20
26		-190	-25
27		-205	-30
28		-220	-30
29		-235	-30
30		-265	-40
31		-290	-50
32		-300	-40
33		-315	-45
35		-345	-50
38		-360	-60
40		-340	-40
44		-350	-45

TABLE 5 - STRAIN DATA - BEAM 4

Active Gage		4-L-1	4-L-1	4-P-1	4-L-2	4-L-2	4-P-2
Compensator Gage		4-P-1	Dummy	Dummy	4-P-2	Dummy	Dummy
Elapsed Time		Strain	Strain	Strain	Strain	Strain	Strain
Days	Hours	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in	x 10^6 in/in
21		0	0	0	0	0	0
22		-15	0	+15	-10	-5	+5
23		-35	0	+30	-20	-5	+15
24		-45	-10	+35	-25	-10	+20
25		-60	-10	+50	-30	-15	+15
26		-75	-10	+65	-35	-15	+20
27		-90	-20	+75	-40	-25	+10
28		-105	-20	+90	-40	-25	+15
29		-120	-15	+110	-40	-20	+20
30		-150	-15	+140	-50	-25	+30
31		-170	-20	+160	-60	-30	+30
32		-185	-20	+165	-50	-30	+15
33		-200	-20	+180	-45	-35	+15
35		-230	-20	+215	-60	-35	+20
38		-245	-15	+235	-70	-45	+10
40		-225	-5	+245	-50	-40	+10
44		-235	+20	+270	-55	-55	0

FIGURES 7 THROUGH 10

GRAPHS OF EARLY STRESS VARIATION

EXPLANATION OF FIGURES 7 THROUGH 10

Since early behaviour of concrete is of special interest and since the performance of the gages was more reliable during the early stages, graphs showing the variation in stress for the first eight days were drawn for each beam.

As design of reinforcing steel is based on the nominal cross-sectional area which, in the case of deformed bars, is less than the actual area, the stresses were calculated using the nominal area. The following formula was used:

$$\text{Stress} = \text{Strain} \times E \times \frac{\text{Ave. Area @ Gages}}{\text{Nominal Area}}$$

Where E = Modulus of Elasticity = 29×10^6 p.s.i.

For Beam 1 the average strain of the three gages was used.

The strain reading of the longitudinal gage with the dummy gage as compensator was used in Beam 2.

Since readings of two longitudinal gages with the dummy gage were made in Beam 3, the average was used.

For Beam 4, a Poisson ratio of 0.30 was assumed so 70 percent of the strain reading given by the longitudinal gage with a Poisson gage as compensator was used as the longitudinal strain. Two readings were available and again the average was used.

