NATIONAL BUREAU OF STANDARDS REPORT

4951

TESTS OF PRESTRESSED CELLULAR SLABS
(Slabs Nos. 5, 7, 8, and 9)

by

M. Chi and A. F. Kirstein

Report to
Bureau of Yards and Docks
Department of the Navy

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NBS PROJECT		NBS REPORT
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NBS

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(Slabs Nos. 5, 7, 8, and 9)

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Abstract

In the continuing study of the properties of prestressed cellular slabs, four additional slabs were tested under concentrated loads. Slabs Nos. 5 and 7 were made of unreinforced NBS blocks, Slab No. 8 was made of NBS blocks containing web reinforcement, and Slab No. 9 was made of structural clay units. Deflections and strains were measured and were compared with the computed values. Maximum load-carrying capacities and crack patterns were recorded. The data reported herein substantiate the data in NBS Report 4396, in that the elastic theory for solid slabs is applicable to slabs of this type. The previously drawn conclusion was confirmed that reinforcement in the webs of the concrete blocks is essential to obtain a high load-carrying capacity for these slabs. The clay tile blocks used in Slab No. 9 had approximately twice the compressive strength of concrete blocks. However, due to the relatively low tensile strength of the tile, no increase in load-carrying capacity was observed.

Comparison of grouted and ungrouted slabs made of precision cast NBS blocks demonstrated the need for grouting the joints even for units cast to closest dimensional tolerance obtainable under laboratory conditions.

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1. INTRODUCTION

As a continuation of the study of the properties of slabs composed of 6-in. cellular blocks, four additional 5- by 5-ft slabs were tested in the Structural Engineering Section Laboratories. These slabs were prestressed in two directions and supported along four edges.

A previous NBS Report, No. 4396, showed conclusively that reinforcement in the webs of the blocks and intimate contact between the blocks served to increase the load-carrying capacity of this type of slab. With this knowledge at hand the tests described in this report were planned as follows:

(1) Cellular blocks were cast in precision molds and were assembled with grouted and ungrouted joints to determine whether closer tolerances on block manufacturing would afford the intimate contact between blocks obtained with grout.

(2) Reinforcing steel was provided in the webs of the blocks used to fabricate one of the slabs. This was done to study the effect of the reinforcing on the previously observed diagonal tension failures.

(3) Since the manufacture of cellular units of this type with steel web reinforcement is a difficult process at best, the thought was entertained that possibly clay tile would be a more suitable material and would exhibit better tensile properties. To explore this possibility one slab of this test series was made of clay tile units and tested to failure.

2. DESCRIPTION OF TEST SPECIMENS

2.1 Cellular blocks

The cellular concrete blocks were hollow 6-in. cubes having an opening 4.5 by 4.5 in. in cross section. There was a 1- by 2-in. elliptical access hole in each web to permit the passage of the prestressing unit. The principal dimensions of the cellular blocks are shown in figure 1.

The concrete blocks used in this test series were of two types: Unreinforced block and block reinforced with a No. 4 gage mild steel wire stirrup in each web. A diagram of the stirrup used in the block is shown in figure 1.

The cellular concrete blocks were made of a mix proportioned of one part type III cement and three parts of sand by weight with a water-cement ratio of 0.57. This mix had a 7-day compressive strength of approximately 6000 psi as determined by tests of 2-in. cubes. However, the actual units were moist-cured continuously until they were assembled into slabs so that the compressive strength of the individual units should be expected to be somewhat greater.

Additional tests on the concrete were conducted to determine the Young's modulus and Poisson's ratio. Axial compression tests were made on columns of three blocks that were grouted together in such a fashion as to make the direction of loading coincide with the axis of the cell. Sonic modulus tests were also performed on 0.75- by 0.80- by 6-in. strips that were cut from the cellular blocks. The results obtained by both methods indicated an average Young's modulus of 4×10^6 psi with a variation of ± 10 percent. Poisson's ratio was found to be approximately 0.15.

Three-unit-gang molds that were constructed to very close tolerances and had polished surfaces were used to form all of the concrete blocks. Due to this method of manufacture, the exterior dimensions of the blocks were well within 0.01 in. of the nominal values and the texture of the surface of the blocks was excellent. Upon close examination of these surfaces, it was also found that there were virtually no shrinkage cracks.

The cellular clay-tile blocks were made of a high grade vitrified clay by the Federal Seaboard Terra Cotta Corporation. The principal dimensions of the tile blocks were approximately the same as those of the concrete blocks except that the tile had circular instead of elliptical holes in the webs. The tile blocks had a good texture but the overall dimensions varied as much as 1/4 in. A sketch of a typical tile block is shown in figure 1.

Several of the clay tile were tested in axial compression with the load applied in the direction of the cell. The average compressive strength was approximately 12,000 psi. The typical stress-strain relationship for this material was essentially linear up to the failure load and yielded a Young's modulus of 4.4×10^6 psi and a Poisson's ratio of 0.15. Even though the tile exhibited a compressive strength that was approximately twice that of the concrete, the tensile strength was presumably not much greater than that of concrete.

2.2 Prestressing steel

A new type of steel bar known as "Elastuff" was used in this test series. Tensile tests of this material indicated a stress-strain relationship that was essentially linear up to 95,000 psi, and exhibited a Young's modulus of approximately 30×10^6 psi. The yield strength of the bar was found to be 120,000 psi as determined by the 0.2 percent offset method and the tensile strength was found to be 133,000 psi. Although "Elastuff" bars are made of cold-worked high carbon steel, they are fairly ductile and can be machined easily.

2.3 Test specimens

The nominal dimensions of each slab containing 100 cellular blocks were 5 ft by 5 ft by 6 in. The blocks were arranged so that the axis through the open ends of one block was perpendicular to the axis of each adjacent block. The holes in the webs of each block were arranged so as to enable the prestressing tendons to be staggered with respect to the midplane of the slab. Thus, the resultant prestressing force produced an axial compression in two directions through the slab.

The slabs in this test series were numbered 5, 7, 8, and 9. Slabs Nos. 5 and 7 were made of unreinforced NBS blocks, with ungrouted and grouted joints, respectively. Slab No. 8 was made of reinforced NBS blocks; the joints in this slab were grouted by dipping the ends of each block in a neat cement paste before they were assembled. Slab No. 9 was made of clay tile blocks and was fabricated in the same fashion as was Slab No. 3, which was described in NBS Report 4396. This slab was constructed in two stages. First, the blocks were assembled into 5-ft beams with about 1/8 in. mortar joints. Then the beams were assembled together with sufficient thicknesses of mortar joints to form a square slab.

All of the slabs gave a good general appearance, and all of the blocks appeared to be in intimate contact with one another. However, Slab No. 9 did not remain in its true plane after it was prestressed. This warping was presumably due to the relatively poorer tolerances of the tile blocks.

2.4 Prestressing procedure

The tensioning force was applied to the prestressing bars by means of a hydraulic jack equipped with a suitable adapter bar. This adapter bar was equipped with bonded wire gages and calibrated so that it could be used as a dynamometer to determine the amount of prestressing that was applied to the tendons. The calibration curve for the adapter is shown in figure 2.

Approximately one half of the prestress was applied in small increments by tightening the anchorage nuts with a wrench. The remaining prestressing force was applied by means of the hydraulic jack. This final stage of the prestressing was accomplished by using a suitable sequence of stressing the tendons so that no unduly large differences in strains would be induced in the blocks.

The total amount of prestress in each bar of Slabs Nos. 5, 7, 8, and 9 was 12,400 pounds. This force was sufficient to produce the specified 1000 psi stress in the blocks. It was

believed that the load-carrying capacity of the slabs could be increased by increasing the amount of prestressing. In order to verify this hypothesis a prestress of 1500 psi was proposed for Slab No. 6. However, supplementary tests reported in NBS Report No. 4813 indicated that the prestressing force necessary to produce a 1500 psi stress in the slab would severely damage the blocks. Therefore, the test of Slab No. 6 was dropped from this series, and the slab was disassembled.

3. TESTING PROCEDURE

3.1 Test setup

Slabs Nos. 5, 7, 8, and 9 were tested to failure in a 600,000-lb capacity hydraulic testing machine. The specimens spanned 54 in. and were simply supported on four edges by 1-in. square aluminum bars. The aluminum supports rested on a frame made of 6- by 12-in. reinforced concrete members that were supported by six 6-in. diameter cylindrical concrete columns. All bearing surfaces were set firmly with high-strength plaster to insure intimate contact between individual members. This setup placed the test specimen about 5 ft above the testing machine platen and permitted visual observation of the bottom face of the specimen during the test.

3.2 Instrumentation

The deflection measurements of Slabs Nos. 5, 7, and 8 were made by 0.001-in. micrometer dial gages attached to steel bars supported by wooden frames. These frames were attached to the testing machine. There were 20 deflection gages disposed over the top surface of the specimens. Figure 3 shows the symmetrical arrangement of these gages. The deflection measurements of Slab No. 9 were made in a different manner. The dial gages were attached to steel angles which rested on the slab directly over the supports. Thus, the dial gage readily gave directly the deflections with reference to the edges of the slab. The general setup of test of Slab No. 9 is shown in figure 4.

The variation of strain in eight prestressing bars was measured by means of bonded wire strain gages. Each of the eight bars was instrumented with two gages that were connected in series to eliminate the effects of any bending that might take place. Four of these bars ran through the slab in one direction, and the other four were perpendicular to them. The locations of the instrumented bars are shown in figure 3.

Figure 3 also shows the location of eight bonded wire strain gages that were applied to the concrete. Four of these gages were on the top surface of the slab and four were on the bottom.

3.3 Test procedure

The test specimens were loaded at the center of the top surface through a 6- by 12- by 12-in. concrete loading block. The load was applied to the slabs in increments of 5000 and 2500 pounds, and gage readings were made for each increment until the maximum load was reached.

4. TEST DATA

4.1 Deflections of slabs

Figure 5 shows the experimental and theoretical relationship between the applied load and center deflection of the slabs. The theoretical calculations were based on the average Young's modulus of 4×10^6 psi. The deflections of the slabs were measured with reference to the datum plane at the centers of the supported edges, and the deflection profiles were obtained by averaging the deflections along two rows of dial gages disposed symmetrically along two lines adjacent to the loading block. Figures 6 through 8 show these profiles for the various increments of load applied to these slabs.

Since the supports did not restrict the upward movement of the slab, the twisting moments induced by the applied load caused a "curl-up" action to take place at the corners of the slabs. The amount of curl-up was measured by the upward movement with respect to the datum plane as described in the preceding paragraph. Figure 9 shows the experimentally determined relationship between the applied load and the vertical displacement upward caused by the twisting moments.

4.2 Variation of prestressing force

After the slabs were fully prestressed the relaxation of the prestressing tendons was observed. These observations are graphically presented in figure 10. The clay tile slab exhibited an average loss of strain in the tendons of 4 percent at three days and 8 percent at seven days, while the tendons in the concrete slabs lost 8 percent of their strain at three days and 13 percent at 7 days. It is evident from these data that the loss of strain in the tendons is not only a function of time but also depends on the material being prestressed. Since the concrete blocks were moist-cured until they were assembled and prestressed, a portion of the loss of strain in the tendons can be attributed to shrinkage of the concrete. However, the shrinkage of the clay tile slab can be assumed to be negligible.

During the load tests, the maximum loss of prestress in the tendons of all the slabs was approximately 2 percent of the total initial strain. However, Slab No. 8, which carried the

largest load of all, registered a gain of almost 4 percent of the original strain in those tendons that were located 3/4 in. below the mid-depth of the slab. Table 1 contains a tabulation of the strain variations in the prestressing tendons with respect to the applied loads.

4.3 Concrete strains

The average strains in the concrete corresponding to a prestress of 1000 psi for Slabs Nos. 5 and 7 were 300×10^{-6} and 200×10^{-6} in./in. respectively. These data were not available for Slabs Nos. 8 and 9.

The loss of strain in the concrete due to shrinkage and creep was measured for the ungrouted Slab No. 5, and the results are presented graphically in figure 11. The average loss in strain for a six-day period was 37 percent of the original strain.

Figures 12 and 13 show the relationship between the applied load and the strain in the concrete.

4.4 Load-carrying capacity

Table 2 lists the maximum loads sustained by the slabs in this series along with the type of blocks and joints used in the construction of the slabs.

4.5 Crack patterns

Figures 14 through 19 show the crack patterns on the top and bottom surfaces of Slabs Nos. 5, 7, 8, and 9. The cracks in the bottom surface of slab No. 8 were more or less circular arcs that developed some distance from the loading block. This crack pattern very closely resembled that of a similar slab (No. 4) that was illustrated in figure 10 of NBS Report 4396.

The crack patterns in the webs of the unreinforced blocks along various sections through the slabs as indicated in figure 20 are shown in figures 21 through 25. These cracks were very wide and extensive, and their direction was usually parallel to the shells of the slabs. It is apparent from the crack pattern in the webs of the reinforced blocks shown in figure 25 that the cracks were confined to relatively few blocks, and upon further inspection after the test, the cracks were found to be narrower than those in the unreinforced blocks.

5. DISCUSSION

The comparison of the load-carrying capacities of Slabs Nos. 5 and 7 leads to the conclusion that slabs of this type require a more intimate contact between the cellular blocks than can be obtained by using precision blocks with a dimensional tolerance of 0.01 inches. Therefore, it appears that grouted joints between the blocks are required to obtain the intimate contact necessary to develop the full strength of these slabs.

