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The Elastic Properties of Concrete Under Bi-Axial Loading

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THE ELASTIC PROPERTIES OF CONCRETE UNDER BI-AXIAL LOADING

BY

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THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

FLOYD HAYS MILLARD

ENTITLED THE ELASTIC PROPERTIES OF CONCRETE
UNDER BI-AXIAL LOADING

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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A N Talbot
In Charge of Major Work

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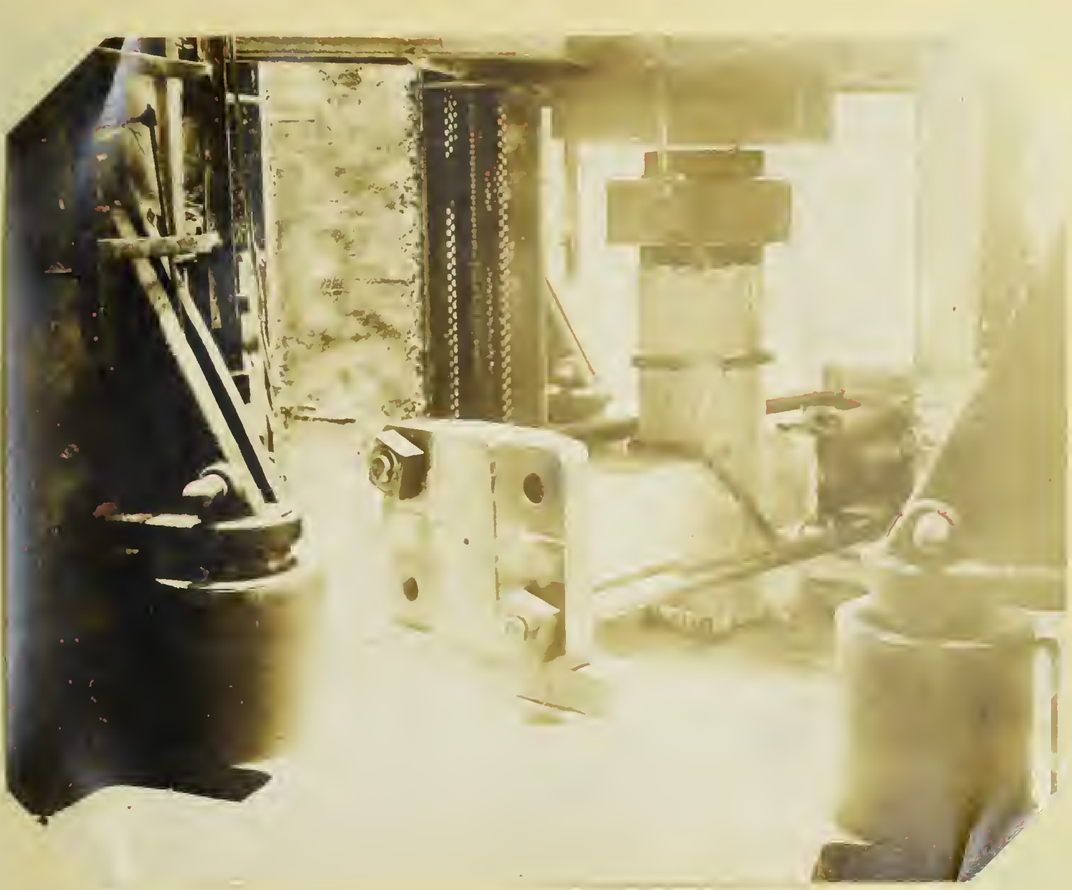
Recommendation concurred in:

Committee
on
Final Examination



Frontispiece.

Compression Specimen, Expansometers in Position.

THE ELASTIC PROPERTIES OF CONCRETE UNDER BI-AXIAL LOADING.

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I.

INTRODUCTION.

THE ELASTIC PROPERTIES OF CONCRETE UNDER BI-AXIAL LOADING.

I. INTRODUCTION.

1. Preliminary.-Many examples of concrete stressed in two directions may be found in buildings and other engineering structures, but the most common and probably the most important example is the comparatively new type of construction found in girderless floors. The flat plate of homogeneous material does not readily lend itself to strict analysis. The analysis is even more difficult for a flat composite structure made of two materials such as concrete and steel. Confidence in this type of construction has been established by continued successful use and by recent tests in which actual elongations of the fibers have been measured. The stresses in the steel are principally pure tension, therefore measured deformation can at once be expressed as stress when the modulus of elasticity is known. The concrete is not under simple stress, but is subject to flexure in multiple directions; therefore the stress can not be exactly stated from a knowledge of the relation between stress and deformation obtained from a test in simple compression.

The present practice in the design of structures is largely empirical. The structure is designed to resist stresses found from bending moment formulas which are based on uncertain analyses or on so-called tests. The ordinary working stresses in the materials have been used. The designs have been quite generally satisfactory but the limit of economy of the flat slab system of construction has not been established.

We must look to the results of tests of actual structures to determine where the stresses are greatest, where the designs should be strengthened and where they may be cut down.

Deformations can be measured but they mean very little to the designer until they have been expressed in terms of stress. Consequently it is desirable to establish an exact relation between stresses and deformations of concrete bi-axially loaded and to find the similarity or difference between the stress-deformation relation thus found and the relation under simple loading. Present practice assumes the same relations under bi-axial loading conditions as under simple loading, an assumption which is made for want of a better one and which may be far from correct.

As far as can be learned, no experiments have previously been made on concrete under compound stress. This pioneer investigation has been made to study the elementary features of that division of the problem which has to do with the design of flat plate floors. The test conditions were ideal, in that the exact nature and amount of the stresses were known.

The writer feels that a step has been made in the right direction, and that additional investigations, in which the several variables of the problem of design are studied singly, can be made, and from a sufficient number of properly planned tests that the uncertainties which are now so numerous may be, one by one, eliminated and that finally the design of a girderless or flat slab floor may be as exact and as well established as the design of a simple beam.

2. Scope of Investigation.- The points which are to be studied in this investigation are

(1) The ultimate unit deformation and the apparent initial modulus of elasticity of concrete stressed in two directions perpendicular to each other, and the relation of these values to the elastic properties of concrete stressed in one direction,

(2) The safe working stress and the ultimate strength of concrete stressed in two directions and the relation of these values to the working stress and ultimate strength of concrete stressed in one direction.

In this preliminary study, the effect of two compressive stresses at right angles and the effect of two bending stresses at right angles are the branches of compound stress taken up. The case of two equal compressive stresses and the case of two compressive stresses with one stress half as great as the other have been investigated and the results have been compared with the results of one compressive stress applied to the same form

of test piece. The case of two equal bending stresses at right angles was studied and the results of tests compared with the results of tests of compression specimens.

Combinations of two compressive stresses other than the two special cases reported here, combinations of compression and shear, or of more than two stresses combined, offer a broad and fruitful field of investigation which, it is hoped, someone will explore in the near future.

3. Acknowledgement.-These tests were made in the Laboratory of Applied Mechanics of the University of Illinois as a part of the research work of the University of Illinois Engineering Experiment Station. The work was in charge of Prof. A. N. Talbot who gave many helpful criticisms and interpretations of the results. W. A. Slater, First Assistant in the Engineering Experiment Station assisted in conducting the tests. Immediate supervision of making the forms and test specimens was given by D. A. Abrams, Associate in the Engineering Experiment Station. To these and other members of the staff acknowledgement is made for valuable assistance and suggestions.

II.

MATERIALS, TEST PIECES AND APPARATUS.

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<u>4. Materials and Their Properties</u>.-<u>Cement</u>. The cement used was furnished by the Universal Portland Cement Co. Tests of samples taken at times during the season were made in the Cement Testing Laboratory and are given in Table I. The tests were made by Mr. B. L. Bowling.

Table I.

BRIQUETTE TESTS OF CEMENT.

Each value is the average from five tests.

Loads are given in pounds per square inch.

Sample No.	Date	Neat Cement		1 - 3 Mortar	
		7 Days	28 Days	7 Days	28 Days
1	Oct. 25, 1911	585	685	239	315
2	Nov. 11, 1911	577	694	225	297
3	Dec. 7, 1911	691	715	242	306
4	Dec. 22, 1911	617	792	231	326
5	Jan. 10, 1912	588	672	246	333
6	Feb. 12, 1912	612	758	253	323
7	Feb. 28, 1912	698	884	287	372
Average		624	743	246	325

Additional tests on this cement showed the initial set to occur after 3-hr. 5-min. and final set after 6-hr. 32-min. Sieve tests showed 97.2 per cent passing a No. 100 sieve and 81.8 per cent passing a No. 200 sieve.

<u>Sand.</u> The sand used was torpedo sand from Attica, Indiana. It was of good quality, fairly sharp, clean and well graded as shown by the mechanical analysis given in Table II. It combined with the coarse aggregates used in a very satisfactory manner. It was from the same locality and of the same quality as the sand used in making the concrete and reinforced concrete test specimens for several years at the University of Illinois.

Table II.

MECHANICAL ANALYSIS OF SAND - 1912

Average of 5 Samples

Sieve No.	Separation Size, in.	Per Cent Passing
3	0.28	100
5	.174	88
10	.091	54.3
12	.067	47.5
16	-	41.7
18	.043	32.9
30	.027	21.2
40	.019	13.3
50	.013	5.1
74	.009	2.7
150	-	1.0

<u>Stone.</u> A good quality of rather hard limestone from Kankakee, Illinois, specified to pass through a 1-in. ring and over a screen with 1/4-in. meshes, was used. A mechanical analysis of the stone has been made and the results are shown in Table III. The stone is representative of the stone most used in building construction of reinforced concrete in Illinois and is the same

grade of stone which has been used in making the laboratory test specimens for some time. Inspection of the fractured specimens did not show that the stone had crushed or split. In one cylinder however the cement did not seem to adhere well to the stone but rather to the fine crusher dust on its surface.

Table III.

MECHANICAL ANALYSIS OF STONE - 1912.

Average of 5 Samples.

Size of Square Opening	Separation Size in.	Per Cent Passing
1-in.	-	100
3/4-in.	-	95.5
1/2-in.	-	66.7
3/8-in.	-	46.3
No. 3	0.28	25.9
No. 5	0.174	8.1
No. 10	0.091	3.4

Steel. The steel used in the crossed beams consisted of plain round bars 5/8 in. in diameter. They were of mild open hearth steel. Tests of two bars cut from lengths used in the beams indicated a yield point of 37850 lb. per sq.in. and an ultimate strength of 58150 lb. per sq.in. The modulus of elasticity as determined from the tests was 31 100 000 and 31 400 000 lb. per sq.in. in the two cases. The stress-deformation diagrams appear among the curves in the back of the thesis.

Concrete. This investigation was in progress at the time the Engineering Experiment Station changed from hand-mixed to

machine-mixed concrete. Consequently both kinds of 1-2-4 concrete were used in making test specimens. This is fortunate in that it gives the opportunity to study the phenomena of both concretes under practically identical conditions.

The hand-mixed concrete was prepared in the same way as the concrete previously used in experimental work by the laboratory. Men skilled in mixing concrete and in making test pieces were employed in the work. The foreman and other workmen are experienced concrete workmen; they have made the specimens for the laboratory for seven seasons. The mixing was done with shovels. The sand and stone were first measured by loose volume, and then weighed to check the measurement. A bag of cement (95 lb.) was considered as one cubic foot of cement. The sand and cement were first mixed dry; the stone which had been previously moistened was added and the mix turned until of a uniform appearance. Usually the first operation included five or six turnings and the second three or more. Water in sufficient quantity to produce a distinctly wet mixture was added. The whole was then turned until thoroughly mixed.

The machine-mixed concrete was prepared in a Marsh-Capron batch mixer with a rated capacity of 9 cu.ft. The materials were measured by loose volume and the measured quantities weighed as before. The mixer was started and the stone which had been previously wet was dumped in; then the sand was introduced, followed by about half the quantity of water which was to be used. The cement was dumped in and the remainder of the water added. The materials were mixed for a period of five

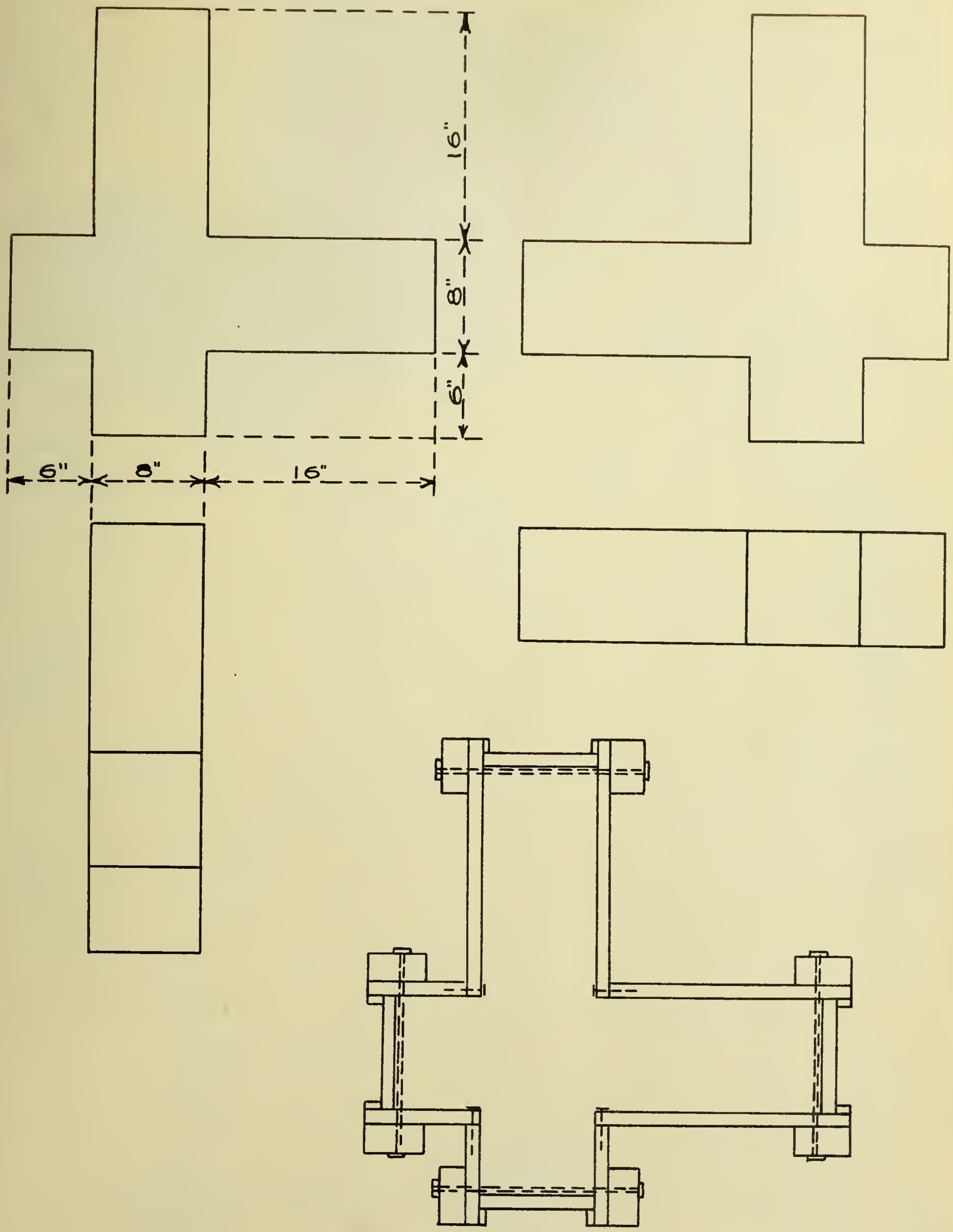
minutes after the last water had been added. The speed of the mixer was about 22 revolutions per minute. The entire charge of the mixer was dumped, when completed, on the cement floor of the mixing laboratory and carried to the forms in buckets. The mass of concrete as discharged from the mixer appeared to be very thoroughly mixed and had the appearance of a richer concrete than was produced by hand-mixing with the same proportions of ingredients.

On account of the small size of the specimens it was convenient to make more than one test piece from each batch.

5. Details of Test Specimens.-As was mentioned above, this investigation takes up the action of two compressions and of two bending stresses. Several unusual types of specimens were used, their form depending on the data sought.

For studying the effect of two compressions a novel type of specimen, shown in Fig. 1, page 21, was used. This specimen has been called the "compression specimen" throughout the report. Its general form is that of a Greek cross with unequal arms. The short arms were designed to be 8 x 8-in., 6-in. long, the long arms were designed to be 3 x 8-in., 16-in. long and the center or cross 8 x 8 x 8-in. All the compression specimens were 1-2-4 plain concrete. They were made on the floor of the mixing laboratory in wooden forms made of one inch pine stock, placed on a layer of building paper. See Fig. 1. Some difficulty was experienced while making the first specimens in keeping the forms square and in keeping them down on the floor. The thickness of the specimen was somewhat greater than shown in

Fig. 1. Compression Specimen and Forms.



the design. In making the later specimens, a wooden bottom was provided for the forms. The actual dimensions of the compression specimens before they were tested are given in Table IV, page 23.

It was anticipated that the compression specimens might not fail at the center, and in order to determine the strength of concrete bi-axially loaded in perpendicular directions, several 8-in. cubes were made. Two 8-in. cubes were made from each batch of concrete used in making a specimen, and in addition several more sets of cubes were made. These separate 8-in. cubes are numbered 2055-A, 2055-B, 2056-A, 2056-B, 2057-A, 2057-B, 2058-A and 2058-B. The 8-in. cubes were made in pairs in steel forms.

For studying the effect of two bending stresses, crossed beams were made. A crossed beam consists of two simple beams 12 in. wide, 10 in. deep to the center of the steel, and 7 ft., 6 in. long over all, crossing at their centers. See Fig. 2. The crossed beams were reinforced with eight 5/8-in. round bars in each direction and had seven stirrups of 1/2-in. round, spaced 4 in. apart, at each end of each beam. The stirrups were bent into U-shapes with hooks at the top of each arm of the U. They were made to pass around six bars on one side of the beam and were staggered. In this way the center four bars were held by a stirrup every four inches and the outside two bars on each side were held by a stirrup every eight inches, as shown in Fig. 2. None of the horizontal rods were bent up but this would have been well, since failure occurred by diagonal tension.

Table IV.

DIMENSIONS OF COMPRESSION SPECIMENS.

No.	Type	Dimensions of Arm	Concrete
2050	Compression Specimen	8 x 8-3/8-in.	1-2-4 Hand-mixed
2051	Compression Specimen	8 x 8-1/4-in.	1-2-4 Hand-mixed
2052	Compression Specimen	8 x 8-1/8-in.	1-2-4 Hand-mixed
2053	Compression Specimen	8 x 8-1/8-in.	1-2-4 Hand-mixed
2054	Compression Specimen	8 x 8-in.	1-2-4 Machine-mixed
2055	8-in. Cubes	8x8x8-in.	1-2-4 Machine-mixed
2056	8-in. Cubes	8x8x8-in.	1-2-4 Machine-mixed
2057	8-in. Cubes	8x8x8-in.	1-2-4 Machine-mixed
2058	8-in. Cubes	8x8x8-in.	1-2-4 Machine-mixed
2059	Compression Specimen	8 x 8-1/8-in.	1-2-4 Machine-mixed
2061	Compression Specimen	8 x 8-1/4-in.	1-2-4 Hand-mixed
2062	Compression Specimen	8 x 8-1/8-in.	1-2-4 Hand-mixed
2063	Compression Specimen	8 x 8-1/8-in.	1-2-4 Hand-mixed
2071	Compression Specimen	8 x 8-1/4-in.	1-2-4 Hand-mixed
2072	Compression Specimen	8 x 8-1/8-in.	1-2-4 Hand-mixed
2073	Compression Specimen	8 x 8-1/8-in.	1-2-4 Hand-mixed

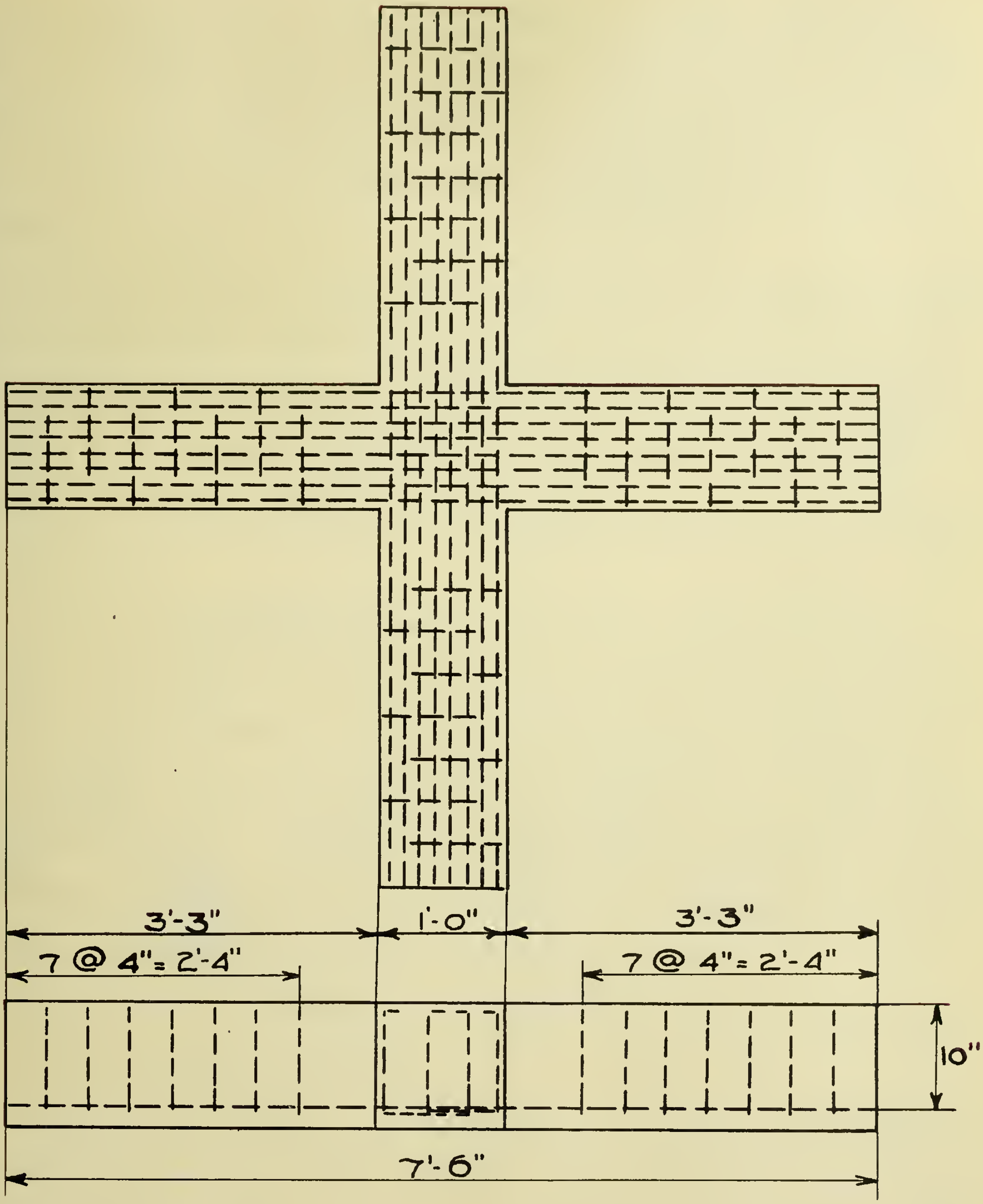


Fig. 2. Crossed Beam.

The crossed beams were made in forms of 2-in. pine stock, placed on a piece of building paper on the floor of the mixing laboratory. The forms were squared and securely blocked in place before they were filled. The forms are shown in detail in Fig. 3.

In order to have a basis for comparison of the various tests, auxiliary specimens were made from each batch of concrete used. One 8 x 16-in. cylinder and three 6-in. cubes were made from the middle of each batch. When two specimens were made from one batch, one cylinder and one set of cubes were made to control both specimens.

6. Method of Making Specimens.-The forms were placed on the floor of the mixing laboratory and were thoroughly sprinkled with water before any concrete was placed. Each specimen was given a number which was painted on the piece itself before the forms were removed. In making the compression specimens, concrete was placed a shovel full at a time, and was spaded on the sides with a plasterer's trowel and tamped with a light bar. After filling the form, the top was troweled level with the side boards and a smooth surface produced.

In making the beams, concrete about 2 in. deep was placed in the forms and the steel and stirrups then placed and spaced. Care was taken to have the stirrups in their proper place and to have the steel at the proper distance from the compression face at all places. Concrete was placed a shovel full at a time and was churned with a small rod and spaded with a trowel as before. The top surface was troweled level with the forms and lifting rings inserted in the soft concrete.

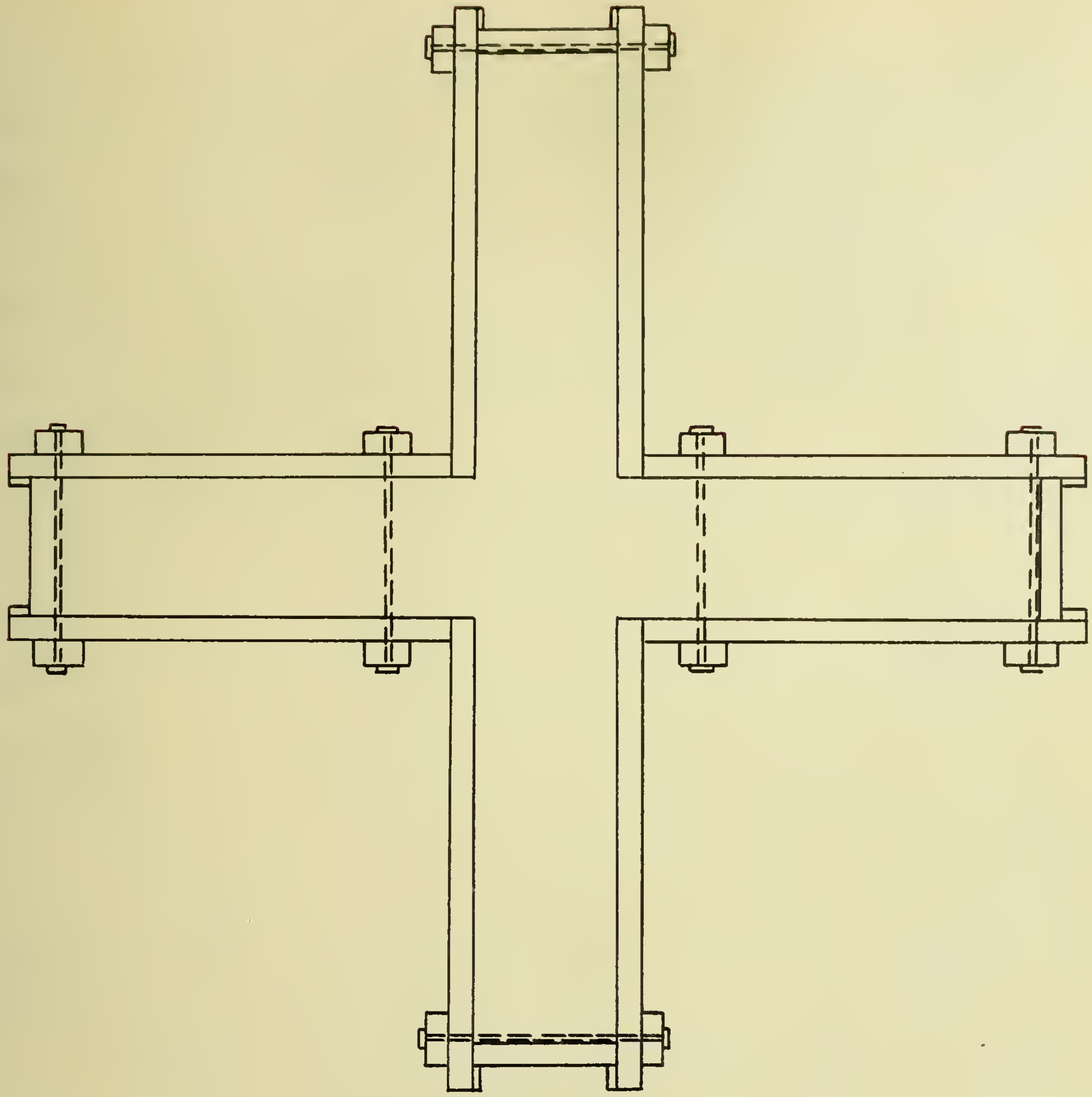


Fig. 3. Detail of Crossed Beam Forms.

The 8-in. and 6-in. cubes and the 8 x 16-in. cylinders were made in steel forms. Concrete was placed a little at a time and carefully spaded and tamped.

The compression specimens were made on their sides, the beams were made flat as tested and the cylinders were made on end. The cubes were tested with load on a face which was vertical during making.

The numbering system was such that from its number, the loading on a specimen could be determined. Compression Specimens which had 5 as the third figure of their number were tested with two equal compressions at right angles, those which had 6 as the third figure of their number were tested with half as great compression in one direction as the other, those which had 7 as the third figure of their number were tested with one compressive stress. The specimens which had 0 as the third figure of their number were crossed beams.

A knowledge of the specimens made from a batch is often valuable in interpreting the results. The dates of making the specimens were as follows: On October 28, 1911, specimens 2051 and 2001with two 8-in. cubes, three 6-in. cubes, one 8-in. cylinder and one control beam were made from one batch. On November 1, 2050 with three 6-in. cubes and one 8-in. cylinder were made. On November 2, 2002 and 2052 with two 8-in. cubes three 6-in. cubes, one 8-in. cylinder and one control beam were made from one batch. On November 8, 2061 and 2071 with two 8-in. cubes, three 6-in. cubes and two 8-in. cylinders were made from one batch. On November 11, 2062 and 2072 with two 8-in.

cubes, three 6-in. cubes and two 8-in. cylinders were made from one batch. On November 18, 2003 and 2053 with two 8-in. cubes, three 6-in. cubes, one 8-in. cylinder and one control beam were made from the same batch. On November 23, 2063 and 2073 with two 8-in. cubes, three 6-in. cubes and one 8-in. cylinder were made from one batch. These comprised the first run of tests and were all hand-mixed concrete. The other specimens were machine-mixed concrete made on the dates given below. On January 25, 1912, 2055 consisting of two 8-in. cubes and three 6-in. cubes was made. On February 7, two 8-in. cubes and three 6-in. cubes were made and marked 2056. On February 20, two 8-in. cubes and three 6-in. cubes were made and marked 2057. On March 1, two 8-in. cubes and three 6-in. cubes were made and marked 2058. On March 6, 2054 and 2059, compression specimens, were made with three 6-in. cubes and one 8-in. cylinder, from one batch.

A summary of all the specimens used in the investigation is given in Table V, page 29.

7. Storage and Handling.-The forms were removed from the specimens seven days after they were made, except that in two instances the forms were removed from the 8-in. cubes at an earlier age to hasten the preparation of other specimens which the large cubes controlled. Both the 6-in. and 8-in. cubes and the cylinders were stored in damp sand until a few days before they were tested. Part of the cubes and cylinders were stored in the mixing laboratory, part in the hydraulics laboratory under the same conditions.

Table V.
SUMMARY OF SPECIMENS.

No.	Kind	Auxiliary Specimens	Date		Age, days
			Made	Tested	
2050	Compression Specimen	6-in. cubes, cylinder	11- 1-11	12-19-11	52
2051	do.	6-in. cubes, 8-in. cubes, cylinder	10-28-11	1- 8-12	73
2052	do.	do.	11- 2-11	1-10-12	69
2053	do.	do.	11-18-11	1-30-12	73
2054	do.	6-in. cubes, cylinder	3- 6-12	5- 7-12	62
2055	Two 8-in. Cubes, three 6-in. cubes		1-25-12	4- 5-12	71
2056	do.	do.	2- 7-12	4- 6-12	60
2057	do.	do.	2-20-12	4-30-12	70
2058	do.	do.	3- 1-12	4-30-12	60
2059	Compression Specimen	6-in. cubes, cylinder	3- 6-12	5- 7-12	62
2061	do.	6-in. cubes, 8-in. cubes, cylinder	11- 8-11	1-15-12	68
2062	do.	do.	11-11-11	1-18-12	68
2063	do.	do.	11-23-11	1-31-12	69
2071	do.	8-in. cube, cylinder	11- 8-11	1-11-12	64
2072	do.	do.	11-11-11	1-20-12	70
2073	do.	do.	11-23-11	2- 2-12	71
2001	Crossed Beam	6-in. cubes, 8-in. cubes, cylinder, control beam	10-28-11	12-29-11	62
2002	do.	do.	11- 2-11	12-30-11	58
2003	do.	do.	11-18-11	1-27-12	70

The compression specimens and beams were left for about two weeks in the position in which they were made on the floor of the mixing laboratory, when they were piled one on top of another with wooden blocks between them. They were sprinkled more or less each day with a hose to prevent drying out, but the indications are that the use of more water would have been better because water was so quickly absorbed by the specimen.

The mixing laboratory in which the specimens were stored was heated by steam pipes. The temperature varied from 78°F to 44°F except that once, on January 16, 1912, the record shows that the temperature dropped to 34°F. Temperature was recorded at 7 a.m. and 5 p.m. each day, and it is probable that the variation was somewhat greater than given above. The general range was from 60°F to 70°F. The actual daily variation is shown in Fig. 4, page 31.

Specimens 2053, 2065 and 2073 were hauled to the testing laboratory some time before they were tested and had an opportunit to dry out more than the other specimens. They were wet every three or four days with a small quantity of water thrown on them by hand from a bucket. The water was so greedily absorbed that there can be no doubt of a drying influence, but these specimens did not differ greatly in strength from the others and the drying action is not of importance.

8. Description of Apparatus.-In reporting this investigation. many terms will be used which have an application to this kind of work only, and somewhat arbitrary definitions will need to be made for them. These should be credited to Mr. Slater.