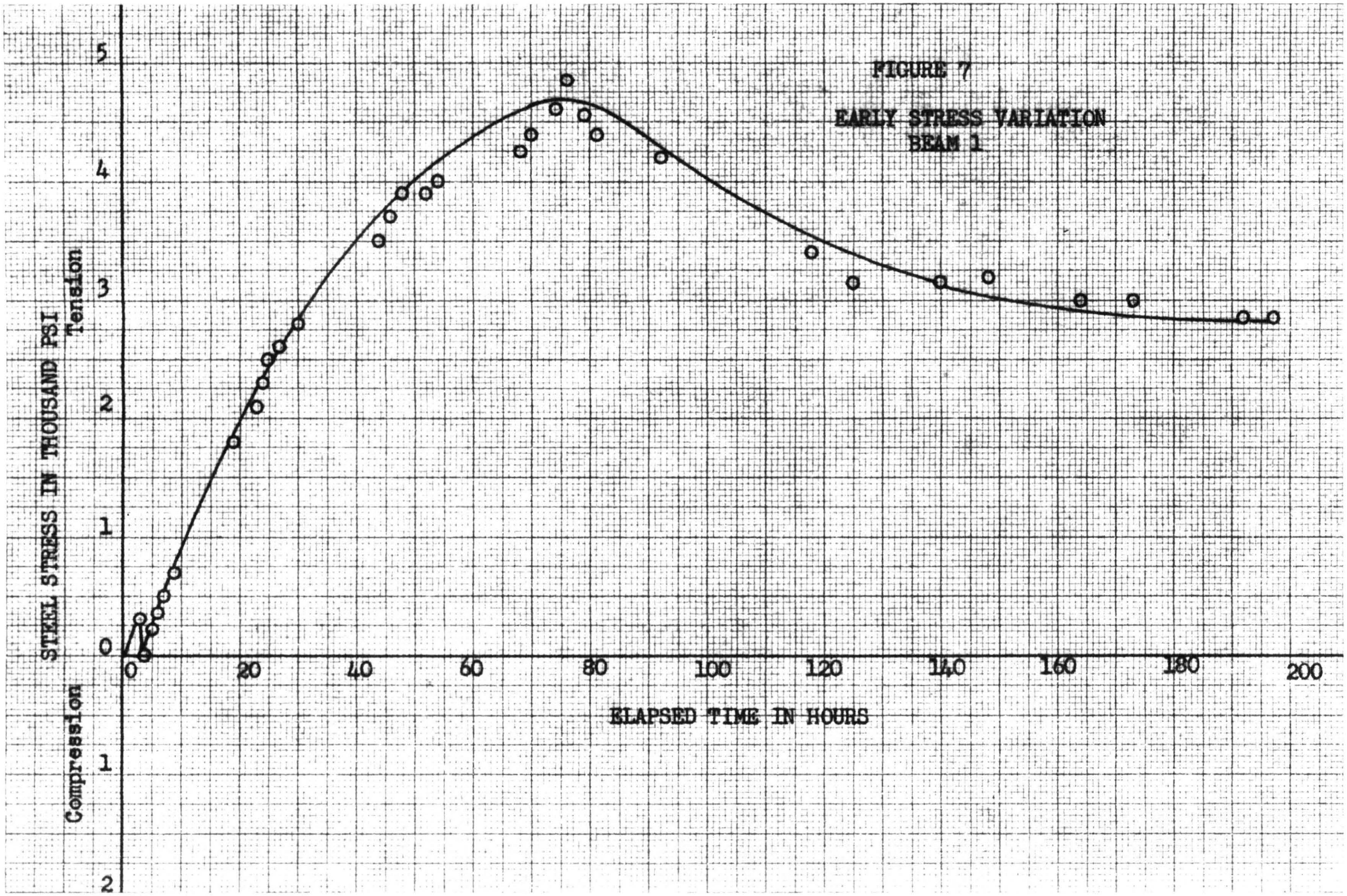

FIGURE 7

EARLY STRESS VARIATION
BEAM 1

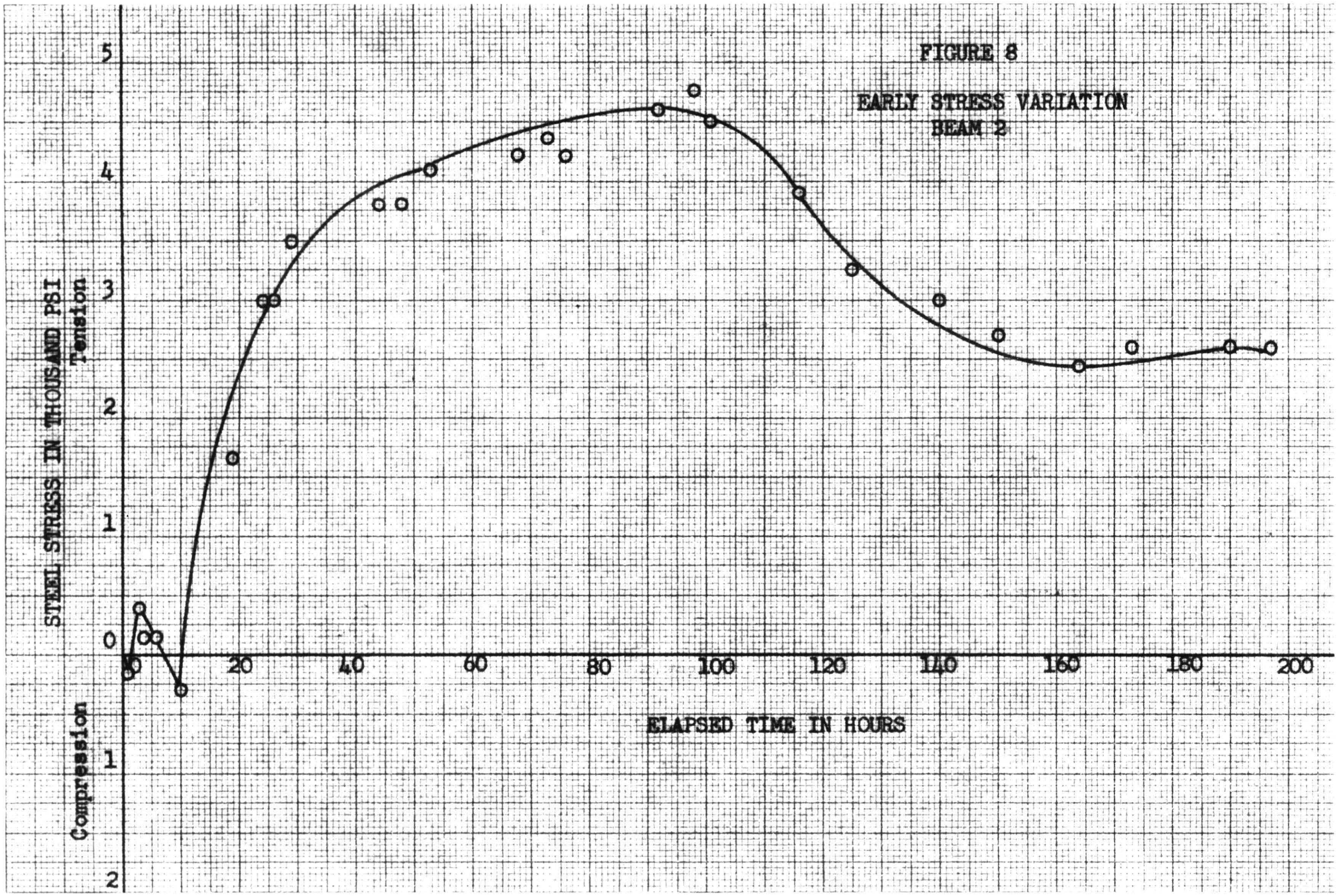

FIGURE 8

EARLY STRESS VARIATION
BEAM 2

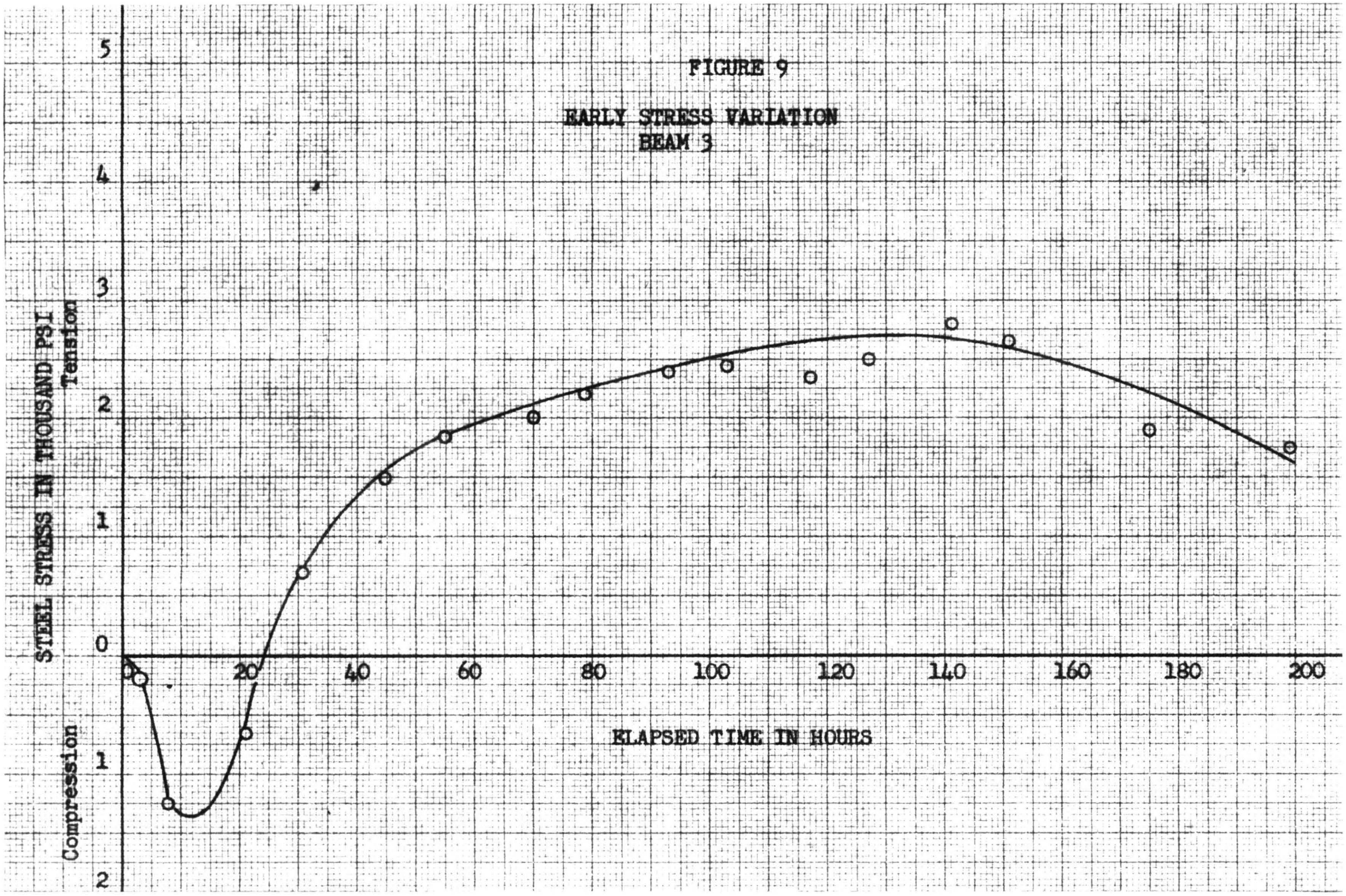

FIGURE 9

EARLY STRESS VARIATION
BEAM 3

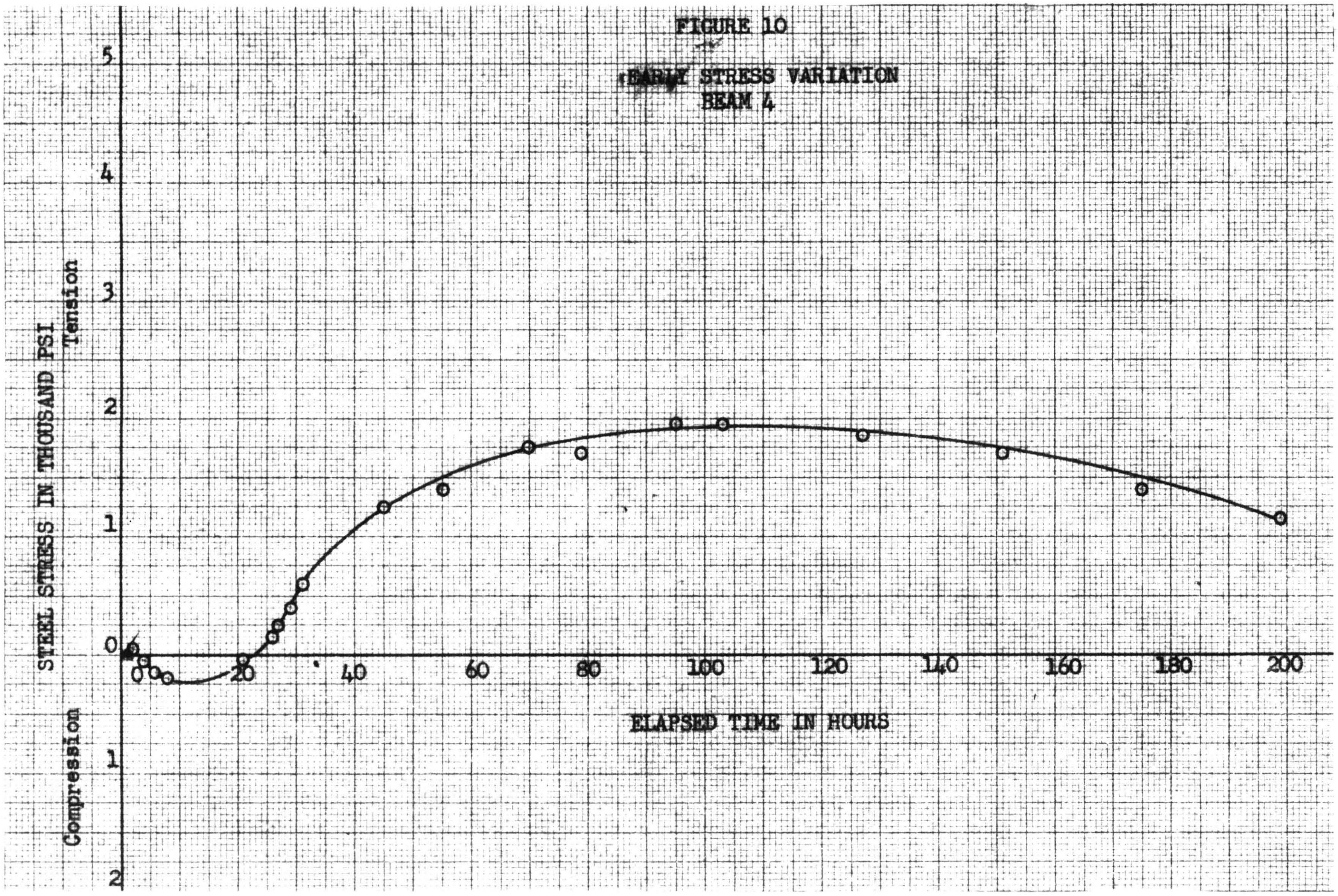

FIGURE 10

EARLY STRESS VARIATION
BEAM 4

FIGURES 11 THROUGH 15

GRAPHS OF STRAIN READINGS VS. TIME

EXPLANATION OF FIGURES 11 THROUGH 15

The strain readings are plotted on a logarithmic time scale beginning at 12 hours from the time of pouring. Due to the lack of space all of the readings taken were not plotted.

Figure 11 shows the three sets of readings taken on Beam 1.

Figure 12 has three sets of SR-4 strain gage readings plus the strain indicated by the 50" gage. The data sheet gives the total strain of the 50" gage length. These values were converted to unit strain for plotting on the graph.

Since the values of similar readings on Beam 3 were close in magnitude, the average values of the three types of readings taken were plotted on Figure 13.

Figure 14 gives both sets of readings that were taken over the entire test period of Beam 4.

On the twenty-first day additional readings were begun on Beam 4. These readings are plotted on Figure 15 with the condition existing on the twenty-first day as the zero point.