If it is assumed that eight blocks bordering the loaded area resist the punching shear, and if the shear resistance of the flanges of the blocks is neglected, then only the webs of each of the eight blocks resist the shear. Calculations based on these assumptions show that the average vertical shear at the ultimate load sustained by Slab No. 7 was approximately 500 psi. When this shear stress was combined with the corresponding flexural stress, the principal tensile stress at the critical section was found to be 480 psi, which approximated the tensile strength of the concrete used to cast the blocks. Furthermore, if it is assumed that the clay tile in Slab No. 9 had the same tensile strength as the concrete blocks in Slab No. 7, then it can be stated that the full strength of both slabs was developed.

Using the same assumptions as before, the average vertical shear in the webs of the eight blocks bordering the loaded area in Slab No. 8 at the maximum load was found to be 740 psi. It is important to note that this value of shear corresponds to a nominal diagonal tensile stress of 740 psi. This theoretical tensile stress could not have been attained if the webs had not been reinforced with mild steel stirrups.

The extensive horizontal cracks in the block having unreinforced webs were attributed to the bursting effect of the prestressing force. This effect was noted in auxiliary tests and reported in the NBS Report No. 4813.

Since no compression failures occurred in these slabs, it appears that the compressive strength of the concrete is adequate for slabs of this type. Therefore, the larger compressive strength of the clay tile was not used to advantage because the diagonal tension failure of the webs precluded all other modes of failure. Furthermore, its brittle nature resulted in the formation of long, abrupt cracks in the webs due to the diagonal tension and the bursting effect of the prestressing force (see figure 26). A more suitable material for use in this type of slab would be one that has a compressive strength comparable to that of concrete, but having a greater extensibility and a greater tensile strength.

6. CONCLUSIONS

The foregoing discussion can be summarized in the following conclusions:

(1) Slabs of this type behave like solid slabs in flexure and shear.

(2) All of the slabs reported herein failed in diagonal tension.

(3) To improve the load-carrying capacity of these slabs it is necessary to provide suitable reinforcement in the block to increase their resistance to diagonal tension failures. An increase in the compressive strength of the material cannot be utilized as long as there is no commensurate increase in the tensile strength.

(4) A suitable joint material must be provided between the blocks to insure intimate contact.

Table 1. Strain increments in prestressing bars due to applied loads

Slab No.	Load kips	Strain increments, 10^{-6} in./in. in bars Nos. 1	2	3	4	5	6	7	8
5	2.5	-6	1	-1	-2	-3	10	5	3
	5	-6	4	-7	-1	-4	3	-2	8
	7.5	-7	4	-8	1	-13	13	-5	9
	10	-6	8	-9	1	-14	7	-6	6
	15	-8	0	-9	-3	-27	13	-18	12
7	2.5	-2	-4	-13	-6	-6	-2	0	-1
	5	-4	-5	-6	-2	-8	8	-1	5
	7.5	1	0	-7	0	-12	8	-5	0
	10	-4	-6	-15	1	-11	8	-3	5
	15	-4	-6	-17	-5	-19	9	-11	4
	20	-2	-4	-21	2	-17	16	-13	8
	22.5	-9	-12	-26	-5	-21	17	-16	6
	25	-8	-5	-21	2	-24	17	-14	10
8	2.5	0	Gage was damaged	0	0	-3	2	-1	2
	5	0		1	-1	-5	7	-4	2
	7.5	-1		0	-1	-7	7	-8	4
	10	-1		0	-1	-7	9	-9	5
	15	-1		-1	-3	-14	12	-12	11
	20	-1		-2	-3	-18	18	-18	13
	22.5	-1		-3	-5	-22	19	-20	17
	25	0		-3	-3	-24	25	-20	20
	27.5	-1		-2	-2	-26	27	-21	22
	30	1		-2	-1	-26	30	-23	28
	32.5	2		-1	-1	-28	36	-27	31
	35	2		0	1	-27	40	-28	39
	37.5	5		0	2	-26	49	-27	49
9	2.5	-1	0	0	2	-22	0	-10	-3
	5	0	0	-3	2	-50	-1	-11	-7
	7.5	-4	-2	-2	-2	-26	-3	-10	-7
	10	-4	-2	-4	-2	-20	-8	-9	-7
	15	-6	-4	-6	-3	-36	-9	-4	-10
	20	-9	-12	-10	-9	+20	-10	-1	-15
	25	-24	-24	-23	-19	+42	-3	+10	-19

Table 2. Schedule of slabs

Slab No.	Type of block	Type of joint	Prestress	Maximum load
			psi	lb
5	NBS, unreinforced	Ungrouted	1,000	18,000
7	NBS, unreinforced	Grouted	1,000	27,275
8	NBS, reinforced	Grouted	1,000	39,850
9	Structural clay	Grouted	1,000	26,850

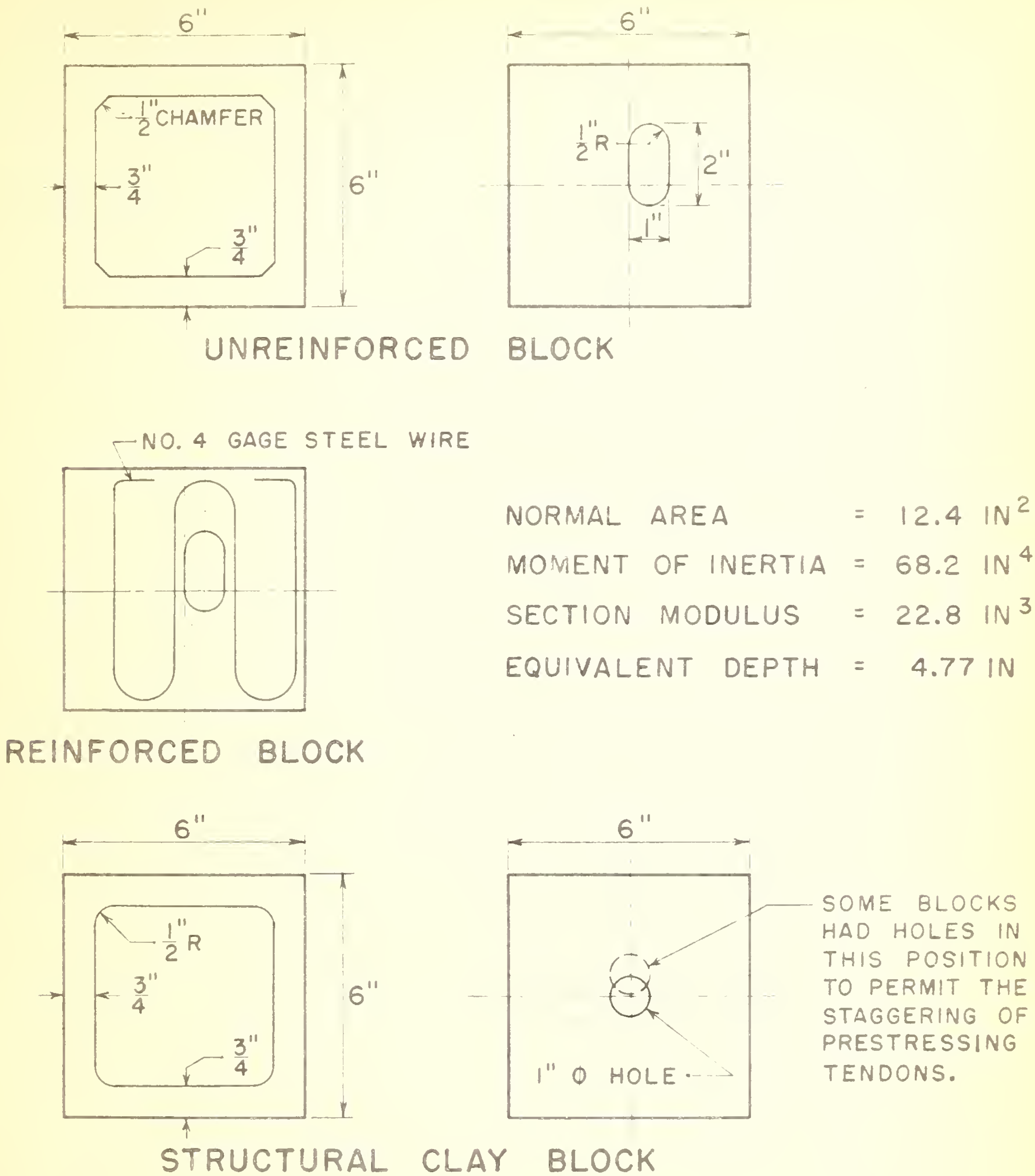


FIGURE 1. CELLULAR BLOCKS

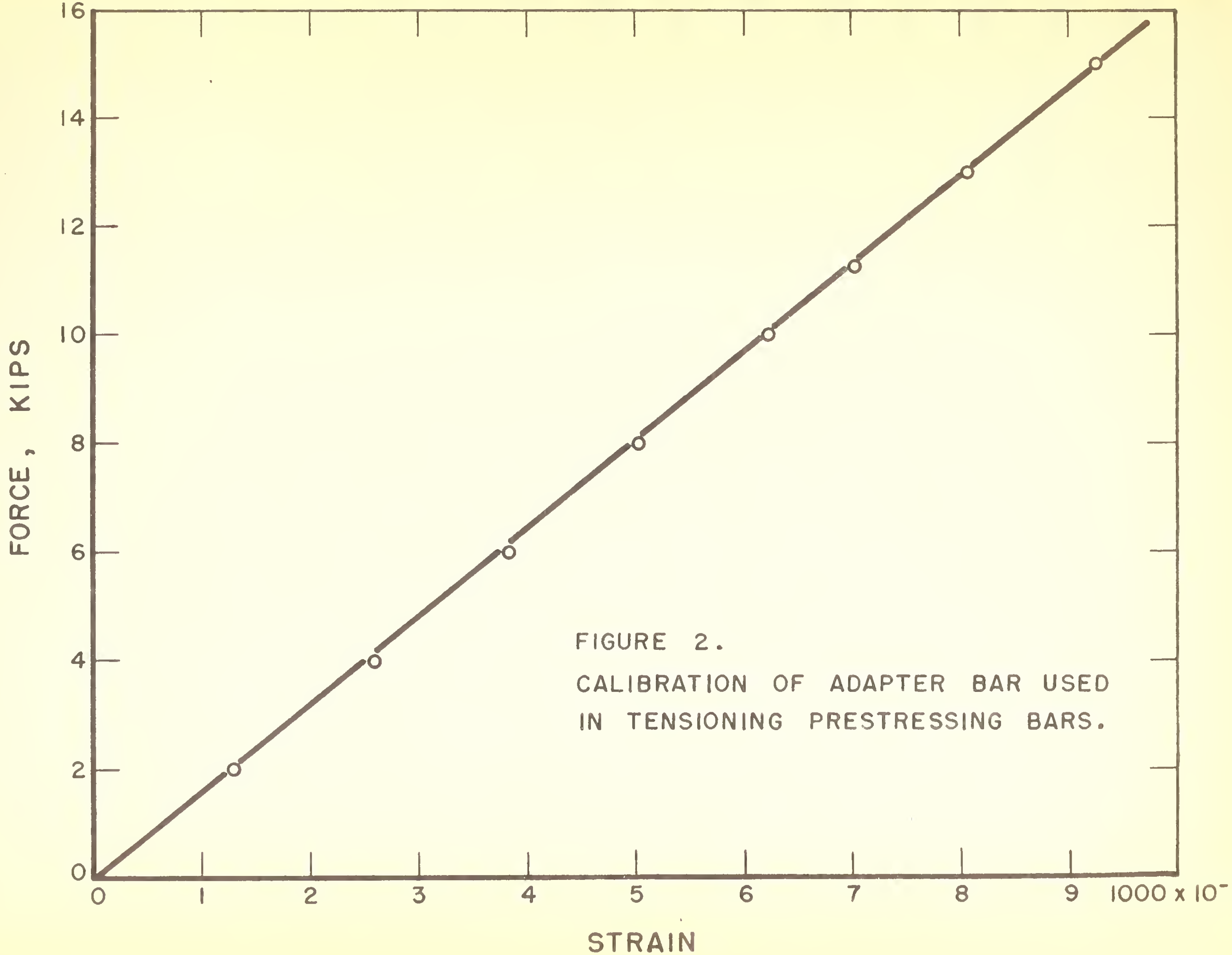
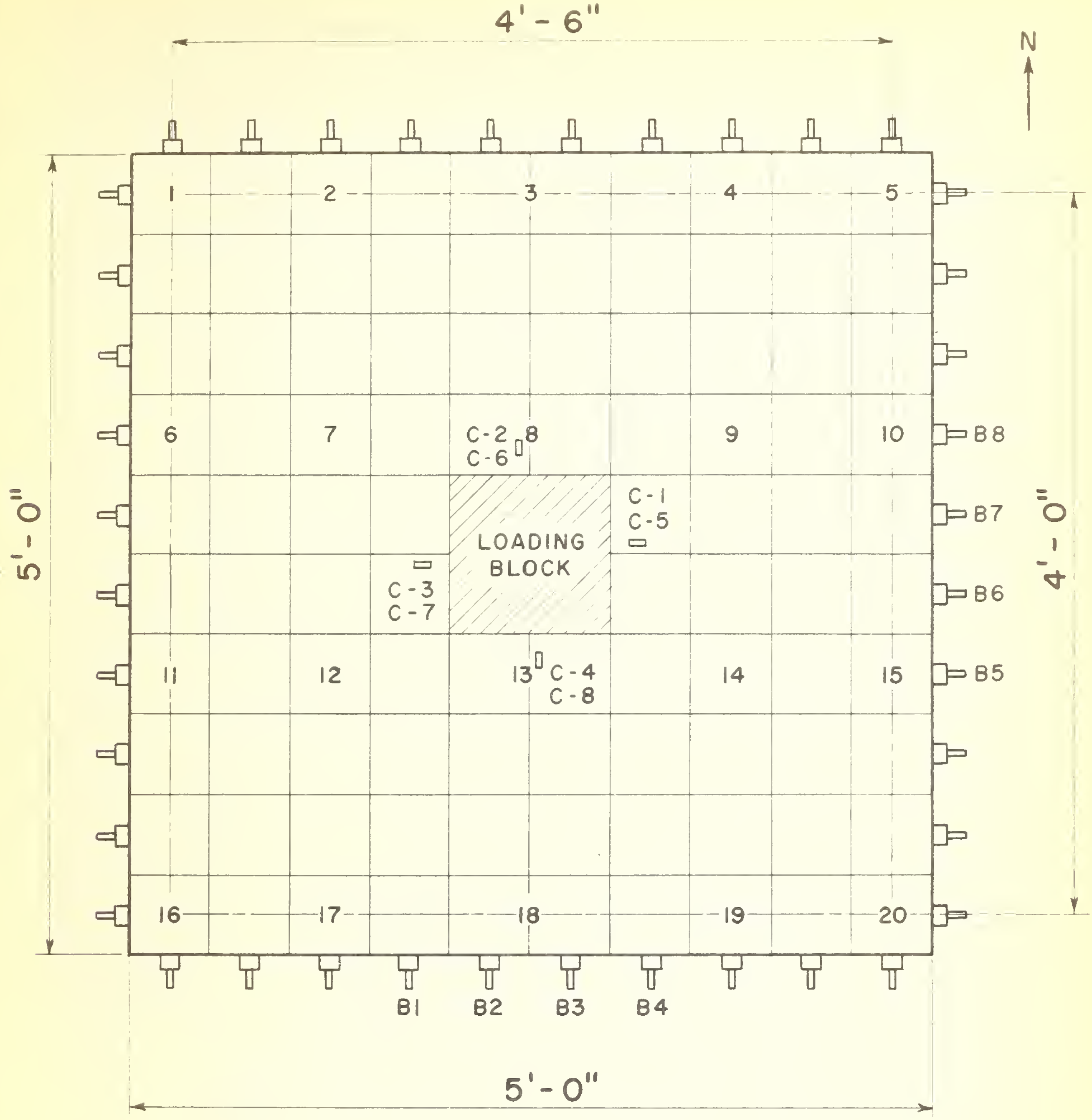