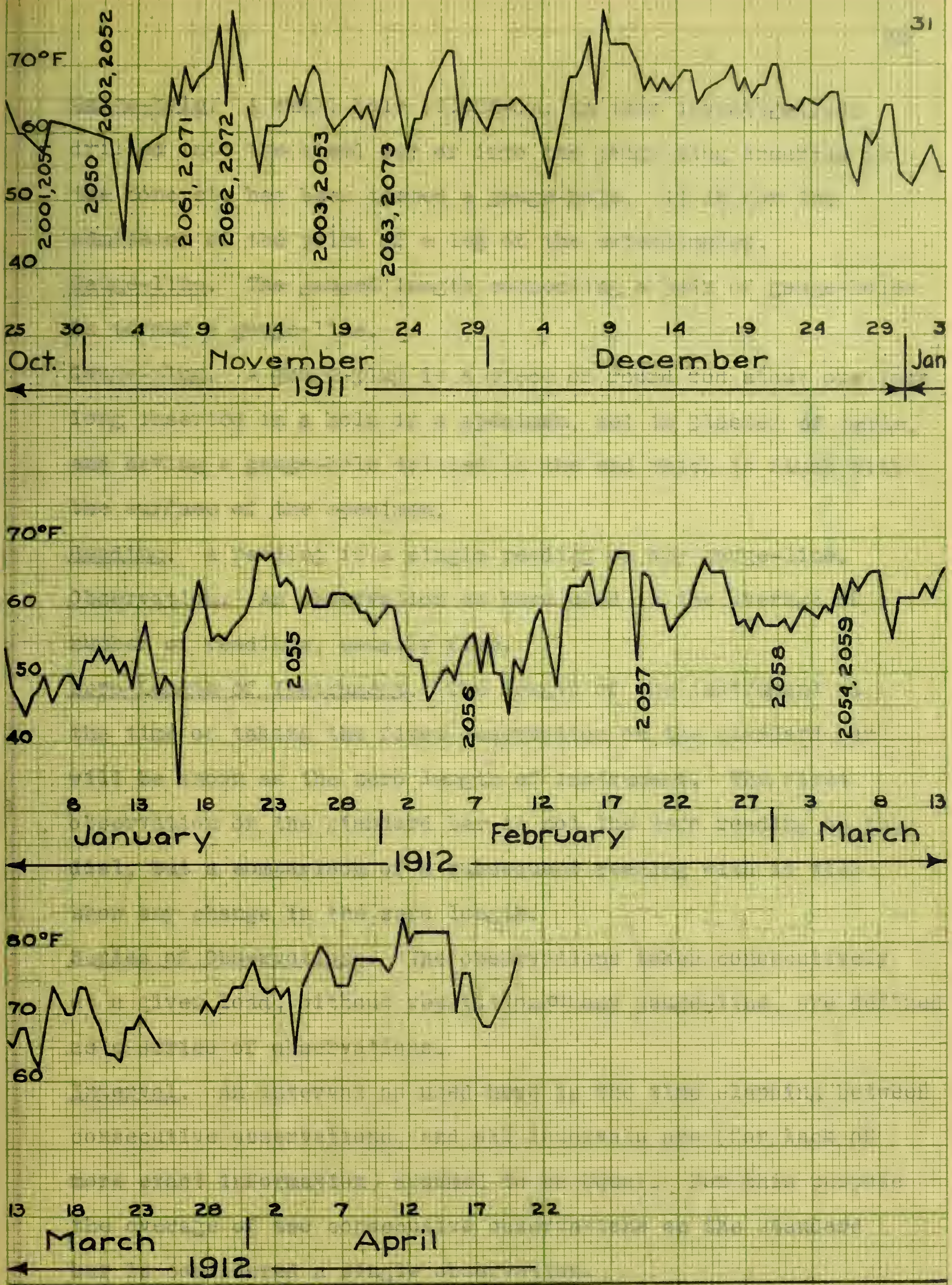


Fig. 4 Daily Temperatures in Storage Room

Gauge-hole. A small hole (0.055-in. in this investigation) drilled into the steel bar or into the gauge-plug inserted in the concrete has been termed a gauge-hole. It is for the admission of the point of a leg of the extensometer.

Gauge-line. The gauged length connecting a pair of gauge-holes is termed a gauge-line.

Gauge-plug. A gauge-plug is a piece of round rod about one inch long inserted in a hole in a specimen, set in plaster of paris, and having a gauge-hole drilled in the end which is flush with the surface of the specimen.

Reading. A reading is a single reading on any gauge-line.

Observation. An observation as here used is the average of a number of readings, usually five.

Zero Length of Instrument. The length of the instrument at the time of taking the first observation on the standard bar will be known as the zero length of instrument. The first observation on the standard bar is not the zero reading on the dial, but a comparison of a subsequent reading with it will show any change in the zero length.

Series of Observations. The observations taken consecutively at a given load, without repetition on any gauge-line, are defined as a series of observations.

Interval. An interval as used here is the time elapsing between consecutive observations, and all intervals are (for lack of more exact information) assumed to be equal. For this purpose the average of two consecutive observations on the standard bar is considered a single observation.

Apparent Initial Modulus of Elasticity. The apparent initial modulus of elasticity is obtained by drawing at the origin a tangent to the stress-deformation diagram obtained under certain external conditions.

Cross. The part of a test specimen at the intersection of the two arms both in the beams and compression specimens has been called the cross in this investigation.

Arm. The parts of a test piece radiating from the cross have been called arms.

In testing compression specimens, vertical load was applied with the testing machine and horizontal load was applied with an hydraulic jack. The arrangement of apparatus used to apply a load to the arm of a compression specimen with an hydraulic jack was as follows. The base of the jack was bolted to a cast iron plate 21 x 16 x 5-in. having a 2.25-in. hole in each of its corners. Two mild steel rods 2-in. in diameter and 5-ft. 6-in. long, threaded on each end, were inserted in the holes at opposite ends of a diagonal of the block, projecting on the side to which the jack was bolted and running through corresponding holes in a similar block. See Fig. 5, page 34. The specimen was placed between one block and the plunger of the jack as shown by the dotted lines. In testing a compression specimen, two side rods were used. In testing the 8-in. cubes, four rods were used, giving a more rigid piece of apparatus.

A free end bearing for the arms of the compression specimens

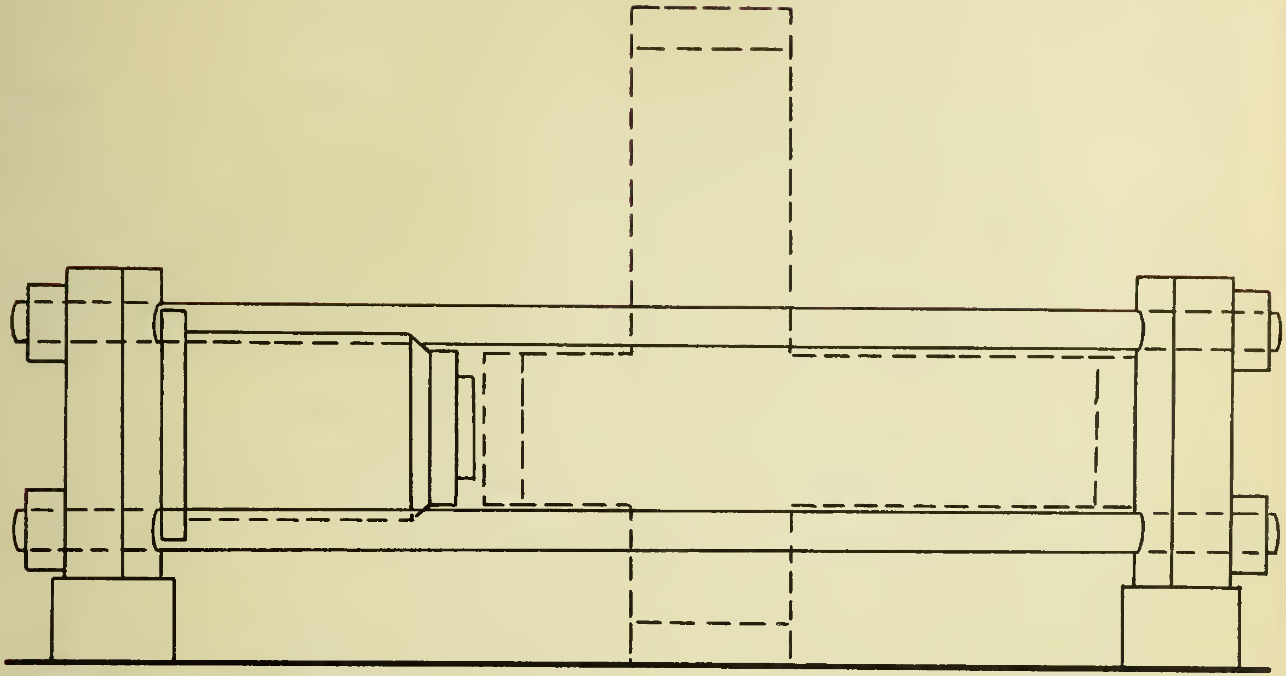


Fig. 5. Hydraulic Jack System.

was provided by placing two crossed pieces of 1-1/4 x 3/8-in. flat between the plate bedded in plaster on the specimen and the block of the loading system, and two similar pieces between the block on the opposite end of the specimen and the plunger of the jack. This arrangement proved quite satisfactory.

The original plan of loading the compression specimens was to use two hydraulic jack systems, such as the one described in the above paragraph, at right angles to each other, and to supply both from one pump, thus insuring, in the case of compression specimens loaded equally on the two arms, equal loads in the two directions at all times. This arrangement was tried in the first test of 2050 but it was not satisfactory for the reason that the two loading systems developed a tendency to twist about an axis perpendicular to the plane of both loads, thus causing a bending action of unknown amount and an uncertain distribution of stress. This apparatus which is shown in Fig. 6, was not used again.

The second plan was to use one hydraulic jack system to apply the horizontal load and a testing machine to apply the vertical load and to apply the greater load, in the tests in which they were unequal, with the testing machine. The second test of preliminary specimen 2050 and the test of 2051 were made in this way in a 200 000-lb. Olsen machine, but it was found that the screws interfered somewhat with the instruments in taking deformation readings. The later tests were made in the 600 000-lb. machine under quite favorable conditions, using the same

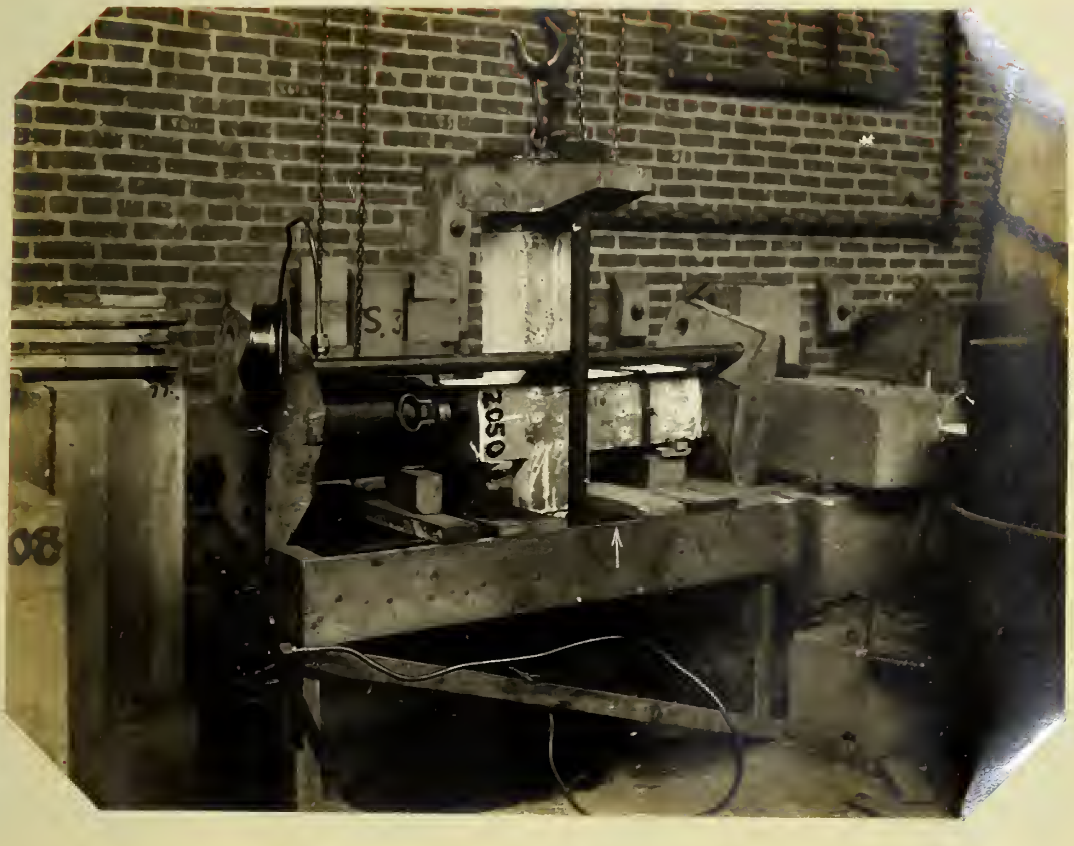


Fig. 6. First Loading Apparatus for 2050.

hydraulic jack for all tests. A spherical bearing-block was placed between the top plate on the specimen and the pulling head of the machine. The usual arrangement of apparatus is shown in the frontispiece.

The arrangement of apparatus for testing 8-in. cubes was practically the same as that for testing compression specimens. The spring-dynamometer was placed next to the end block opposite the one to which the jack was bolted. In place of the two crossed pieces of flat at each end of the compression specimen, a spherical block was placed between the plunger of the jack and the plate bearing on the cube. A second spherical block was placed on the top plate of the cube to transfer the load from the testing machine, as in the tests of compression specimens.

The crossed beams were tested in a special testing machine, made in the Laboratory of Applied Mechanics. It is shown in Fig. 7 and 8, pages 38 and 39. It consists of a system of reinforced concrete beams cast in one piece, a steel I-beam with connecting bolts, and a jack which loads the specimens. The base is shown in Fig. 9, page 40. The brackets in the corners of the base strengthen the whole and permit its use in testing certain other types of specimens. Four 1-1/4-in. round rods, with their ends upset and threaded, pass through holes in the base, and up to a plate over the I-beam shown crossing the opening in the base on Fig. 9. The beam on top of the machine was removed while a specimen was placed, leaving clear space

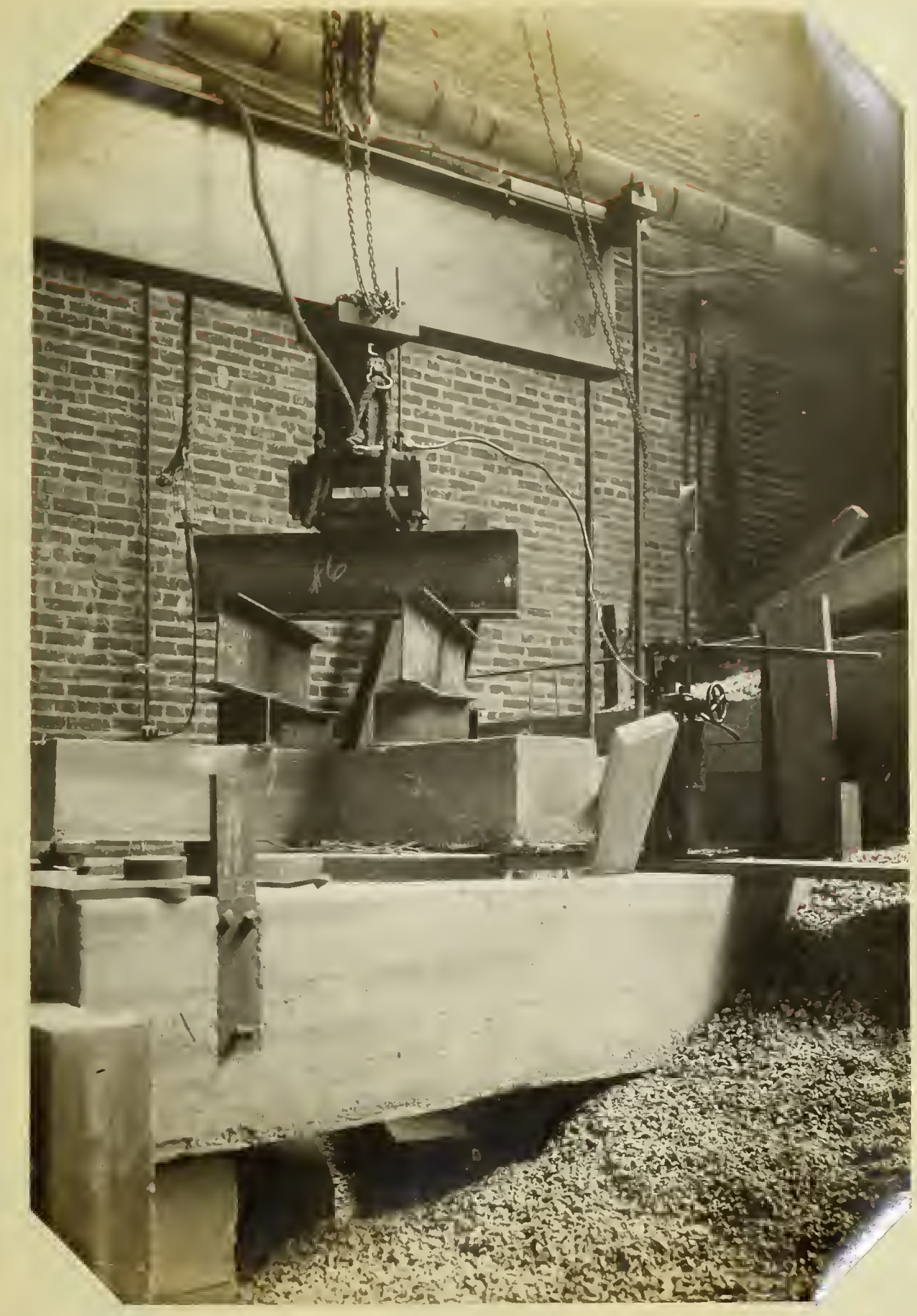
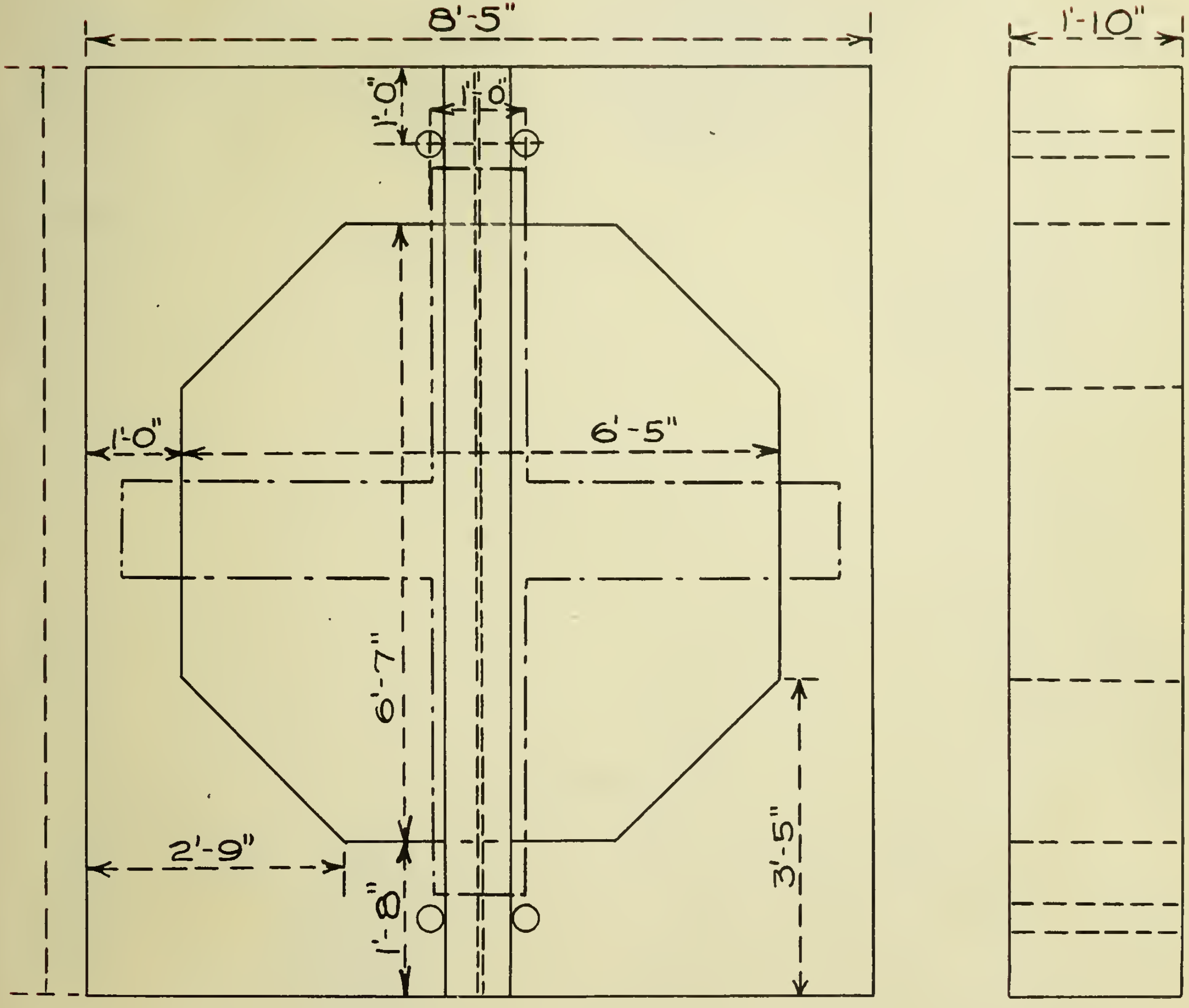


Fig. 7. Photograph of 2001 after Failure, Showing Apparatus.

Fig. 8. Photograph of 2003 after Failure, Showing Apparatus.

Fig. 9.



Crossed Beam Machine

for the use of the overhead crane in handling the specimens.

The procedure in placing a crossed beam in the machine was as follows. Two plates 1 x 4 x 12-in. were placed on top of each other at the places on the base of the machine where a reaction of the crossed beam was to come. A bed of freshly mixed plaster paris about one-half inch thick was placed on top of each pair of 1 x 4 x 12-in. plates, and the beam carefully lowered in its place, with the ends in this soft plaster. After the plaster had acquired its set, the specimen was raised about two inches, the upper one of each pair of plates sticking to the bottom of the beam. A roller was then placed between the plates, while the specimen was thus suspended, and placed in the desired position of the reaction. The crossed beam was then lowered to a bearing on the rollers. In this way it was certain that the distribution of the reaction across the end of the beam was uniform and that the position of the reaction was as figured. A piece of 7-in. x 15-lb. I-beam about 14-in. long was set in plaster along each of the four lines where load was to be applied. On top of these pieces, two 12-in. x 31.5-lb. I-beams were placed and these in turn loaded with a third beam of the same size or with two 8-in. beams side by side. This last mentioned beam or, in the case of 2003, the two 8-in. beams, carried a plate and the dynamometer. The base of an hydraulic jack bore directly on top of the dynamometer, and the plunger of the jack acted on a plate on the bottom of the large I-beam across the top of the machine.

Three methods of determining the amount of load were used in this investigation. In the tests of compression specimens, the vertical load was applied by a testing machine and the horizontal load was applied by an hydraulic jack and indicated by a pressure gauge. In the tests of crossed beams the load was applied by an hydraulic jack and indicated by a spring dynamometer. In the tests of 8-in. cubes the horizontal load was applied by an hydraulic jack and indicated by a spring dynamometer while the vertical load was applied by a testing machine.

The testing machine used was the 600 000-lb. Riehle, two screw, vertical machine in the Laboratory of Applied Mechanics of the University of Illinois, and needs no description.

The jack used in compression tests and in the tests of 8-in. cubes was a 5-1/2-in. ram rated at 100 tons. Two of these are shown in Fig. 6. The jack was carefully cleaned before the experiments and was in good condition. The working fluid was medium machine oil with a specific gravity of 0.87. The oil for the jack was supplied by a hand pump through a copper pipe 1/8-in. in internal diameter. In the test of a compression specimen and for low loads (up to 67000-lb.) a Crosby Hydraulic pressure gauge reading to 3000 lb. per sq.in. was used, and for loads between 67000-lb. and 230 000-lb. a Watson-Stillman indicator reading directly in tons was employed. The jack was carefully calibrated several times with each jack in the 600 000-lb. machine before the tests, and again after the completion of all tests. Calibration curves, drawn from the data thus obtained,

Fig. 10

Calibration Curve

Gauge 1355 Jack B-2161

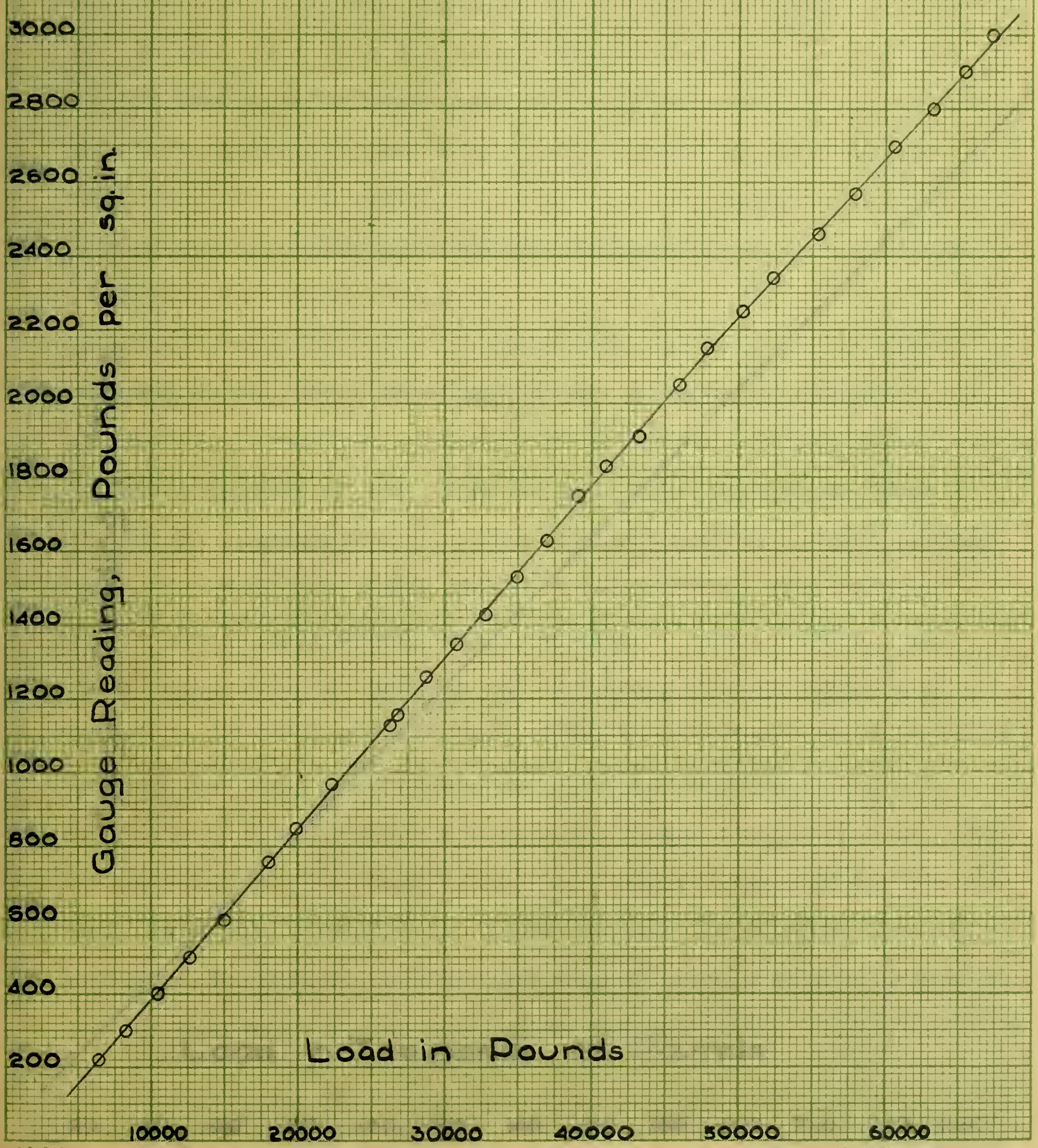
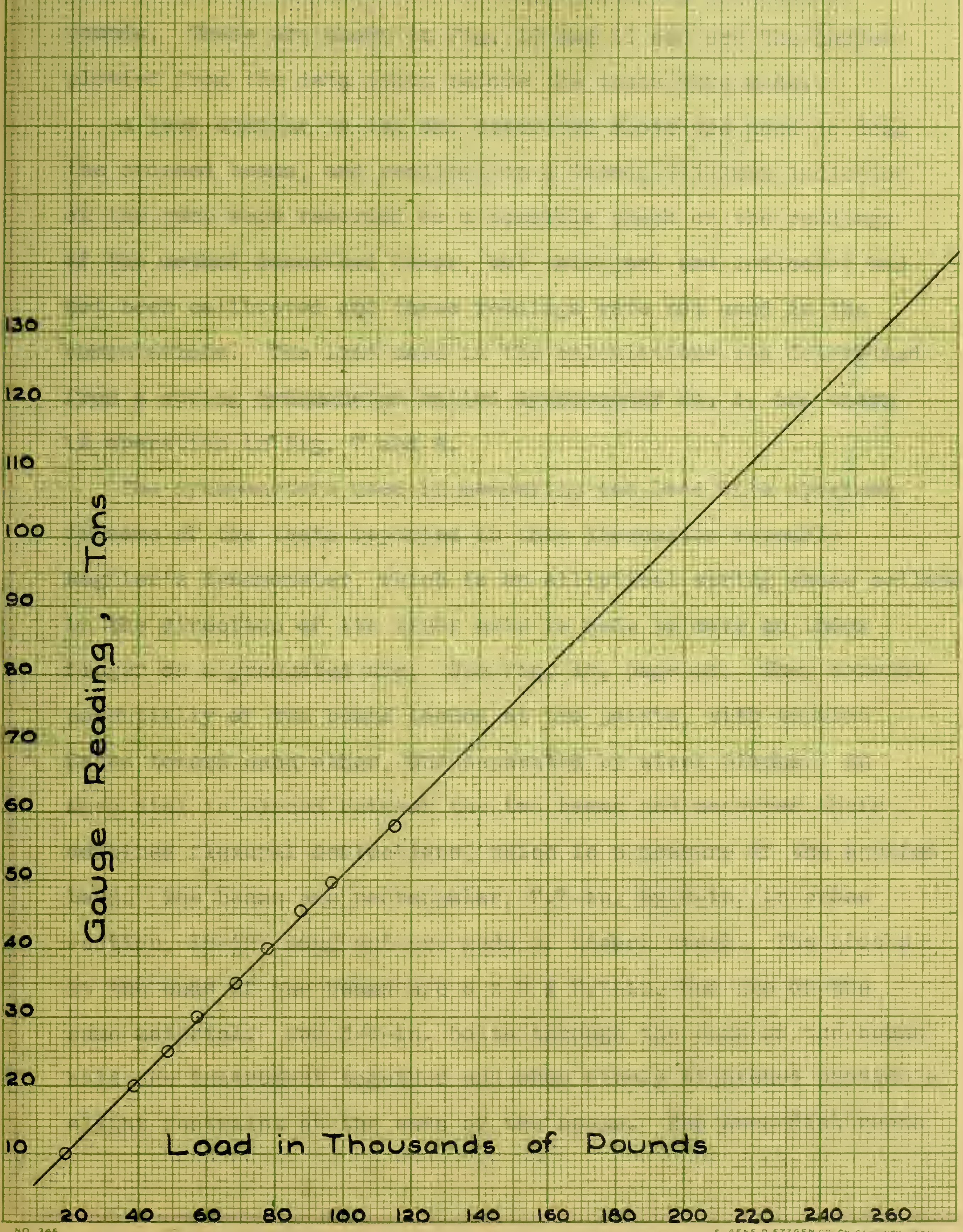


Fig. 11.

Calibration Curve

Gauge 849 Jack B-2161

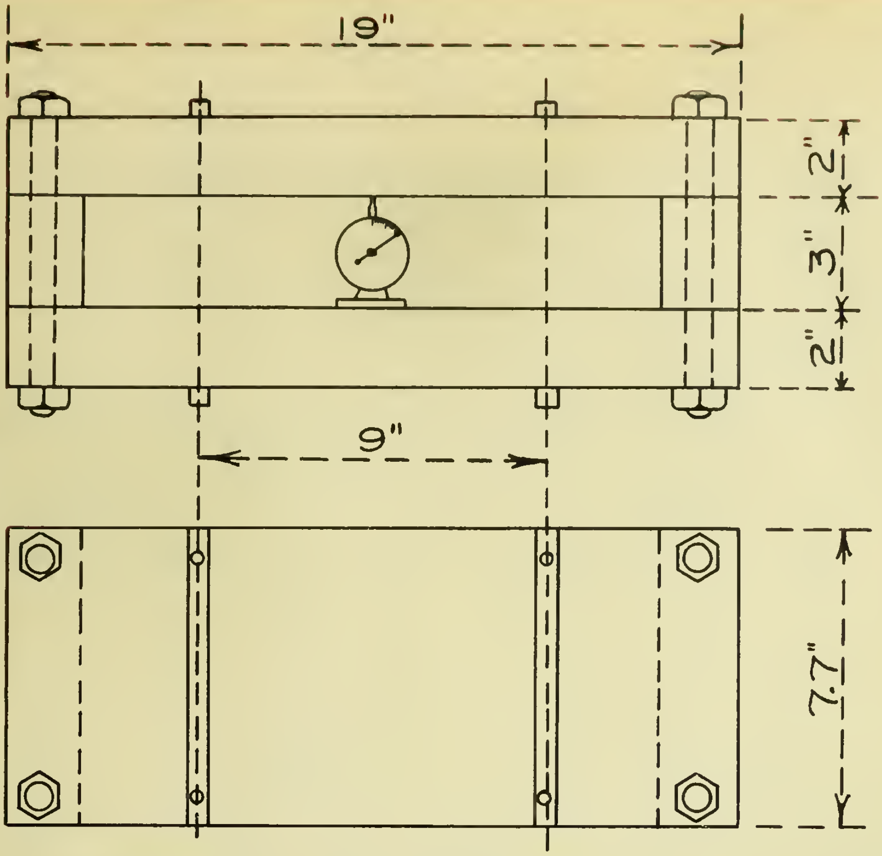


were used in the tests to read the load on the specimen in pounds. These are shown in Fig. 10 and 11 and are the curves plotted from the data taken before the tests were made.