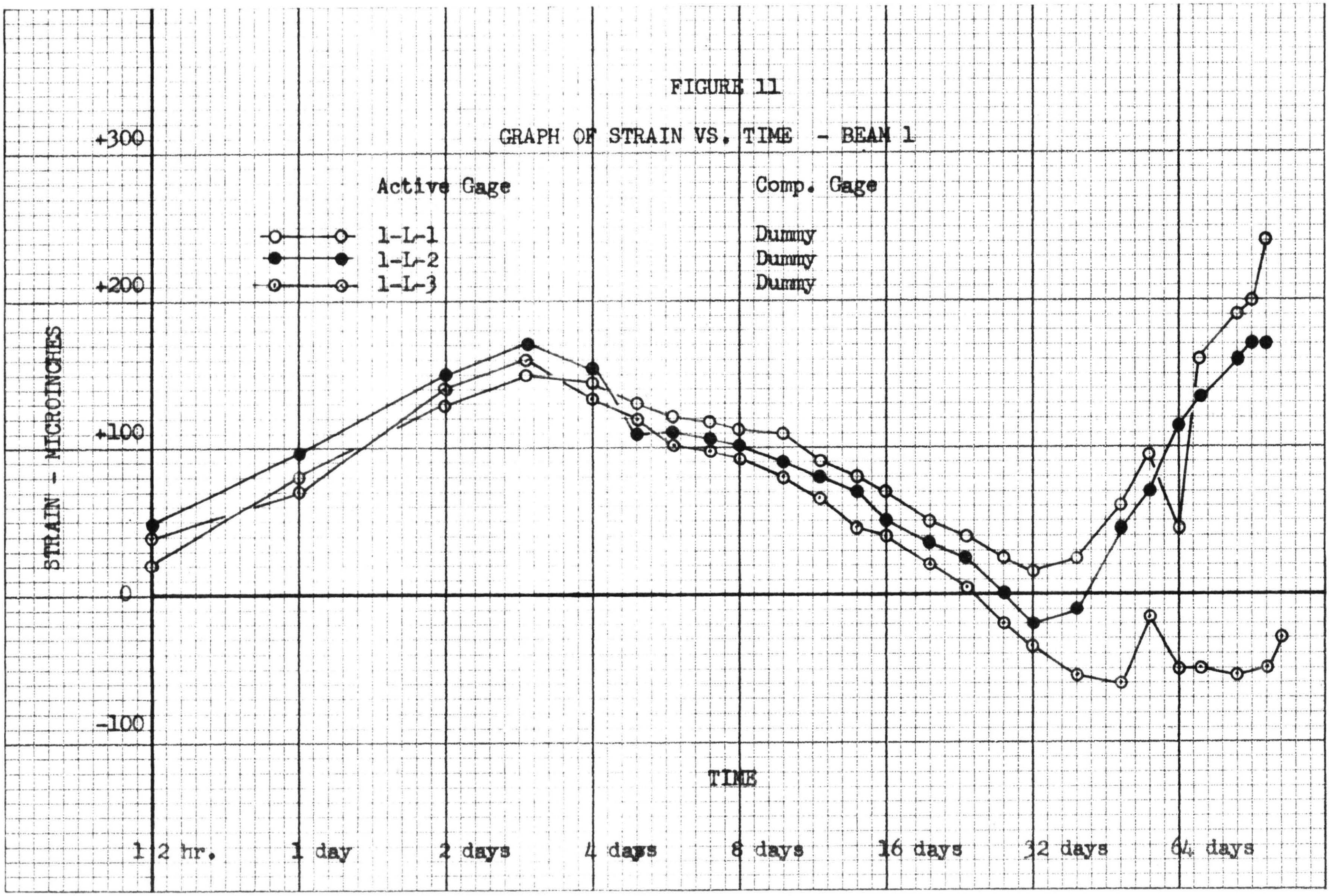

FIGURE 11

GRAPH OF STRAIN VS. TIME - BEAM 1

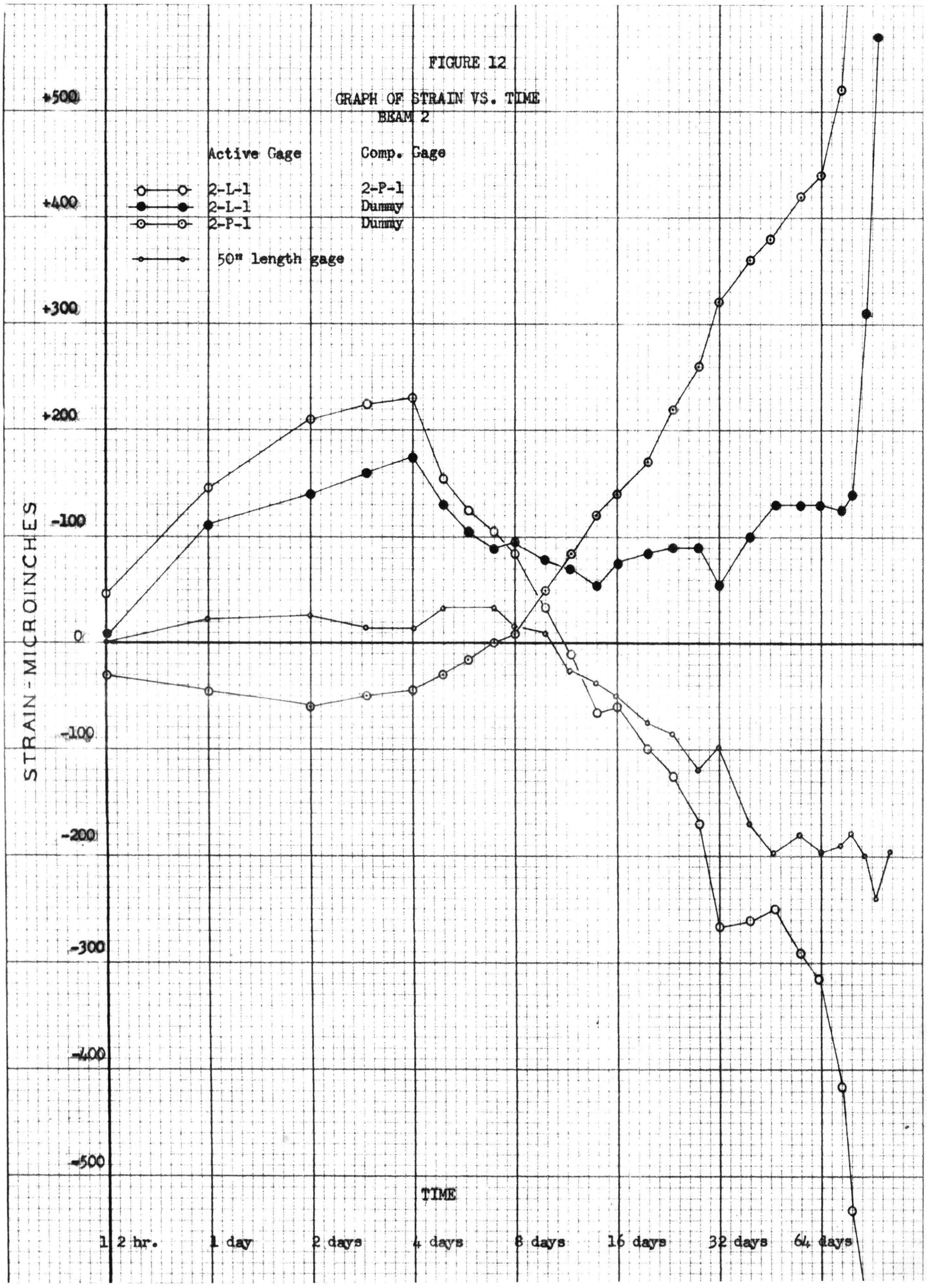

FIGURE 12