FIGURE 2.
CALIBRATION OF ADAPTER BAR USED IN TENSIONING PRESTRESSING BARS.

FIGURE 2.



LEGEND:

GAGES 1 THROUGH 20 INDICATE DIAL GAGES
B1 THROUGH B8 INDICATE GAGES ON BARS
C1 - C4 INDICATE SR-4 GAGES ON BOTTOM SURFACE OF SLAB
C5 - C8 " " " " TOP " " "

FIGURE 3. LOCATION OF DIAL GAGES AND STRAIN GAGES.

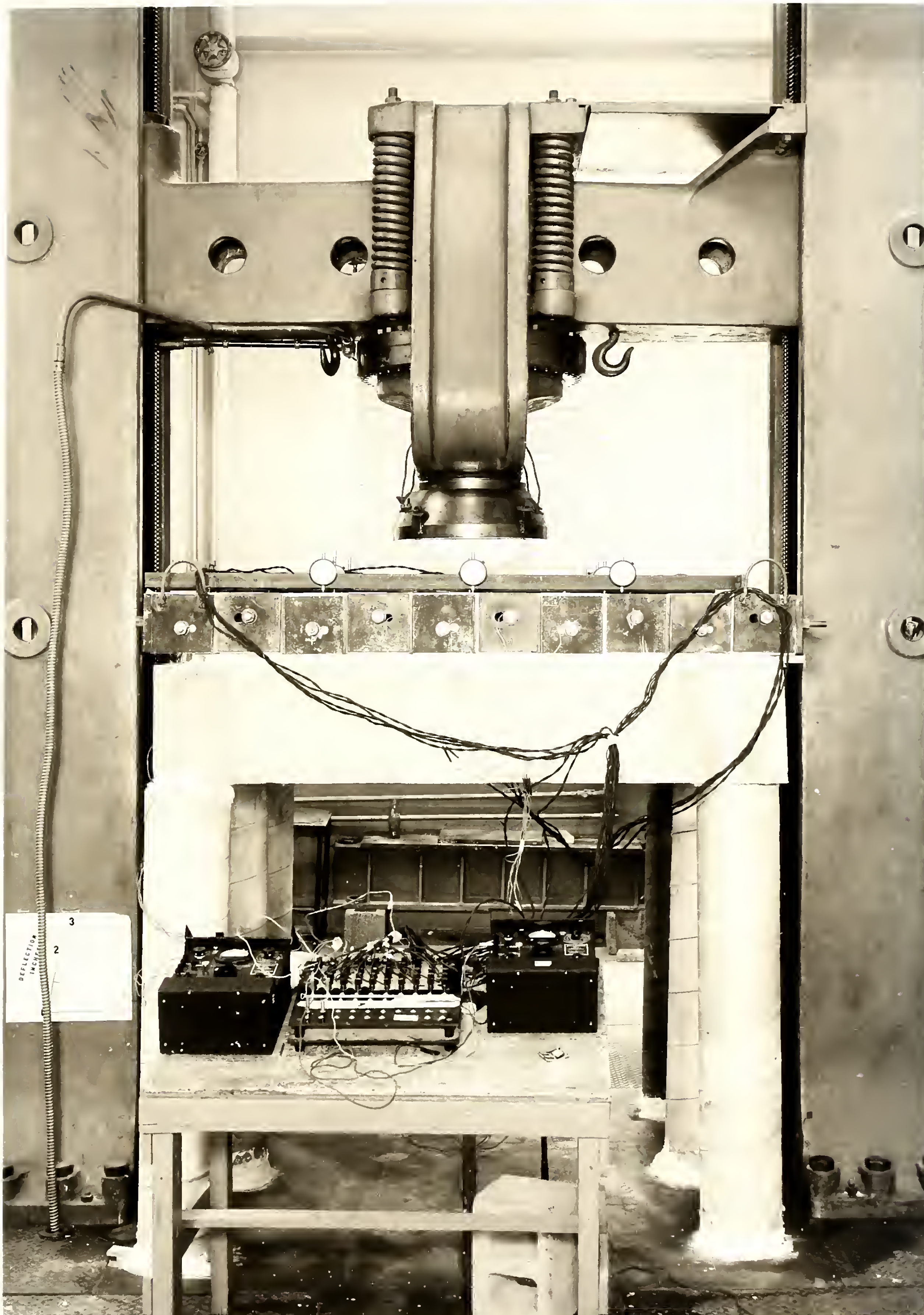


Fig. 4. View of the test setup of Slab No. 9.

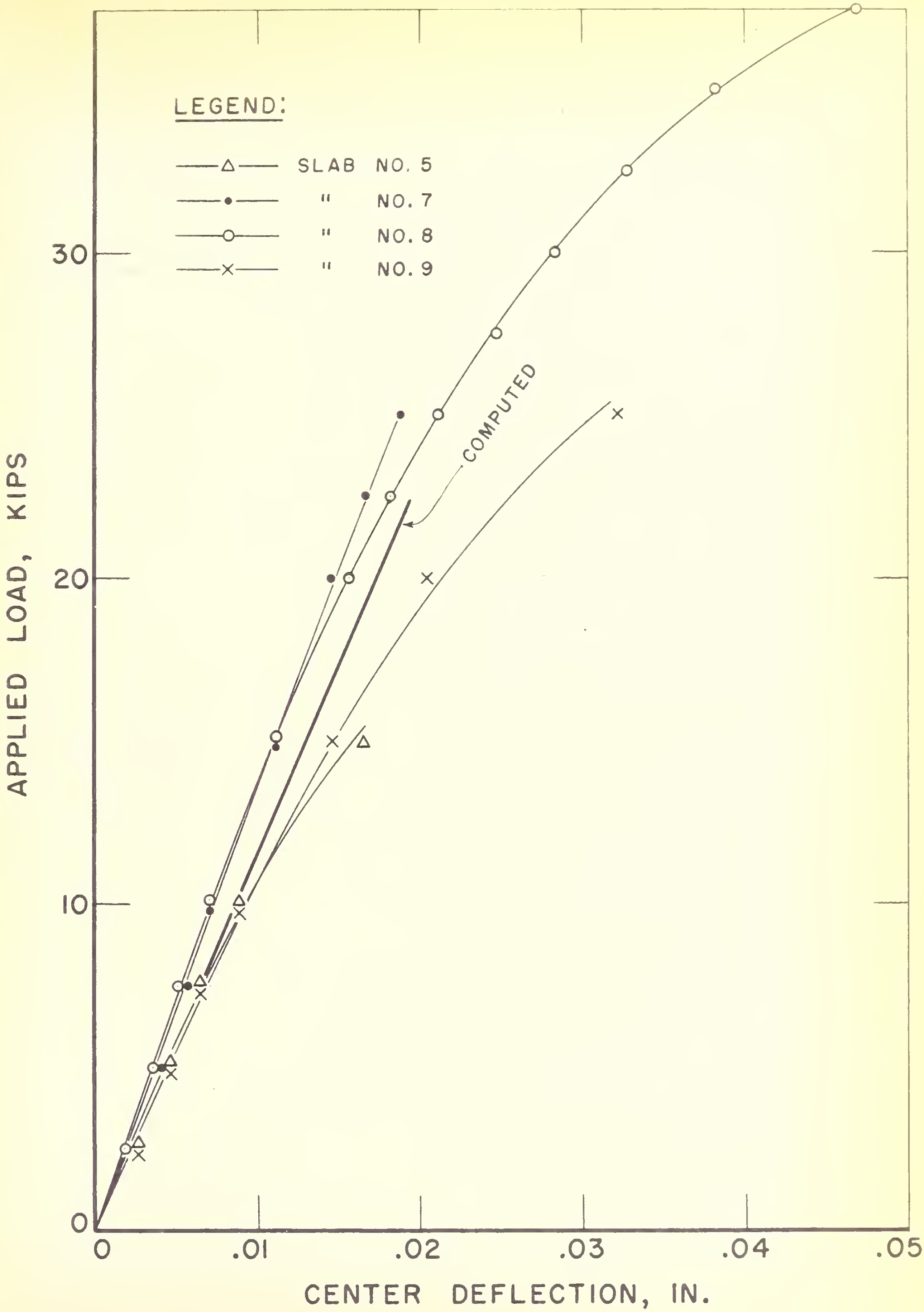
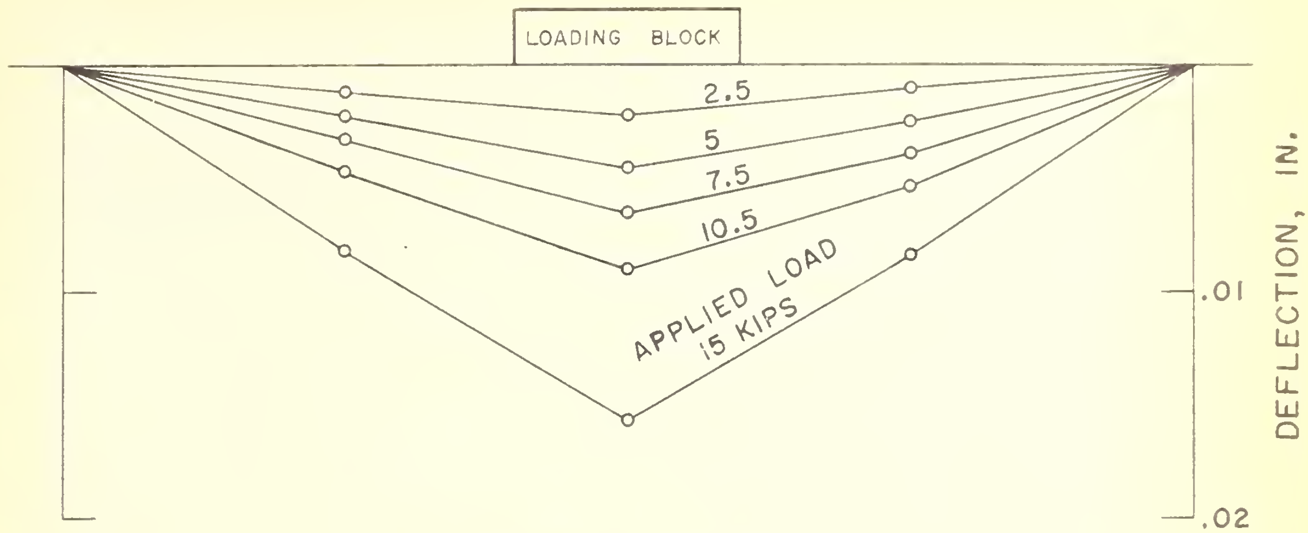
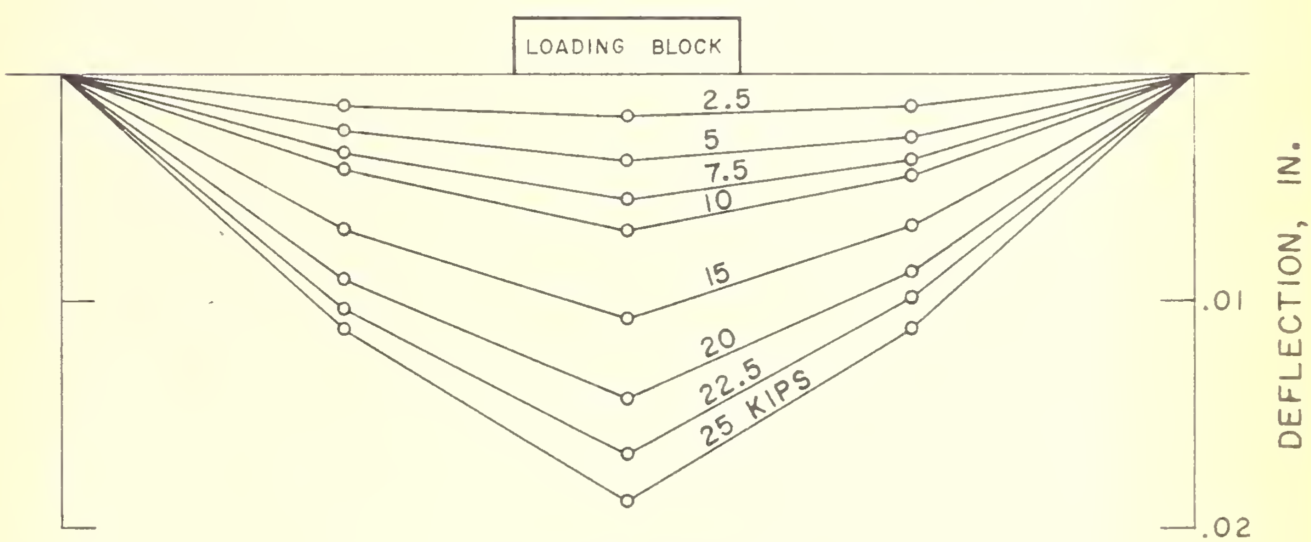


FIGURE 5. COMPUTED AND OBSERVED CENTER DEFLECTIONS IN SLABS NOS. 5, 7, 8 AND 9.