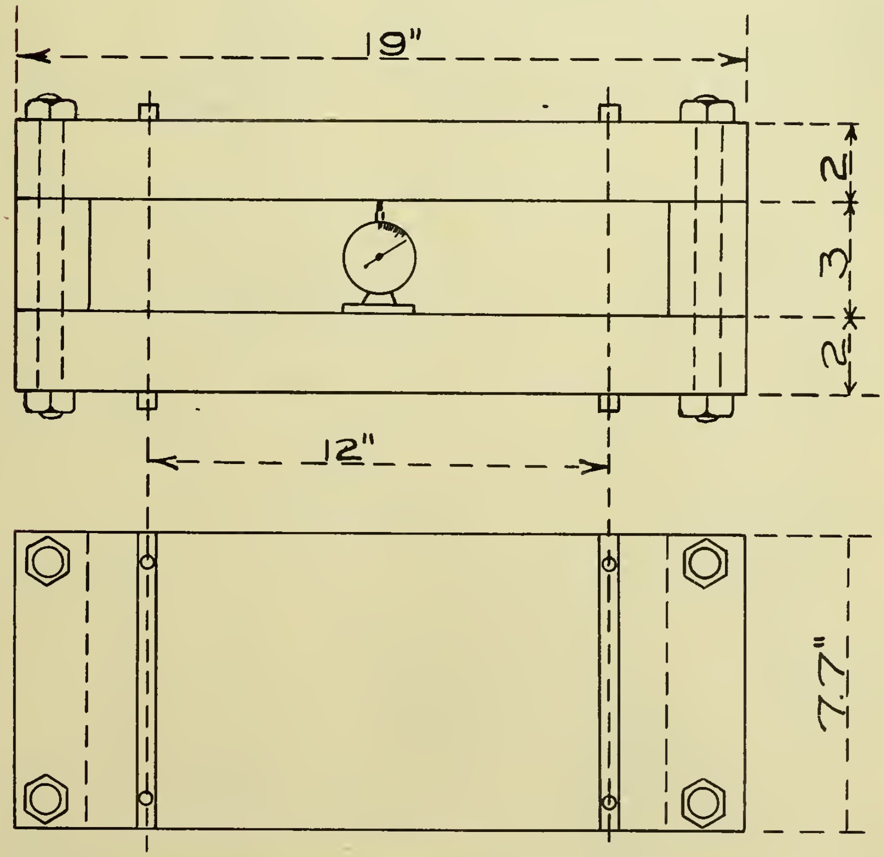
A jack similar to the one described above was used to load the crossed beams, and readings on a Watson-Stillman indicator on the pump were recorded as a possible check on the readings of the method described below, but this jack and indicator had not been calibrated and these readings were not used in the computations. The load used in the calculations was determined from a spring dynamometer called dynamometer No. 1, and shown in operation in Fig. 7 and 8.

The dynamometers used in measuring the load on a specimen in some of the tests reported in this discussion resemble Regnier's dynamometer, which is an elliptical spring whose collapse in the direction of its minor axis is made to move an index finger on a graduated arc. See Fig. 12, page 46. They consist essentially of two beams loaded at two points, with tension faces toward each other, and separated by steel blocks. An Ames dial is placed between the two beams and measures their combined flexural deflections, which is a measure of the applied load. The beams are rectangular, 7.7-in. by 2-in. in cross section, 19-in. long and are made of nickel steel. The blocks at the ends of the beams are 3 x 2 x 7.7-in. and are of the same material. Two 3/4-in. bolts through the ends of the beams hold the instrument together and when firmly tightened provide a slight restraint at the ends of the beams. The Ames dial reads

Fig 12.



Dynamometer No. 1.



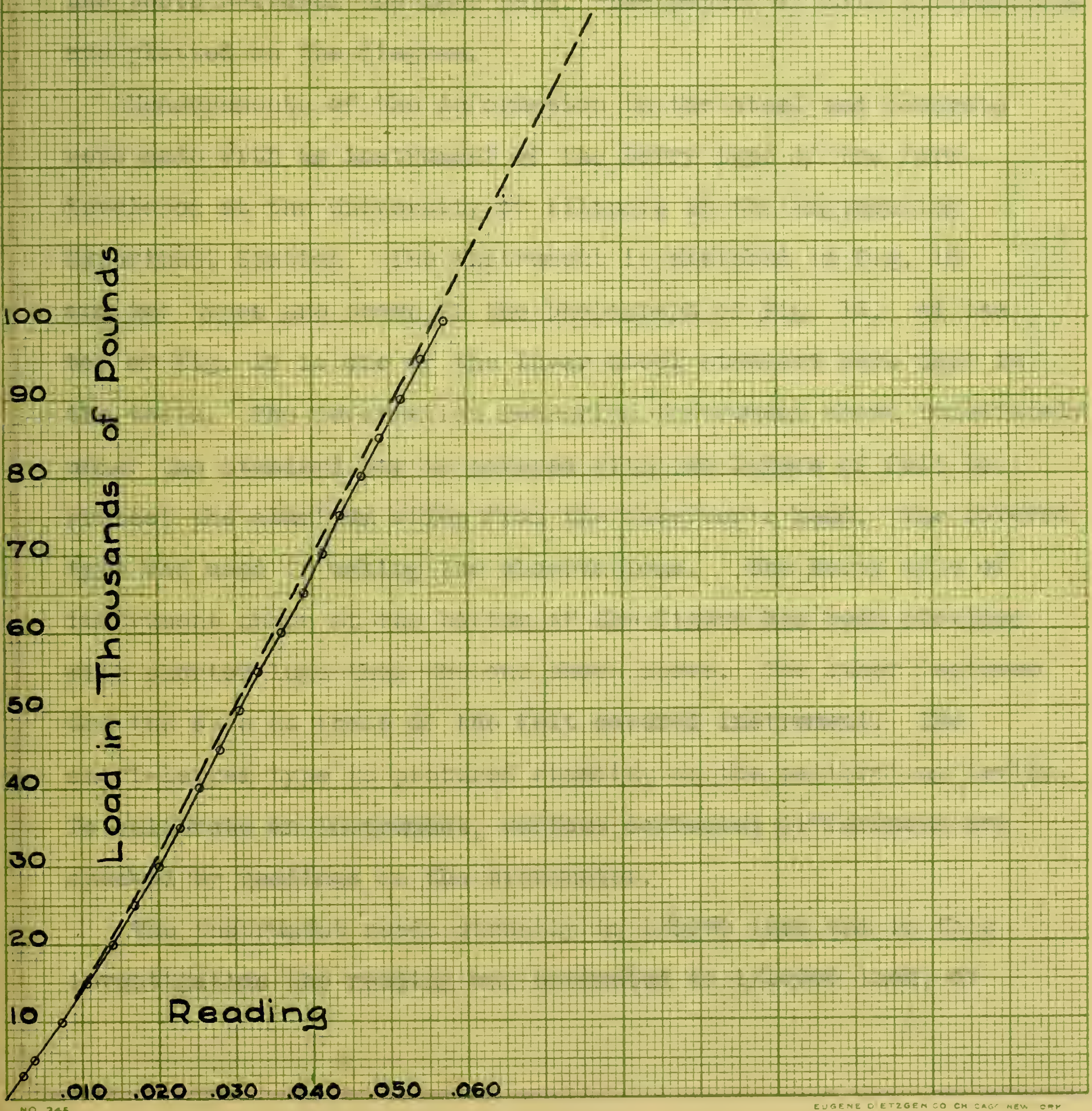
Dynamometer No. 2

directly to 1/1000 inch and by estimation to 1/10000 inch, or in terms of load as measured by dynamometer No.1, to units of about 1500-lb. directly and by estimation to 150-lb. Dynamometer No.1 was calibrated in a 200 000-lb. Olsen screw testing machine several times, both with increasing and decreasing increments of load. The effect of the end bolts on the load-deflection diagram was not great, but the curve was smoother and the instrument gave better results when these were quite firmly set. The calibration curve followed the same path during several successive trials. The dynamometer proved to be quite sensitive in indicating a falling off of the load, and promptly returned to a zero reading when the load was removed. The load-deflection curve used in the crossed beam tests is shown in Fig. 13 with the full line. The dotted line is drawn from a calibration made after this series of tests was completed and after the instrument was used in another series of tests and loaded to about 140000-lb. The number of times which the instrument was calibrated before the tests points to the conclusion that the change in the curve was due to a subsequent higher loading than that reached by the first calibrations. The tests of crossed beams were made within a few days of the first calibrations of the dynamometer, but the second calibration was made over three months later.

Dynamometer No. 2, used in the tests of 8-in. cubes, resembled No. 1 in every way except the position of the two loading points on the beams. See Fig. 12, page 46. The points were 9-in. center to center on No. 1 and 12-in. center to center on No. 2. The greater distance between these points reduces the bending

Fig. 13.

Calibration Curve
Dynamometer
No. 1



moment and the deflection and increases the capacity of the instrument. Dynamometer No. 2 was calibrated several times in the 600 000-lb. testing machine and was found quite similar in action to the other dynamometer. The calibration curve used in computing the results of tests of 8-in. cubes is drawn in Fig. 14, page 50. A calibration of Dynamometer No. 2 made after the tests followed the same path. The points of both calibrations are plotted on the diagram.

Measurements of the deformation in the steel and concrete were made with an instrument of the Berry type of the form developed at the University of Illinois in the Engineering Experiment Station. The instrument is sketched in Fig. 15 and two types are shown in the photograph of Fig. 16. At the top of Fig. 16 is one of the Invar steel standard bars used in the tests. The deformation measuring instrument shown immediately under the standard bar is covered with two layers of felt to protect the aluminum sides from the observer's hand. The covered type was used in making the observations. The Berry type of instrument shown at the bottom of the figure has been provided with shorter legs than the one shown above. The other features are the same as those of the felt covered instrument. The short-legged type is pictured standing on the calibrating device. To calibrate an instrument, various corrected differences are checked by readings on the micrometer.

The instrument reads directly to 1/5000 inch and in this investigation the reading was estimated to 1/10000 inch, or

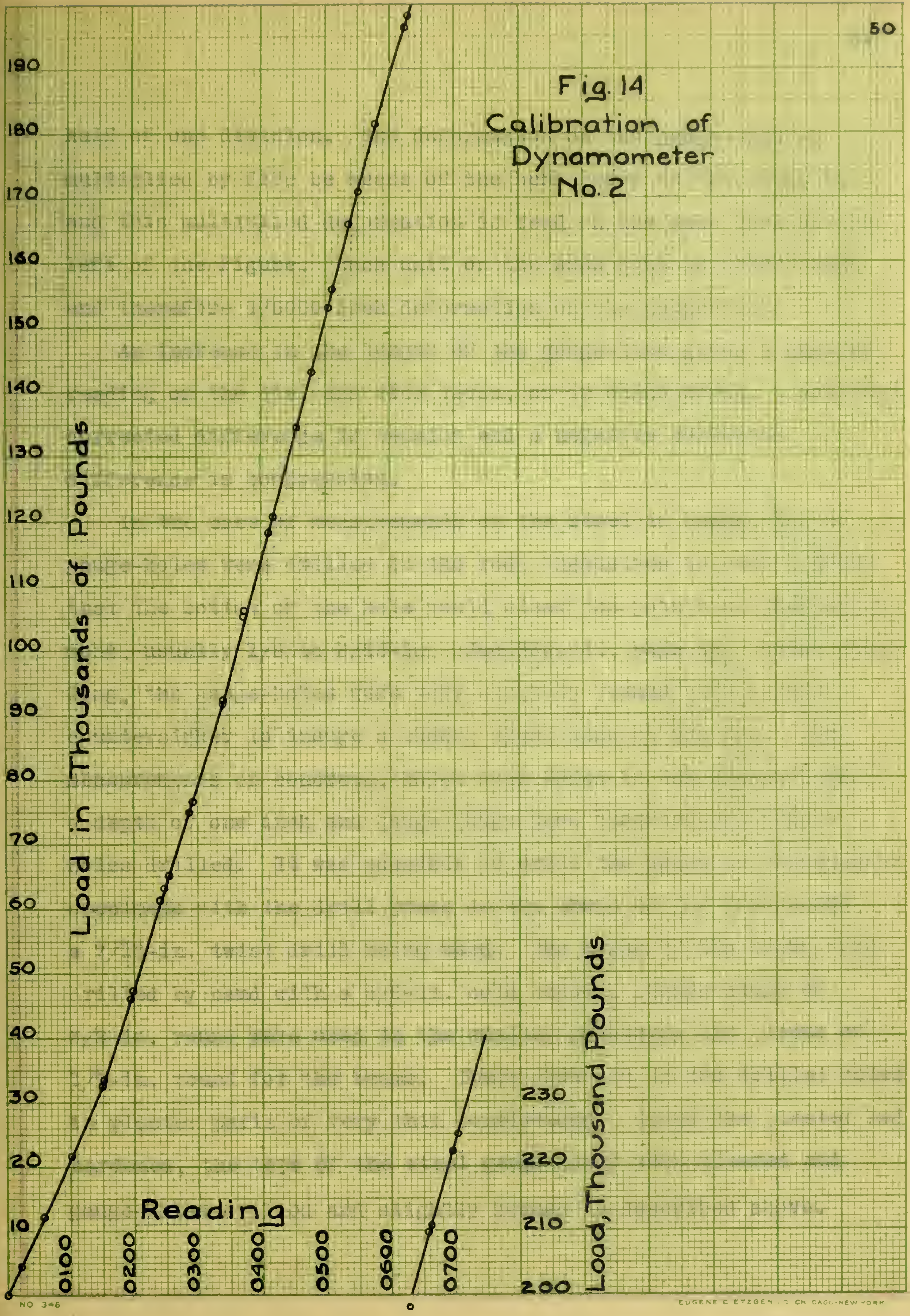
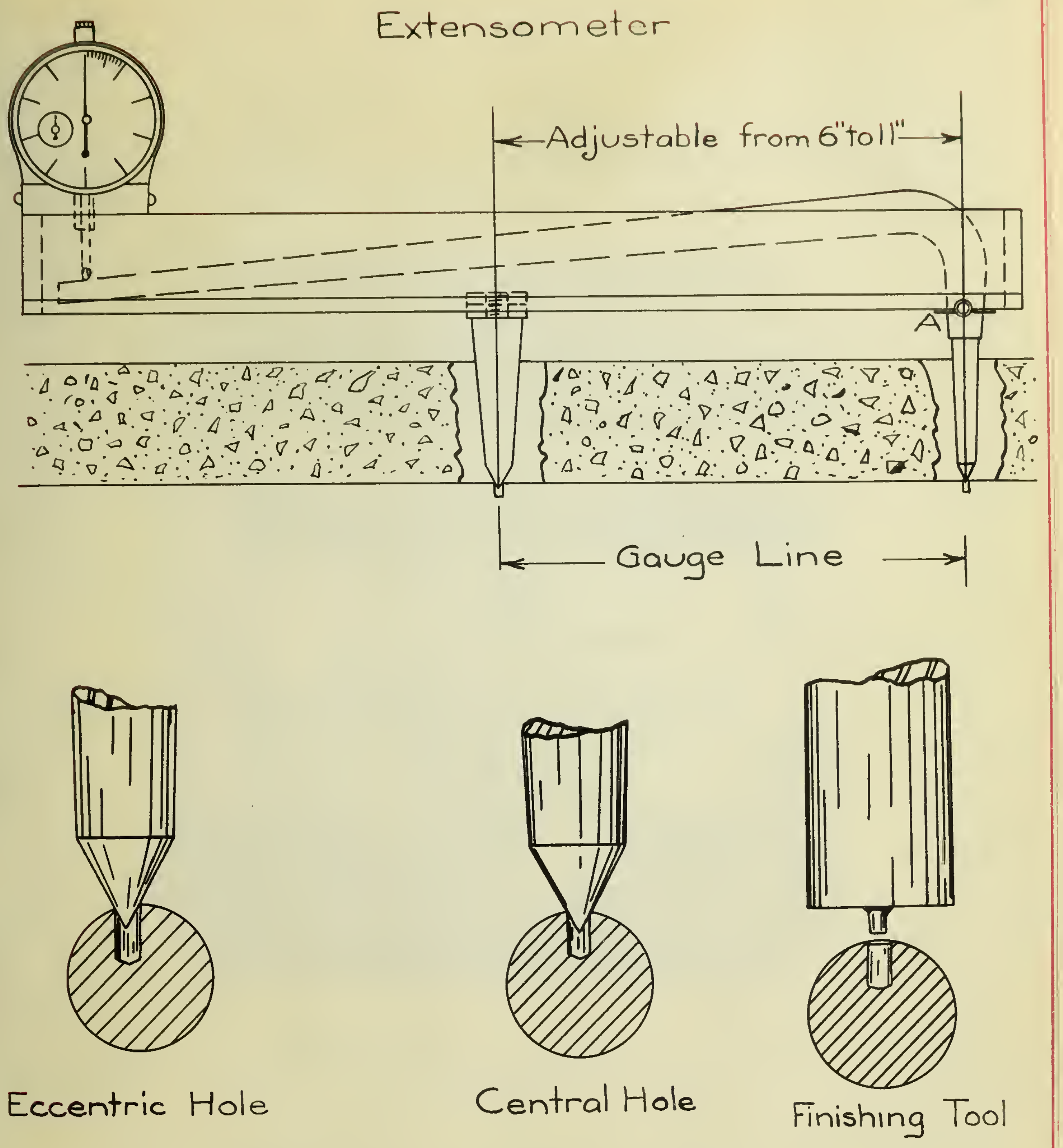


Fig. 14
Calibration of
Dynamometer
No. 2

half of one division. The deformation on the gauge-line is multiplied by five be means of the bent lever at "A", Fig. 15, and this multiplied deformation is read on the Ames dial at the left of the figure. Each unit on the Ames dial is 1/1000 inch and therefore 1/5000 inch deformation on the gauge-line.

An increase in the length of the gauge-line gives a smaller reading on the dial and vice versa, or in other words, a positive corrected difference is tension and a negative corrected difference is compression.

In the case of measurements on the steel in beams, No. 54 gauge-holes were drilled in the rods themselves to such a depth that the bottom of the hole would clear the points of the instrument, usually 1/8 to 3/16-in. See Fig. 15, page 52. After drilling, the gauge-holes were very slightly reamed with a dull countersinker to insure a clean, sharp edge at the top. For measurements on concrete, holes were bored in the specimen to a depth of one inch and gauge-plugs were inserted and gauge-holes drilled. It was possible to drill the holes in the smaller specimens with the drill press in the shops of the laboratory, a 7/16-in. twist drill being used. The holes in the beams were drilled by hand with a 5/8-in. cold chisel. Gauge-plugs of 3/8-in. round were used in the smaller specimens and pieces of 1/2-in. round for the beams. These were set in the drilled holes in plaster paris of very thin consistency. After the plaster had hardened, the tops of the steel gauge-plugs were cleaned and gauge-holes drilled and slightly reamed as described above.



Details of Gauge Holes.

Fig. 15.

Fig. 16. Standard Bar, Extensometers and Calibrating Device.

The gauge-line was six inches for all specimens tested.

To take a reading, the points of the instrument were inserted in the gauge-holes of a gauge-line, and a slight pressure applied to the instrument to give a firm bearing of the points in the holes. A reading was taken, the points of the instrument removed from the holes, then inserted again as before and a second reading taken. Five readings in succession were taken and all five given to the recorder at once. If these were inconsistent with previous readings, or if there was a total variation among the five of one and a half divisions on the dial, five more readings were taken and recorded. In the later tests five readings were taken as above, but only the average was recorded. It was found that the results were quite as reliable while the labor of recording and of computing was greatly curtailed by the process.

The expansion of the arm perpendicular to the load and the expansion of the cross perpendicular to both loads were measured in a number of tests by a new type of instrument called the expansometer, devised by the writer and built in the shops of the laboratory. The two expansometers used are shown in Fig. 17, page 55. The expansion of the specimen is multiplied by ten by the lever which moves the plunger of an Ames dial. The frame is of 1 x 3/16-in. flat framed with small angles in the corners. It is adjustable to the size of the specimen. Rough adjustment is made by using different sets of holes in the side bars, finer ones are made with the thumb-screw.

The instrument is held in its place on the specimen by

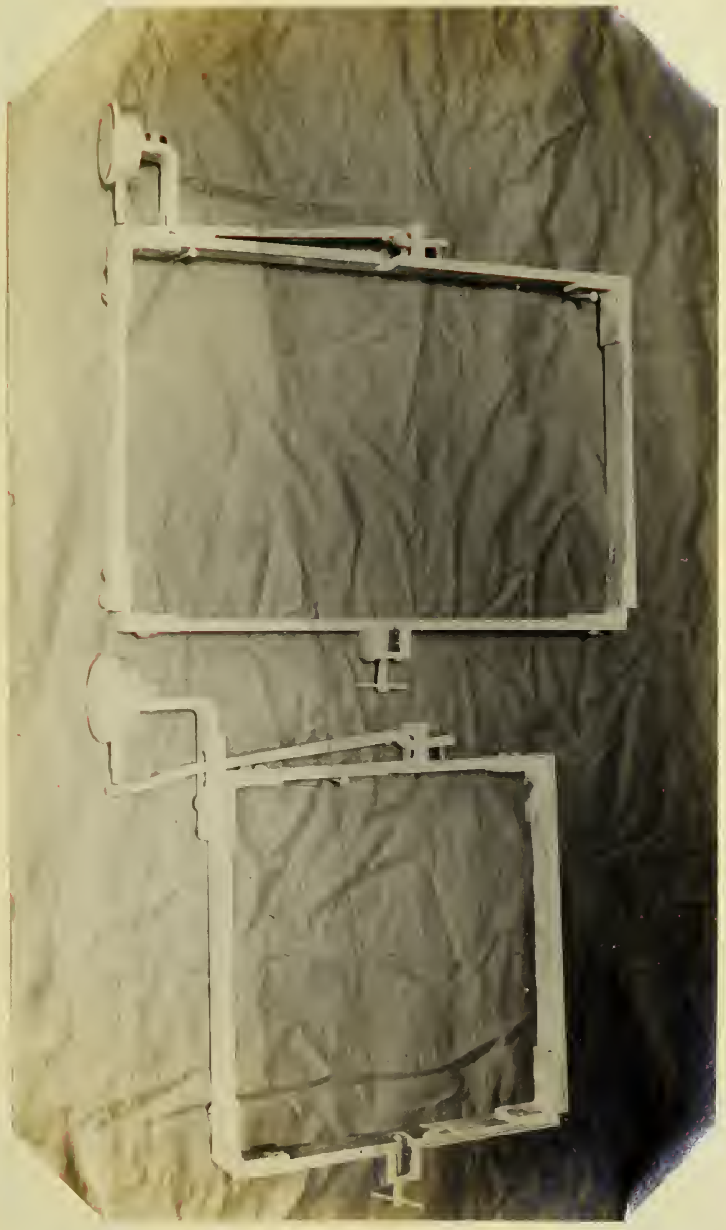


Fig. 17. Photograph of Expansometers.

means of two bearings on short plugs. These plugs are set in holes in the face of the specimen, so shallow that practically the whole expansion of the specimen may be determined by measuring the change in the distance between the outer ends of the plugs. The holes are about 3/16-in. deep. The plugs have spherical outer ends and square ends in the specimen. The position of the expansometers on a compression specimen may be seen in the frontispiece.

9. Methods of Testing.-The methods of testing have already been mentioned in the discussion of test specimens and testing apparatus. For testing compression specimens with arms equally loaded, the arrangement which was first used on compression specimen 2050 (two jack systems) would have been better than the combination of one jack and the testing machine if some means of keeping the jacks in their proper positions could have been found. A falling off of the load would have affected the two arms more nearly equally with two jacks. However a comparison of the stress-deformation curves of the horizontal and vertical arms shows that the method of testing finally adopted was very satisfactory.

Three compression specimens in addition to the preliminary tests of 2050, were loaded with equal loads on the two arms, and deformations parallel to the axis of each arm both on the cross and on the arm were measured. Expansions on the cross and on the arm were determined by the expansometers. When the results of the expansion measurements on 2051, 2052 and 2053 were computed, it was found that the expansometers had not

worked satisfactorily on the cross of 2052. Two other compression specimens, 2054 and 2059, were then made with the intention of testing them for expansion only, since it was felt that a knowledge of the expansion was important and that conclusions could not be based on two curves.

To investigate the effect on the unit deformation of unequal compressive stresses in two directions, three specimens were tested with half as great horizontal compression as vertical compression. These were 2061, 2062 and 2063.

To determine the effect of the enlarged section at the cross on the unit deformation at the cross, three compression specimens were loaded on one arm and the same measurements of deformation made as were made in the other two cases.

The horizontal load was applied with the jack and the vertical load with the testing machine. Ordinarily two men applied load, one with the testing machine, the other with the pump. The observer running the testing machine called out each 5000-lb. increment of load (73 lb. per sq.in. increment of stress) and the observer at the pump kept the jack load as close to the other as possible. The slowest speed of the testing machine (0.05-in. per minute) was employed. It was not hard to keep the loads within 2000 or 3000-lb. of each other. After the load was applied, the motor on the testing machine was stopped and a wait of two or three minutes followed, during which time the stress conditions in the specimen could adjust themselves somewhat to the new loading. The loads used in computing the data were read just before the first deformation observations were made and

just after the set of observations was complete.

The load on the faces of the 8-in. cubes was increased in the manner described in the previous paragraph. When one observer applied both loads as was the case in some of the tests, an increment of 5000-lb. was applied in the horizontal direction and the load in the vertical direction brought up to it, then 2500-lb. more added in the vertical direction, followed by 5000-lb. in the horizontal direction then 5000-lb. in the vertical direction, then another 5000-lb. in the horizontal direction, and finally by 2500-lb. in the vertical direction making the loads equal.

The arrangement of the loading apparatus for the crossed beams is taken up in "8. Description of Apparatus." The load was very slowly applied in increments of 15000-lb. between series of observations. The pointer on the dynamometer could be quite accurately read and it was found easy to stop at any desired load. Failure could be predicted by a backward motion of the dynamometer needle between strokes of the pump and a rapid falling off of the load when the pump was stopped. The same indications of failure were present in the 8-in. cube tests in which a dynamometer was used to indicate the load.

10. Time Effect of Load.-Except in the first stages of a test, the load fell off while a series of readings was being taken, both in the compression tests and in the beam tests. A series of readings required from fifteen to thirty minutes, depending on the number of observations made, time taken to observe phenomena of the tests and the personnel of the party,

and during this time the change of load was often appreciable. It is probable that concrete does not adjust itself to a new condition of stress speedily, and that during the time consumed in taking the whole number of readings, the specimen was undergoing internal changes.

In a test, the readings were taken in the order of the number of the gauge-line, but a study of these readings and of the plotted curves does not show a relation between the deformation and the number of the point, which is to say that the new condition of stress in the specimen at the time of the last observations of the series was not enough different from the condition at the time of the first observations to be noticed by instruments as delicate as those used in these tests.

In the test of 2071 the power on the testing machine failed after the first increment of load had been applied and it was necessary to leave the specimen in this condition over night. In the morning the load was weighed and a set of observations taken to check those of the evening before. It was noticed that the load had fallen off somewhat in the night, but not more than it fell off during the length of time occupied by an ordinary series of observations, and that the deformation had apparently increased greatly, also that the deformation perpendicular to the applied load indicated an increase of compression while the observations of the evening before had pointed to tension deformations as we should expect. Furthermore the increase of shortening was nearly the same in all cases, but where we should expect an increase of tension, gauge-lines 7, 8, 17 and 18,

there was shown an increase of compression about equal to the increase of compression on the arm. See some of the curves of 2071 which have been drawn in Fig. 18 on page 61. With this in mind it was thought that the change in this case was due to some change in temperature in the laboratory or to a change of zero length of instrument caused by temperature, and not to a time effect of the load.

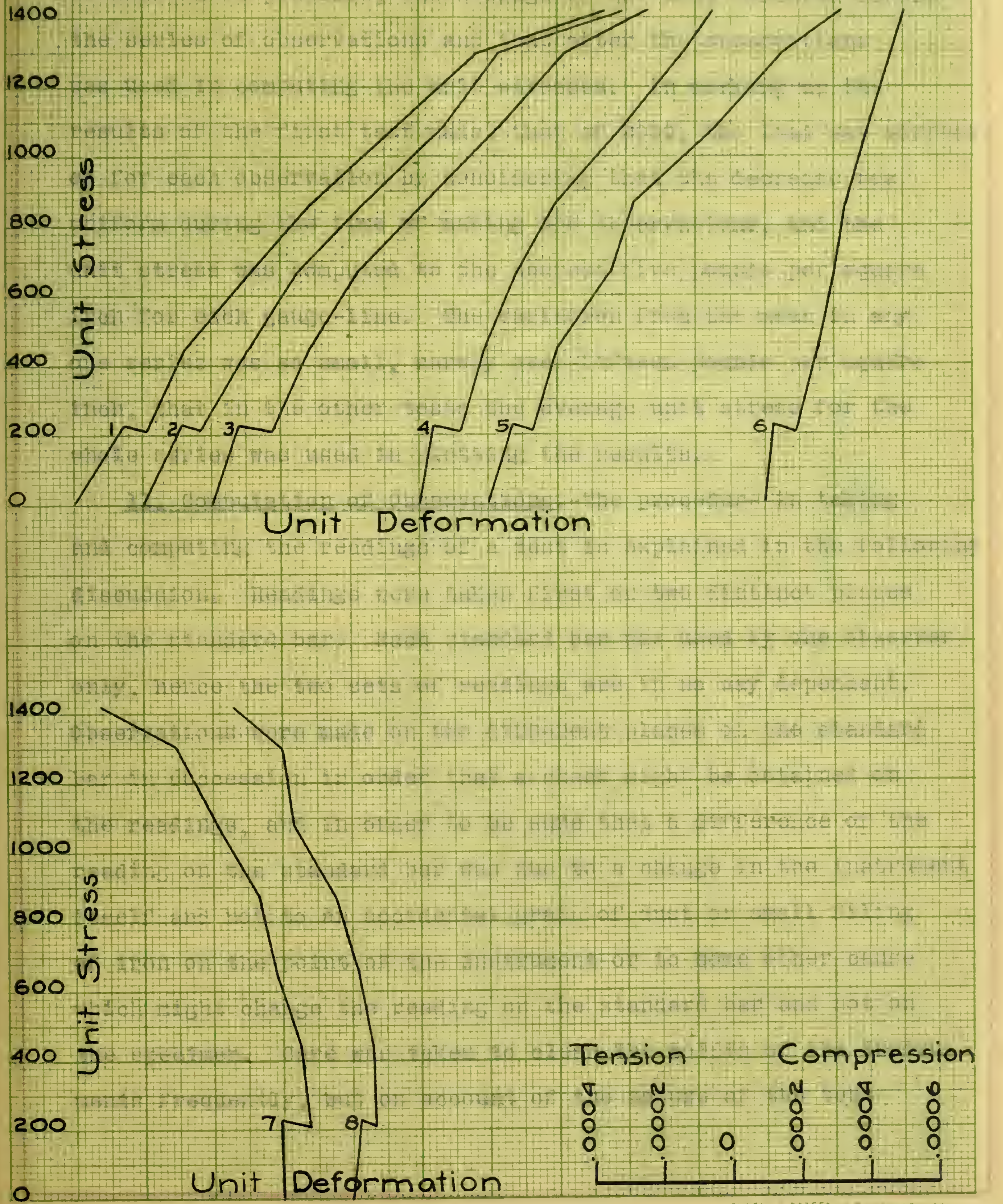
A time effect causes an increase of deformation under the same load, but in the measurements on gauge-lines 7, 8, 17 and 18 the effect was an apparent reversal of stress. The amount of change of deformation was so nearly the same on all gauge-lines, both in magnitude and direction, that it is certain that the change is due to causes other than the time effect of load. A change of temperature in the laboratory might cause the test specimen to change its dimensions, or might change the standard bar or the instruments themselves. That the effect is not produced by an accidental change in an instrument is demonstrated by the fact that the two instruments used, each with a distinct standard bar and in the hands of a spearate observer, gave the same results, qualitatively and quantitatively. A change of temperature of 12°F is sufficient to cause this change on the ordinary theory of temperature expansion.

At such a small unit stress as 230 lb. per sq.in. we should not expect a great time effect. At any rate the effect is small compared with the time.

Assuming from the above discussion that the effect of time is too small to be shown in these tests, the time effect was

2071

Fig. 18


1400
1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
5
6
Unit Deformation
1400
1200
1000
800
600
400
200
0
Unit Stress
7
8
Unit Deformation
Tension
Compression
.0004
.0002
0
.0002
.0004
.0006

neglected in the computations, and in order to make the results as uniform as possible, the average of the load observed before the series of observations and that after the observations was used in computing the unit stresses. In working up the results of the first test made, that of 2050, the load was corrected for each observation by considering that the decrease was uniform during the time of making the observations, and the unit stress was computed to the nearest five pounds per square inch for each gauge-line. The variation from the mean in any one series was so small, rarely over fifteen pounds per square inch, that in the other tests the average unit stress for the whole series was used in plotting the results.