GRAPH OF STRAIN VS. TIME
BEAM 2

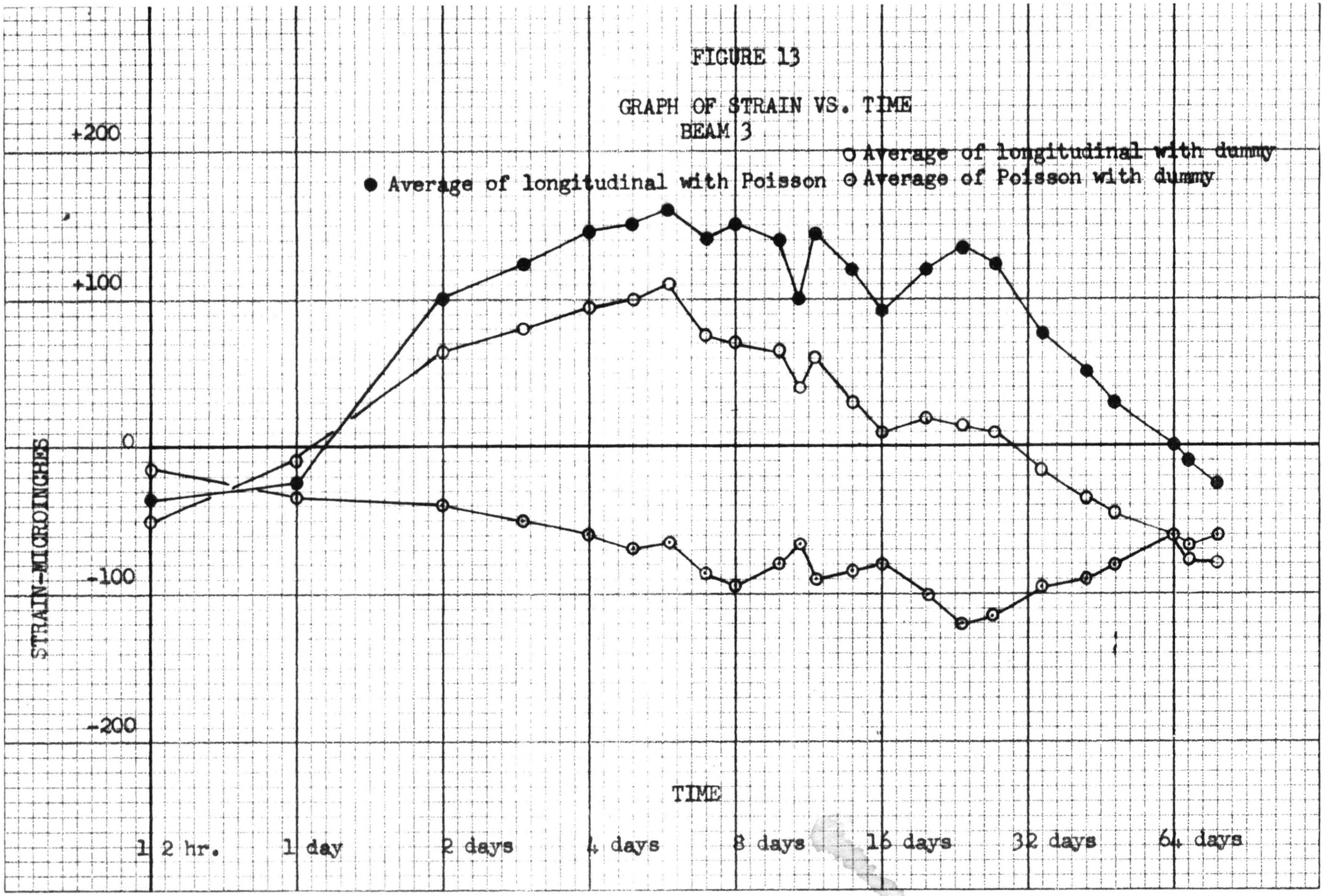

FIGURE 13

GRAPH OF STRAIN VS. TIME
BEAM 3

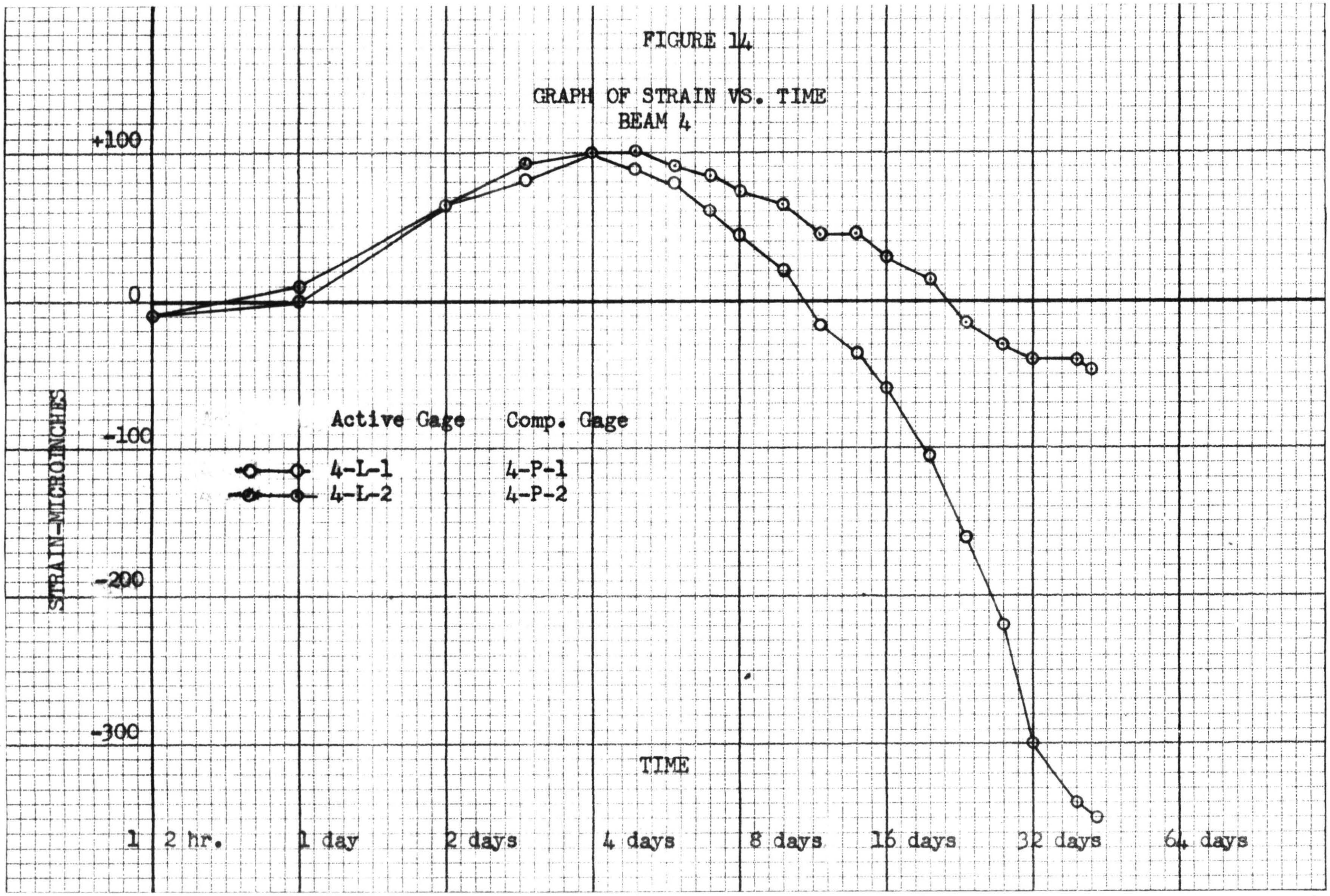