SLAB NO. 5



SLAB NO. 7

FIGURE 6. DEFLECTION PROFILES FOR SLABS NOS. 5 AND 7.

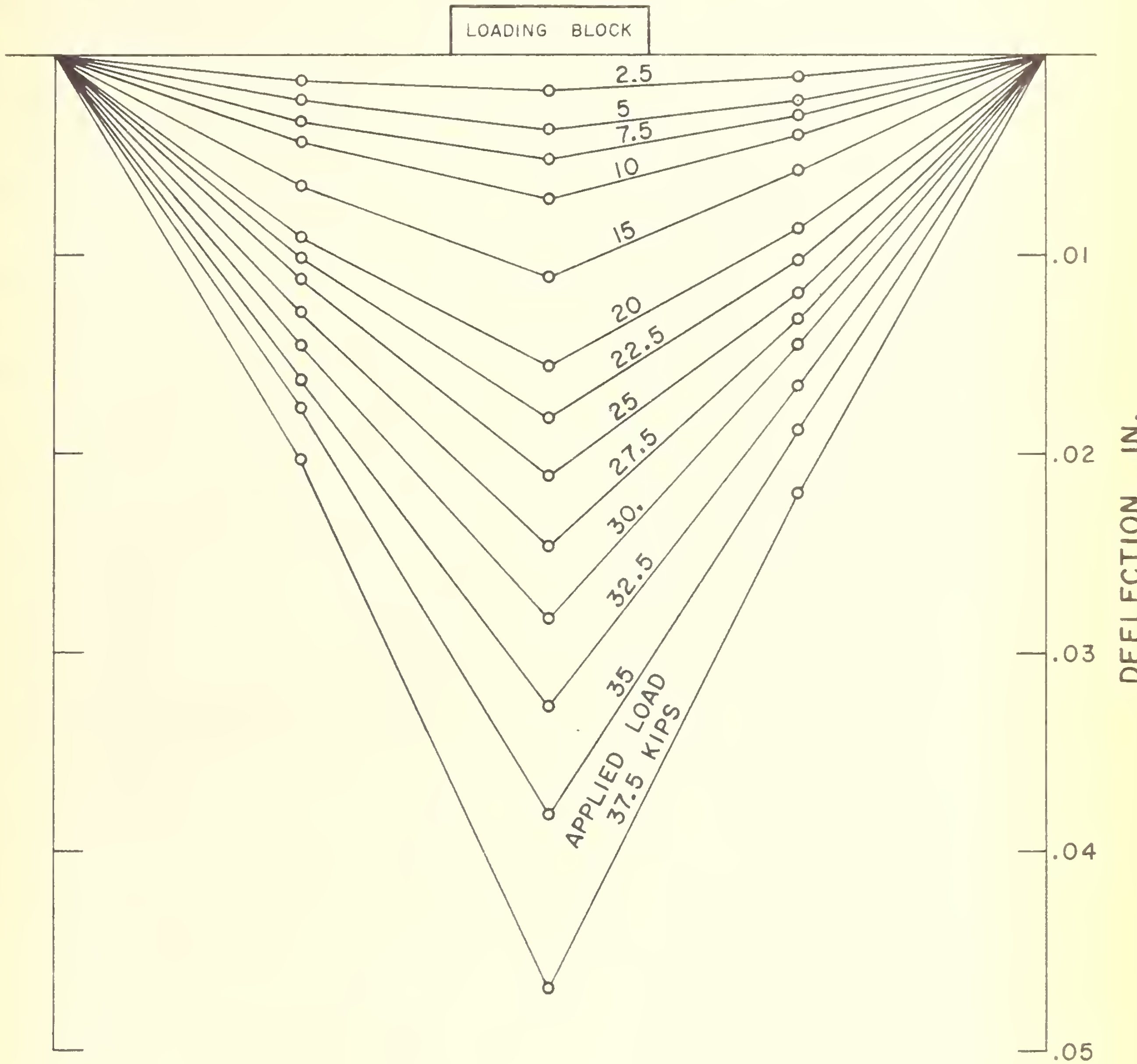


FIGURE 7. DEFLECTION PROFILE FOR SLAB NO. 8.

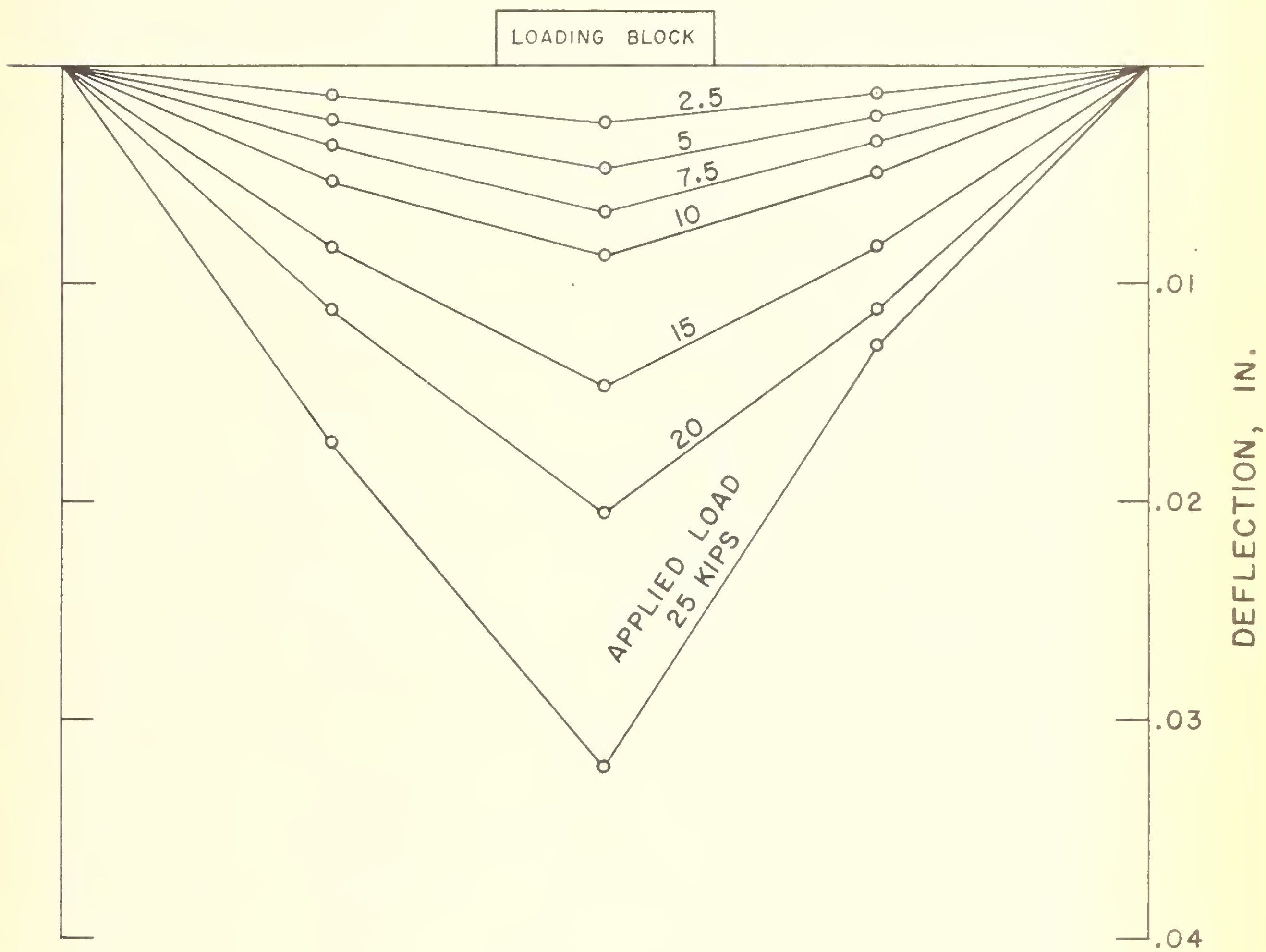


FIGURE 8. DEFLECTION PROFILE FOR SLAB NO. 9.

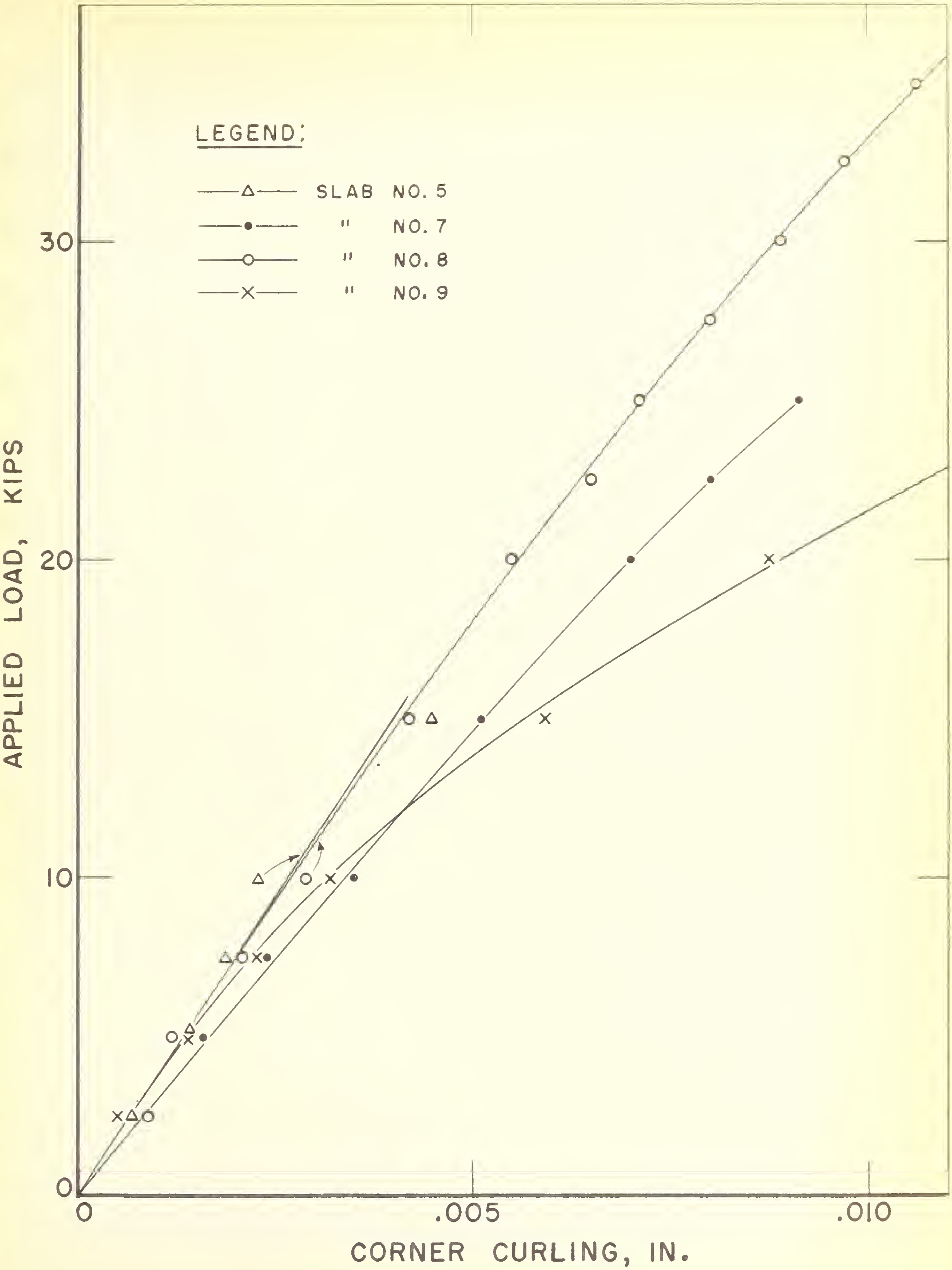


FIGURE 9. EXPERIMENTAL RELATIONSHIP BETWEEN APPLIED LOAD AND VERTICAL MOVEMENT OF CORNERS.