<u>11. Computation of Observations</u>.-The procedure in taking and computing the readings of a test is explained in the following discussion. Readings were taken first on two distinct places on the standard bar. Each standard bar was used by one observer only, hence the two sets of readings are in no way dependent. Observations were made on two different places on the standard bar in succession in order that a check might be obtained on the readings, and in order to be sure that a difference of the reading on the standard bar was due to a change in the instrument itself and not to an accidental grain of dust or small filing of iron on the point of the instrument or to some other cause which might change the reading on the standard bar and not on the specimen. Care was taken to clean the points of the instruments frequently, but on account of the nature of the test

specimens it was difficult to keep foreign particles out of the holes and off the instruments.

Following the observations on the standards, readings were taken on the gauge-lines on the specimen in the order in which they appear in the records. When a large number of observations were made, observations were taken on the standard bar in the middle of the series. In every case both standards were observed at the end of a series.

The first set of observations by each observer on his standard bar was taken as standard for the test and all other readings of the test reduced to terms of these observations. Since differences and not direct quantities were observed, any quantity might have been chosen for this purpose at will, and the computed differences would be the same. This observation was chosen because small corrections result form its use and because computations could proceed as the test progressed.

The zero readings on the gauge-lines were reduced to terms of the first standard as follows: Each observation on the standard after a number of observations on gauge-lines on the specimen was subtracted from the first observation on the same standard, and the corrections as determined separately from the two standards averaged. This average correction was divided by the number of intervals between the first and last standard observations, which is the number of observed gauge-lines plus one, and added with its proper sign to the first uncorrected zero average. Twice the correction to the first uncorrected zero average was applied to the second uncorrected zero average,

three times the correction to the first uncorrected zero average to the third, and so on. These operations give the "corrected zero averages".

A load was then put on the specimen and another complete series of observations taken, which were preceded and followed by observations on the standard bar as before. The separate readings were averaged, called "uncorrected average", and subtracted from the corrected zero averages giving the "uncorrected differences". By subtracting the first standard observations of this series from the original standard observations of the first series, the amount of change in the instrument between the beginning of the test and the beginning of this series of observations was determined from the average of the two values of the change. By subtracting the final standard observations of this series from the first standard observations of the first series, the amount of change in the instrument between the beginning of the test and the end of this series was found as before. The change in the instrument during a series is of course the difference of the changes after and before. The "correction" for the first observation was found by dividing the change during a test by the number of intervals and adding this fraction of the change during a series to the amount of change between the beginning of the test and the beginning of this series of observations. The correction for the second observation was found by adding twice this fraction of the change during the series, to the change between the beginning of the test and

the beginning of this series, and so on for the other readings. These quantities are called the "corrections". The "corrected differences" were obtained by subtracting the "corrections" from the "uncorrected differences". This subtraction gives the same result as adding the correction to the uncorrected average before subtracting from the corrected zero averages, as was done for the zero series, for the uncorrected average was itself subtracted from the corrected zero average. This operation has the advantage of giving smaller numbers with which to deal.

In Table VI on page 66 the process of computing a set of readings is explained symbolically, the subscript of the quantity denoting the number of the gauge-line on the specimen. In Table VII on pages 67 and 68 a complete set of readings and the computations for them are given for one test, and may be taken as a sample of the form used in recording the readings and other data of a test.

The order of the numbered gauge-lines on a specimen was such that the two observers while taking observations on points in the order of numbering, were also working on points directly opposite each other at all times. Each observer read the gauge-lines on one side of a specimen. In the beam tests one observer read the deformations in the steel and one series of concrete gauge-lines, while the other read another series of concrete gauge-lines related among themselves but not dependent on the gauge-lines read by the first observer. In this way the personal equation is not eliminated during the readings, but it is kept constant. When differences are computed the

Table VI.

Load	Interval →	0		1	2	n - 2	n - 1	n	
	Gaugeline →	Standards		Arbitrary numbering of gauge-lines				Standards	
		a	b					a	b
Dead load only	Uncorr. Av.	S'_a	S'_b	R_1	R_2	R_{n-2}	R_{n-1}	S''_a	S''_b
	Correction	0	0	$\frac{1}{n}\frac{C''_a+C''_b}{2} = C_1$	$\frac{2}{n}\frac{C''_a+C''_b}{2} = C_2$	$\frac{n-2}{n}\frac{C''_a+C''_b}{2} = C_{n-2}$	$\frac{n-1}{n}\frac{C''_a+C''_b}{2} = C_{n-1}$	$S'_a - S''_a = C''_a$	$S'_b - S''_b = C''_b$
	Corr. Zero Av.			$R_1 + C_1 = A_1$	$R_2 + C_2 = A_2$	$R_{n-2} + C_{n-2} = A_{n-2}$	$R_{n-1} + C_{n-1} = A_{n-1}$		
Any live load	Uncorr Av.	s'_a	s'_b	r_1	r_2	r_{n-2}	r_{n-1}	s''_a	s''_b
	Uncorr. Diff			$A_1 - r_1 = d_1$	$A_2 - r_2 = d_2$	$A_{n-2} - r_{n-2} = d_{n-2}$	$A_{n-1} - r_{n-1} = d_{n-1}$		
	Correction	$S'_a - s'_a = c'_a$	$S'_b - s'_b = c'_b$	$c'_{ab} + \frac{1}{n}(c''_{ab} - c'_{ab}) = c_1$	$c'_{ab} + \frac{2}{n}(c''_{ab} - c'_{ab}) = c_2$	$c'_{ab} + \frac{n-2}{n}(c''_{ab} - c'_{ab}) = c_{n-2}$	$c'_{ab} + \frac{n-1}{n}(c''_{ab} - c'_{ab}) = c_{n-1}$	$S'_a - s''_a = c''_a$	$S'_b - s''_b = c''_b$
	Corr. Diff.	Note: Put $\frac{c'_a + c'_b}{2} = c'_{ab}$		$d_1 - c_1 = e_1$	$d_2 - c_2 = e_2$	$d_{n-2} - c_{n-2} = e_{n-2}$	$d_{n-1} - c_{n-1} = e_{n-1}$	Note: Put $\frac{c''_a + c''_b}{2} = c''_{ab}$	

Test of
Ar
Age

Observer	Slater			Bar No. 1.						Exponsometer	
Gauge Line	7-0S	6-10S	1	2	19	20	7-0S	6-10S		Arm	Cross
Load Gauge 0 Test.Mach. 0 Time 9:25 a.m.	161.5 2.0 2.0 2.0 2.0	062.5 2.5 2.5 3.0 3.0	235.0 5.0 5.0 5.0 5.0	19 0 .0 .0 .0 .0	88.0 8.0 8.0 8.0 8.0	73.0 3.0 3.0 3.0 3.0	203.0 3.0 3.0 3.0 3.0	217.0 7.0 7.0 7.0 7.5	Load G. 0 T.M. 0 Time 9:45 a.m.		
Gauge No. 1355											
Uncorrected Av.	161.9	062.7	235.0	19 0	88.0	73.0	203.0	217.1			
Correction			-0.1	-0 3	+0.3	+0.4	0	+0.9		0561	0396
Cor. Zero. Av.			234.9	19 3	88.3	73.4	+0.4				
Load G 630 T.M. 15400 Time 9:50	162.0 2.0 2.0 2.0 2.0	061.5 1.5 1.5 1.5 1.5	235.0 5.0 5.5 5.5 5.5	19 .0 .0 .0 .0 .5	90.0 0.0 0.0 0.0 0.0	73.0 3.0 3.0 3.0 3.0	202.5 2.5 2.5 2.5 3.0	17.0 7.0 7.0 7.0 7.0	Load G 530 TM 14300 Time 10:00		
Gauge No. 1355											
Uncorrected Av.	162.0	61.5	235.3	19 1	90.0	73.0	202.6	17.0			
Uncor. Difference	-0.1	+1.2	-0.4	-1 3	-1.7	-0.4	+0.4	+1.0			
Correction	+0.5		+0.5	+0 7	+0.7	+0.7	+0.7			0570	0430
Corrected Diff.			-0.9	-2 5	-2.4	-1.1				0009	0034
Unit Deformation											
Load G 1310 T.M. 30000 Time 10:05	162.0 2.0 2.0 2.0 2.0	062.0 2.0 2.0 2.0 2.0	240.0 0.0 0.0 0.0 0.0	9 .0 .0 .0 .0 .0	94.0 4.0 4.0 4.5 4.5	175.0 5.0 5.0 5.0 5.0	202.0 2.0 2.0 2.0 2.0	216.0 6.5 6.5 6.5 6.5	Load G. 1160 T.M. 28700 Time 10:20		
Gauge No. 1355											
Uncorrected. Av.	162.0	62.0	240.0	9 0	94.2	75.0	202.0	216.4			
Uncor. Difference	-0.1	+0.7	-5.1	- 7	-5.9	-1.6	+1.0	+1.6			
Correction	+0.3		+0.2	+ 3	+1.3	+1.3	+1.3			0591	0448
Corrected Diff			-5.3	- 0	-7.2	-2.9				0030	0052
Unit Deformation											
Load G. 2000 T.M. 45000 Time 10:25	163.0 3.0 3.0 3.0 3.0	62.5 3.0 3.0 3.0 3.0	244.0 4.0 4.5 4.5 4.5	2 0 .0 .0 .0 0	96.0 6.0 6.0 6.0 6.0	77.0 7.0 7.0 7.0 7.0	202.5 2.5 2.5 2.5 2.5	217.0 7.0 7.0 7.0 7.0	Load G 1840 T.M. — Time 10:40		
Gauge No. 1355											
Uncorrected Av.	163.0	62.9	244.3	2 0	96.0	77.0	202.5	217.0			
Uncor. Difference.	-1.1	-0.2	-9.4	- 7	-7.7	-3.6	+0.5	+1.0			
Correction	-0.6		-0.6	- 7	+0.7	+0.7	+0.7			0810	0480
Corrected Diff			-8.8	- 4	-8.4	-4.3				0049	0084
Unit Deformation											

Table VII.

Test of Compression Specimen 2051

Arms 8 x 8¼ in. = 66.0 sq.in. 1-8-'12
Age 73 days Recorder: Eells

Observer	Slater, Standard Bar No.2														Millard, Standard Bar No. 1.														Exponsometer	
Gauge Line	7-0S	6-10S	1	2	3	4	5	6	7	8	9	10	7-0S	6-10S	7-0S	6-10S	11	12	13	14	15	16	18	19	20	7-0S	6-10S		Arm	Cross
Load Gauge 0 Test.Mach. 0	161.5	062.5	235.0	191.0	119.0	171.0	102.0	175.5	149.5	145.0	090.0	112.0	164.0	063.0	203.0	218.0	271.0	258.0	124.0	200.0	97.0	49.0	65.0	88.0	73.0	203.0	217.0	Load G. 0 T.M. 0		
	2.0	2.5	5.0	1.0	9.0	1.0	2.0	5.5	50.0	5.0	0.0	3.0	4.0	3.5	3.0	8.0	1.0	8.0	4.0	0.0	7.0	9.5	5.0	8.0	3.0	3.0	7.0			
	2.0	2.5	5.0	1.0	9.0	1.0	2.0	6.0	0.0	5.0	0.0	3.0	4.0	3.5	3.0	8.0	1.0	8.0	4.0	0.5	7.0	9.5	5.0	8.0	3.0	3.0	7.0			
	2.0	3.0	5.0	1.0	9.0	1.0	2.5	6.0	0.0	5.0	0.0	3.0	4.0	3.5	3.0	8.0	1.0	8.0	4.5	0.5	7.0	9.5	5.0	8.0	3.0	3.0	7.0			
Time 9:25 a.m	2.0	3.0	5.0	1.0	9.0	1.0	2.5	6.0	0.0	5.0	0.0	3.0	4.0	3.5	3.0	8.0	1.0	8.0	4.5	0.5	7.0	9.5	5.0	8.0	3.0	3.0	7.5	Time 9:45 a.m.		
Gauge No.1355																														
Uncorrected Av.	161.9	062.7	235.0	191.0	119.0	171.0	102.2	175.8	149.9	145.0	090.0	112.8	164.0	063.4	203.0	218.0	271.0	258.0	124.2	200.3	97.0	49.4	65.0	88.0	73.0	203.0	217.1			
Correction			-0.1	-0.2	-0.4	-0.5	-0.7	-0.8	-1.0	-1.1	-1.3	-1.4	-2.1	-0.7			0	0	+0.1	+0.1	+0.2	+0.2	+0.3	+0.3	+0.4	0	+0.9		0561	0396
Cor. Zero. Av.			234.9	190.8	118.6	170.5	101.5	175.0	148.9	143.9	88.7	111.4	-1.4				271.0	258.0	124.3	200.4	97.2	49.6	65.3	88.3	73.4	+0.4				
Load G 630 T.M. 15400	162.0	061.5	235.0	192.5	123.5	171.0	103.5	179.0	184.5	148.5	93.0	14.5	162.0	62.5	203.0	217.0	74.0	261.0	130.0	204.0	199.5	50.0	67.0	90.0	73.0	202.5	17.0	Load G 530 TM 14300		
	2.0	1.5	5.0	2.5	3.5	1.5	3.5	9.0	4.5	8.5	3.0	4.5	2.0	2.5	3.0	7.0	4.0	1.0	0.5	4.0	9.5	0.0	7.0	0.0	3.0	2.5	7.0			
	2.0	1.5	5.5	2.5	3.5	1.5	3.5	9.0	4.5	8.5	3.0	5.0	2.0	2.5	3.0	7.0	4.0	1.0	0.5	4.0	9.5	0.0	7.0	0.0	3.0	2.5	7.0			
	2.0	1.5	5.5	2.5	4.0	1.5	4.0	9.5	4.5	8.5	3.0	5.0	2.0	2.5	3.0	7.0	4.0	1.0	0.5	4.5	9.5	0.0	7.0	0.0	3.0	2.5	7.0			
Time 9:50	2.0	1.5	5.5	2.5	4.0	1.5	4.0	80.0	4.5	8.5	3.5	5.0	2.0	2.5	3.0	7.0	4.0	1.0	0.5	4.5	200.0	0.5	7.5	0.0	3.0	3.0	7.0	Time 10:00		
Gauge No. 1355																														
Uncorrected Av.	162.0	61.5	235.3	192.5	123.7	171.4	103.7	179.3	154.5	148.5	93.1	14.8	162.0	62.5	203.0	217.0	74.0	61.0	30.4	204.2	199.6	50.1	67.1	90.0	73.0	202.6	17.0			
Uncor. Difference	-0.1	+1.2	-0.4	-1.7	-5.1	-0.9	-1.2	-4.3	-5.6	-4.6	-4.4	-3.4	-0.1	+0.2	0	+1.0	-3.0	-3.0	-6.1	-3.8	-2.4	-0.5	-1.8	-1.7	-0.4	+0.4	+1.0			
Correction	+0.5		+0.5	+0.4	+0.4	+0.3	+0.3	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1		+0.5		+0.5	+0.5	+0.6	+0.6	+0.7	+0.7	+0.7	+0.7	+0.7	+0.7			0570	0430
Corrected Diff.			-0.9	-2.1	-5.5	-1.2	-1.5	-4.5	-5.8	-4.7	-4.5	-3.5					-3.5	-3.5	-6.7	-4.4	-3.1	-1.2	-2.5	-2.4	-1.1				0009	0034
Unit Deformation																														
Load G 1310 T.M. 30000	162.0	062.0	240.0	97.5	133.5	75.0	109.0	188.0	62.5	65.0	98.5	18.5	63.5	63.0	202.0	2.6.0	78.0	66.0	136.5	206.0	202.0	54.5	69.0	94.0	175.0	202.0	216.0	Load G. 1160 T.M. 28700		
	2.0	2.0	0.0	7.5	3.5	5.0	9.0	8.0	2.5	5.0	9.0	8.5	3.5	3.0	2.5	6.0	8.0	6.0	6.5	6.0	2.0	54.5	9.0	4.0	5.0	2.0	6.5			
	2.0	2.0	0.0	7.5	3.5	5.0	9.0	8.0	2.5	5.0	9.0	8.5	3.5	3.0	2.5	6.0	8.0	6.0	6.5	6.0	2.0	54.5	9.0	4.0	5.0	2.0	6.5			
	2.0	2.0	0.0	8.0	4.0	5.0	9.0	8.0	2.5	5.0	9.0	9.0	3.5	3.0	2.5	6.5	8.5	6.0	6.5	6.0	2.0	54.5	9.0	4.5	5.0	2.0	6.5			
Time 10:05	2.0	2.0	0.0	8.0	4.0	5.0	9.0	8.0	2.5	5.0	9.5	9.0	3.5	3.0	2.5	6.5	8.5	6.0	6.5	6.0	2.0	54.5	9.0	4.5	5.0	2.0	6.5	Time 10:20		
Gauge No. 1355										(Most Likely 55.0 Slater)																				
Uncorrected. Av.	162.0	62.0	240.0	97.7	133.7	75.0	109.0	188.0	62.5	55.0	99.0	18.7	63.5	63.0	202.4	216.2	78.2	66.0	136.5	206.0	202.0	54.5	69.0	94.2	75.0	202.0	216.4			
Uncor. Difference	-0.1	+0.7	-5.1	-6.9	-15.1	-4.5	-7.5	-13.0	-13.6	-11.1	-10.3	-7.3	-1.6	-0.3	+0.6	+1.8	-7.2	-8.0	-12.2	-5.6	-4.8	-4.9	-3.7	-5.9	-1.6	+1.0	+1.6			
Correction	+0.3		+0.2	+0.1	0	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.9		+1.2		+1.2	+1.2	+1.2	+1.2	+1.2	+1.3	+1.3	+1.3	+1.3	+1.3			0591	0448
Corrected Diff			-5.3	-7.0	-15.1	-4.4	-7.3	-12.7	-13.2	-10.6	-9.7	-6.6					-8.4	-9.2	-13.4	-6.8	-6.0	-6.2	-5.0	-7.2	-2.9				0030	0052
Unit Deformation																														
Load G. 2000 T.M. 45000	163.0	62.5	244.0	204.0	140.5	76.5	11.0	95.0	71.0	62.0	105.0	22.5	63.5	63.0	202.0	216.5	84.0	75.5	44.5	212.0	207.0	61.0	74.0	96.0	77.0	202.5	217.0	Load G 1840 T.M. —		
	3.0	3.0	4.0	4.0	1.0	6.5	1.0	5.0	1.5	2.0	5.0	3.0	3.5	3.0	2.0	6.5	4.0	5.5	4.5	2.0	7.0	1.0	4.0	6.0	7.0	2.5	7.0			
	3.0	3.0	4.5	4.0	1.0	7.0	1.0	5.0	1.5	2.0	5.0	3.0	3.5	3.0	2.0	6.5	4.0	5.5	4.5	2.0	7.0	1.5	4.0	6.0	7.0	2.5	7.0			
	3.0	3.0	4.5	4.0	1.0	7.0	1.0	5.0	1.5	2.0	5.0	3.0	3.5	3.0	2.0	7.0	4.0	5.6	4.5	2.5	7.0	1.5	4.0	6.0	7.0	2.5	7.0			
Time 10:25	3.0	3.0	4.5	4.0	1.0	7.0	1.0	5.0	2.0	2.0	5.0	3.0	3.5	3.0	2.0	7.0	4.0	5.5	4.5	2.5	7.0	1.5	4.0	6.0	7.0	2.5	7.0	Time 10:40		
Gauge No.1355																														
Uncorrected Av.	163.0	62.9	244.3	204.0	140.9	76.8	11.0	95.0	71.5	62.0	105.0	22.9	63.5	63.0	202.0	216.7	84.0	75.5	44.5	212.2	207.0	61.3	74.0	96.0	77.0	202.5	217.0			
Uncor. Difference.	-1.1	-0.2	-9.4	-13.2	-22.3	-6.3	-9.5	-20.0	-22.6	-18.1	-16.3	-11.5	-1.6	-0.3	+1.0	+1.3	-13.0	-17.5	-20.2	-11.8	-9.8	-11.7	-8.7	-7.7	-3.6	+0.5	+1.0			
Correction	-0.6		-0.6	-0.6	-0.7	-0.7	-0.8	-0.8	-0.9	-0.9	-0.9	-0.9	-0.9		+1.1		+1.0	+1.0	+0.9	+0.9	+0.8	+0.8	+0.7	+0.7	+0.7	+0.7			0810	0480
Corrected Diff			-8.8	-12.6	-21.6	-5.6	-8.7	-19.2	-21.7	-17.2	-15.4	-10.6					-14.0	-18.5	-21.1	-12.7	-10.6	-12.5	-9.4	-8.4	-4.3				0049	0084
Unit Deformation																														

	7-05	6-105	1			19	20	7-05	6-105		Arm	Cross
Load G 2760 T.M.59600 Time 10:45	163.0 3.0 3.0 3.0 3.0	62.0 2.0 2.5 2.5 2.5	249.5 9.5 9.5 9.5 50.0	2	5 .5 .5 .5 .5	200.0 0.0 0.0 0.0 0.0	81.0 1.0 1.0 1.0 1.0	202.0 2.0 2.0 2.0 2.0	217.0 7.0 7.0 7.0 7.0	Load G 2530 T.M.56900 Time 10:55		
Gauge No.1355												
Uncorrected. Av.	163.0	62.3	249.6	2	5	200.0	81.0	202.0	217.0			
Uncor. Difference	-1.1	+0.4	-14.7	-	2	-11.7	-7.6	+1.0	+1.0			
Correction	-0.3		-0.3	-		+1.0	+1.0	+1.0				
Corrected Diff.			-14.4	-	2	-12.7	-8.6				0624	0563
Unit Deformation											0063	0167
Load G 39.0 T.M. 74700 Time 11:00	62.0 2.0 2.0 2.0 2.0	61.5 2.0 2.0 2.0 2.5	55.0 5.0 5.0 5.0 5.5	1	.0 .0 .0 .5 .5	202.5 2.5 2.5 2.5 2.5	82.5 2.5 3.0 3.0 3.0	201.5 1.5 1.5 2.0 2.0	216.0 6.0 6.0 6.0 6.0	Load G 35.5 T.M. — Time 11:12		
Gauge No.849												
Uncorrected Av	62.0	62.0	55.1		2	202.5	82.8	201.8	216.0			
Uncor. Difference	-0.1	+0.7	-20.2	-	9	-14.2	-9.4	+1.2	+2.0			
Correction	+0.3		+0.3	+		+1.6	+1.6	+1.6				
Corrected Diff			-20.5	-	5	-15.8	-11.0				0690	0692
Unit Deformation											0129	0296
Load G 46.0 T.M.81000 Time 11:20	60.5 0.5 0.5 0.5 1.0	60.5 0.5 0.5 0.5 0.5	266.5 6.5 6.5 6.5 6.5	2	5 5 5 0 0	215.0 5.0 5.0 5.0 5.0	192.0 2.0 2.0 2.0 2.0	201.0 1.0 1.5 1.5 1.5	215.5 6.0 6.0 6.0 6.0	Load G 45.0 T.M.75400 Time 11:30		
Gauge No.849												
Uncorrected Av.	60.6	60.5	266.5	2	7	215.0	192.0	201.3	215.9			
Uncor. Difference	+1.3	+2.2	-31.6	-	.4	-26.7	-18.6	+1.7	+2.1	Max. Load: G 49.0 T.M 90000		
Correction	+1.8		+1.7	+		+1.9	+1.9	+1.9				
Corrected Diff.			-33.3	-	3	-28.6	-20.5				.1235	0852
Unit Deformation											0674	0556

	7-05	6-105	1	2	3	4	5	6	7	8	9	10	7-05	6-105	7-05	6-105	11	12	13	14	15	16	18	19	20	7-05	6-105		Arm	Cross
Load G 2760 T.M.59600 Time 10:45	163.0 3.0 3.0 3.0 3.0	62.0 2.0 2.5 2.5 2.5	249.5 9.5 9.5 9.5 50.0	211.0 1.0 1.0 1.0 1.0	150.0 0.0 0.0 0.5 0.5	80.5 0.5 0.5 1.0 1.0	16.0 6.0 6.0 6.0 6.0	205.0 5.0 5.0 5.0 5.5	81.0 1.0 1.0 1.0 1.0	69.5 9.5 9.5 9.5 9.5	110.0 0.0 0.0 0.0 0.0	29.0 9.0 9.0 9.0 9.0	62.5 3.0 3.0 3.5 3.5	62.5 2.5 2.5 2.5 2.5	202.0 2.0 2.0 2.0 2.5	216.5 6.5 6.5 6.5 6.5	91.0 1.0 1.0 1.0 1.0	82.5 2.5 3.0 3.0 3.0	55.0 5.5 5.5 5.5 5.5	22.5 2.5 2.5 2.5 2.5	212.5 2.5 2.5 2.5 2.5	69.0 9.0 9.5 9.5 9.5	79.5 9.5 9.5 9.5 9.5	200.0 0.0 0.0 0.0 0.0	81.0 1.0 1.0 1.0 1.0	202.0 2.0 2.0 2.0 2.0	217.0 7.0 7.0 7.0 7.0	Load G 2530 T.M.56900 Time 10:55		
Gauge No.1355																														
Uncorrected. Av.	163.0	62.3	249.6	211.0	150.2	80.7	16.0	205.1	81.0	69.5	110.0	29.0	63.1	62.5	202.1	216.5	91.0	82.8	55.4	22.5	212.5	69.3	79.5	200.0	81.0	202.0	217.0			
Uncor. Difference	-1.1	+0.4	-14.7	-20.2	-31.6	-10.2	-14.5	-30.1	-32.1	-25.6	-21.3	-17.6	-1.2	+0.2	+0.9	+1.5	-20.0	-24.8	-31.1	-22.1	-15.3	-19.7	-14.2	-11.7	-7.6	+1.0	+1.0			
Correction	-0.3		-0.3	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5		+1.2		+1.2	+1.2	+1.1	+1.1	+1.0	+1.0	+1.0	+1.0	+1.0	+1.0			0624	0563
Corrected Diff.			-14.4	-19.9	-31.3	-9.8	-14.1	-29.7	-31.6	-25.1	-20.8	-17.1					-21.2	-26.0	-32.2	-23.2	-16.3	-20.7	-15.2	-12.7	-8.6				0063	0167
Unit Deformation																														
Load G 39.0 T.M. 74700 Time 11:00	62.0 2.0 2.0 2.0 2.0	61.5 2.0 2.0 2.0 2.5	55.0 5.0 5.0 5.0 5.5	13.0 3.0 3.0 3.0 3.0	59.0 9.0 9.0 9.0 9.0	84.0 4.0 4.0 4.0 4.0	20.0 0.0 0.0 0.5 0.5	18.5 8.5 8.5 8.5 8.5	95.5 5.5 5.5 6.0 6.0	81.5 1.5 1.5 1.5 1.5	20.0. 0.0 0.5 0.5 0.5	37.0 7.0 7.0 7.0 7.0	62.0 2.5 2.5 2.5 3.0	61.5 1.5 2.0 2.0 2.0	201.5 2.0 2.0 2.0 2.0	216.0 6.0 6.5 6.5 6.5	302.0 2.0 2.0 2.0 2.0	92.5 2.5 3.0 3.0 3.0	66.0 6.0 6.0 6.0 6.0	229.0 9.0 9.0 9.5 9.5	220.5 0.5 0.5 0.5 0.5	78.0 8.0 8.0 8.0 8.0	87.0 7.0 7.0 7.5 7.5	202.5 2.5 2.5 2.5 2.5	82.5 2.5 3.0 3.0 3.0	201.5 1.5 1.5 2.0 2.0	216.0 6.0 6.0 6.0 6.0	Load G 35.5 T.M. — Time 11:12		
Gauge No.849																														
Uncorrected Av	62.0	62.0	55.1	13.0	59.0	84.0	20.2	18.5	95.7	81.5	20.3	37.0	62.5	61.8	201.9	216.3	302.0	92.8	66.0	229.2	220.5	78.0	87.2	202.5	82.8	201.8	216.0			
Uncor. Difference	-0.1	+0.7	-20.2	-22.2	-40.4	-13.5	-18.7	-43.5	-46.8	-37.6	-31.6	-25.6	-0.6	+0.9	+1.1	+1.7	-31.0	-34.8	-41.7	-28.8	-23.3	-28.4	-21.9	-14.2	-9.4	+1.2	+2.0			
Correction	+0.3		+0.3	+0.3	+0.3	+0.2	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1		+1.4		+1.4	+1.4	+1.5	+1.5	+1.6	+1.6	+1.6	+1.6	+1.6	+1.6			0690	0692
Corrected Diff			-20.5	-22.5	-40.7	-13.7	-18.9	-43.7	-46.9	-37.7	-31.7	-25.7					-32.4	-36.2	-43.2	-30.3	-24.9	-30.0	-23.5	-15.8	-11.0				0129	0296
Unit Deformation																														
Load G 46.0 T.M. 81000 Time 11:20	60.5 0.5 0.5 0.5 1.0	60.5 0.5 0.5 0.5 0.5	266.5 6.5 6.5 6.5 6.5	240.5 0.5 0.5 0.5 0.5	180.0 0.0 0.0 0.0 0.0	196.5 6.5 6.5 6.5 6.5	131.0 1.5 1.5 2.0 2.0	249.5 9.5 9.5 9.5 9.5	230.5 0.5 0.5 1.0 1.0	205.0 5.5 5.5 5.5 5.5	133.5 3.5 3.5 4.0 4.0	147.0 7.0 7.0 7.0 7.0	62.0 2.0 2.0 2.5 2.5	60.5 1.0 1.0 1.0 1.0	201.0 1.0 1.5 1.5 1.5	216.0 6.0 6.0 6.0 6.0	314.0 4.0 4.5 4.5 4.5	315.5 5.5 5.5 5.5 5.5	180.0 0.0 0.0 0.0 0.0	234.0 4.0 4.0 4.0 4.0	221.0 1.0 1.0 1.0 1.0	189.0 9.0 9.0 9.0 9.0	193.5 3.5 3.5 4.0 4.0	215.0 5.0 5.0 5.0 5.0	192.0 2.0 2.0 2.0 2.0	201.0 1.0 1.5 1.5 1.5	215.5 6.0 6.0 6.0 6.0	Load G 45.0 T.M. 75400 Time 11:30		
Gauge No.849																														
Uncorrected Av.	60.6	60.5	266.5	240.5	180.0	196.5	131.7	249.5	230.7	205.4	133.7	147.0	62.2	60.9	201.3	216.0	314.3	315.5	180.0	234.0	221.0	189.0	193.7	215.0	192.0	201.3	215.9			
Uncor. Difference	+1.3	+2.2	-31.6	-49.7	-61.4	-26.0	-30.2	-74.5	-81.8	-61.5	-45.0	-35.6	-0.3	+1.8	+1.7	+2.0	-43.3	-57.5	-55.7	-33.6	-23.8	-39.4	-28.4	-26.7	-18.6	+1.7	+2.1	Max. Load: G 49.0 T.M 90000		
Correction	+1.8		+1.7	+1.6	+1.5	+1.4	+1.3	+1.2	+1.1	+1.0	+0.9	+0.8	+0.8		+1.8		+1.8	+1.8	+1.8	+1.8	+1.8	+1.9	+1.9	+1.9	+1.9	+1.9			.1235	0852
Corrected Diff.			-33.3	-51.3	-62.9	-27.4	-31.5	-75.7	-82.9	-62.5	-45.9	-36.4					-45.1	-59.3	-57.5	-35.4	-25.6	-41.3	-30.3	-28.6	-20.5				0674	0556
Unit Deformation																														

personal equation drops out entirely. Averages under these conditions probable mean more than if such a distribution of work was not made.

11. Discussion of Deformation Measurements and Their Accuracy. The corrected differences of the readings of the Berry instrument were expressed in five-thousandths of an inch and in tenths of this unit. This deformation occurred in a gauged length of six inches. Therefore, to get unit deformation (inches per inch), divide the corrected difference by 30000, but since tenths of the reading unit were expressed, tenths of $\frac{1}{30000}$ -th part are found in the unit deformations. An uncertainty of one-tenth of a point in the corrected difference made an uncertainty of 0.000003 in the unit deformation. In the tables of unit deformations in the back of the thesis it will be noticed that the sixth figure to the right of the decimal point is either 3, 7, or 0, or in other words, that the unit deformation is expressed in units of 0.00001 and thirds of this unit. But since the corrected difference of the instrument was figured to one-tenth of 1/30000-th inch and since there may be an uncertainty of one-tenth of 1/30000-th inch in the corrected difference (expressed in terms of unit deformation), the unit deformation is uncertain in the sixth place. This uncertainty depends on the personal equation of the observer who may keep or discard halves of the recorded reading unit, and on the policy of the computer in keeping or dropping fractions of the quantities dealt with. For instance, a corrected difference of -3.1 is a unit compressive deformation of 0.000103, but in adjusting the readings

it is possible that the result might have been computed either as -3.2 or -3.0. This may be seen in the sample computations in Table VII. The unit deformation might then be 0.000107 or 0.000100. The unit deformation might well be written 0.000103 ± 0.000003 in such a case, or simply 0.00010 if the thirds of the fifth figure to the right of the decimal point are ignored. The sixth place to the right of the decimal point is nevertheless given in the tables and it must be remembered that its significance is only to make the fifth place more certain.

We may express the accuracy of deformation measurements in terms of unit stress. Three units in the sixth place of decimals (0.000003) are equivalent to a stress of 6 lb. per sq.in. in concrete having a modulus of 2 000 000 lb. per sq.in. The uncertainty, then, is very small, smaller than the uncertainty of weighing the load with the testing machine.

III.

EXPERIMENTAL DATA AND DISCUSSION.