FIGURE 14

GRAPH OF STRAIN VS. TIME
BEAM 4

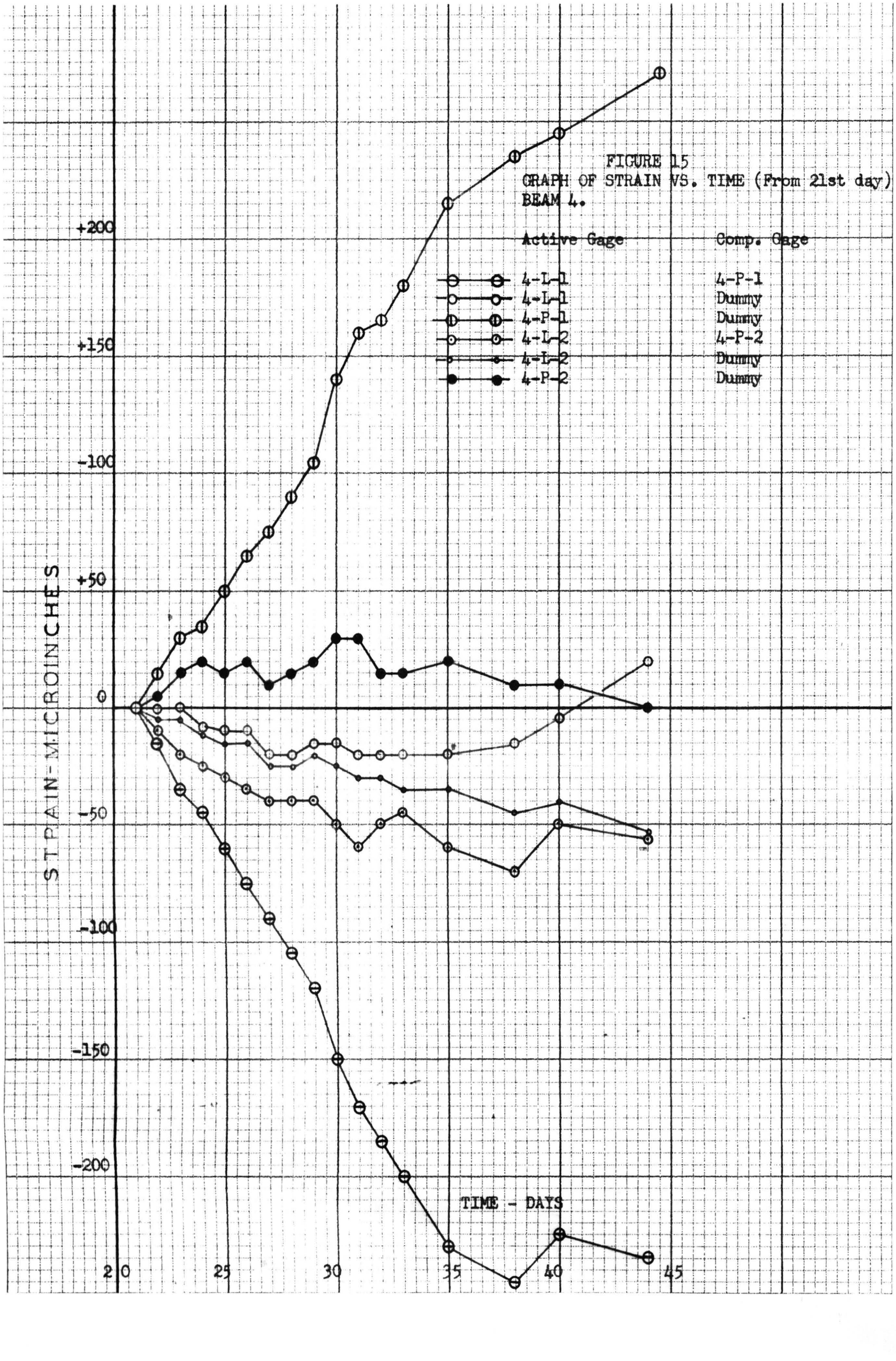

FIGURE 15
GRAPH OF STRAIN VS. TIME (From 21st day)
BEAM 4.