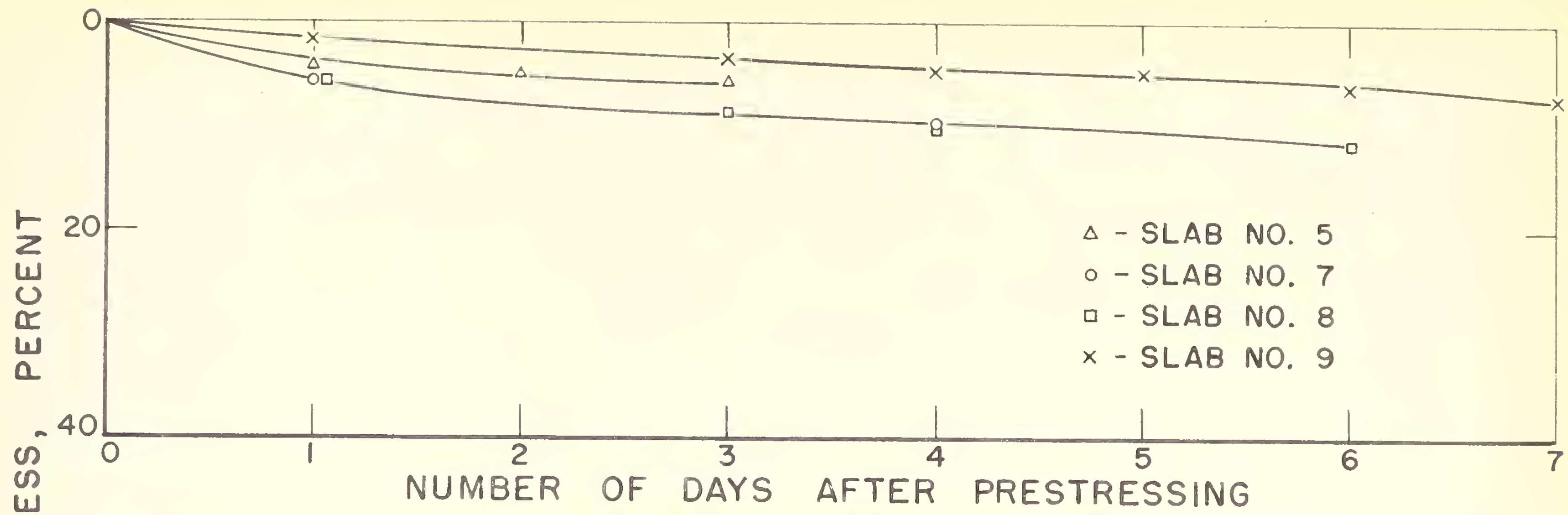


FIGURE 10. LOSS OF STRAIN IN PRESTRESSING TENDONS PRIOR TO TEST.

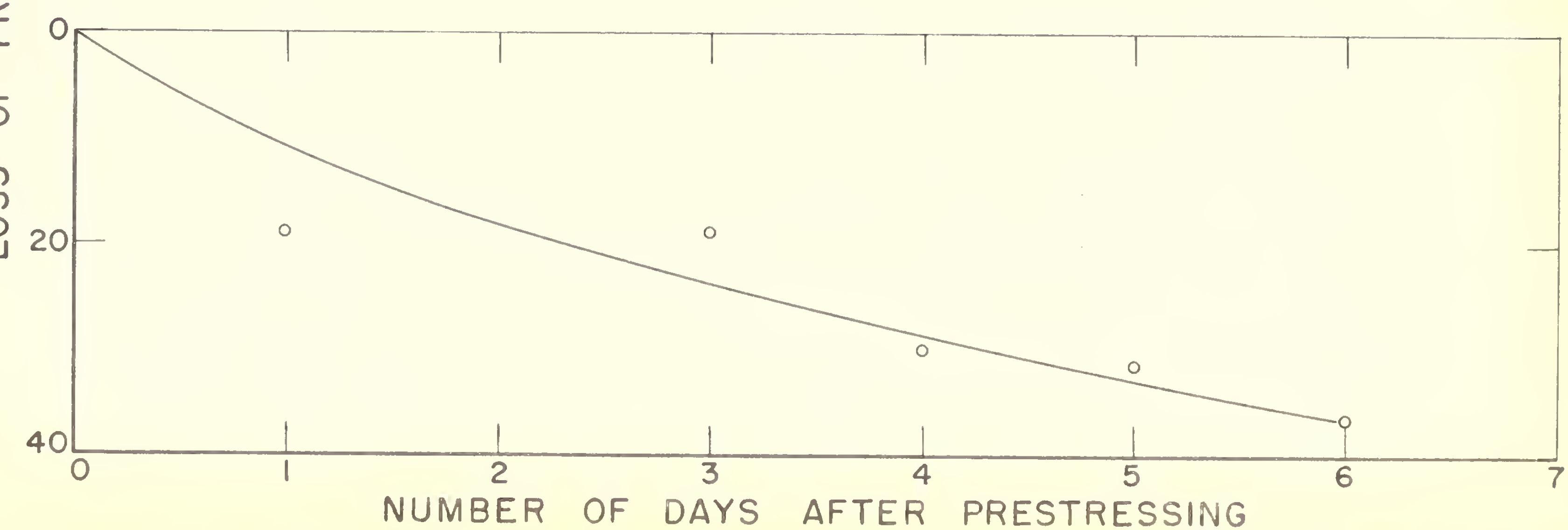


FIGURE 11. LOSS OF PRESTRESS IN CONCRETE OF SLAB NO. 5 PRIOR TO TEST.

FIGURES 10 & 11.

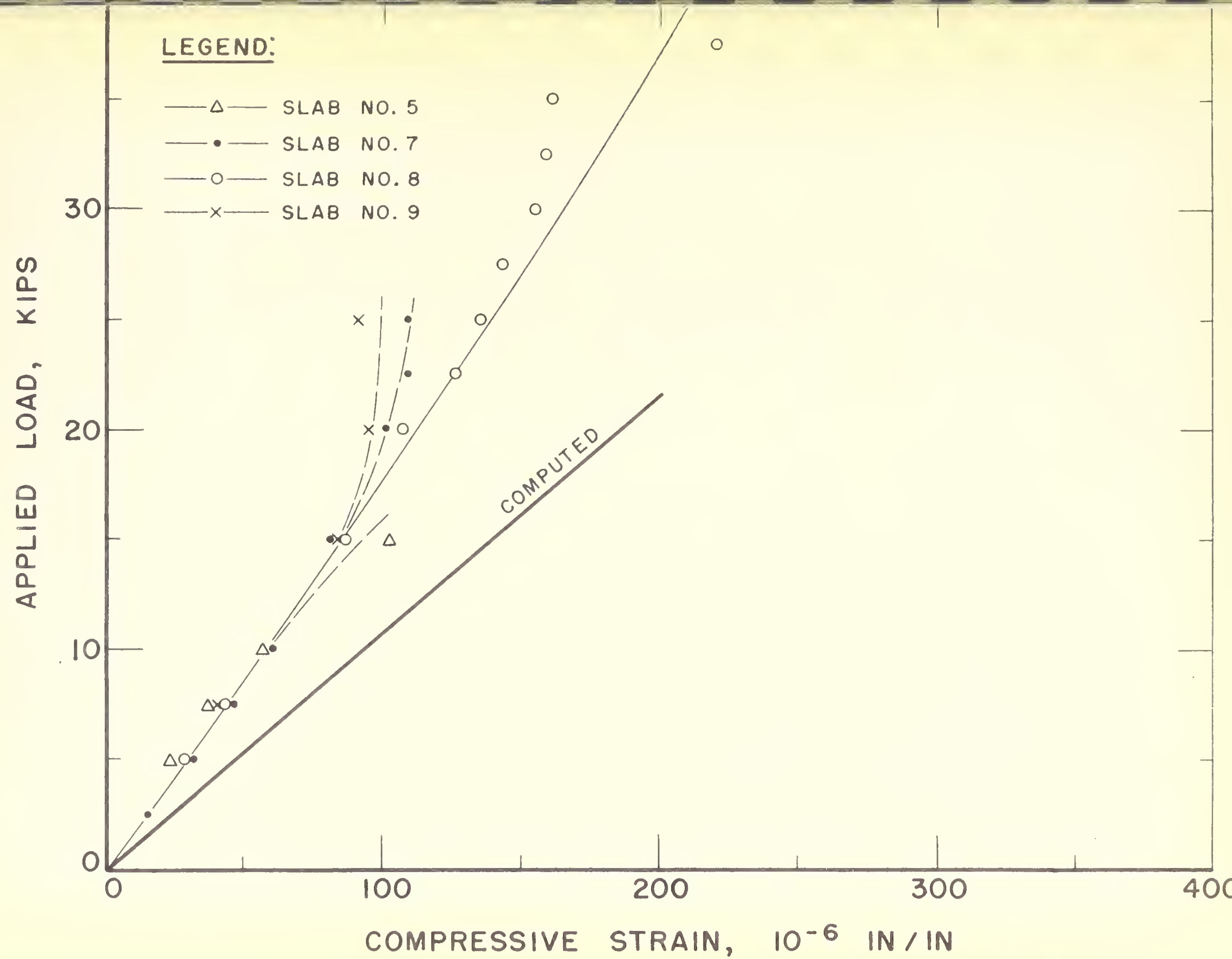


FIGURE 12. RELATIONSHIP BETWEEN APPLIED LOAD AND COMPRESSIVE STRAIN IN CONCRETE.

FIGURE 12.

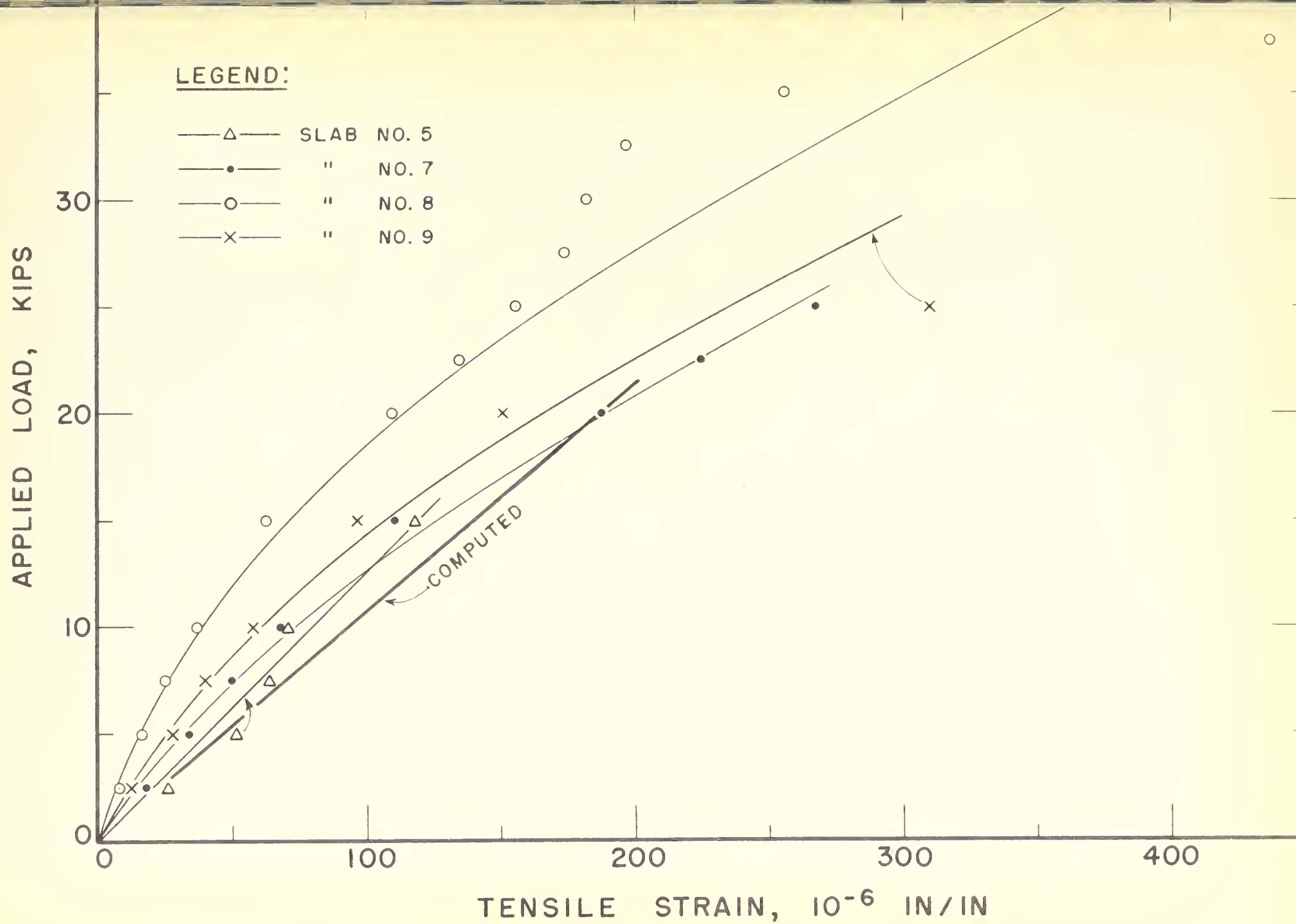
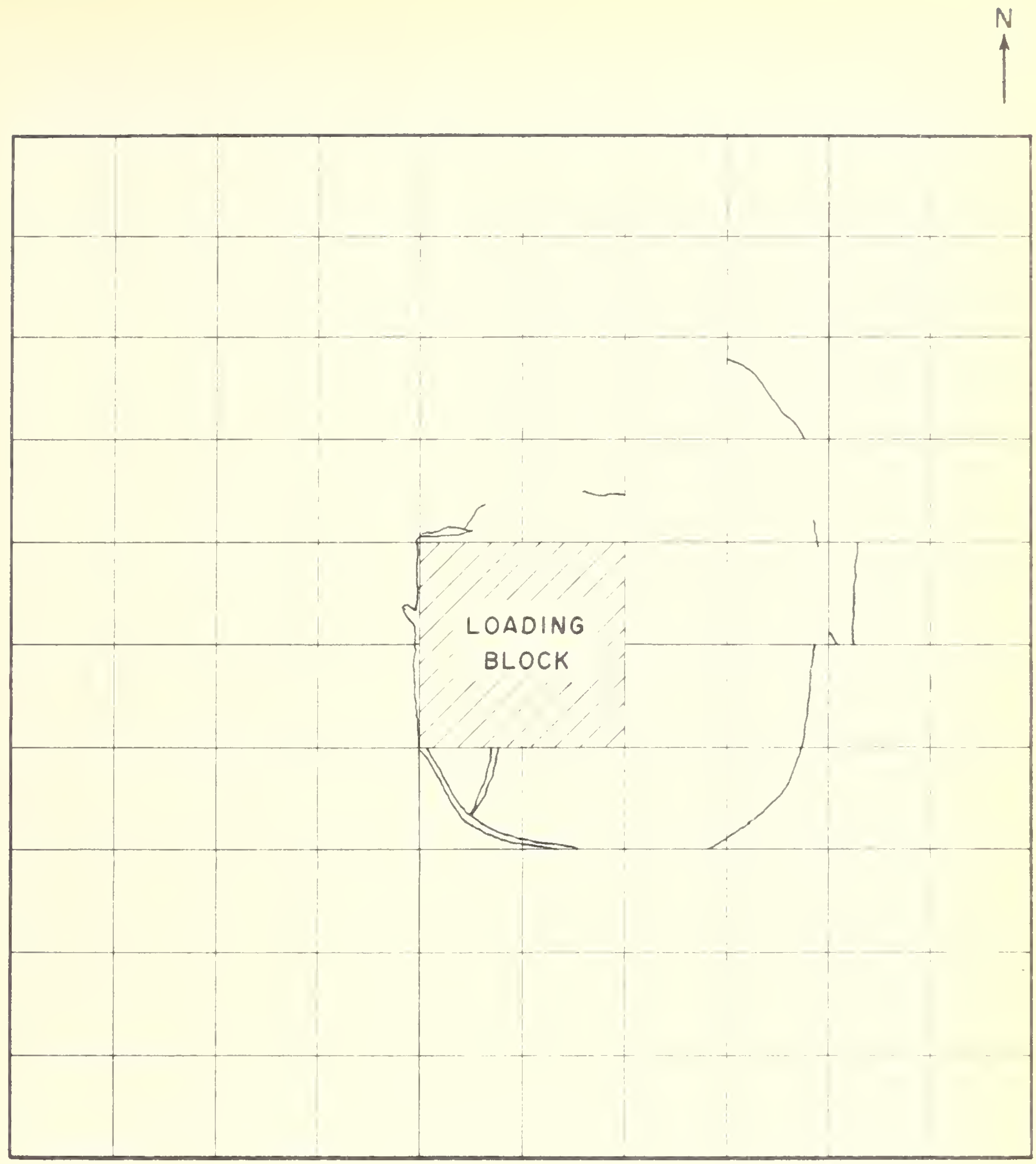