III. EXPERIMENTAL DATA AND DISCUSSION.

A. COMPRESSION SPECIMENS.

13. Procedure of Test.-A few days before a test, the ends of the specimen were fitted with a two inch cast iron plate set in plaster. The gauge-plugs had been previously set and gauge-holes drilled in them. The expansometer plugs were set after the specimen was in the machine. The expansometers were adjusted and the side rods on the jack tightened to an even bearing. The plate on the short vertical arm rested directly on the weighing table of the machine. The long vertical arm bore against a spherical block attached to the pulling head. The horizontal arms had round ends as described under "8. Description of Apparatus." When all was ready, a series of observations was made, as described before, and an increment of load applied slowly. The increment was 15000-lb. in all tests except the first. Seven points were obtained on the curve, often more than seven, with increments of this size. The maximum load reached was recorded after each increment. Four or five minutes after the load was applied, its amount was observed and recorded again. Readings on the expansometers were commonly taken at the time of the first observations on the gauge-lines. It was very difficult to avoid touching the collar or the thumb-screw of the expansometer while taking readings between gauge-holes on opposite sides of it, and the slightest touch

disturbed the reading materially. To eliminate this source of error, readings were taken in most of the tests both before and after the series of observations. If the reading had changed, no attempt was made to set the pointer to its original reading, but the change was corrected in the final plotting of the curves. On the curve sheets in the back of the thesis an expansion curve as actually measured is drawn in full line while the adjusted curve is dotted. The reason for the adjustment is evident from the form of the curve itself.

After the maximum load, the cracks on the specimen were sketched to scale and a photograph was taken of the specimen. If there was doubt as to the real manner of failure a further deformation was produced and the performance of the test piece observed.

The sketches of failures and photographs of some of the failed specimens appear in the back of the book.

14. Phenomena of Tests and Failure of Compression Specimens.- The phenomena of tests and manner of failure are described in the following paragraphs. No. 2050, 2051, 2052, 2053, 2054 and 2059 were tested with equal loads on the two arms, 2061, 2062 and 2063 were tested with half as great loads on the horizontal arm as on the vertical arm, and 2071, 2072, and 2073 were tested with a load on the vertical arm and none on the horizontal arm.

2050. This specimen was made with the intention of testing it an early age to acquire skill in the use of instruments and to develop the loading apparatus. The first test was not successful for the reason that the two jack systems could not be kept

in their proper positions. A stress of 950 lb. per sq.in. was reached and a number of series of observations taken. The pieces of flat used to give free ends were but one inch wide and 1/8-in. thick. After the first two or three increments of load the horizontal jack system was raised from its place on the frame by the eccentric action of the load. It seems that the bearing pieces between the arm of the specimen and the ram were at the center of the cross-section of the arm but not at the center of the ram. This eccentricity threw the jack out of line. Further loading developed so great a stress in these flat pieces that they failed and the jack tipped so far out of line that the plunger bore directly on one side of the plate on the end of the specimen as well as on the flat pieces. The test was abandoned at this point.

The second test was made using a testing machine to apply the vertical load, and a jack to apply the horizontal load as before. Some trouble was found in keeping the jack from turning out of line at higher loads as before. The pieces used to provide free ends were 1 x 3/8-in. in this test, but in the later tests they were 1-1/4 x 3/8-in. Failure occurred by crushing the longer arms of the specimen. Cracks developed on both long arms, and two cracks were found on the short horizontal arm. Small pieces fell from the arms, but no cracks or other marks were noticed on the cross.

Because of the lack of experience at the time of this test and since the specimen was considerably younger than the others tested, it might be well to drop the results out of the

averages from which conclusions are to be drawn.

<u>2051</u>. This specimen was tested in the same manner as were the rest of the specimens used in this investigation. The vertical load was applied with a testing machine and the horizontal one with a jack. Increments of load of 15000-lb. were simultaneously applied to the two arms. No cracks were found until after a load of 75000-lb. had been applied and the readings taken. During the application of the next increment of load, cracks and splitting were noted on the horizontal arm and immediately afterward on the vertical arm. These cracks did not extend to the face of the intersecting arm, and no cracks were found on the short arms. A load of 90000-lb. was applied with the testing machine but it rapidly fell off, and before observations could be made the cracks mentioned above were formed. Immediately after failure, the loads were removed and the cracks sketched. The specimen was again loaded with 60000-lb. in the horizontal direction and 70000-lb. in the vertical direction. The long horizontal arm crushed badly, followed by the upper part of the vertical arm, and then the whole test piece split apart through the cross in a plane containing both loads. This would seem to indicate that while the deformation on the cross was not as great as on the arm, the concrete was nevertheless in a critical condition and was about to fail by tension due to expansion perpendicular to the plane of the two loads. The character of the fracture was the same on the arms as on the cross. It is noticeable that the expansion on the cross is about twice as great as that on the arm.

2052. The expansometers were on the horizontal arm and on the cross. Increments of load of 15000-lb. were applied as before. At 90000-lb. a crack was observed on the horizontal arm running through the expansometer collar. While the next load was being applied this crack opened rapidly, and the expansometer was removed. At 105000-lb. a crack was observed in the bearing plate on the horizontal arm. Possibly this accounts for the formation of the crack and the rapid expansion at a load of 90000-lb. When the load was increased to 108000-lb. the split plate broke with a report and a considerable portion of the horizontal arm fell off. This is shown by the shading in the sketch on page 238. While the vertical load remained, observations were made on some of the gauge-lines to determine the effect on the deformation at the cross of removing the horizontal load. This effect is shown by the dotted lines on the stress-deformation curves for gauge-lines 9 and 10, page 181. It is noticed that there is a reversal and that the deformation becomes tensile when the horizontal load is made zero. This is in agreement with the results of compression specimens tested with load on only one arm, and agrees with those results in amount as well as direction. See the curves for gauge-lines 9 and 10 of 2073, page 173. Failure occurred on the horizontal arm by splitting, as already described, and on the vertical arm by general crushing. The cross itself was not greatly damaged.

2053. The expansometers were on the horizontal arm and on the cross as in the test of 2052. It was thought from the

results of the previous tests that the enlarged section at the cross must have an effect on the deformation, and in the test of this specimen four additional gauge-lines were observed. These were placed parallel to the vertical arm and one inch outside the cross on the horizontal arm. See the sketch of the gauge-lines on page 242. The stress-deformation curves for these gauge-lines show that the deformation at a distance of one inch from the vertical arm is reduced to about 1/5-th the deformation on the cross. This is in agreement with the results of tests on compression specimens loaded on only one arm.

Throughout the test, an observer watched the expansometers to see if their movement was smooth and how soon after loading they responded to the load. The instrument on the arm responded quickly, but the one on the cross did not work well during the test. For several increments of load the reading remained the same. At a unit stress of 1200 lb. per sq.in. the cross expansometer was disturbed and reset. Expansion readings on the cross after this indicated that the expansion on the cross was greater than on the arm, as in the other tests of similar specimens. After the 90000-lb. load was applied and readings taken, the vertical load was increased to 105000-lb. and the horizontal load increased. The flat pieces used to give free ends to the arm were so over-stressed that they yielded and the jack and side rods shifted to one side. The gauge reading indicated that no further load could be applied, and more pumping only served to throw the jack more out of line. The horizontal load was removed and the vertical load applied to a maximum.

The cracks which were noticed at the maximum load opened wider when the specimen was further deformed. The horizontal arm cracked at its junction with the cross, as shown in the sketch, and fell off. The failed specimen is shown in the photograph on page 243.

An inspection of the fracture showed no instances of stone crushing but several cases of mortar pulling away from the stone. The surface of the specimen was pitted but the interior was fairly dense.

2054. This specimen and 2059 were tested to determine expansion. No deformations other than expansions were measured. The expansometers were on the vertical arm and on the cross. Increments of load of 15000-lb. were applied simultaneously to the two arms. The expansometers were read immediately after the desired load was reached, and another increment applied. At the nominal load of 60000-lb. the horizontal load was removed to change gauges on the pump, and the expansometers were reset after the load had been reapplied. At a vertical load of 133000-lb. and a horizontal load of 100000-lb. no cracks or other signs of failure could be found on the specimen, but the load fell off rapidly. After standing about one minute, during which time the vertical load fell to 113000-lb., more load was applied. The maximum vertical load was 137000-lb., or 2140 lb. per sq.in., and the maximum horizontal load was 105000-lb., or 1640 lb. per sq.in. Failure occurred in the vertical arm, showing a distinct splitting and bulging on two opposite faces. See the sketch on page 248. The horizontal load was not increased

after 105000-lb. because the small crossed pieces between the jack and the plate on the end of the specimen had failed, and additional pumping threw the jack out of line.

2059. The arrangement of expansometers and the increments of load were the same as for 2054. After four increments of load, the expansometer on the cross had scarcely moved, so it was disturbed and reset to the same reading. Load was removed from the horizontal arm and reapplied twice during the test to change the bearing pieces. The maximum vertical load was 143000-lb., or 2200 lb. per sq.in. and the maximum horizontal load was 142500-lb. or 2200 lb. per sq.in. Failure occurred in the vertical arm under tha maximum load while the horizontal load was 10000-lb. lower than its maximum. After the vertical arm had failed, the horizontal load was increased to its maximum causing general failure in the horizontal arm and a very noticeable splitting in the plane of both loads. See the sketches on page 258.

2061. Half as great loads were applied to the horizontal arm as to the vertical one. Increments of 15000-lb. vertical load were applied as before. The expansometers were on the vertical arm and on the cross. Failure occurred by crushing the long vertical arm. See the sketch on page 260. The largest crack extended just to the horizontal arm but did not enter it. There were no cracks on the horizontal arm. The maximum load applied to the vertical arm was 120000-lb, which is a unit stress of 1790 lb. per sq.in.

In order to investigate the effect of the previous test on

the cross of the specimen, the undamaged arm was tested in simple compression, using the testing machine for the purpose. The specimen was centered and then loaded at the speed used in applying load during the original test. The maximum load carried by the horizontal arm was 113500-lb., or 1720 lb. per sq.in. Failure of this arm was caused by the formation of a diagonal crack on the long arm, extending from the end to the cross. No cracks developed in the cross during either test.

2062. The expansometers were on the vertical arm and the cross. Increments of load were applied as in the test of 2061. Failure occurred by crushing at the top of the vertical arm. See the sketch on page 265. The horizontal arm did not develop any marks during the test. The maximum load carried by the vertical arm was 98400-lb., or 1510 lb. per sq.in. The jack and side rods were removed after the test and the horizontal arm turned into a vertical position and tested for ultimate load. No deformations were measured. The load carried was 73500-lb., or 1130 lb. per sq.in. Failure of this arm occurred by crushing of the arm above the cross and the formation of a wedge in the arm. Some of the cracks extended to the cross and appeared to enter the cross. When a greater deformation was produced, the specimen fell apart and it was seen that the main crack, along which failure occurred, reached from the top of the long arm to the top of the short vertical arm, passing through the cross. The cracks developed in this second test extended into both the long and short arms which were vertical in the first test. The specimen after this second test is shown in Fig. 19, page 81.

Fig. 19. Compression Specimen 2062 after Second Test.

2063. While the specimen was being centered in the machine and the spherical block lowered, a load of 75000-lb. was accidentally applied to the vertical arm of the specimen. The expansometers were on the horizontal arm and the cross. Increments of load were the same as for 2061 and 2062. Failure occurred at the top of the vertical arm at a load of 140000-lb., or 2160 lb. per sq.in. Cracks extended to the horizontal arm but not into it. The undamaged arm was tested and carried a load of 150800-lb., or 2320 lb. per sq.in. Failure was very gradual and extended from the top to the bottom of the specimen. The failed arm dropped off when deformation was increased past that at the ultimate load.

2071. Expansometers were on the vertical arm and on the cross. No load was applied to the horizontal arm. Increments of load of 15000-lb. were applied to the vertical arm. The test was begun on January 11, 1912, and series of observations at zero load and after the first increment of load were taken. During the series at 15000-lb. load, power failed and it was necessary to postpone the test until the next morning, when another series of observations at the first load was taken and the test continued. The effect of leaving the specimen in the machine over night is discussed under "10. Time Effect of Load." Failure occurred at a load of 114300-lb., or a unit stress of 1730-lb. A great number of small vertical cracks formed in the long vertical arm but these did not reach the cross. When the specimen was further deformed the arm crushed badly but none of the cracks reached the cross. The horizontal arm was bedded

in plaster on the ends and tested as before. Failure occurred at a load of 96400-lb., or 1460 lb. per sq.in. by splitting of the short arm followed by splitting of the cross and general crushing below the top of the cross. Apparently the concrete in the cross was not damaged by the first loading. Failure started at the bottom and in rising, split the previously loaded long arm somewhat and cracked the previously loaded short arm off entirely. Gauge-lines 6 and 16 were placed 1/2-in. outside the lines of the vertical arm and parallel to the vertical arm to determine the distribution of stress and the distance out on the horizontal arm to which the stress was carried. The distribution was investigated further in the tests of 2072 and 2073.

2072. No expansometers were used in this test. Additional gauge-lines were observed, as shown in the sketch on page 219. in order to determine the distribution of deformation. Failure occurred at a load of 96600-lb., or a stress of 1490 lb. per sq.in., by crushing the cross. Cracks extended diagonally across the specimen, through the cross and out into the unloaded arms. Crushing was first noticed at the junction of the two long arms, as shown in Fig. 20. When the specimen was further deformed the long horizontal arm dropped off, the short one was ready to drop away, and a cone of crushing was formed in the cross as shown in Fig. 21. The distribution of deformation on the cross in this test may be seen from the curves of Fig. 22 and 23, pages 86 and 87. Possibly the spherical block failed to work properly and caused an uncertain distribution of load.

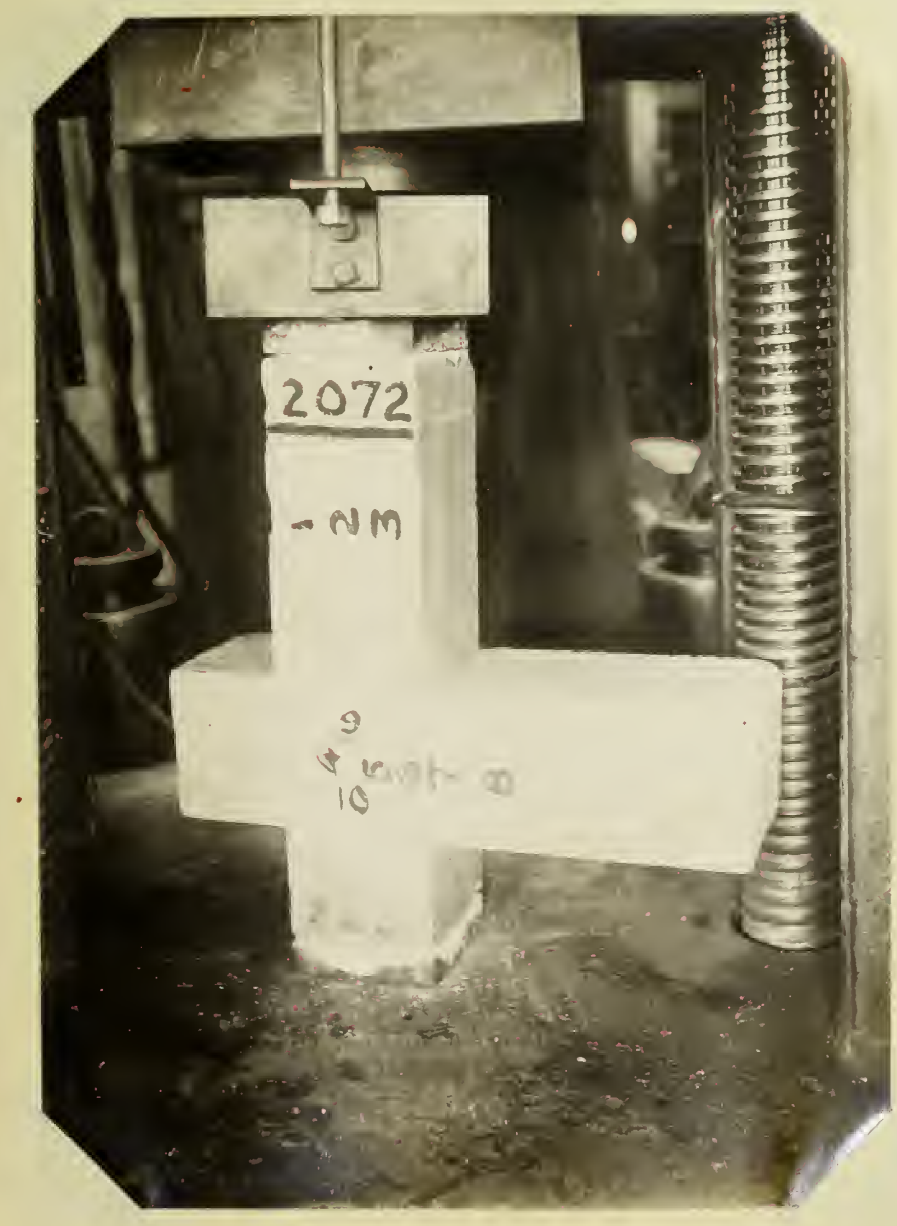


Fig. 20. Compression Specimen 2072, First Signs of Failure.

Fig. 21. Compression Specimen 2072 after Failure.

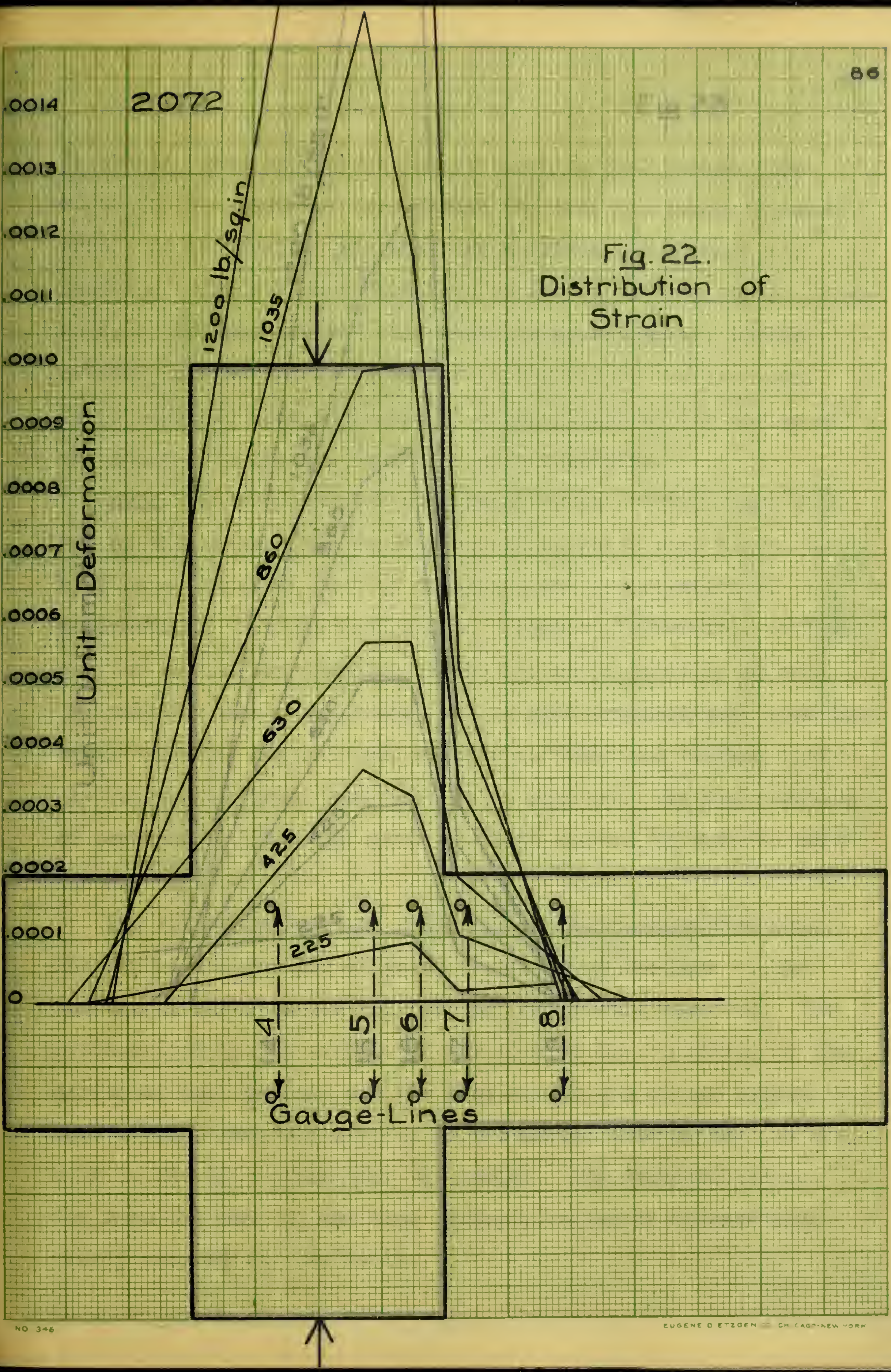


Fig. 22.
Distribution of Strain

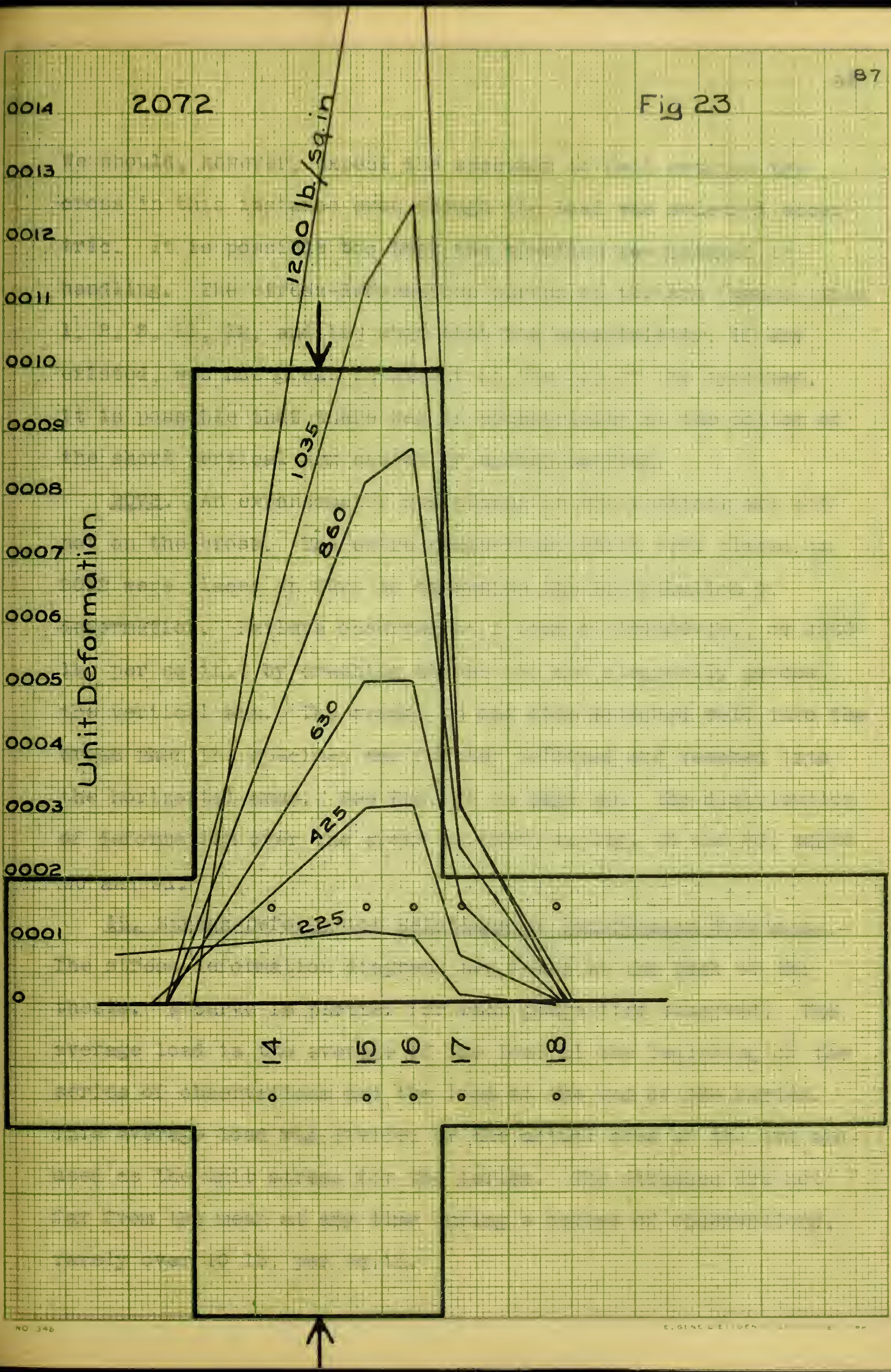

2072
.0014
.0013
.0012
.0011
.0010
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
0
Unit Deformation
1200 lb./sq. in
1035
860
630
425
225
14
15
16
17
18

Fig 23

We should, however, expect the specimen to fail outside the cross in this instance even though the load was somewhat eccentric. It is possible too that the specimen was damaged in handling. The stress-deformation curves on the arm (gauge-lines 1, 2, 3, 11, 12, and 13) show that the eccentricity, if any existed, was not great in amount at the top of the specimen. It is possible that there was an eccentricity at the bottom of the short vertical arm caused by uneven bedding.

2073. An expansometer was placed on the vertical arm but not on the cross. The extra gauge-lines which were placed on 2072 were placed on 2073 to determine the distribution of deformation. Failure occurred at a load of 127500-lb., or 1960 lb. per sq.in., by crushing at the top and diagonally across the vertical arm. The cracks on one side extended well into the cross when the specimen was further deformed and reached into the horizontal arms. See Fig. 24 on page 89. The distribution of deformation over the cross is shown in Fig. 25 and 26, pages 90 and 91.

15. Stress-Deformation Relations of Compression Specimens.- The stress-deformation diagrams are found at the back of the thesis. A curve is plotted for each gauge-line observed. The average load is the average of the load at the beginning of the series of observations and the load at the end of the series. This average load was divided by the actual area of the arm and used as the unit stress for the series. The stresses are not far from the mean at any time during a series of observations, rarely over 10 lb. per sq.in.

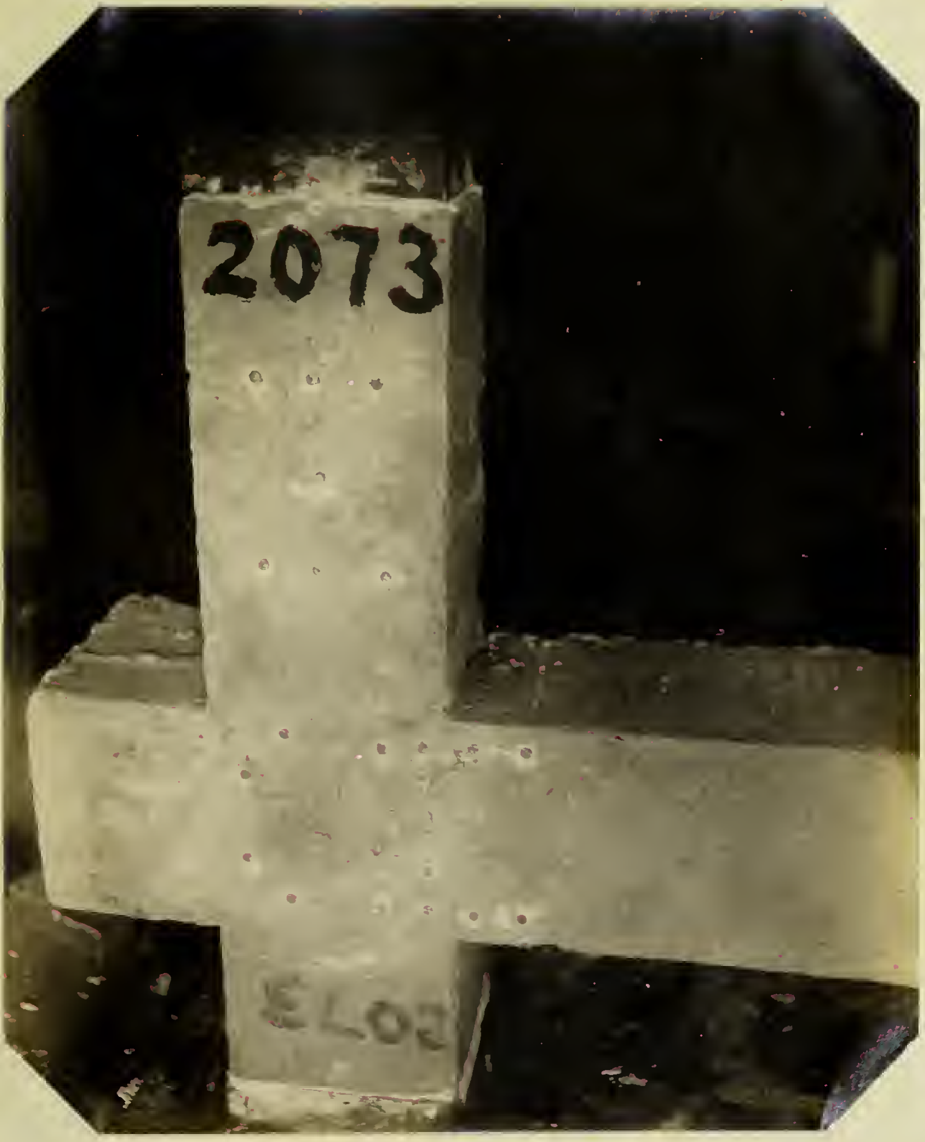
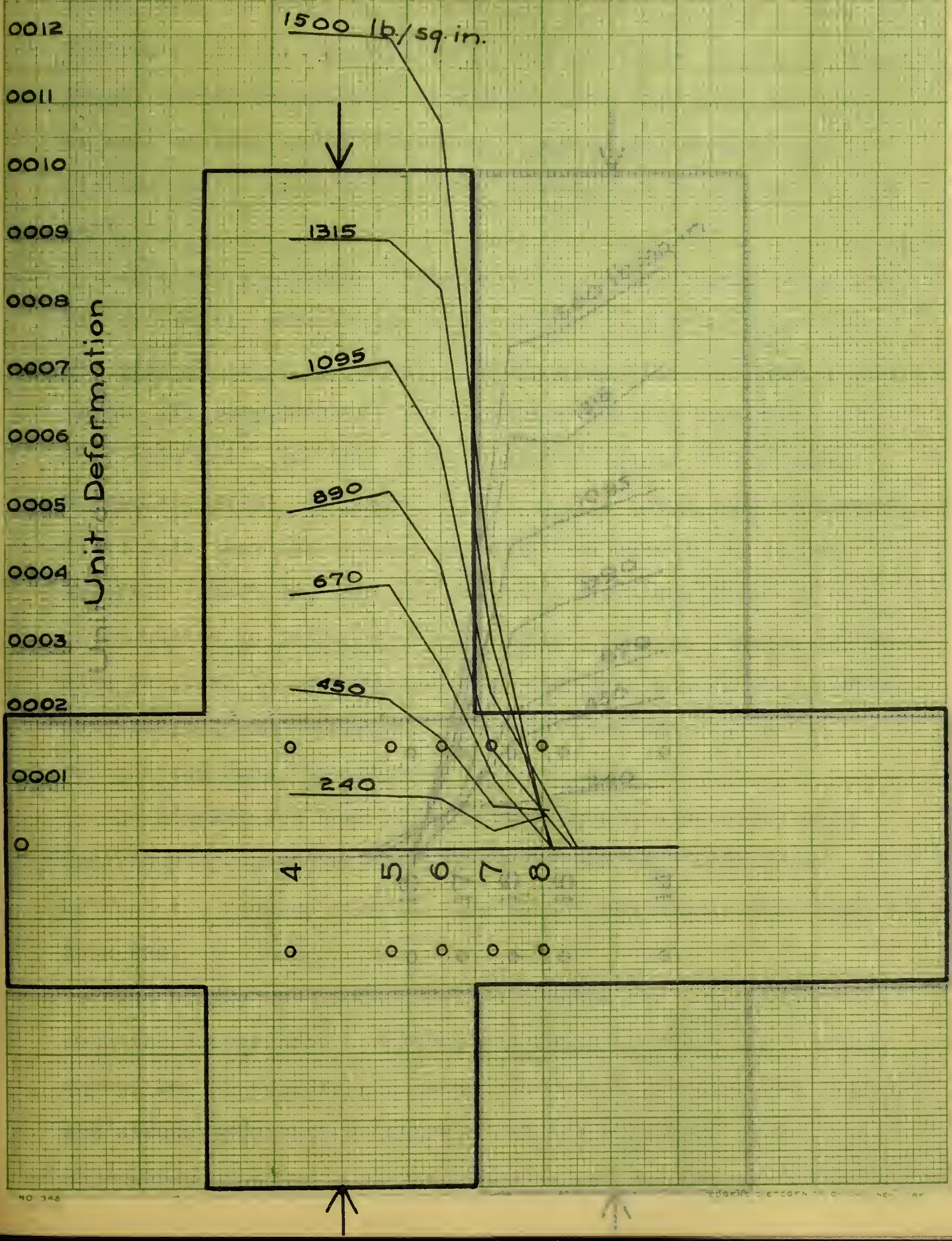


Fig. 24. Compression Specimen 2073 at Failure.