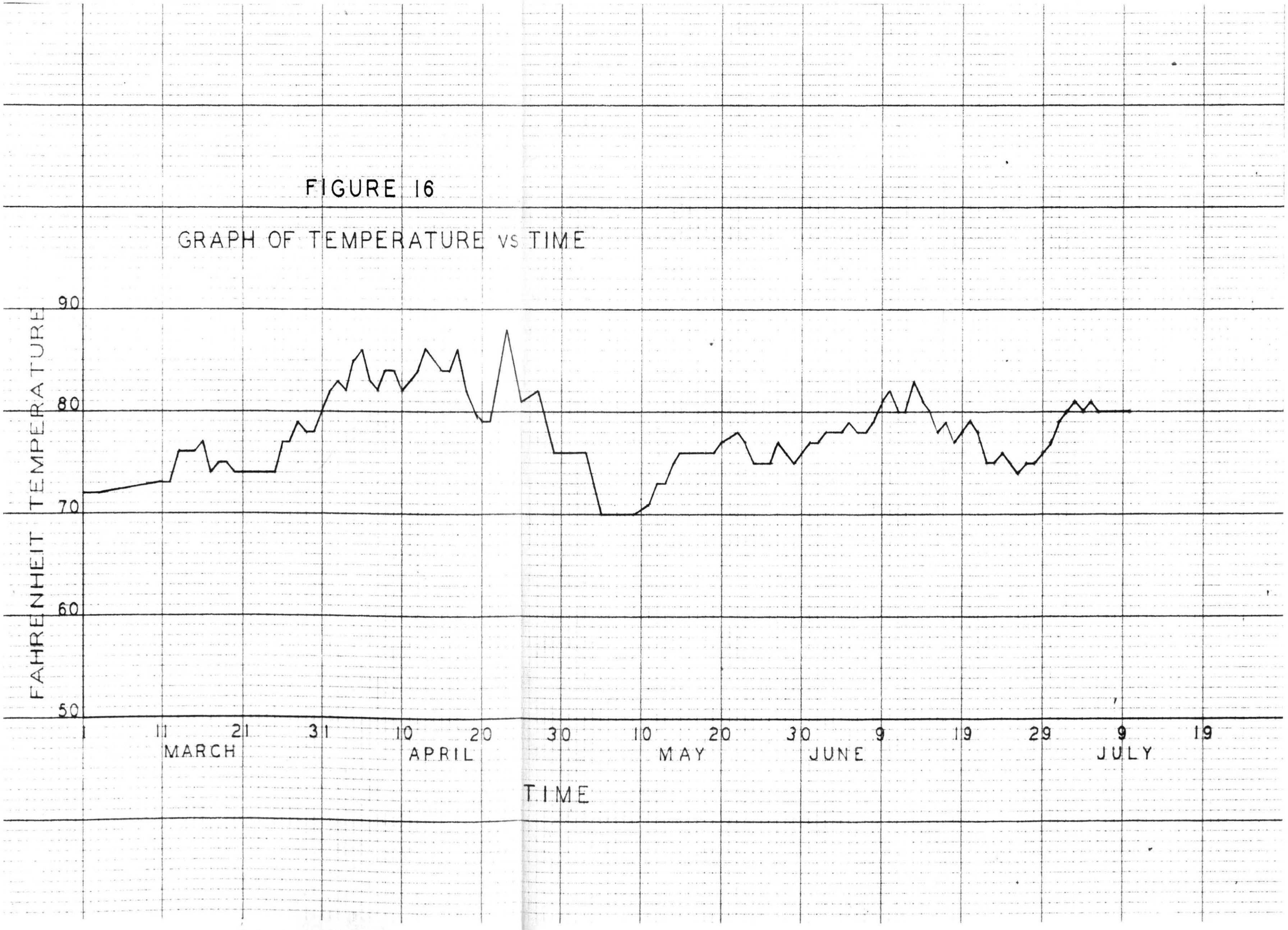

FIGURE 16

GRAPH OF TEMPERATURE vs TIME

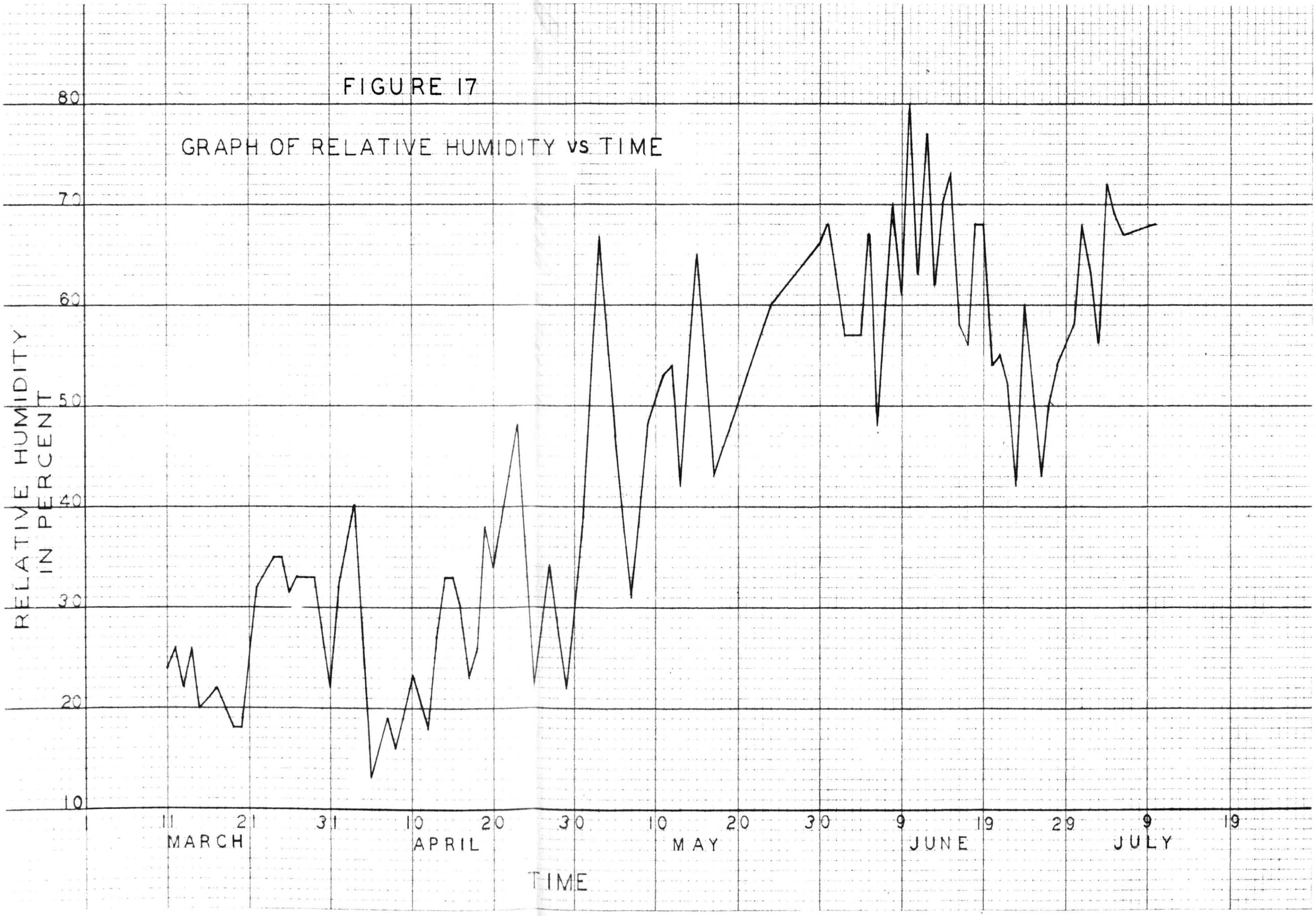

FIGURE 17

GRAPH OF RELATIVE HUMIDITY vs TIME

DISCUSSION OF RESULTS

The graphs for early stress variation show the closest similarity to previous experiments of this type. Until initial set has taken place, no bond exists between the steel and concrete so no load can be transferred to the reinforcing bars. There is an early decrease in volume that reaches a maximum about ten hours after pouring. Then the concrete begins to expand and continues to expand as long as moist curing is continued. The maximum early compressive stress in the steel was 1300 psi and occurred in Beam 3 about ten hours after pouring. This would indicate a tensile stress in the concrete of about 24 psi. Maximum early tensile stresses in the steel were about 4500 psi and occurred in Beams 1 and 2 with 0.28 percent reinforcement. Maximum in Beam 3 with 0.48 percent reinforcement was 2800 psi and Beam 4 with 0.69 percent reinforcement was 2000 psi. As would be expected, the steel stress varied inversely as the steel percentage.

Behaviour of the gages after the first seven to ten days failed to follow any set pattern though Beam 1 was similar to Beam 3 and Beam 2 was similar to Beam 4.

In Beam 1 the readings of the three longitudinal gages followed the same pattern for the first month after which two gages indicated the bar was in tension, the third that it was in compression. Variation from expected behaviour was evident shortly after the end of the curing period. The usual decrease in bar tension occurred at that time, but after a few days the rate of decrease became very small.

On Beam 2 the measurements made with the 50-inch length gage gave a mechanical check on the amount of shrinkage. For the first two months, except during the curing period, there was close agreement between the change in length indicated by the 50-inch gage and that by the longitudinal gage using the Poisson gage as a compensator. The length change gage indicated a change from tension to compression on the tenth day, the strain gage a day later. A delay would be expected as drying occurred faster on the surface where the 50-inch gage plugs were located than near the strain gages in the center of the beam.

Also on Beam 2 the longitudinal gage with the dummy gage as compensator indicated the bar stayed in tension. The readings of the Poisson gage with the dummy should be about one-third the reading of the longitudinal gage and opposite in sign. This held true for the first week but then the Poisson gage began to show a continual expansion of the bar laterally (or compression in the bar) while the longitudinal gage indicated a consistent level of tension.

Beam 3 had two sets of gages and thus readings of similar pairs of gages could be compared. There was close agreement of the readings so only the average values were plotted. Behaviour of this beam was similar to Beam 1. The longitudinal gages with the dummy as compensator showed a gradual decline of the bar tension that existed at the end of the curing period and a change to compression about thirty days after pouring. The Poisson gages remained in compression which sharply contrasts to the high tension readings given by the Poisson gage in Beam 2.