FIGURE 13. RELATIONSHIP BETWEEN APPLIED LOAD AND TENSILE STRAIN IN CONCRETE.

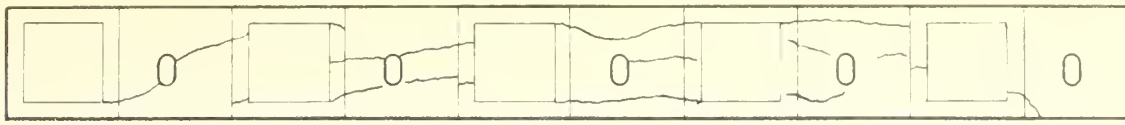
FIGURE 13.



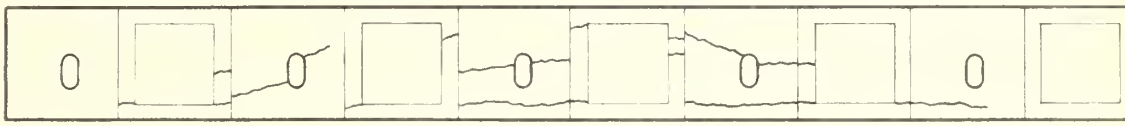
TOP VIEW AFTER FAILURE

(BOTTOM SURFACE INTACT)

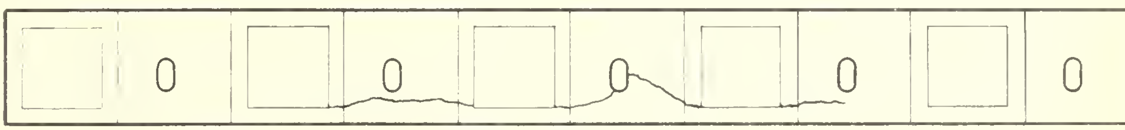
FIGURE 14. VIEW OF TOP SURFACE OF SLAB NO. 5 AFTER TEST.



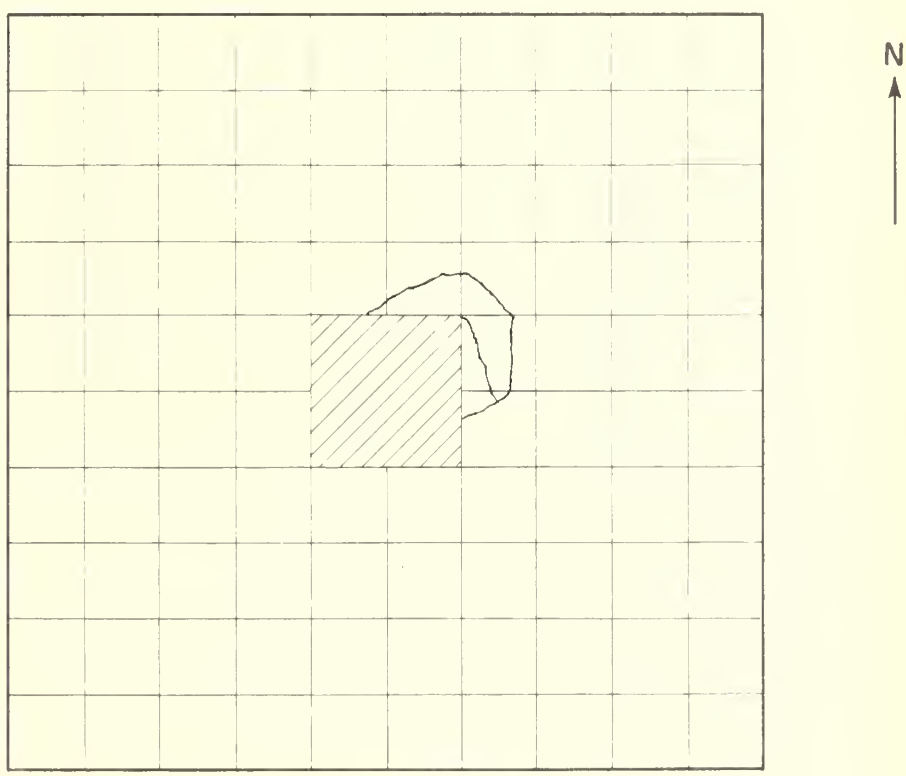
SECTION 8-8



SECTION 9-9



SECTION 10-10



TOP VIEW

(BOTTOM INTACT)

FIGURE 15. VIEW OF TOP SURFACE OF SLAB NO. 7 AFTER TEST.

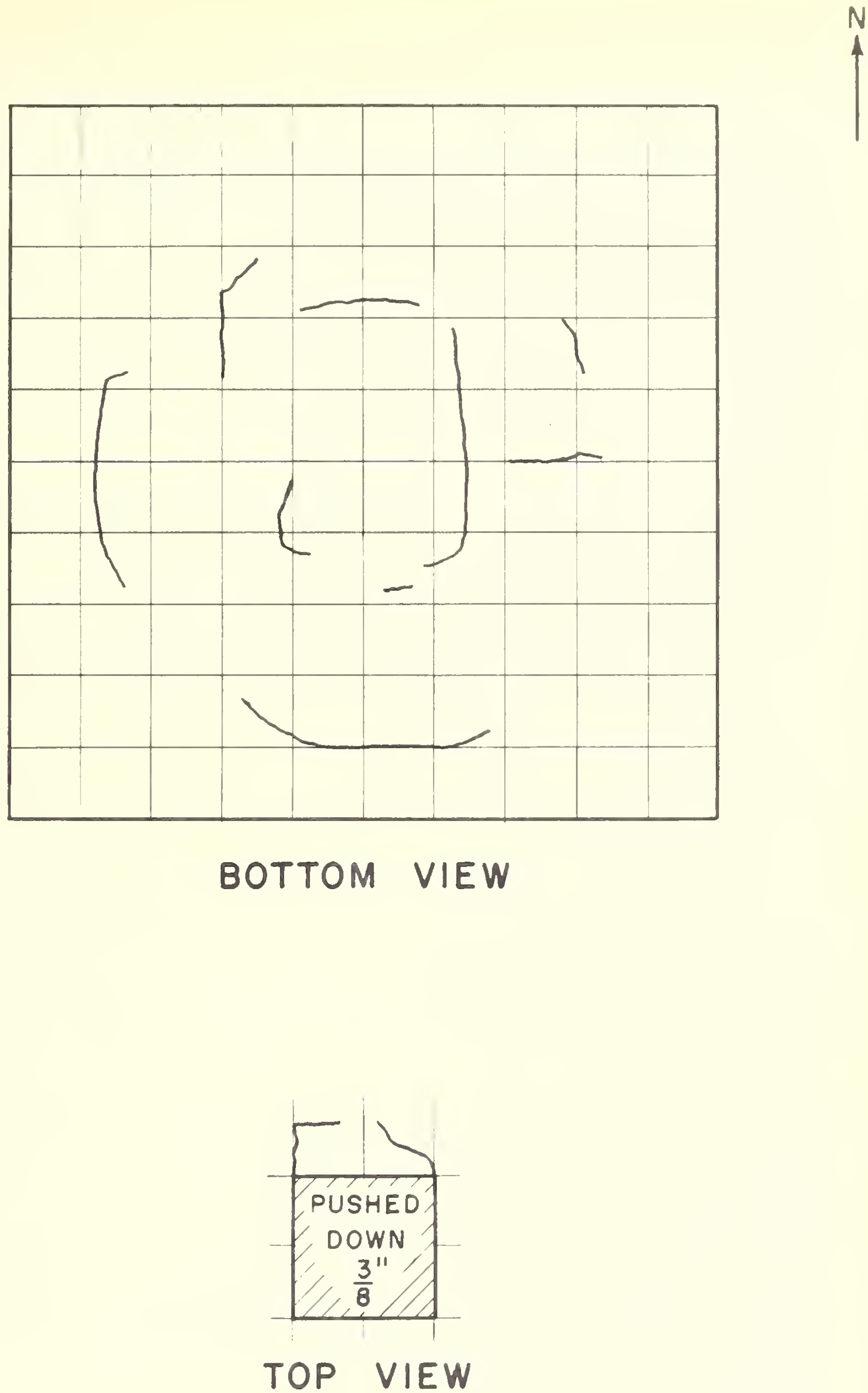


FIGURE 16. VIEWS OF SLAB NO. 8 AFTER TEST.