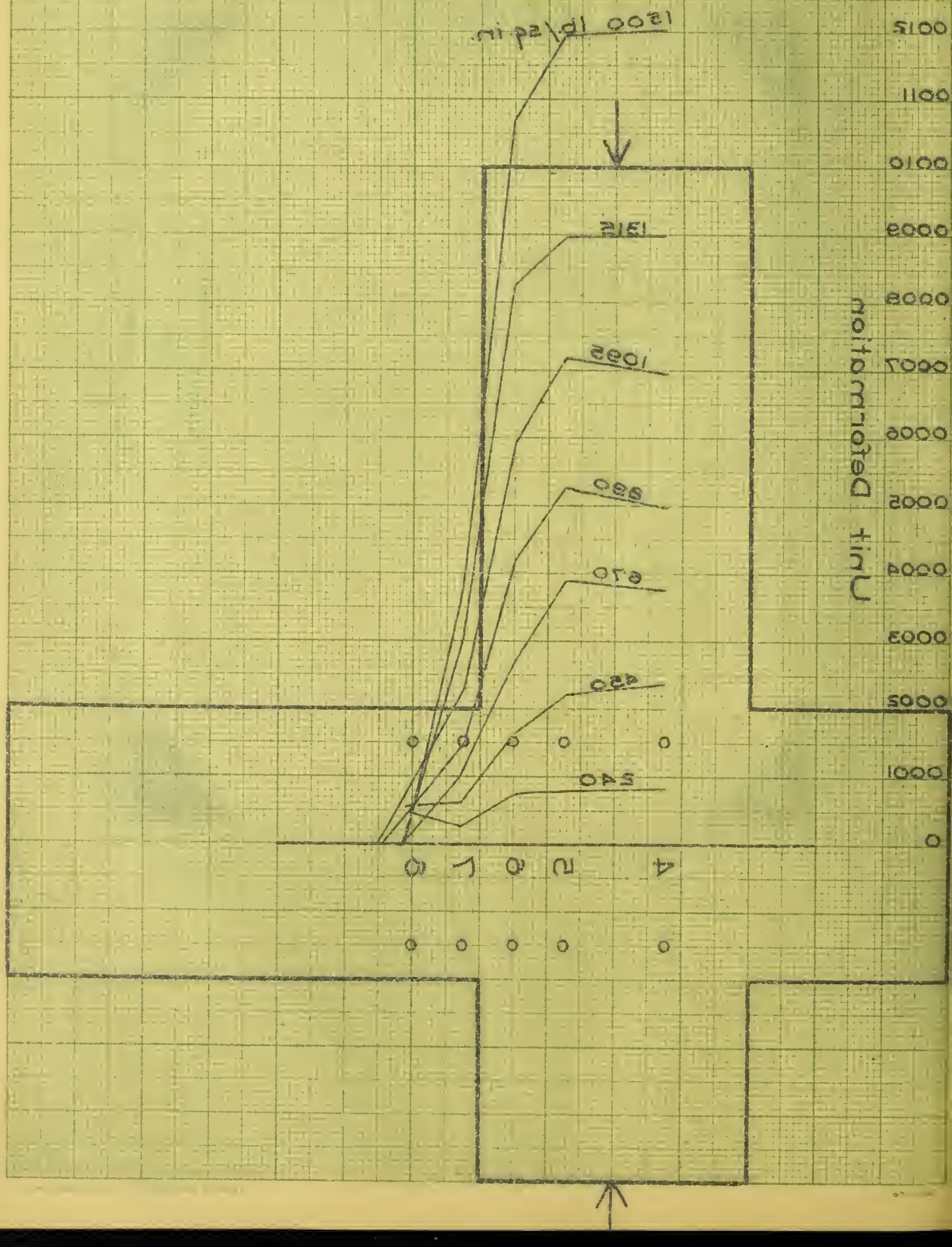
2073

Fig. 25


1500 lb./sq. in.
1315
1095
890
670
450
240
.0012
.0011
.0010
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
0
Unit Deformation
4
5
6
7
8

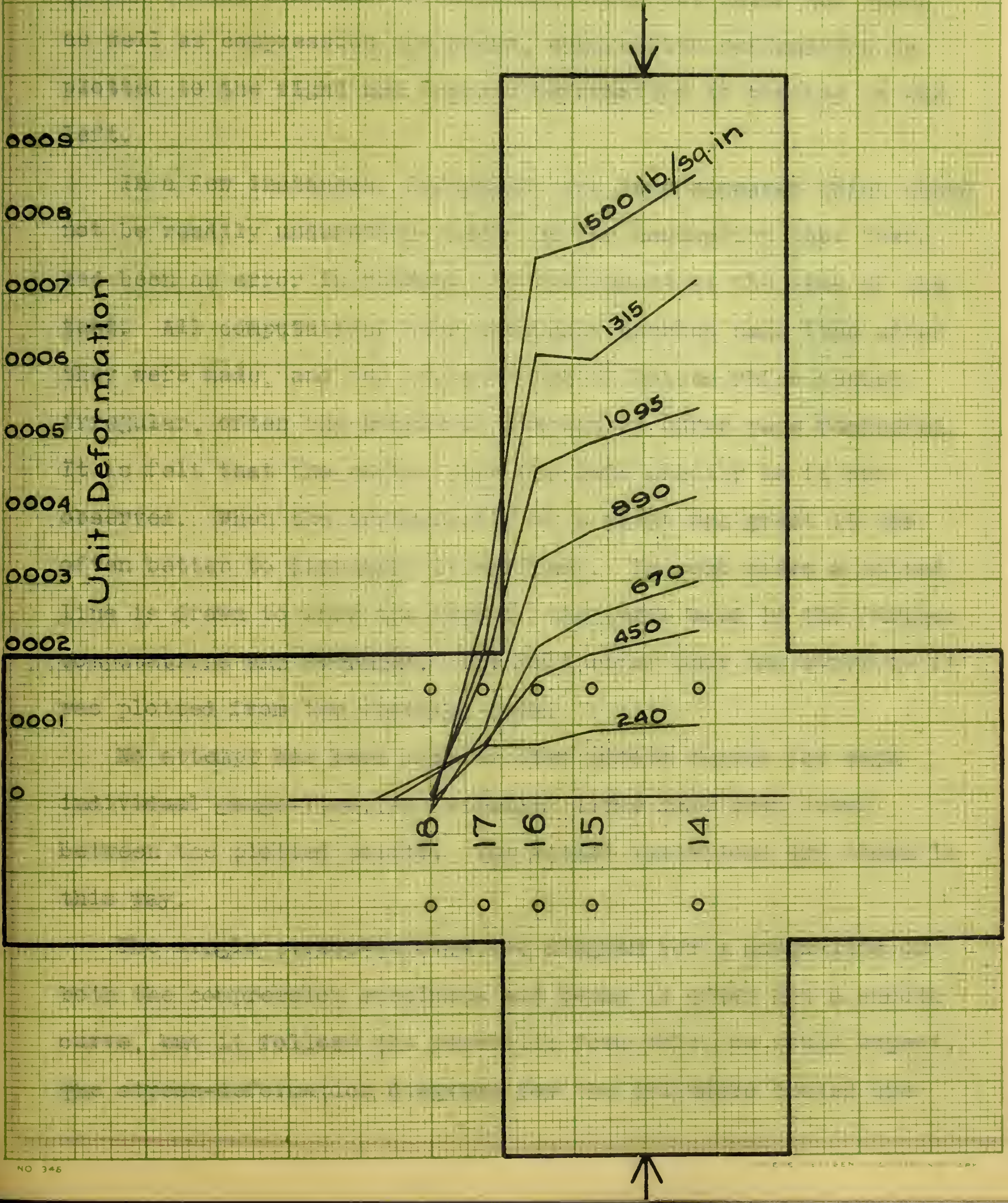
2073

Fig. 25


1500 lb/sq in.
1315
1095
890
670
450
240
Unit Deformation
0012
0011
0010
0009
0008
0007
0006
0005
0004
0003
0002
0001
0
4
5
6
7
8

2073

Fig. 26.


Unit Deformation
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
0
1500 lb/sq.in
1315
1095
890
670
450
240
18
17
16
15
14

The deformation used in plotting a point is the deformation found from the corrected differences of the readings of the Berry instrument on this gauge-line at the particular stress in question. In all stress-deformation diagrams, those for beams and cubes as well as compression specimens, compressive deformation is plotted to the right and tensile deformation is plotted to the left.

In a few instances, irregularities have appeared which could not be readily understood except on the assumption that there had been an error in reading the instrument at the time of the test. All computations were carefully checked some time after they were made, and the computations of points which seemed irregular, often the points of the entire curve were rechecked. It is felt that the curves show the data exactly as it was observed. When the irregularity of a point was great it was often better to disregard it entirely. In such cases a dotted line is drawn to show the form of the curve used in the further computations and averages. The full lines show the curve as it was plotted from the observed data.

No attempt has been made to draw smooth curves for each individual gauge-line, but straight lines have been drawn between the plotted points. The actual variations are shown in this way.

The single stress-deformation diagram for a gauge-line on both the compression specimens and beams is often not a smooth curve, but it follows the parabolic form which we would expect. The stress-deformation diagrams for the cylinders tested are

uniformly smooth curves. An effort to account for this difference led to the conclusion that the cylinder curve was smooth because the deformations at various points on its surface were mechanically averaged by the yoke arrangement which was used in testing such specimens. Deformations on the compression specimens and beams were measured at several points separately and therefore varied with the nature of the concrete at the particular part of the test piece considered. Any eccentricity of loading in the cylinder was not indicated in the resulting curve because of the averaging device, while an eccentricity of loading on a compression specimen was shown in the series of computed curves because they gave relations at particular points on the surface of the specimen.

It would seem probable that failure in a concrete compression piece occurs progressively, that is to say, first one point becomes deformed to its ultimate and yields, allowing neighboring points to come to a fuller loading and they in turn crush and yield. This phenomenon could occur unnoticed in a cylinder or other test piece where an averaging extensometer is used. Quite frequently vertical cracks are seen in a cylinder before the maximum load is reached. A gradual or progressive failure could be noticed if deformations were obtained at particular points. This point is strikingly brought out in the figures showing the distribution of deformation in 2072 and 2073 at the several stages of the test. See Fig. 22, 23, 25 and 26. It is seen that 2072 was eccentrically deformed but 2073 was axially loaded. The variation of deformation on the separate gauge-lines at a

common stress is significant.

The length of the gauge-line in the two cases of the cylinder and the compression specimens is perhaps significant. A 10-in. gauge-line was used on the cylinder and a 6-in. gauge-line was measured on the test specimens. Concrete is considered as a homogeneous mixture of cement, sand and stone, so graded that the smaller particles of the aggregate will substantially fill the voids between the larger particles, and the cement will also fill the voids between the smaller and make a dense, homogeneous mass. Well-mixed concrete approaches these requirements and behaves more or less as a homogeneous material when considered as a whole. But when such a short gauge-line as 6-in. is used and averages are not taken, it is easy to see that the presence or absence of one or two pieces of the coarse aggregate in this region would affect the stress-deformation curve. When a 10-in. gauge-line is used and an average of several deformations is produced mechanically, the effect of a few pieces of aggregate is not so marked.

A noticeable feature is that the average of these individual curves drawn for gauge-lines distributed around the surface of the specimen gives a smooth curve in every case, both at the region under two compressions and on the arms of the specimen where simple compression exists. An average curve is made from at least four single stress-deformation curves, and often from as many as eight or twelve, by averaging the individual deformations on the gauge-lines distributed around a specimen at a

certain unit stress, and plotting these average deformations. Tables of the values used in plotting these average curves appear in the data in the back of the book.

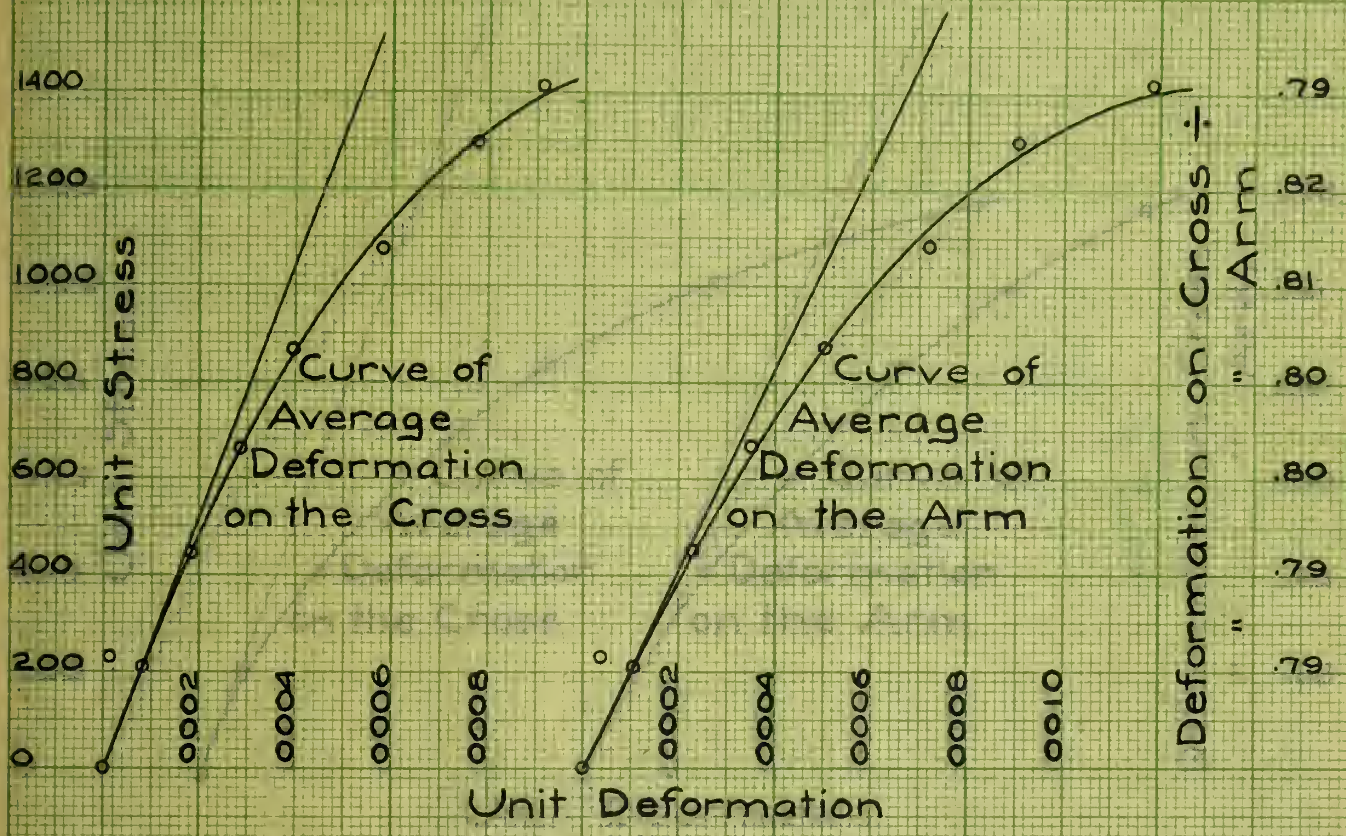
This discussion accounts in a measure for the appearance of some of the diagrams which might be considered as unsatisfactory. The interpretation of the data and all conclusions are based on average curves.

Three compression specimens were tested with load on only one of the arms to determine the effect of the enlarged section at the cross on the unit deformation and on the apparent initial modulus of elasticity. The results are shown in the average curves of these specimens, 2071, 2072, 2073, Fig. 27, 28 and 29, pages 96, 97 and 98. The curves of average deformation on the arm and on the cross are similar in form but the deformation on the cross is less than on the arm at any definite load.

Consider the curves showing the distribution of vertical deformation across the horizontal arms of the specimens, Fig. 22, 23, 25 and 26. The enlarged section at the cross decreases the deformation and from these distribution curves something of the amount of reduction can be learned. If we figure the area under the highest curve, which is the curve showing the distribution at the highest load, we find that the area within the vertical lines of the arm is, in the four cases, 0.86, 0.90, 0.87, and 0.86 of the total area. These average 0.87. Choosing another set of curves, say the ones at the third increment of load, and figuring the areas as before, we get 0.87, 0.89, 0.80 and 0.79 of the total area under the curve is within the vertical lines

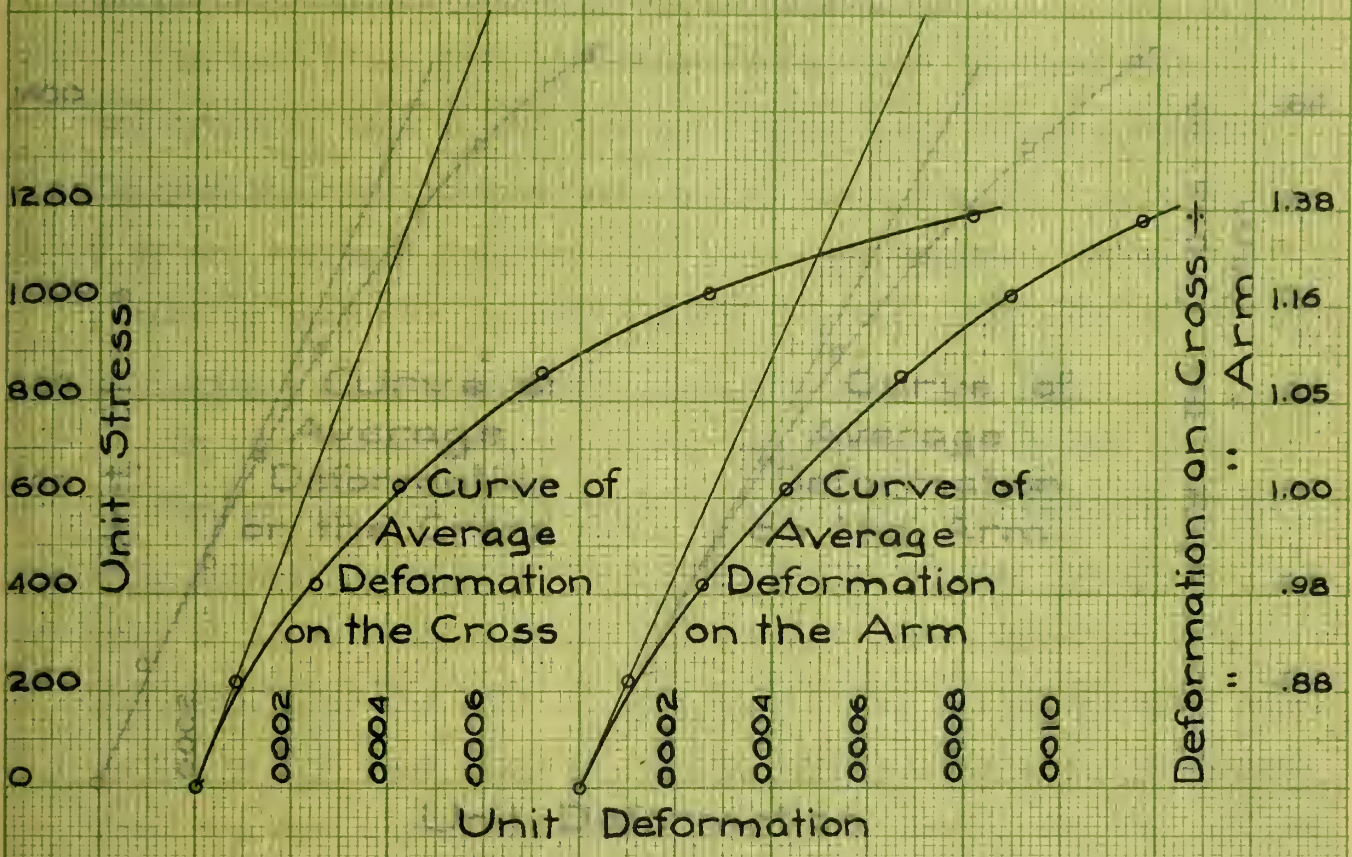
2071

Fig 27


1400
1200
1000
800
600
400
200
0
Unit Stress
0002
0004
0006
0008
0010
Curve of Average Deformation on the Cross
Curve of Average Deformation on the Arm
Unit Deformation
Deformation on Cross ÷ Arm
.79
.82
.81
.80
.80
.79
.79

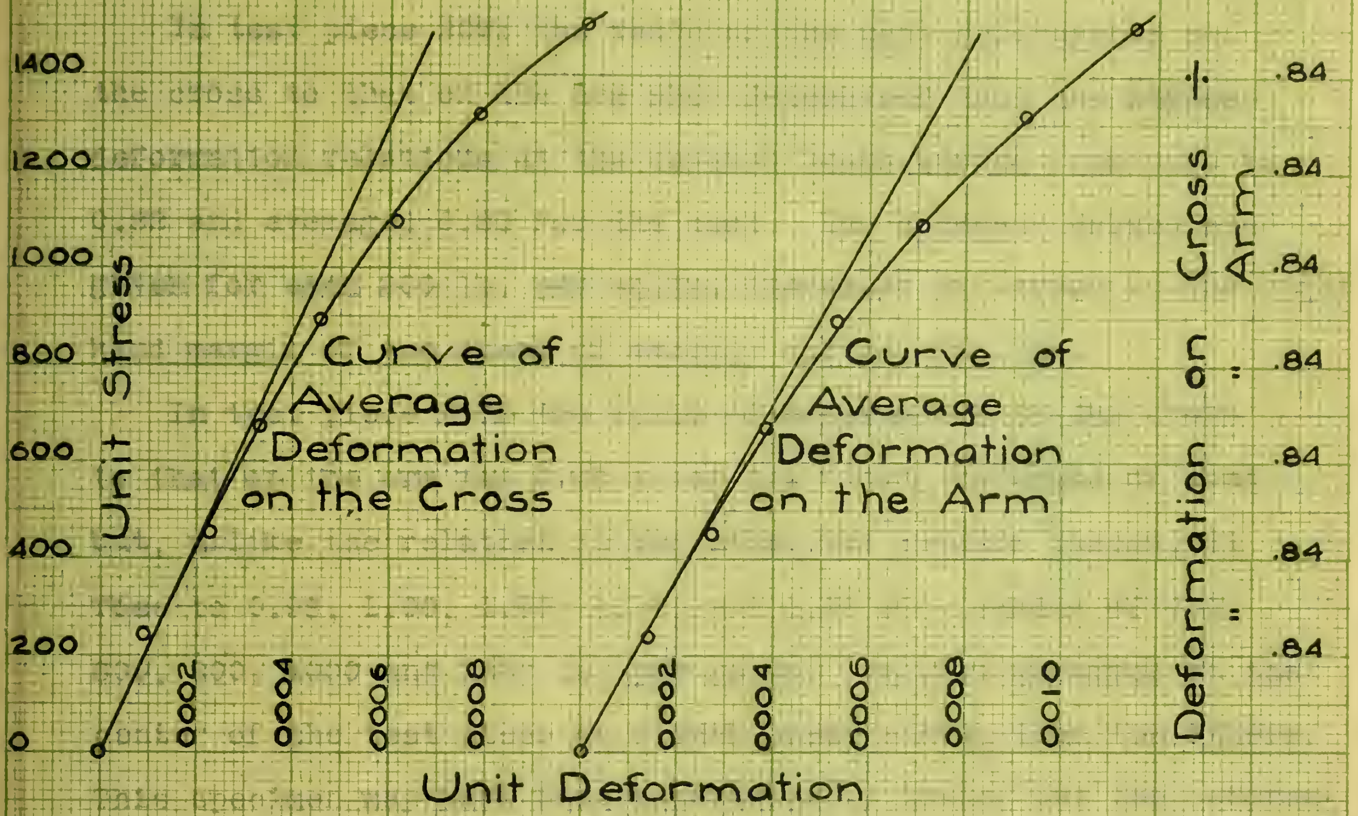
2072

Fig. 28


Unit Stress
1200
1000
800
600
400
200
0
0002
0004
0006
0002
0004
0006
0008
0010
Unit Deformation
Curve of Average Deformation on the Cross
Curve of Average Deformation on the Arm
Deformation on Cross ÷ Arm
1.38
1.16
1.05
1.00
.98
.88

2073

Fig. 29


Unit Stress
1400
1200
1000
800
600
400
200
0
.0002
.0004
.0006
.0008
.0002
.0004
.0006
.0008
.0010
Curve of Average Deformation on the Cross
Curve of Average Deformation on the Arm
Unit Deformation
Deformation on Cross ÷ Arm
.84
.84
.84
.84
.84
.84
.84

of the arm. These average 0.84. We may say from these numbers that the deformation on the cross is reduced to from 0.87 to 0.84 of the deformation on the arm as determined from the curves showing the distribution of deformation.

In test piece 2071 the ratio of the unit deformation on the cross to that on the arm when determined from the stress-deformation relations at the several loads varied from 0.79 to 0.82 and averaged 0.80 for the test. The separate values are given for each 200 lb. per sq.in. increment of stress on the right hand margin of the sheet of average curves, Fig. 28.

In test piece 2072 the ratio of deformation on the cross to that on the arm was 0.88 after the first increment of load but, unlike the relation in the other two similar pieces, it rose to 0.98, 1.00, 1.05, 1.16, and 1.38 at stresses of 400, 600, 800, 1000 and 1200 lb. per sq.in. Failure occurred at the center of the test piece at a much lower stress than the others. This specimen may have been eccentrically loaded but the deformations on the gauge-lines on the arm (1, 2, 3, 11, 12 and 13) seem to show decidedly that it was not eccentrically loaded. See these curves on page 170. It is felt that the concrete in this specimen must have been injured in some way before the test and that the increased unit deformation at the center was abnormal. This opinion is strengthened by two facts: (1) that in all other specimens tested the ratio of the deformation on the cross to that on the arm was practically a constant for all stresses, while the variation in 2072 was over 60 per cent., and (2) that in all other specimens tested, the deformation at

Table VIII.

Compression Specimens 2071, 2072, 2073

Summary of Ratios of Deformation on the Cross to Deformation on the Arm.

Unit Stress	$\frac{\text{Deformation on Cross}}{\text{Deformation on Arm}}$				
	2071	2072	2073	Av. {2071 {2073	Average
1800					
1600					
1400	.79		.84	.82	.82
1200	.82	1.38	.84	.83	1.01
1000	.81	1.16	.84	.83	.94
800	.80	1.05	.84	.82	.90
600	.80	1.00	.84	.82	.88
400	.79	.98	.84	.82	.87
200	.79	.88	.84	.82	.84
Average	.80	1.07	.84	.82	.89

the cross was less than on the arm by a practically constant proportion even though failure occurred in the cross of the specimen. The very striking uniformity of the results of tests of 2071 and 2073 add weight to this conclusion.

In 2073 the ratio of the unit deformation on the cross to that on the arm as determined from the curves of average deformation was 0.84 for every separate increment of load throughout the test. Such close agreement of results among themselves gives confidence in the method of obtaining results.

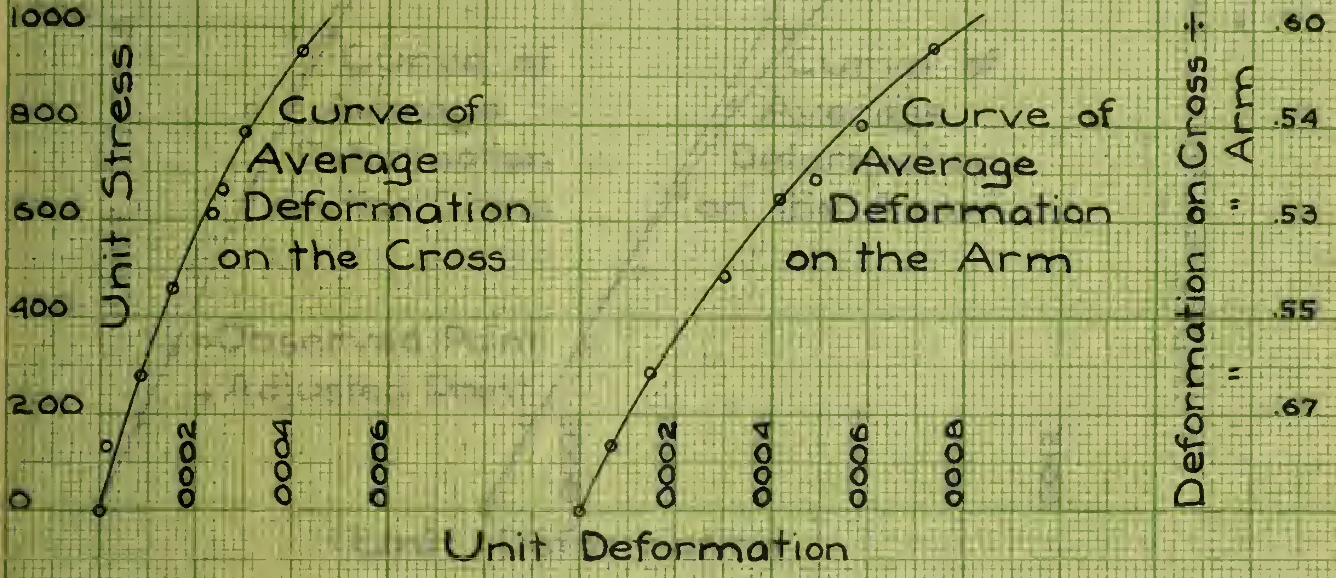
A summary of the ratios derived from results of these three tests is shown in Table VIII. The columns marked "Deformation on Cross/Deformation on Arm" give the average of the ratios at the unit stress noted in the column marked "Unit Stress". The line of averages at the bottom of the page gives the average for each compression specimen at all stages of the test.

The mean of all these averages is 0.89 for all three tests including the results of 2072 which are thought to be abnormal. Considering only specimens 2071 and 2073 the conclusion is that, for the shape of specimen considered, the unit deformation on the cross is 0.82 of the unit deformation on the arm.

Four compression specimens were tested with equal compressions on the two arms to determine the effect of the enlarged section at the cross and the effect of two equal stresses at right angles on the unit deformation and on the apparent initial modulus of elasticity. The results are shown in the averaged curves of 2050, 2051, 2052 and 2053, Fig. 30, 31, 32, 33, and 34 on pages 102, 103, 104, 105 and 106.

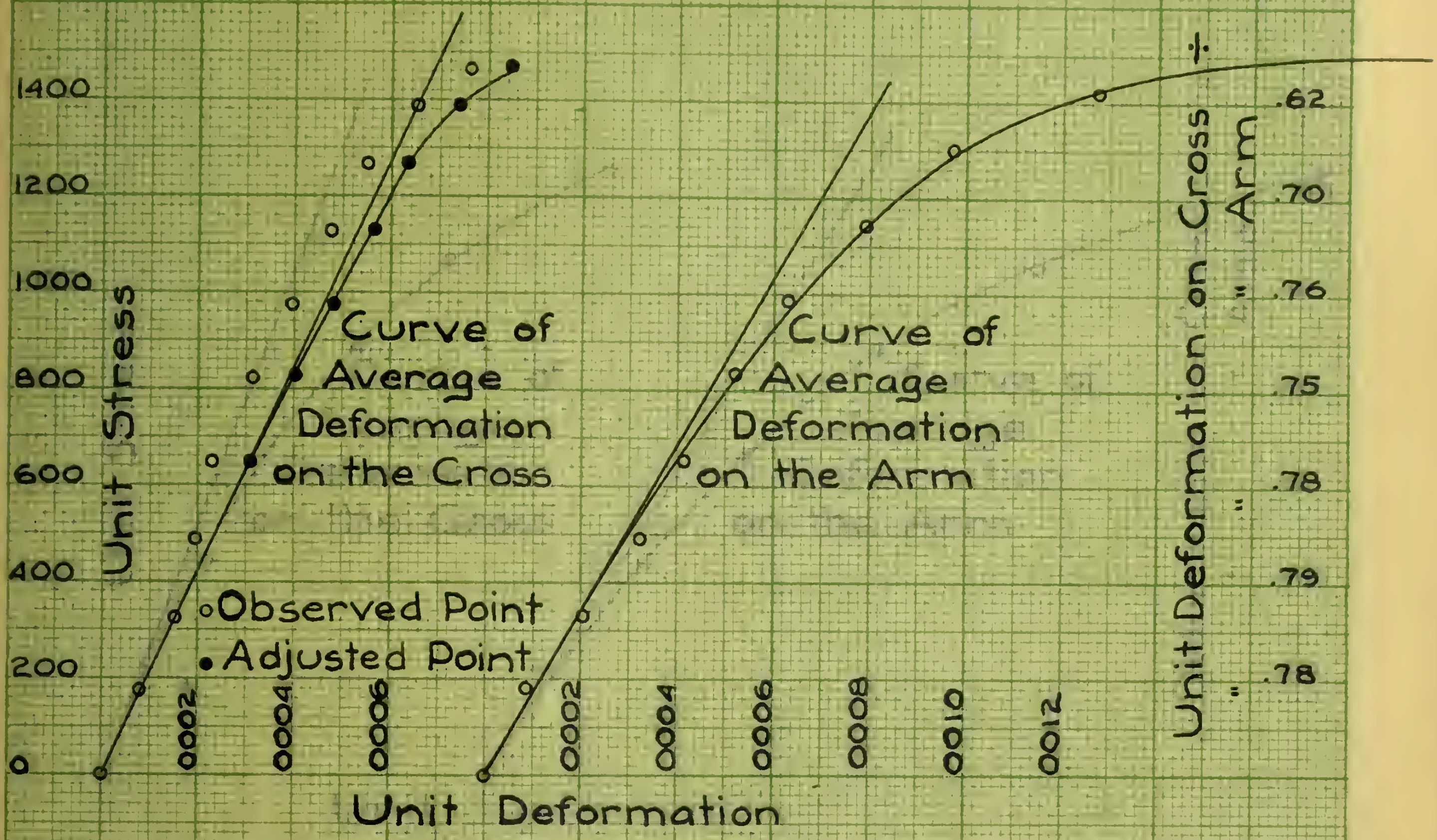
2050 First Test

Fig. 30



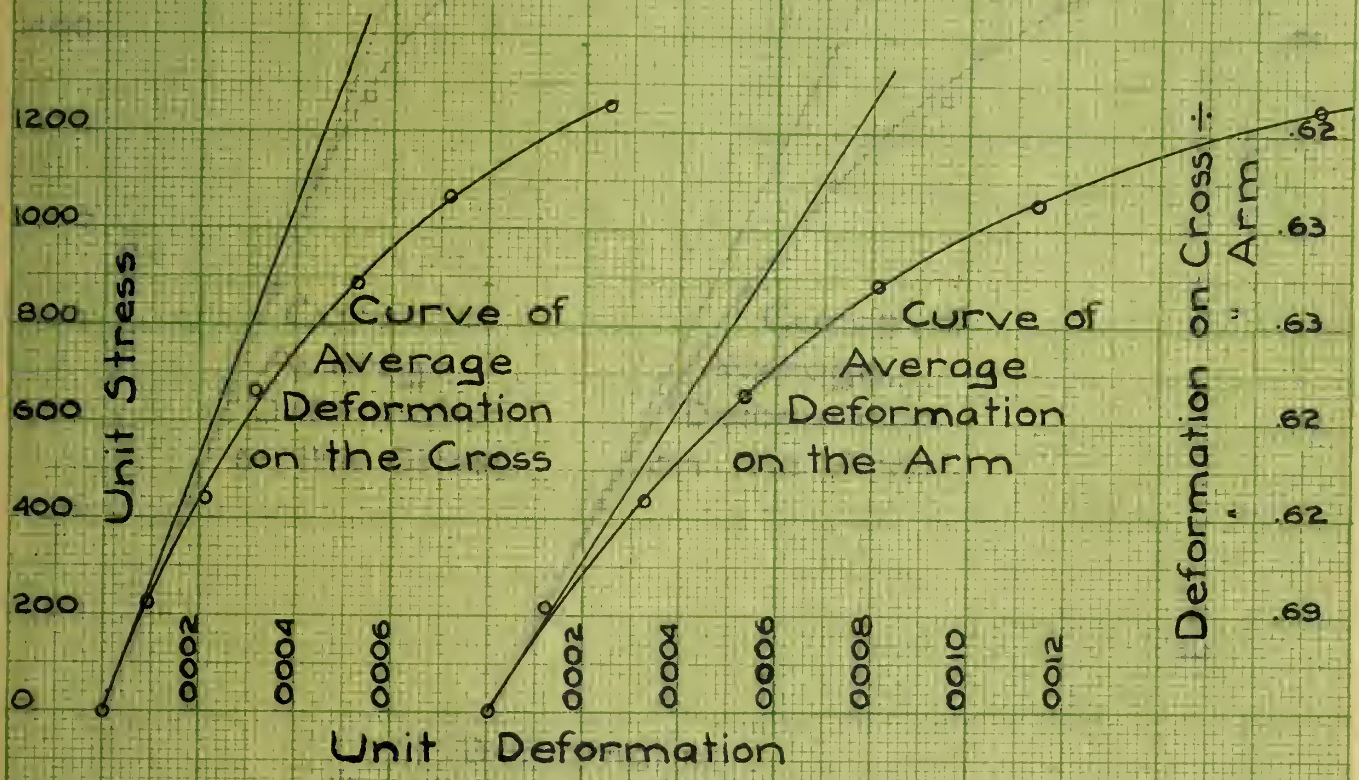
2050 Second Test

Fig. 31.