The readings of the two sets of gages in Beam 4 were essentially identical for the first four days. After the curing period, set one of the gages indicated a rapid shrinkage with the bar changing to compression about eleven days after pouring while set two indicated tension up until the twenty-second day. The graph of set one is very close to the usual variation in steel stress due to shrinkage and shows a steel stress of about 7000 psi a month after the end of the curing period. Noting the variation in the two sets of readings, on the twenty-first day a check on the variation of the strain in the individual gages on the bar was begun by use of the dummy gage. These readings showed that nearly all of the strain being shown by set one was coming from the Poisson gage. Thus similar to Beam 2, the Poisson gage was showing greater strain than the longitudinal gage.

In general, there was close agreement between the results of Beams 1 and 3 and between those of Beams 2 and 4. This would indicate the behaviour was independent of the physical conditions as beams 1 and 2 were the same size and had the same steel percentage. Beams 3 and 4 had the same size but a different steel percentage.

Several possibilities exist as to the cause of the variation in readings. Creep of the gage cement with resulting relaxation of the strain in the gages is probably a factor in Beam 3 where all of the strain readings are tending to zero. The high tension readings of the Poisson gages in Beams 2 and 4 could be due to a small depression beneath the gage. Pressure exerted by the shrinking concrete could elongage the strain sensitive wires by forcing them to conform to the depression. Another possibility is that there was movement of the bar relative to the wax. This could have distorted the gage and resulted in high tension readings.

The pressure in the wax may reach a high value if it was unable to flow into the voids of the surrounding concrete. To check this possibility a hole was drilled in Beam 2 with a star drill until the wax was penetrated. The immediate result was a decrease in the tension reading of the Poisson gage but was probably due to the action of the drill as subsequent readings showed tension increasing at about the previous rate.

To confirm the performance of the dummy gage, two A-7 gages--one longitudinal and the other as a Poisson gage--were placed on a short bar and then covered with Petrosene-A wax and splicing compound. Using these two gages as dummy gages with the gages on Beam 2, the readings were in substantial agreement with those taken using the original dummy gage. Readings were taken over a period of ten days. The bar was also loaded in a testing machine and the following readings were taken: longitudinal gage with Poisson gage, longitudinal gage with original dummy gage, Poisson gage with original dummy gage. Again there was close agreement in the readings. These tests seem to indicate satisfactory performance of the dummy gage.

The strain gage readings were adequately compensated for temperature effects by use of the dummy gage and Poisson gages. A possible source of variation was that the strain indicator was kept in a cabinet some distance from the beams and thus may have been at a different temperature than the gages. Temperature would have a definite effect upon the 50-inch length change gage readings. However, since the maximum temperature variation was only 18°, the effect upon the results in general was not significant. The most abrupt temperature rise was recorded on April 23, the thirty-second day after pouring Beam 2. On April 21 temperature inside the beam and at the beam surface was 79° F. Two days later the surface temperature was up 9° to 88° F. while the inside temperature was only up 5°. The result was to reverse the trend of drying shrinkage to an expansion due to temperature as far as the surface 50-inch gage was concerned. The strain gages still indicated shrinkage. Just how rapid was the temperature rise is not known as temperature readings were taken only at the time of taking the strain readings.

Variations in relative humidity were considerable. The values were low during the start of the tests and then rose to a higher level at the end of the heating season. The minimum value recorded was 12% on April 5, the maximum 80% on June 10. The effect of higher humidity would be to decrease the rate of drying and thus the shrinkage rate, but no numerical values of the effect were obtained.

CONCLUSIONS

Test results over the first seven to ten days were reasonably consistent with each other and with the results of published tests of a similar nature. After that period there was considerable variation and was probably due to improper functioning of the gages. However, disagreement with previous results need not be cause for disregarding the data. Since concrete is a complex material, a slight change in the proportioning or in the mixing procedure may be sufficient to alter its behaviour.

One example of the variation in results of concrete tests recently came to the attention of the author. Experiments conducted by the U. S. Corps of Engineers indicate that the strength of concrete sometimes decreases with age, in contrast to the almost universal belief that the opposite is always true.

Considering the results of these tests, as well as information on previous tests, several conclusions can be drawn:

1. Reinforcing steel is subject to three stages of stress due to shrinkage (or expansion). In the first stage, starting during initial set, the steel is in compression reaching a maximum about ten hours after pouring. Expansion of the concrete then begins and the steel stress changes to a tension that continues to increase as long as moist curing is continued. After the end of the curing period, the magnitude of the tensile stresses begins to decrease. This is the beginning of the third stage. Most experimental results indicate a rapid change of the steel stress to compression that increases, though at a decreasing rate, for the life of the structure unless it is rewetted. Results from Beams 1 and 3 of this test indicate that the change to compression in the third stage may be at a slow rate.

2. A 1/4 inch coating of Petrosene-A wax wrapped with splicing compound is a satisfactory means of waterproofing strain gages on reinforcing steel.

3. Pressure on the waterproofing from the shrinking concrete does not seriously affect the strain readings.

4. SR-4 strain gages with a paper base are not satisfactory for measuring constant strains over a period of more than about ten days.

5. SR-4 strain gages are extremely sensitive and the utmost care is required in their handling and application.

No conclusive answer can be given as to the possibility of considering shrinkage stresses in the design of tensile steel. The amount of such stresses would have to maintain a certain level over the life of the structure to permit their consideration. This would eliminate structures exposed to the weather as moisture could cause expansion and loss of all shrinkage. However, for interior structures where the chance of moisture is almost non-existent, the majority of the evidence available points to the fact that a consideration of shrinkage stresses would result in a substantial saving in tensile steel requirements.

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VITA

C. Raymond Nowacki was born August 8, 1923 in Beckemeyer, Illinois, the son of Mr. & Mrs. Charles M. Nowacki.

He received his elementary education at St. Anthony School in Beckemeyer. He attended Beckemeyer High School for one year and then completed his secondary education at St. Mary High School in Carlyle, Illinois, graduating in 1940.

He was employed at the Moran Shoe Company in Carlyle until he entered military service in March 1943. In May 1943 he was assigned to the Army Specialized Training Program at the University of Oklahoma and remained there nine months completing three terms of a basic engineering course. Remaining army service was spent in the field artillery and included nine months in the European Theatre of Operations. He was discharged in February 1946 and a month later enrolled at the University of Illinois.

In February 1949 he received the degree of Bachelor of Science in Civil Engineering from the University of Illinois and then accepted employment with McDonnell Aircraft Corporation in St. Louis, Missouri. During the next four and one-half years he was also employed in the engineering departments of Stupp Brothers Bridge & Iron Co. and R. W. Booker & Associates, both in St. Louis. For three years while in St. Louis he was a part-time student at Washington University taking graduate courses in Civil Engineering.

In November, 1953 he accepted a position in the Bridge Department of the St. Louis-San Francisco Railway in Springfield, Missouri. Since September, 1956 he has been an Instructor in the Civil Engineering Department at the Missouri School of Mines and Metallurgy.

In November, 1953 he was married to Rose Marie Roth, daughter of Mr. & Mrs. Anton Roth of St. Louis, Missouri.

He is the father of three daughters, Jeanne Therese, age 3, Claire Elaine, age 2, and Ann Elizabeth, 10 weeks.