NOTE:

SOLID LINE INDICATES CRACKS ON BOTTOM SURFACE
DOTTED LINE INDICATES CRACKS ON TOP SURFACE

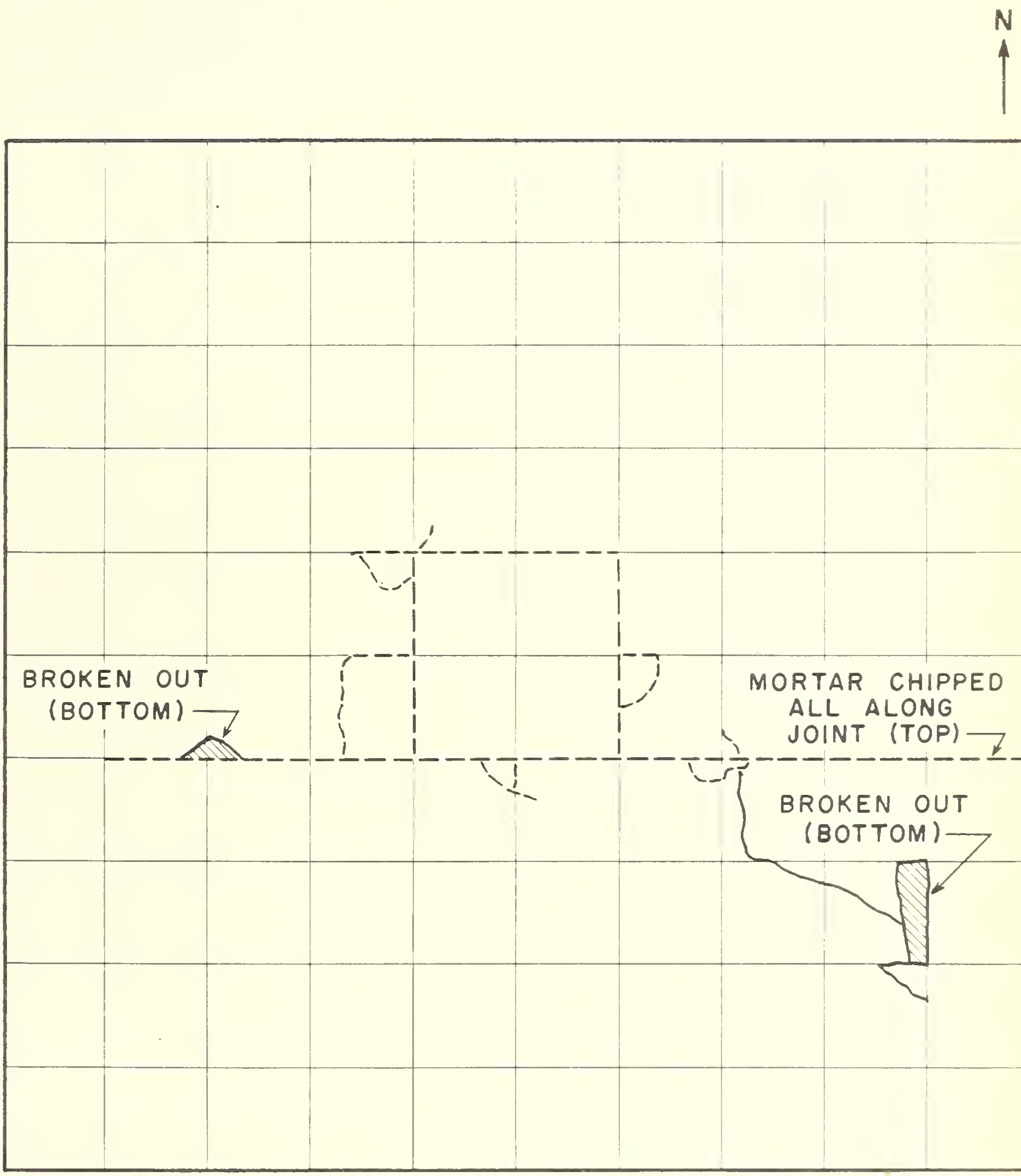


FIGURE 17. VIEWS OF SLAB NO. 9 AFTER TEST.

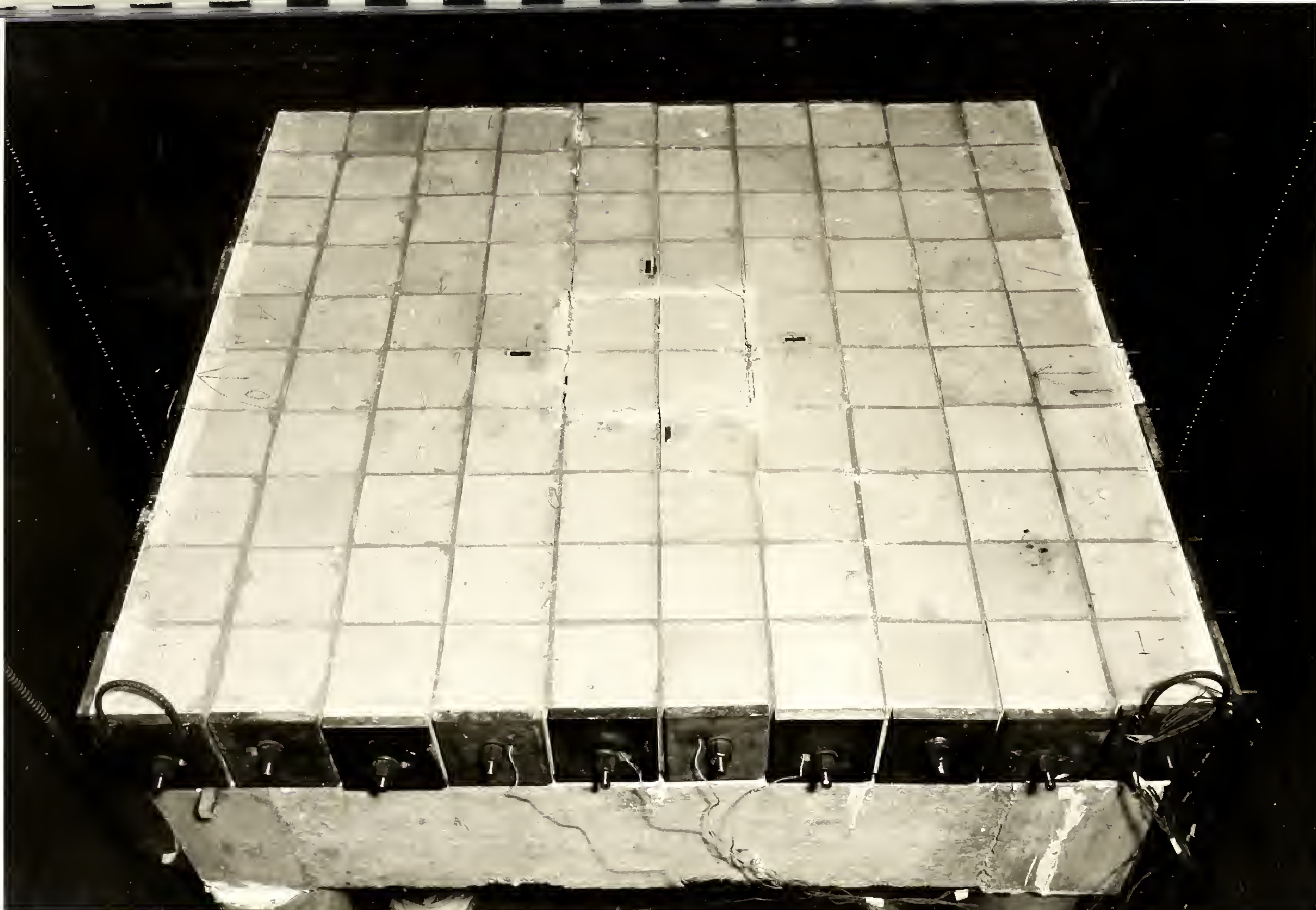


Fig. 18. Top view of Slab No. 9 after test.

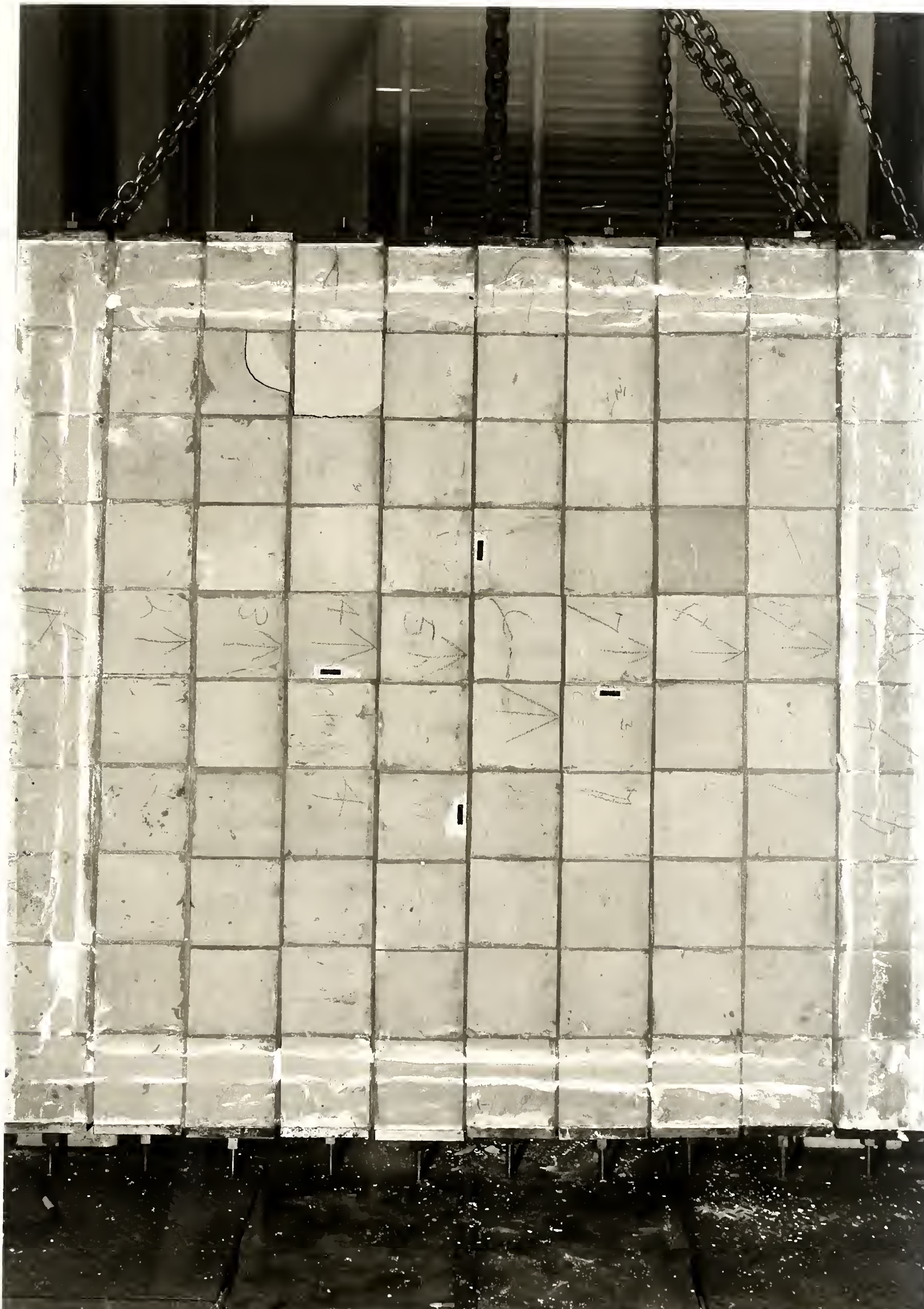


Fig. 19. Bottom view of Slab No. 9 after test.

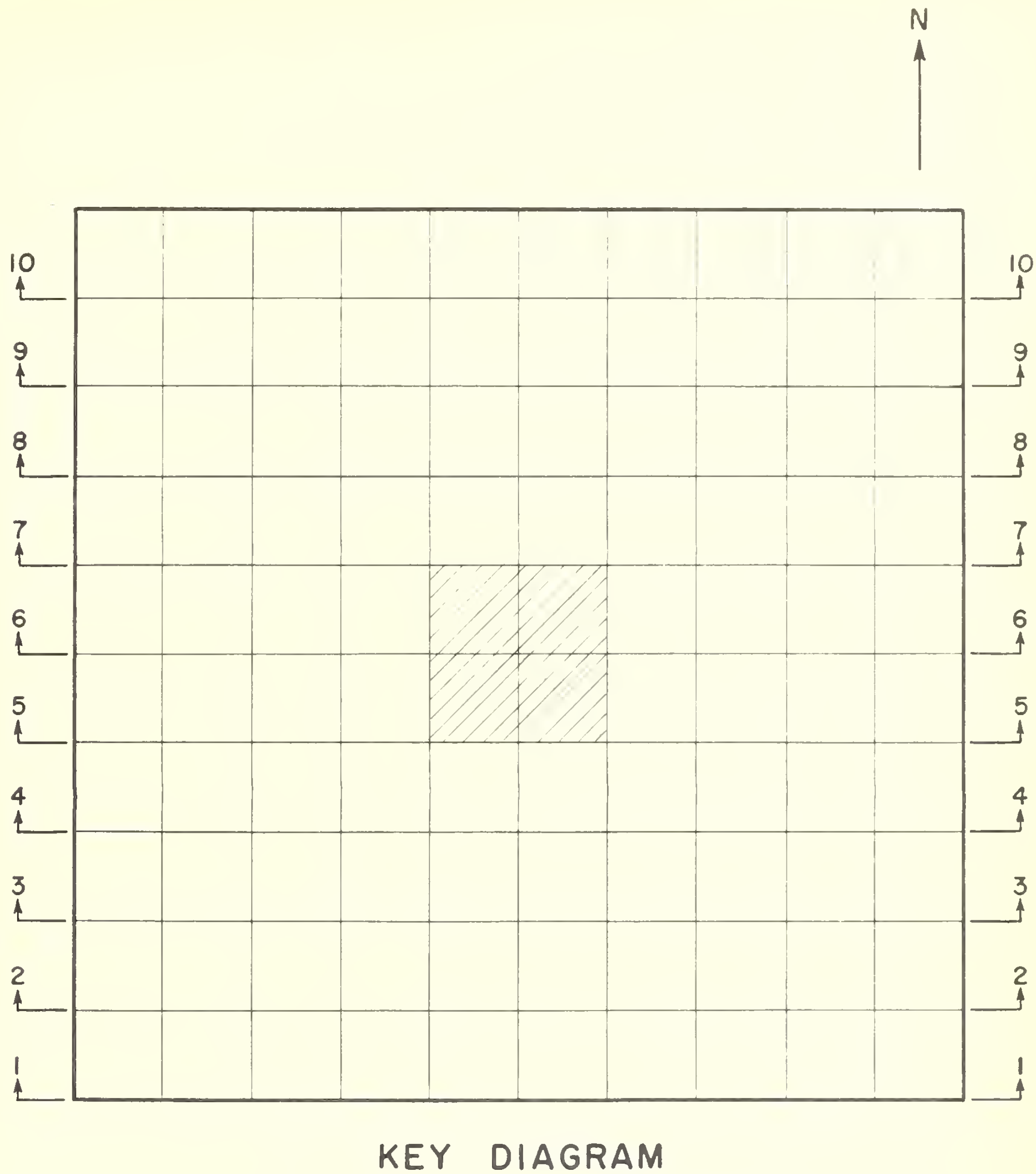
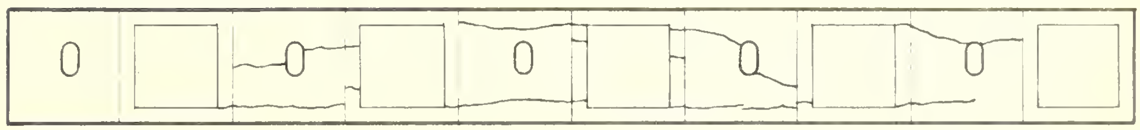
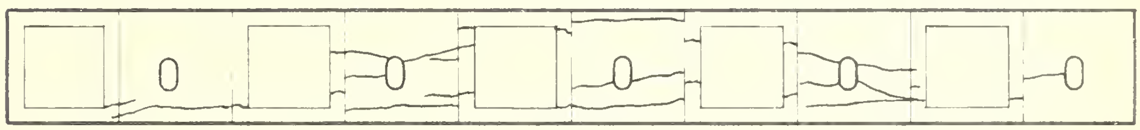


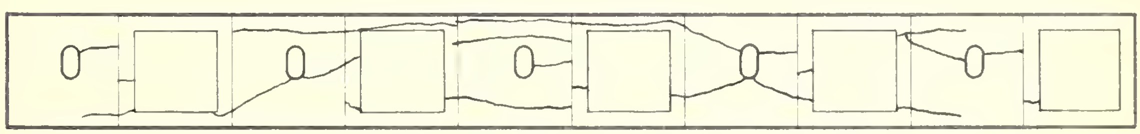
FIGURE 20. DIAGRAM SHOWING LOCATION OF SECTIONS OF SLABS IN FIGURES 21 THROUGH 25.