2051

Fig. 32


1200
1000
800
600
400
200
0
Unit Stress
.0002
.0004
.0006
Curve of Average Deformation on the Cross
.0002
.0004
.0006
.0008
.0010
.0012
Curve of Average Deformation on the Arm
Unit Deformation
Deformation on Cross ÷ Arm
.62
.63
.63
.62
.62
.69

2052

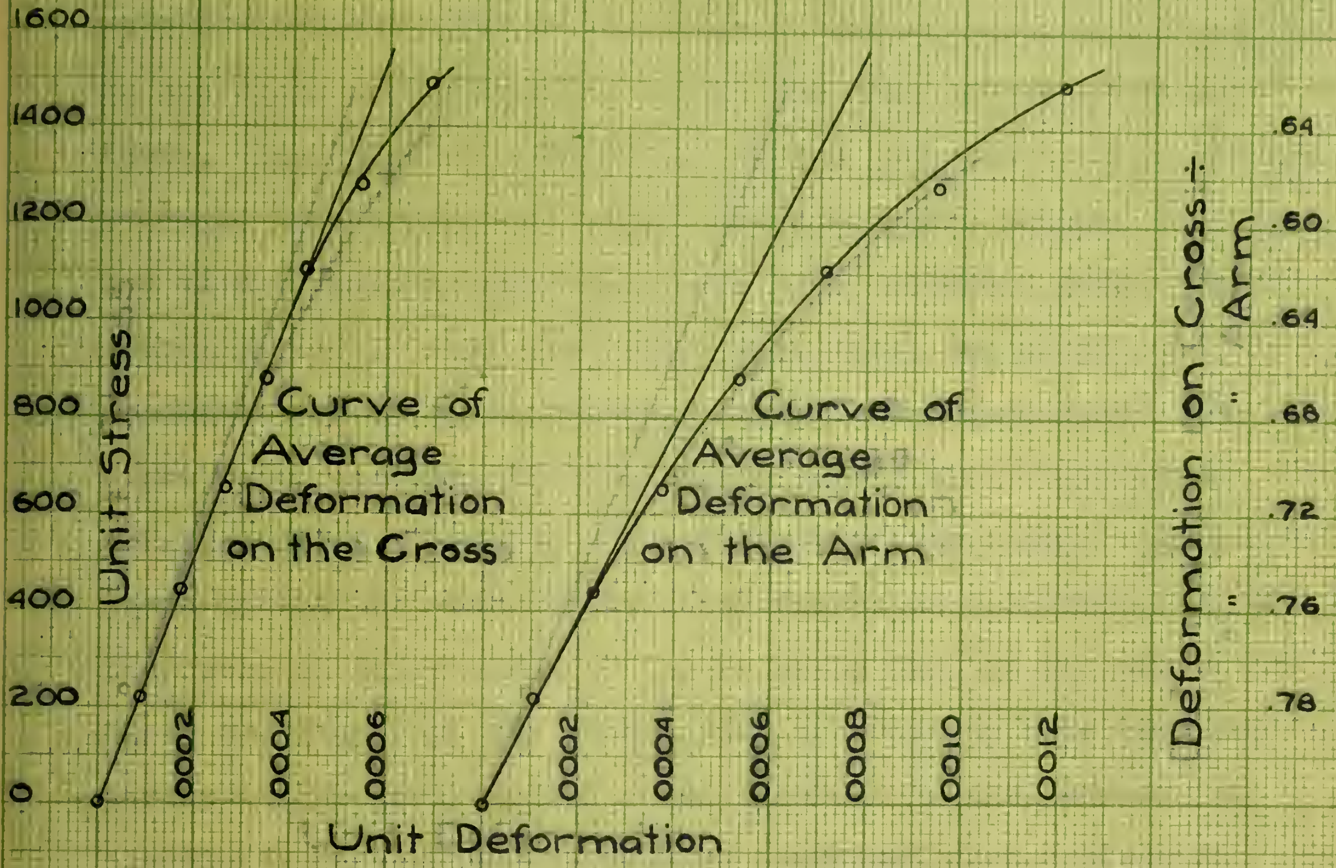
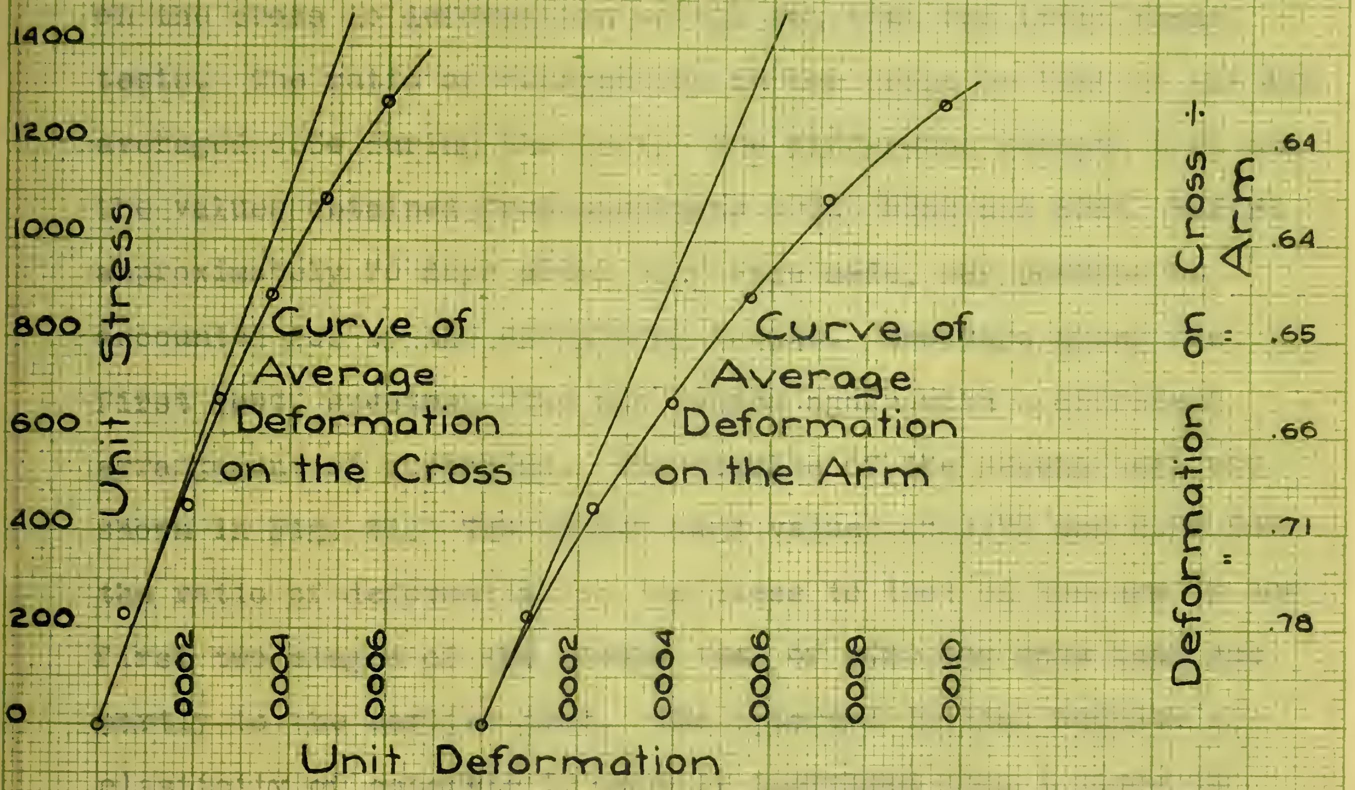

1600
1400
1200
1000
800
600
400
200
0
Unit Stress
Curve of Average Deformation on the Cross
Curve of Average Deformation on the Arm
.0002
.0004
.0006
.0002
.0004
.0006
.0008
.0010
.0012
Unit Deformation
Deformation on Cross ÷ Arm
.64
.60
.64
.68
.72
.76
.78

Fig. 33.

Fig. 34


1400
1200
1000
800
600
400
200
0
Unit Stress
.0002
.0004
.0006
.0008
.0010
Unit Deformation
Curve of Average Deformation on the Cross
Curve of Average Deformation on the Arm
Deformation on Cross ÷ Arm
.64
.64
.65
.66
.71
.78

At an age of 50 days, compression specimen 2050 was loaded to about 950 lb. per sq.in., and the test discontinued. The results of this preliminary test were computed and it was found that they were consistent although they show a smaller ratio of deformation on the cross to deformation on the arm than the later three tests. The ratio of deformation on the cross to that on the arm averaged 0.54 during the test. The difference between this and the values obtained from specimens 2051, 2052 and 2053, tested approximately 70 days after they were made, may perhaps be accounted for by the difference in age. Two days after the first test, specimen 2050 was loaded again with a different arrangement of apparatus. The results of the second test are shown in Fig. 31. The rather high values of 0.78 and 0.79 for the ratio of deformation on the cross to that on the arm in the first two stages of the second test of 2050 may have been due partly to the earlier test. The apparent initial modulus of elasticity of concrete is usually increased when a piece is tested after having been previously loaded, while the stress-deformation relations at stresses higher than those reached by the preliminary tests are not changed. This is brought out in Bulletins 4 and 10 of the University of Illinois Engineering Experiment Station. The apparent initial modulus of elasticity is found in both cases from the experimental stress-deformation curve and it must be remembered that the zero readings of the later test are not those of the first test by the amount of the set produced by the first loading, and that the origin of the stress-deformation curve is changed in the second trial. At

least a part of the difference must have been the result of a different method of applying the load and lack of experience in dealing with test specimens of this sort.

The average ratio of deformation on the cross to deformation on the arm for the complete second test of 2050 made two days after the first, is 0.74. The separate ratios at each increment of load do not vary greatly from the mean. It would probably be well to drop the results of tests of this preliminary specimen, but the average of the two tests is the same as the average of the three later tests and it is of no consequence whether they are dropped or kept.

In compression specimen 2051 the ratio of the unit deformation on cross to that on the arm, as determined from the stress-deformation curves, varied from 0.62 to 0.69 and averaged 0.63 for the test. The very small variation of this ratio with the stress at loads higher than the first is evident.

The values of the ratio of the deformation on the cross to the deformation on the arm of 2052 varied from 0.78 to 0.60, which is a greater variation than is found in the other specimens of this kind. The average for the test was 0.69.

The test of 2053 indicated that the compressive deformation on the cross varied from 0.64 to 0.78 times that on the arm, and averaged 0.68 for the test.

A summary of the ratios of the deformation on the cross to the deformation on the arm as found in these tests is given in Table IX. Averages have been computed at each 200 lb. per sq.in. of stress and also for the entire test of each specimen.

Table IX.

Compression Specimens 2050, 2051, 2052 and 2053

Summary of Ratios of Deformation on the Cross to Deformation on the Arm.

Unit Stress	Deformation on Cross / Deformation on Arm				
	2050	2051	2052	2053	Average
1800					
1600					
1400	.62		.64		.63
1200	.70	.62	.60	.64	.64
1000	.60 .76	.63	.64	.64	.65
800	.54 .75	.63	.68	.65	.65
600	.53 .78	.62	.72	.66	.66
400	.55 .79	.62	.76	.71	.69
200	.67 .78	.69	.78	.78	.74
Average	.58 .74	.63	.69	.68	.66

The grand average of these gives the result that, for the shape of specimen tested, the unit deformation on the portion of the specimen under two equal stresses, i.e. the cross, is 0.66 of the unit deformation on the portion of the specimen under one stress of the same intensity, the arm.

If we assume that the relation of the enlarged section at the cross to the reduction in the unit deformation on the cross is the same when a specimen is tested under one load as when it is tested under two equal loads, we can deduce a relation between the unit deformation of any specimen loaded in two directions with equal loads and the unit deformation which would occur if the same specimen were loaded with one of these same loads, as follows: From the average of all specimens loaded with two equal compressions we have that the unit deformation at the center of the specimen is 0.66 of the deformation on the arm, and from the average of all specimens tested with one compression, we have (Table VIII) that the unit deformation on the cross of the specimen is 0.89 of the unit deformation on the arm. The quotient of these ratios, 0.66/0.89 or 0.74, is the relation between the unit deformation on the cross and that on the arm with the effect of the shape of specimen eliminated. In other words, when a portion of concrete is loaded in two directions perpendicular to each other, the unit deformation in each direction is 0.74 of the unit deformation which would occur if the same portion of concrete were loaded with one of these loads. If we drop the results of 2072 and use the average of the specimens which failed normally,

we have that the unit deformation on the cross is 0.66/0.82 or 0.80 of the deformation on the arm. The deformation is reduced to 80 per cent of that on the arm instead of the value of 74 per cent obtained by considering 2072 in with the results of 2071 and 2073. The value of 0.80 seems the more probable one because it is taken from the results of specimens which failed normally.

Three compression specimens were tested with half as great compression on one arm (the horizontal one) as on the other arm to determine the effect on the unit deformation and the apparent initial modulus of elasticity of this loading. The results are shown in the average curves for compression specimens 2061, 2062 and 2063 in Fig. 35, 36 and 37, pages 112, 113 and 114.

The relations found on the arm under the greater load will be discussed first, followed by those found on the arm under the smaller one.

The average unit deformation on the cross of 2061 measured parallel to the line of action of the greater load varied from 0.75 to 0.79 of the unit deformation measured on the arm under the greater load, and averaged 0.77 for the test.

In compression specimen 2062 the ratio of deformation on the cross to that on the arm was found to vary from 0.85 to 0.92 with but one exception. The average for the test was 0.87.

In specimen 2063 the ratio of deformation on the cross to that on the arm under the greater load varied from 0.76 to 0.84 and averaged 0.80 for the test. A summary of the ratios computed from the results of these three tests is given in the upper part of Table X, page 115.

2061

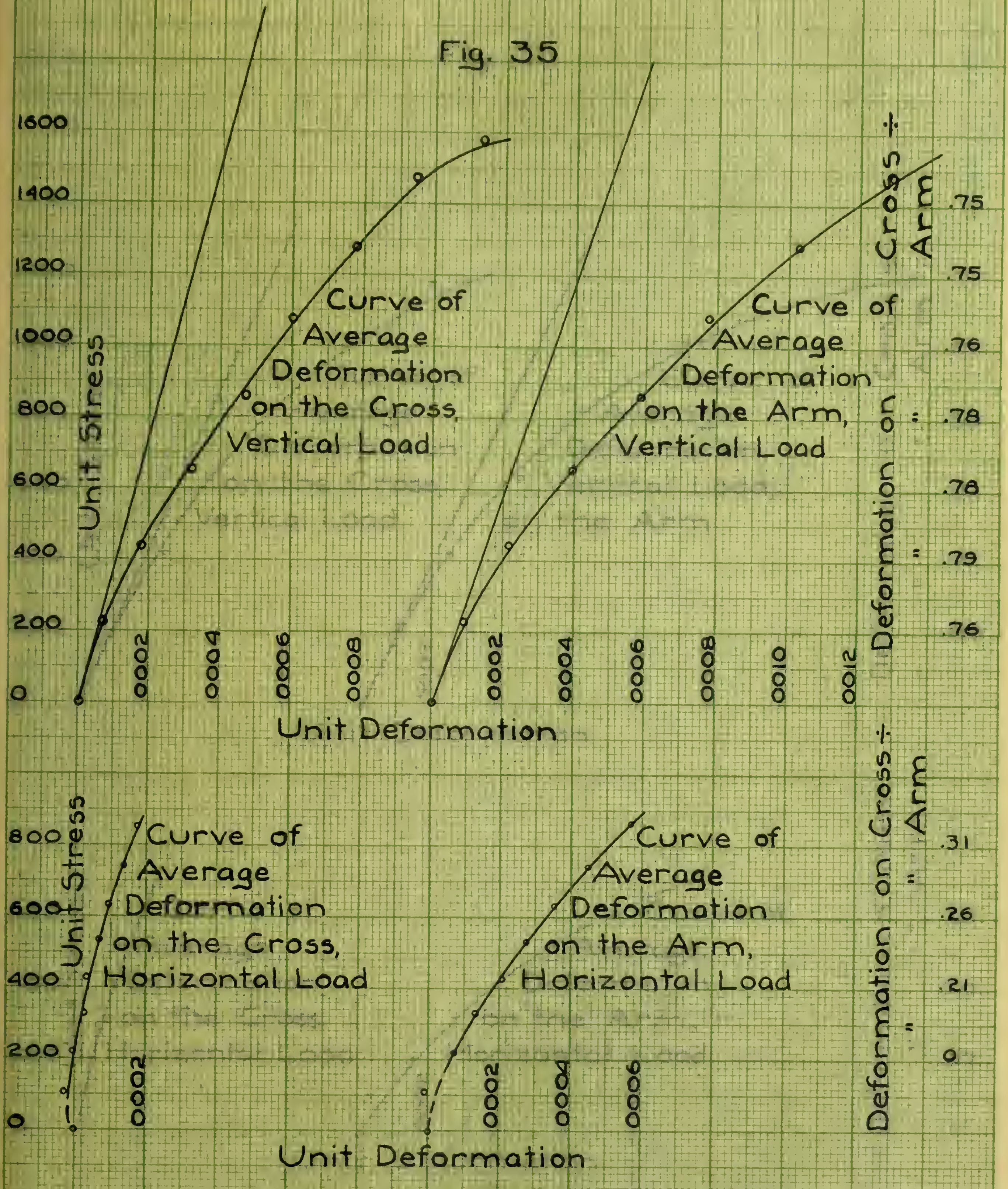
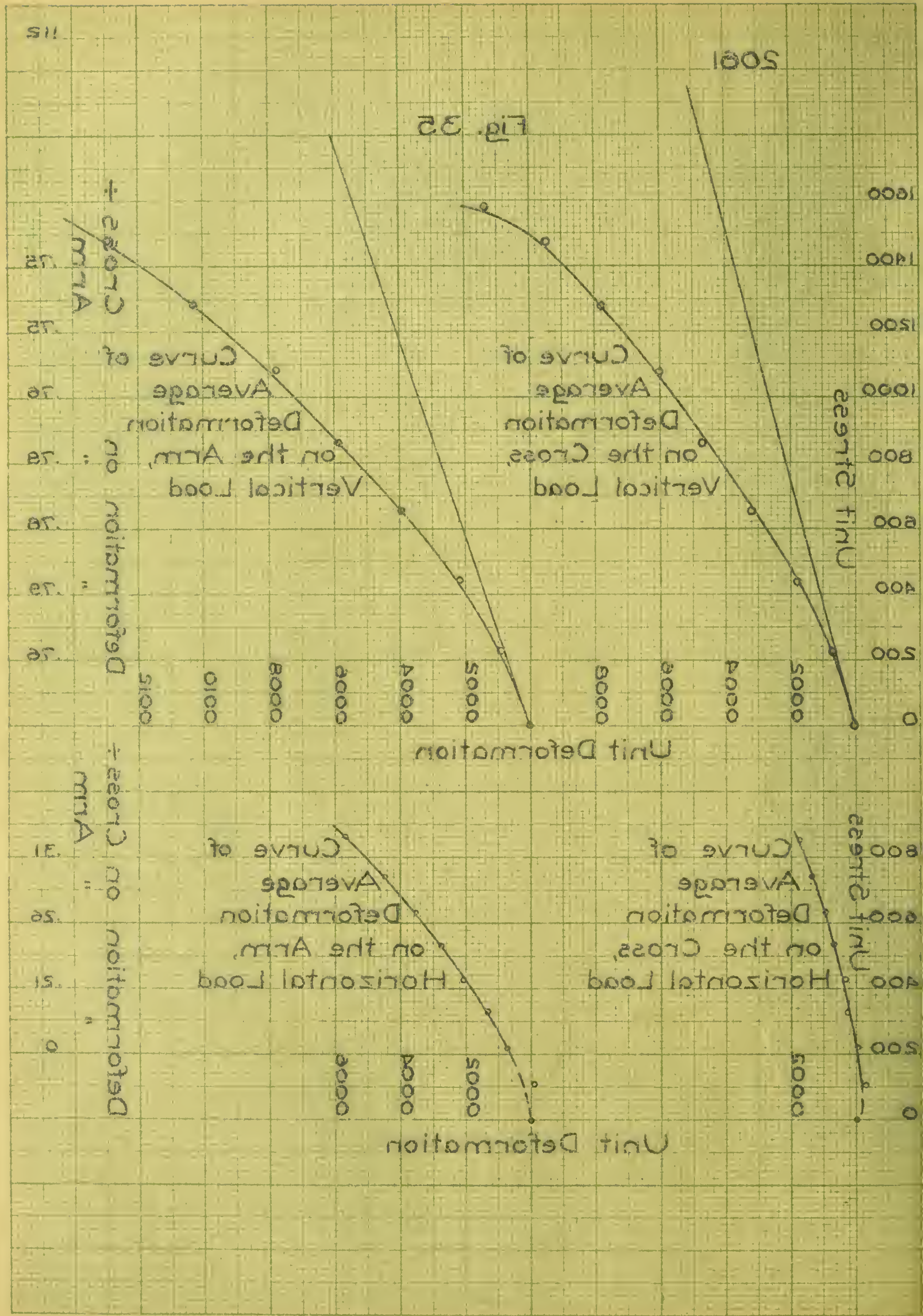


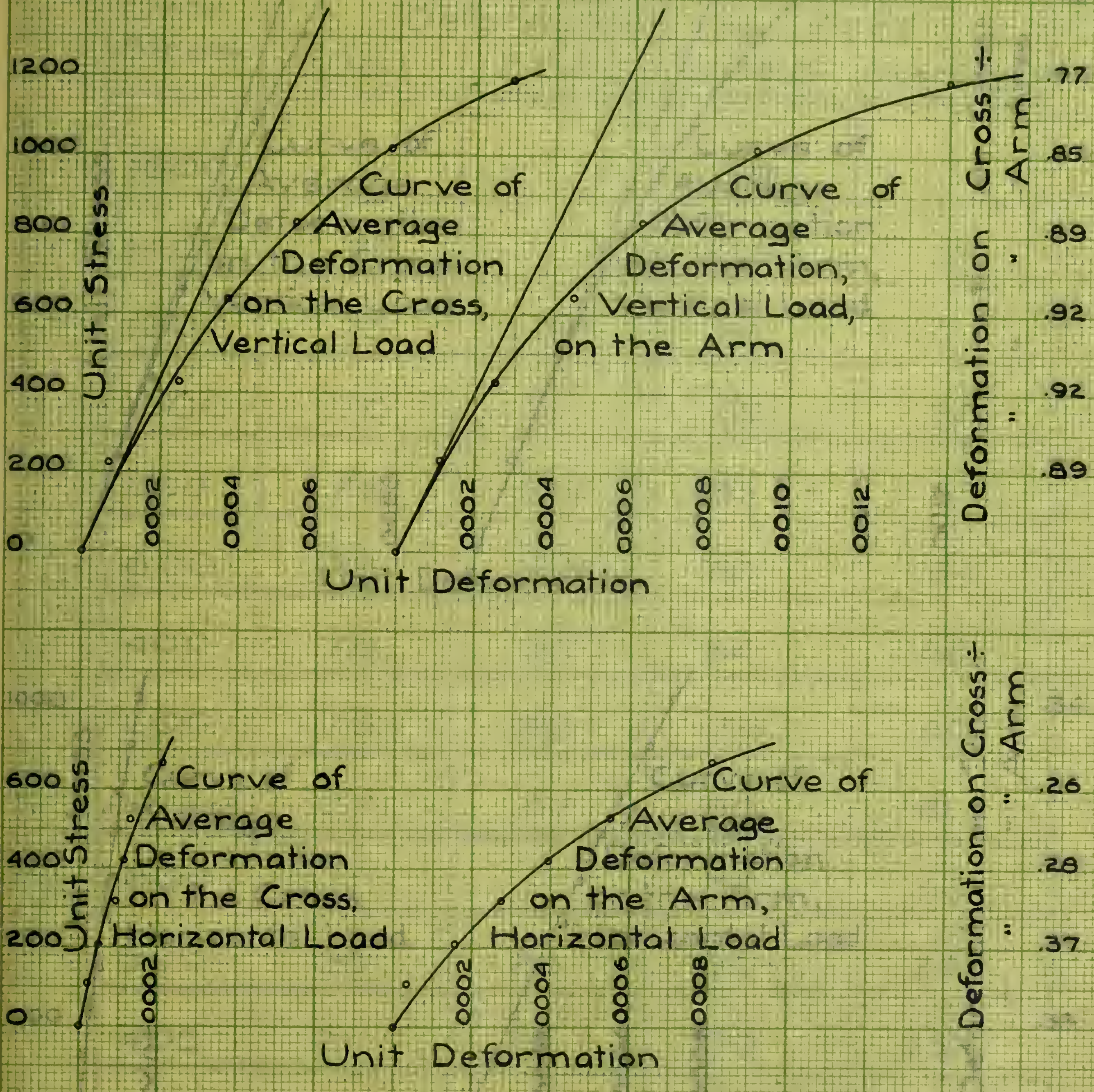
Fig. 35

Unit Stress
1600
1400
1200
1000
800
600
400
200
0
.0002
.0004
.0006
.0008
Curve of Average Deformation on the Cross, Vertical Load
.0002
.0004
.0006
.0008
.0010
.0012
Curve of Average Deformation on the Arm, Vertical Load
Unit Deformation
Deformation on Cross ÷ Arm
.75
.75
.76
.78
.78
.79
.76
Unit Stress
800
600
400
200
0
.0002
Curve of Average Deformation on the Cross, Horizontal Load
.0002
.0004
.0006
Curve of Average Deformation on the Arm, Horizontal Load
Unit Deformation
Deformation on Cross ÷ Arm
.31
.26
.21
0



2062

Fig. 36


1200
1000
800
600
400
200
0
Unit Stress
Curve of Average Deformation on the Cross, Vertical Load
.0002
.0004
.0006
Curve of Average Deformation, Vertical Load, on the Arm
.0002
.0004
.0006
.0008
.0010
.0012
Unit Deformation
Deformation on Cross ÷ " " Arm
.77
.85
.89
.92
.92
.89
600
400
200
0
Unit Stress
Curve of Average Deformation on the Cross, Horizontal Load
.0002
Curve of Average Deformation on the Arm, Horizontal Load
.0002
.0004
.0006
.0008
Unit Deformation
Deformation on Cross ÷ " " Arm
.26
.28
.37

2063

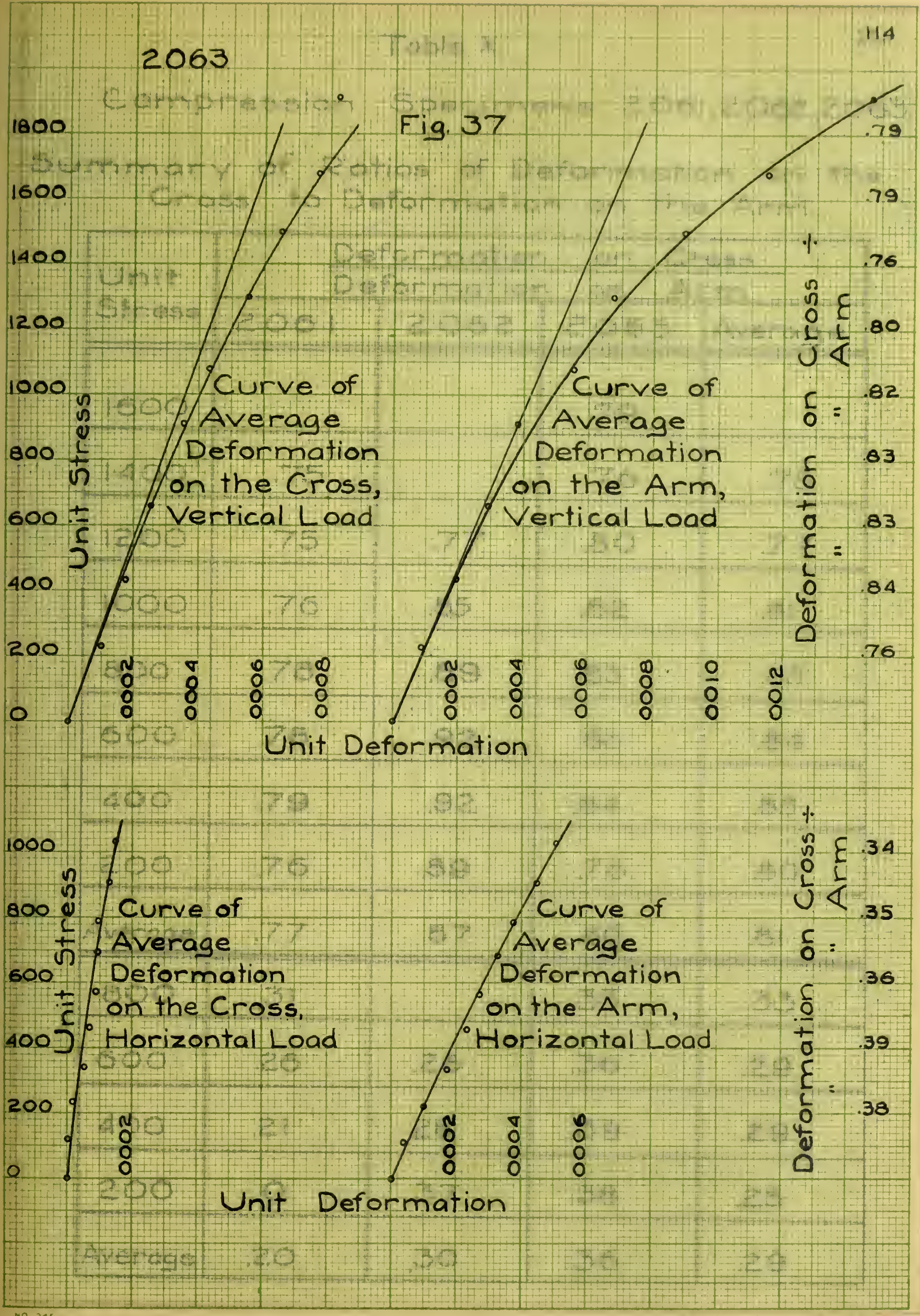


Fig. 37

Unit Stress
1800
1600
1400
1200
1000
800
600
400
200
0
.0002
.0004
.0006
.0008
.0010
.0012
Unit Deformation
Curve of Average Deformation on the Cross, Vertical Load
Curve of Average Deformation on the Arm, Vertical Load
Deformation on Cross ÷ Arm
.79
.79
.76
.80
.82
.83
.83
.84
.76
Curve of Average Deformation on the Cross, Horizontal Load
Curve of Average Deformation on the Arm, Horizontal Load
.34
.35
.36
.39
.38

Table X.

Compression Specimens 2061, 2062, 2063

Summary of Ratios of Deformation on the Cross to Deformation on the Arm.

Unit Stress	$\frac{\text{Deformation on Cross}}{\text{Deformation on Arm}}$			
	2061	2062	2063	Average
1600			.79	
1400	.75		.76	.75
1200	.75	.77	.80	.77
1000	.76	.85	.82	.81
800	.78	.89	.83	.83
600	.78	.92	.83	.84
400	.79	.92	.84	.85
200	.76	.89	.76	.80
Average	.77	.87	.80	.81
800	.31		.35	.33
600	.26	.26	.36	.29
400	.21	.28	.39	.29
200	0	.37	.38	.25
Average	.20	.30	.36	.29

Averages of the results of all three tests at each 200 lb. per sq.in. increment of stress have been calculated as well as the averages for the whole of each test. The grand average gives the result that the unit deformation in the line of action of the greater load at the portion of the test piece subject to two perpendicular compressions, one compression half as great as the other, is 0.81 of the unit deformation on the arm under the greater compression. Assuming, as in the case of comparison between compression specimens stressed in only one direction and compression specimens stressed equally in two directions, that the effect of the enlarged section is the same when two stresses are present as when only one is present, we get the result that the presence of the smaller compression reduces the unit deformation on the cross, measured in the direction of the greater compression, to 0.81/0.89 or 0.91 of the unit deformation on the arm under the greater load. If we take 0.82 as the final value of the ratio obtained from specimens 2071 and 2073 only, we get the result that the effect of two compressions, when one is half as great as the other, is to decrease the unit deformation on the cross to 0.81/0.82 or 0.99 of the unit deformation on the arm of the specimen. In either case, the effect of this smaller compression on the stress-deformation relations perpendicular to it is not great, probable not greater than that of the increased section only.