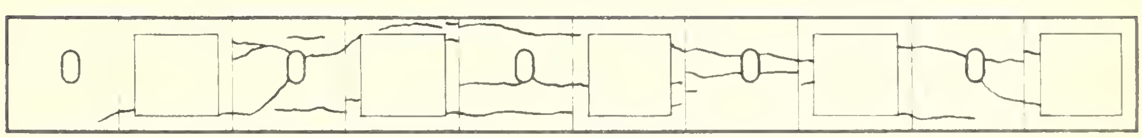
SECTION 2-2



SECTION 3-3

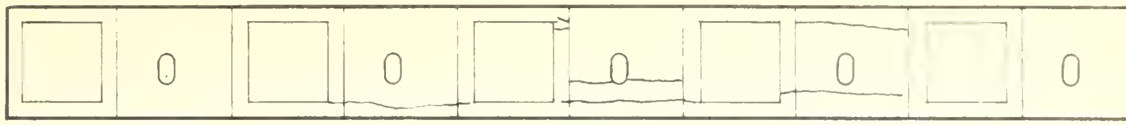


SECTION 4-4

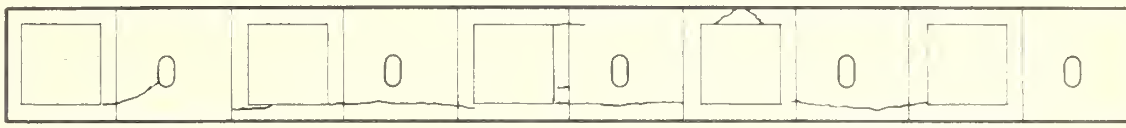


SECTION 6-6

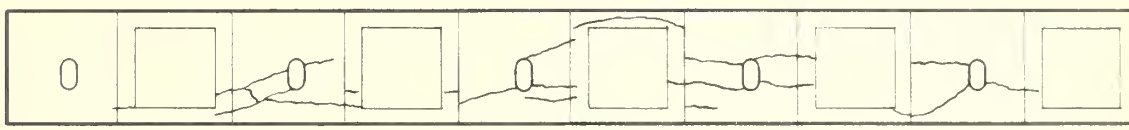
FIGURE 21. CRACK PATTERN IN SECTIONS OF SLAB NO. 5.



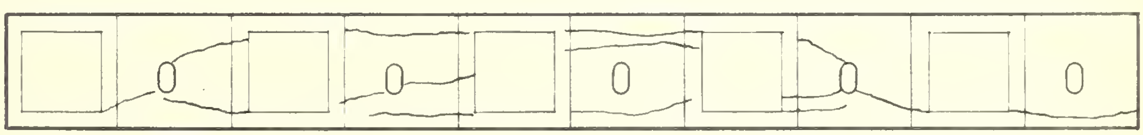
SECTION 1-1



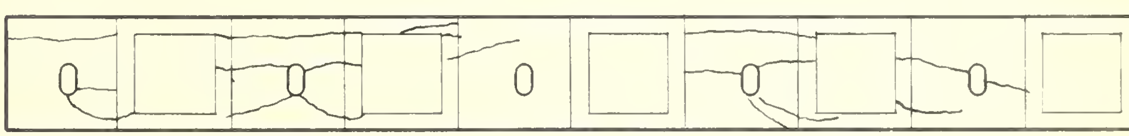
SECTION 2-2



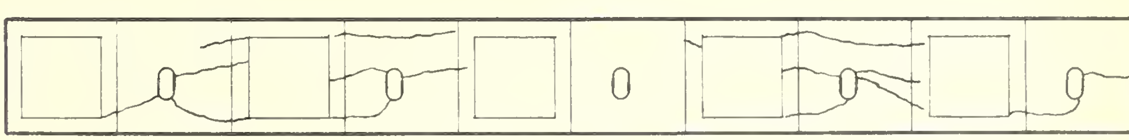
SECTION 3-3



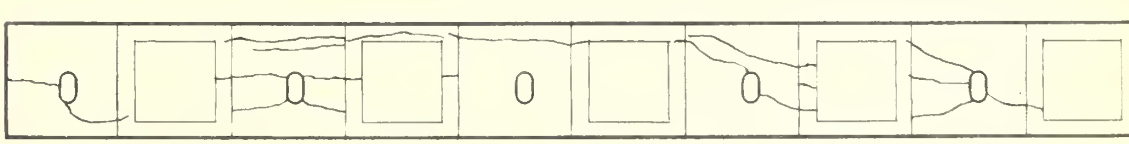
SECTION 4-4



SECTION 5-5

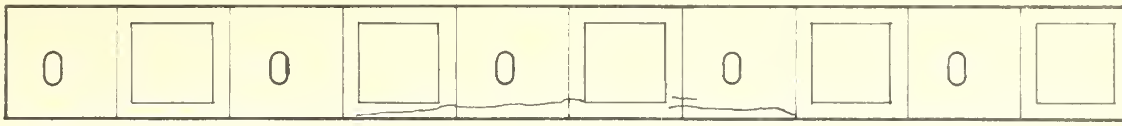


SECTION 6-6

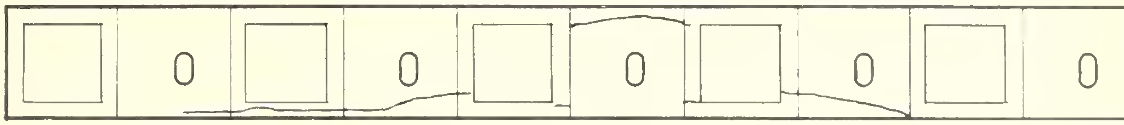


SECTION 7-7

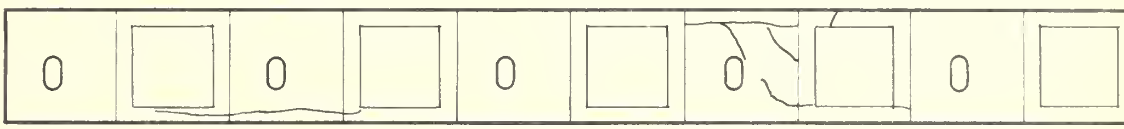
FIGURE 22. CRACK PATTERN IN SECTIONS OF SLAB NO. 7.
(CONTINUED IN FIGURE 15).



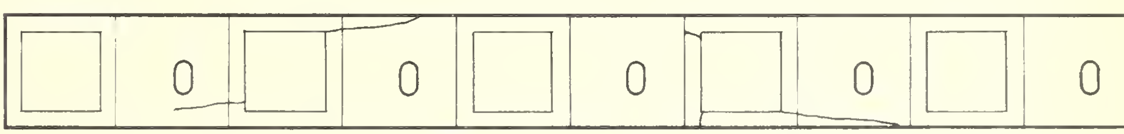
SECTION 3-3



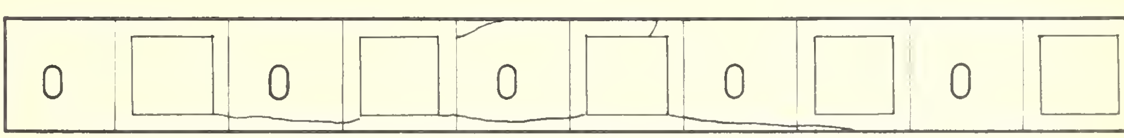
SECTION 4-4



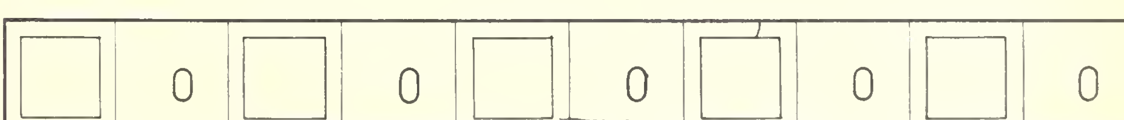
SECTION 5-5



SECTION 6-6

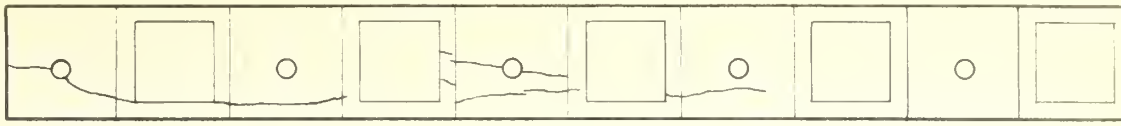


SECTION 7-7

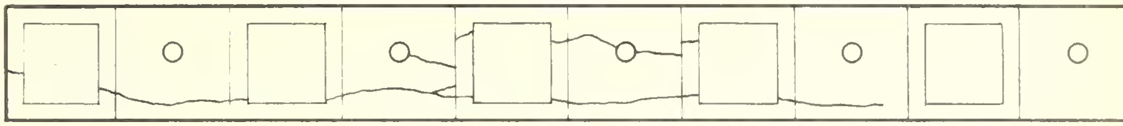


SECTION 8-8

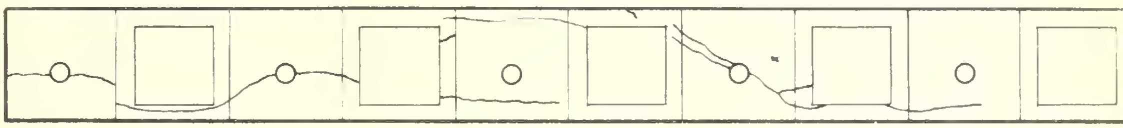
FIGURE 23. CRACK PATTERN IN SECTIONS OF SLAB NO. 8.



SECTION 2-2



SECTION 3-3



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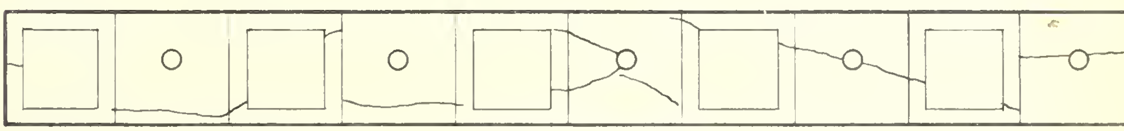
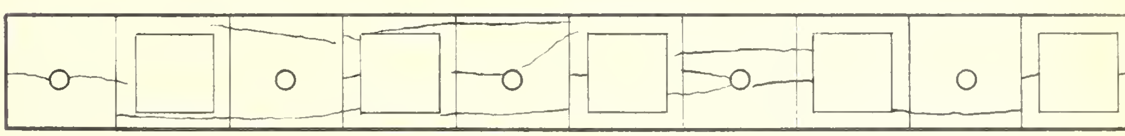
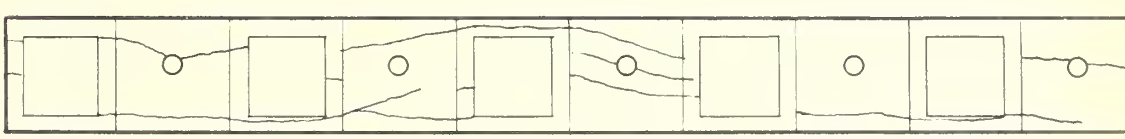


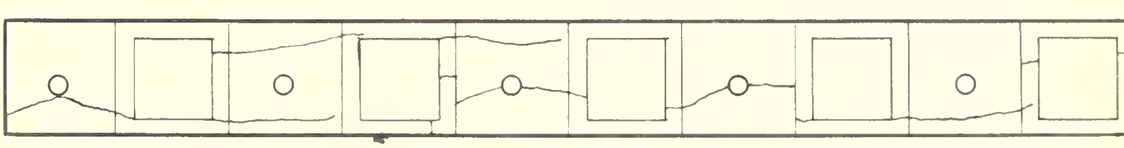
SECTION 5-5



SECTION 6-6



SECTION 7-7



SECTION 8-8

FIGURE 24. CRACK PATTERN IN SECTIONS OF SLAB NO. 9.

Fig. 25. View of sections through Slab No. 9.

Fig. 26. Bursting effect of prestressing force on structural clay units.

THE NATIONAL BUREAU OF STANDARDS

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