Now consider the effect of the greater compression on the deformation along the line of action of the smaller one. The deformation on the cross averaged 0.20 as great as the deformation

on the arm for the test of 2061, 0.30 for the test of 2062 and 0.36 for the test of 2063. The per cent of variation of the quantities entering into these average ratios was greater than the variation of the separate ratios on the more highly stressed arm, but the agreement is quite good above a stress of 200 lb. per sq.in. These ratios are shown in the lower part of Table X, page 115. As before, averages are computed at a certain unit stress for all three tests and for each test at all stresses. The grand average of these gives the result that when a compression specimen is loaded with two compressions at right angles, one compressive stress being half as great as the other, the unit deformation on the cross measured along the line of action of the smaller load is 0.29 of the unit deformation on the arm under the smaller load. Eliminating the effect of the enlarged section as before, this becomes 0.29/0.82 or 0.35 of the deformation on the arm.

The effect of the smaller stress on the deformation produced by the larger one is negligible, but the effect of the larger stress on the deformation produced by the smaller one is to reduce it to about one-third of its normal value.

On a portion of concrete bi-axially loaded, one load half as great as the other, the unit deformation measured along the line of action of the smaller load does not, in the light of these tests, give an adequate idea of the stresses.

Modulus of elasticity. The modulus of elasticity, or rather the apparent initial modulus of elasticity on the cross is changed in somewhat the same manner as is the unit deformation.

For convenience, all the moduli of compression specimens are tabulated in Table XI, page 119. The modulus of the control cylinder is included in the table but the agreement between the values obtained from the compression specimens and from these cylinders is not close. In general the cylinder gave a higher modulus. Perhaps the fact that the cylinders were made on end and the compression specimens on their sides may have influenced the modulus. The fact that the cylinders were stored in damp sand while the compression specimens were stored in the open air and sprinkled frequently may have a bearing on the modulus of elasticity.

Referring to the compression specimens it is seen that the modulus on the cross is always higher than on the arm. The modulus of elasticity on the cross of 2071 is 1.26 times the modulus on the arm. For 2072 the modulus on the cross is 1.18 times that on the arm and for 2073 it is 1.19 times the modulus on the arm. The average gives the result that, with compression specimens loaded on only one arm, the modulus of elasticity on the cross is 1.21 times as great as the modulus on the arm.

The modulus on the cross of 2050 is 1.23 times the modulus on the arm. On the cross of 2051 the modulus is 1.64 times that on the arm, on the cross of 2052 it is 1.30 times that on the arm and on the cross of 2053 it is 1.20 times that on the arm. Averaging and neglecting 2050, we have that the modulus on the cross is 1.38 times as great as on the arm of compression specimens loaded with two equal loads.

If we assume, as was done in the consideration of the ratio

Table XI.

MODULI OF ELASTICITY OF COMPRESSION SPECIMENS.

No.	Manner of Loading	Modulus of Elasticity of 8-in. Cylinder	Modulus of Elasticity of Vertical Arm	Modulus of Elasticity of Cross	$\frac{E_x}{E_a}$
		E_c	E_a	E_x	
2050	Equal Loads on Arms	2 440 000	1 740 000	2 140 000	(1.23)
2051	do.	2 460 000	1 600 000	2 620 000	1.64
2052	do.	2 480 000	1 960 000	2 550 000	1.30
2053	do.	2 280 000	2 360 000	2 840 000	1.20
				Av.	1.38
2061	Half as Great Load on Horizontal Arm as on Vertical Arm	2 300 000	2 980 000	3 900 000	1.31
2062	do.	2 100 000	2 020 000	2 240 000	1.11
2063	do.	2 590 000	2 400 000	2 840 000	1.18
				Av.	1.20
2071	Vertical Arm Only Loaded	2 300 000	2 080 000	2 620 000	1.26
2072	do.	2 100 000	2 240 000	2 640 000	1.18
2073	do.	2 590 000	1 820 000	2 170 000	1.19
				Av.	1.21

of the deformation on the cross to the deformation on the arm, that the effect of the enlarged section on the modulus of elasticity is the same whether one load or two loads are applied, we can eliminate the effect of the shape of specimen. We have, then, that the modulus of elasticity of concrete is 1.38/1.21 or 1.14 times as great under the action of two equal compressive stresses at right angles as under one compressive stress. This agrees in sense with the effect of two compressive stresses on the unit deformation but the average unit deformation is decreased a greater amount than the initial modulus of elasticity is increased.

This follows from the fact that the reduction in unit deformation is computed for all stresses, while the modulus of elasticity is the initial modulus and is computed from the data obtained at low loads. From Table VIII, page 100, we have the result that, under simple compressive loading, the deformation on the cross of a compression specimen at a stress of 200 lb. per sq.in. is 0.84 of the deformation on the arm if we consider 2072, and it is 0.82 of the deformation on the arm if we neglect 2072. From Table IX, page 109, we have the result that, under bi-axial loading with equal loads on the two arms, the deformation on the cross of a compression specimen at a stress of 200 lb. per sq.in. is 0.74 of the deformation on the arm. Eliminating the effect of the shape of the specimen as usual, we have the result that at 200 lb. per sq.in., the deformation of the concrete under bi-axial loading with equal loads in two directions perpendicular

to each other is 0.74/0.84 or 0.88 of the deformation which would occur under simple loading. Neglecting 2072 we have 0.74/0.82 or 0.90. When the deformation is reduced to 0.88 or 0.90 by bi-axial loading conditions, we expect the modulus of elasticity at low loads, i.e., the initial modulus of elasticity, to be increased to 1/0.88 = 1.14 or 1/0.90 = 1.11 of its value under simple loading conditions. These results, computed for the low loads only, agree with the value of 1.14 found by drawing tangents to the stress-deformation curves.

The form of the stress-deformation curve for concrete under bi-axial loading seems to indicate that the loading conditions stiffen the concrete near failure and make the stress-deformation curve more nearly a straight line.

When one compressive stress is half as great as the other, and considering deformations parallel to the arm under the greater load, we find that the modulus of elasticity of the cross is increased to 1.31 times the modulus on the arm in the test of 2061, 1.11 times in the test of 2062 and 1.18 times in the test of 2063. The average of these ratios of increase is 1.20. Eliminating the effect of the shape of specimen we find that the modulus of elasticity of the concrete in the cross is 1.20/1.21 or 0.99 times as great as on the arm. With the modulus, as well as with the unit deformation, the presence of a compressive stress half the size and at right angles to the stress considered does not seem to have an effect.

<u>Expansion</u>. The expansion curves have been plotted together in Fig. 38, page 122. Specimens 2051, 2052 and 2054 indicate

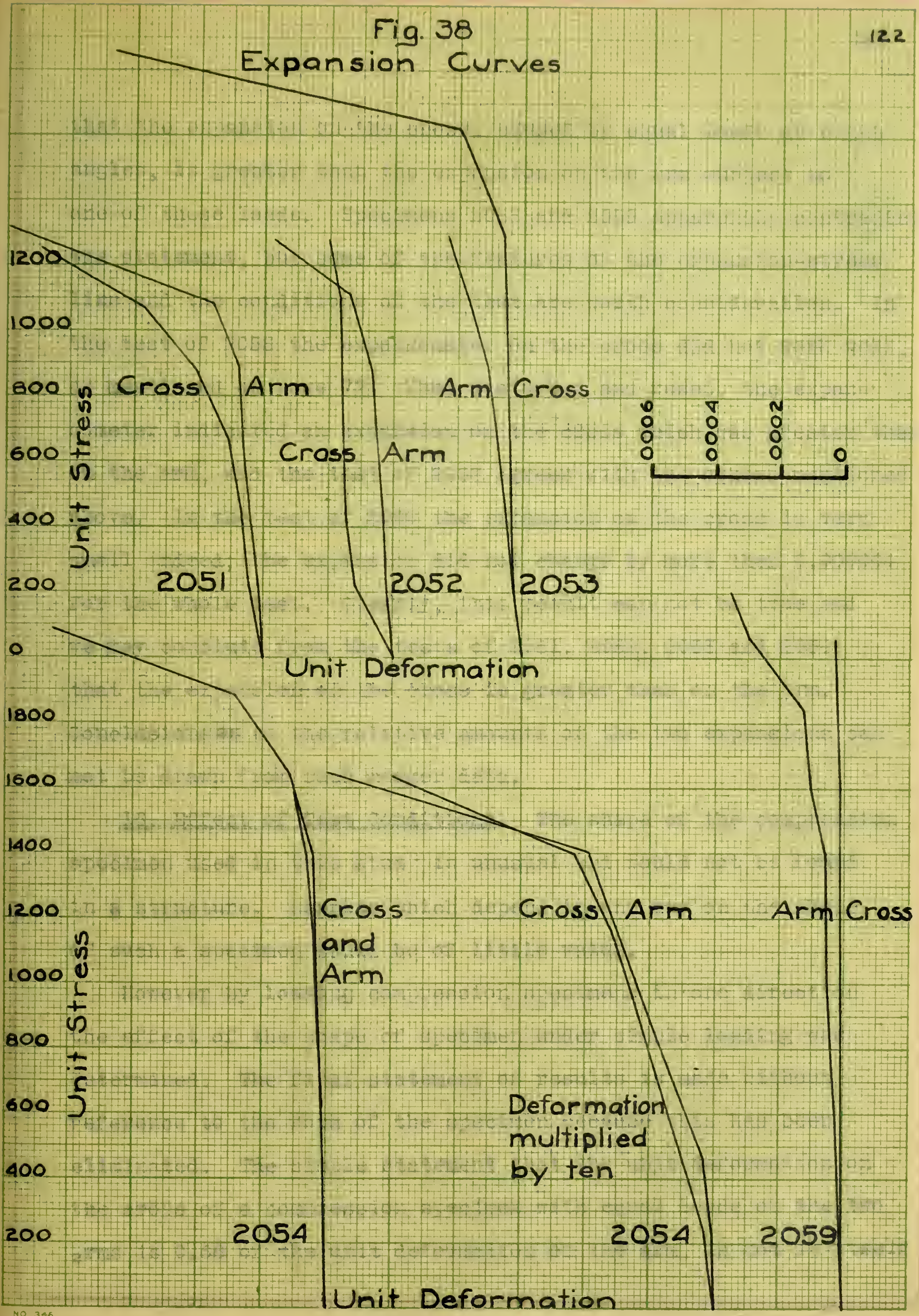


Fig. 38
Expansion Curves

that the expansion on the cross, caused by equal loads at right angles, is greater than the expansion on the arm subject to one of these loads. Specimens 2053 and 2059 apparently contradict the statement, but some of the features of the expansion-stress line and the conditions of the test are worth consideration. In the test of 2053 the expansometer on the cross did not work well, as mentioned on page 77. When disturbed and reset, the expansometer indicated an expansion on the cross which was greater than on the arm, and the test of 2053 agrees with the others mentioned above. In the test of 2059 the expansion on the cross is very small indeed; the expansion did not change by more then 0.000004 for the whole test. Clearly, this result can not be true and we may conclude from the tests of 2051, 2052, 2053 and 2054 that the expansion on the cross is greater than on the arm. Conclusions as to the relative amounts of the two expansions can not be drawn from such meager data.

16. Effect of Test Conditions. The shape of the compression specimen used in this study is unusual and would not be found in a structure. Results which depend in any way on the shape of such a specimen would be of little value.

However by loading compression specimens in one direction the effect of the shape of specimen under simple loading was determined. The final statement of results is made without reference to the form of the specimen because this has been eliminated. The simple statement that the unit deformation on the cross of a compression specimen with equal loads on the two arms is 0.66 of the unit deformation on the arm, is not in itself

important. But when we know that the unit deformation on the cross of a compression specimen tested with load on one arm is 0.82 of the deformation on the arm, we can combine these two results and say, as was stated in the discussion of stress-deformation relations, that the unit compressive deformation of a <u>portion of concrete</u> bi-axially loaded with equal loads is 0.66/0.82 or 0.80 of the deformation which would be produced if this same portion of concrete were simply loaded with one load of the same size as each of the two. This last statement contains no reference to the compression specimen. It is independent of the shape of the specimen and might be interpreted as applying to a portion of concrete on the compressive face of a flat slab floor. The stress in a flat slab floor is bending and not direct compression, but there appears to be no reason why the result should not be applicable to a compression produced by bending as well as to one produced by purely compressive loading.

Actually the result does apply to bending, as will be brought out in the discussion of crossed beams. Crossed beams gave the result that the deformation under equal bi-axial loads is 0.78 of the deformation under simple loading of the same intensity, while the tests of compression specimens gave this ratio as 0.80.

The shape of the specimen has also been eliminated from the final statement of the effect of bi-axial loading on the initial modulus of elasticity.

B. CROSSED BEAMS.

17. Phenomena of Tests and Failure of Crossed Beams.-The preparations for a test of a crossed beam are described under "8. Description of Apparatus." The ends were on rollers and were free as the ends of a simple beam.

2001. Increments of load of 10000-lb. were applied in this test. The usual cracks on the tension side of the beam appeared at a load of 40000-lb. At 90000-lb. diagonal cracks were noticed on all arms. While the load was being increased to 100000-lb., these cracks widened and the load started to fall off. More pumping widened the cracks but the load could not be made to pass 100000-lb. Failure occurred by diagonal tension which may have been combined with slipping of the rods. A small area of crushing was noticed just outside one load point. The area of crushing is cross-hatched on the beam and the diagonal cracks on two arms are marked on the photograph in Fig. 7, page 39.

2002. Increments of load of 20000-lb. were applied up to 60000-lb. load, and increments of 10000-lb. load at higher loads. Tension cracks appeared at 20000-lb., and at 40000-lb. cracks were formed on the lines of intersection of the vertical faces of the two beams. Diagonal tension cracks appeared on all arms at 60000-lb. load and these widened at each higher load. Failure occurred by diagonal tension combined with tension in the steel. More pumping after the maximum load of 97000-lb. only

served to widen the cracks. Pumping was stopped and the load fell slowly to 72500-lb., where it remained for some time. Some observations were made on steel gauge-lines to see if the elastic limit had been passed. Load was removed entirely and observations made on steel gauge-lines to determine the set. On the stress-deformation diagrams in the back of the thesis, the observations at a load of 72500-lb. and after the load had been removed are plotted and connected by dotted lines to the other points on the curves. See page 201.

2003. Some additional gauge-lines were observed on this crossed beam to determine more accurately how far compression extended out into the enlarged section at the cross and how rapidly this compression fell off. It was thought that the compression fell off more rapidly than was indicated by the stress-distribution diagrams of 2001 and 2002. It was found that this was the case. See the stress-distribution diagrams in Fig. 39, 40 and 41. Increments of load of 15000-lb. were applied. Diagonal cracks formed in two adjacent arms at 71000-lb. load. These widened rapidly and failure occurred at 75000-lb. by diagonal tension in one arm, probably accompanied by slipping of the bars. This specimen carried less load than the two other similar specimens, but its behavior was the same as the others at equal loads. See the photograph of failure shown as Fig. 8 on page 40.

18. Stress-Deformation Relations of Crossed Beams.-The crossed beams were tested to determine the effect of the presence of two bending actions upon the unit deformation and initial

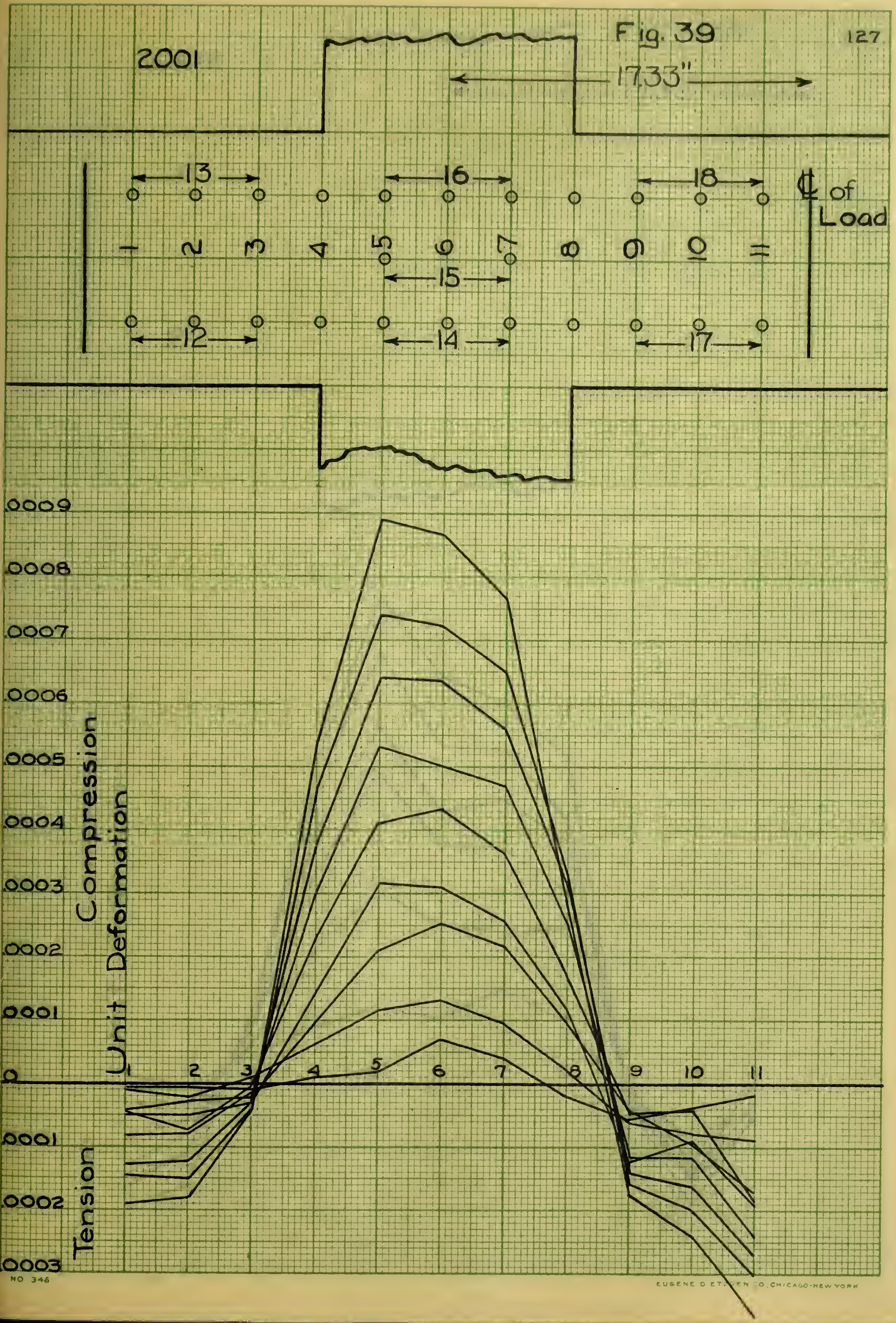


Fig. 39

2001
17.33"
13
16
18
℄ of Load
1
2
3
4
5
6
7
8
9
10
11
12
15
14
17
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
0
.0001
.0002
.0003
Compression
Unit Deformation
Tension
NO 346

Fig. 40.

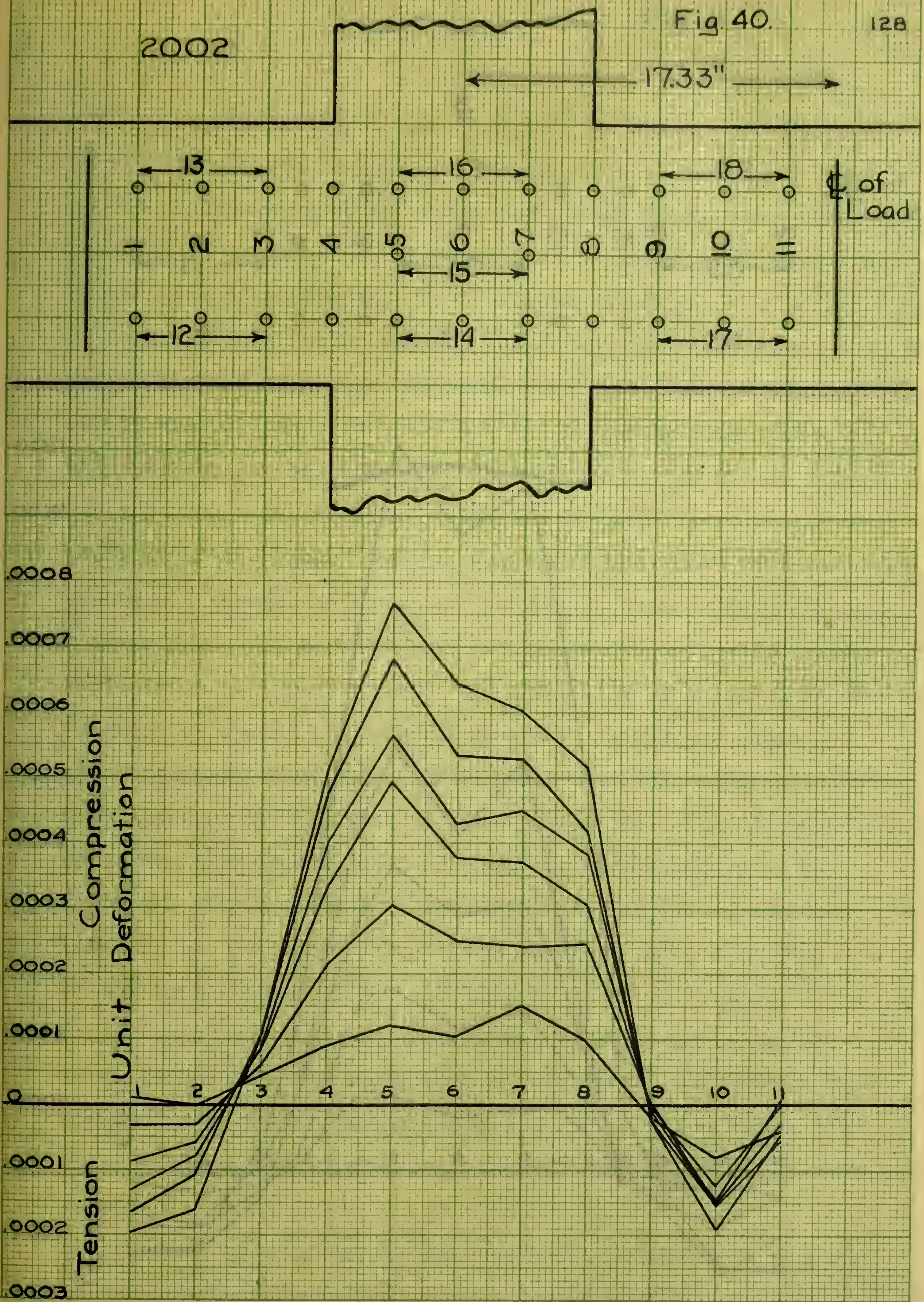
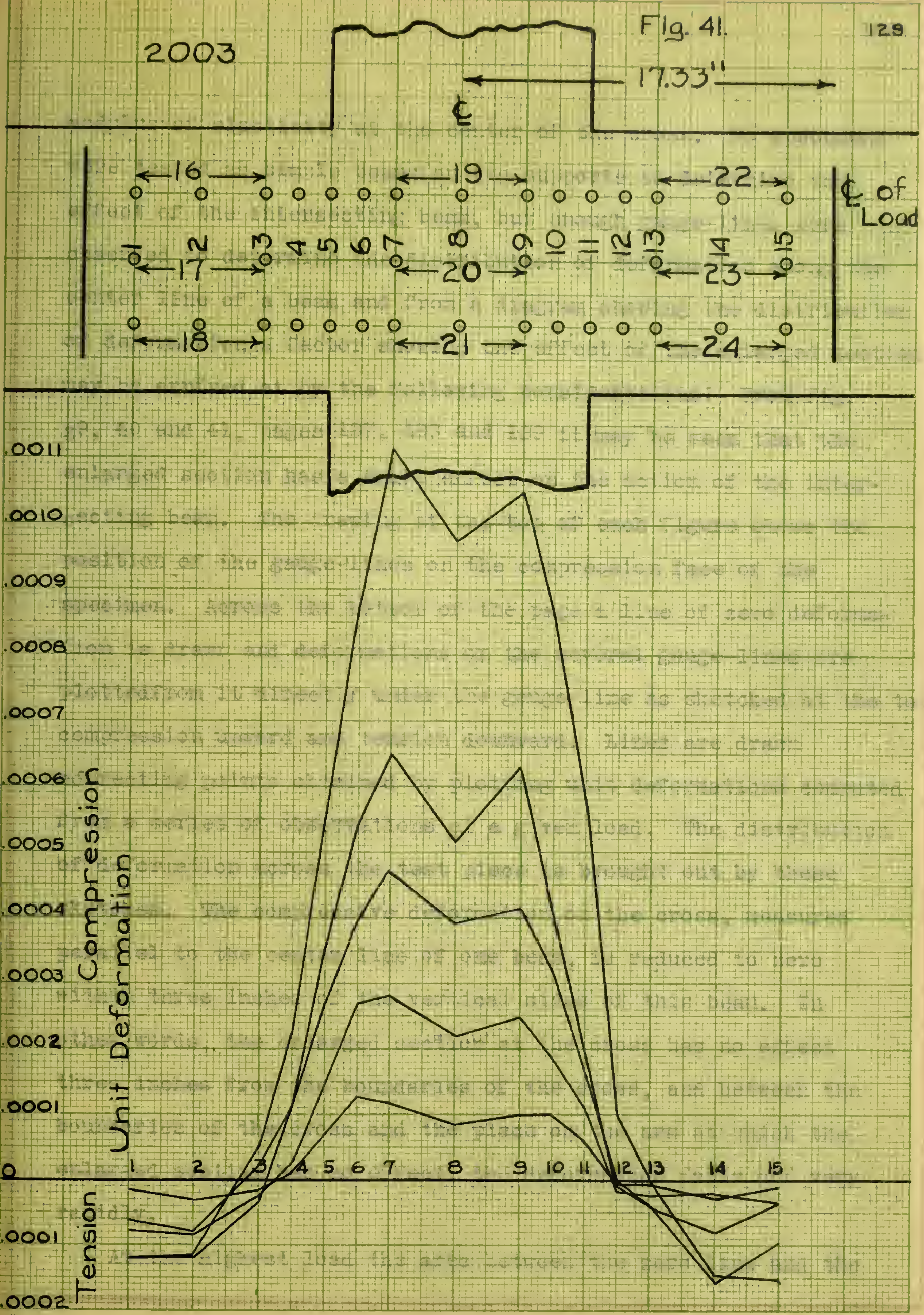

2002
17.33"
13
16
18
℄ of Load
1
2
3
4
5
6
7
8
9
10
11
15
12
14
17
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
0
.0001
.0002
.0003
Compression
Unit Deformation
Tension
1
2
3
4
5
6
7
8
9
10
11

Fig. 41.


2003
17.33"
℄
16
19
22
℄ of Load
17
20
23
18
21
24
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
.0011
.0010
.0009
.0008
.0007
.0006
.0005
.0004
.0003
.0002
.0001
0
.0001
.0002
Compression
Unit Deformation
Tension

modulus of elasticity at the center of the cross. No specimens were tested as simple beams on two supports to determine the effect of the intersecting beam, but enough gauge-lines were observed to determine the distribution of deformation along the center line of a beam and from a diagram showing the distribution of deformation a factor showing the effect of the enlarged section may be arrived at by the following considerations: From Fig. 39, 40 and 41, pages 127, 128 and 129 it may be seen that the enlarged section has a small effect on the action of the intersecting beam. The drawing at the top of each figure shows the position of the gauge-lines on the compression face of the specimen. Across the bottom of the page a line of zero deformation is drawn and deformations on the several gauge-lines are plottedfrom it directly under the gauge-line as sketched at the top compression upward and tension downward. Lines are drawn connecting points obtained by plotting unit deformations computed from a series of observations at a given load. The distribution of deformation across the test piece is brought out by these sketches. The compressive deformation on the cross, measured parallel to the center line of one beam, is reduced to zero within three inches of the vertical sides of this beam. In other words, the enlarged section at the cross has no effect three inches from the boundaries of the cross, and between the boundaries of the cross and the place on the arm at which the enlarged section has no effect, the deformation falls off very rapidly.

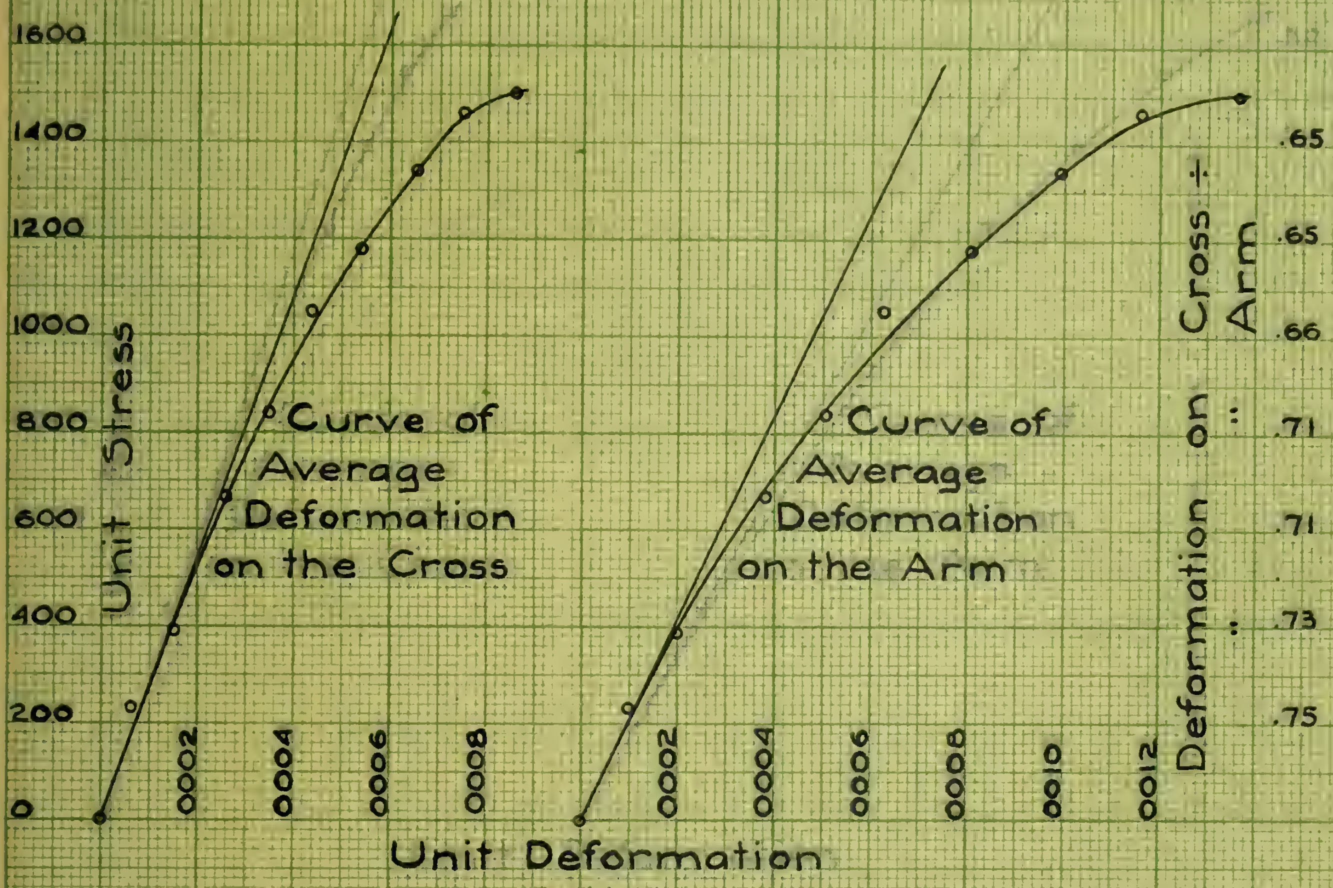
At the highest load the area between the zero line and the

curve, and outside the lines of the intersecting beam is 0.123 of the area inside the lines of the intersecting beam and between the zero line and the curve showing the distribution of deformation across the beam for 2001; 0.208 for crossed beam 2003; and 0.103 for crossed beam 2003. Averaging, we have that the area outside the lines of the intersecting beam and under the line showing the distribution of deformation over the beam is 0.145 of the area inside the lines of the beam and under the distribution curve. (The curves showing the distribution of deformation for compression specimens 2072 and 2073, Fig. 22, 23, 25 and 26, show that the area under the distribution curve, at the highest load, and outside the lines of the intersecting prism is 0.13 of the area inside the lines of the compression specimen and under the distribution curve.) From this distribution of deformation it would seem that the deformation which would occur on the cross if the specimen were tested as a simple beam would be 1.00 - 0.145 or 0.855 of the deformation on the arm of the test piece. This value agrees well with the one found for the effect of enlarged section in the compression specimens.

Individual stress-deformation diagrams for each gauge-line may be found among the curves in the back of the book. Unit deformation is plotted as the abscissa and load on the specimen as the ordinate. The curves of average deformation for both arm and cross are plotted for each beam. In these curves the average measured deformation is plotted as the abscissa and the computed fiber stress, obtained as explained in "20. Comparison of Measured and Computed Results", is plotted as the ordinate.

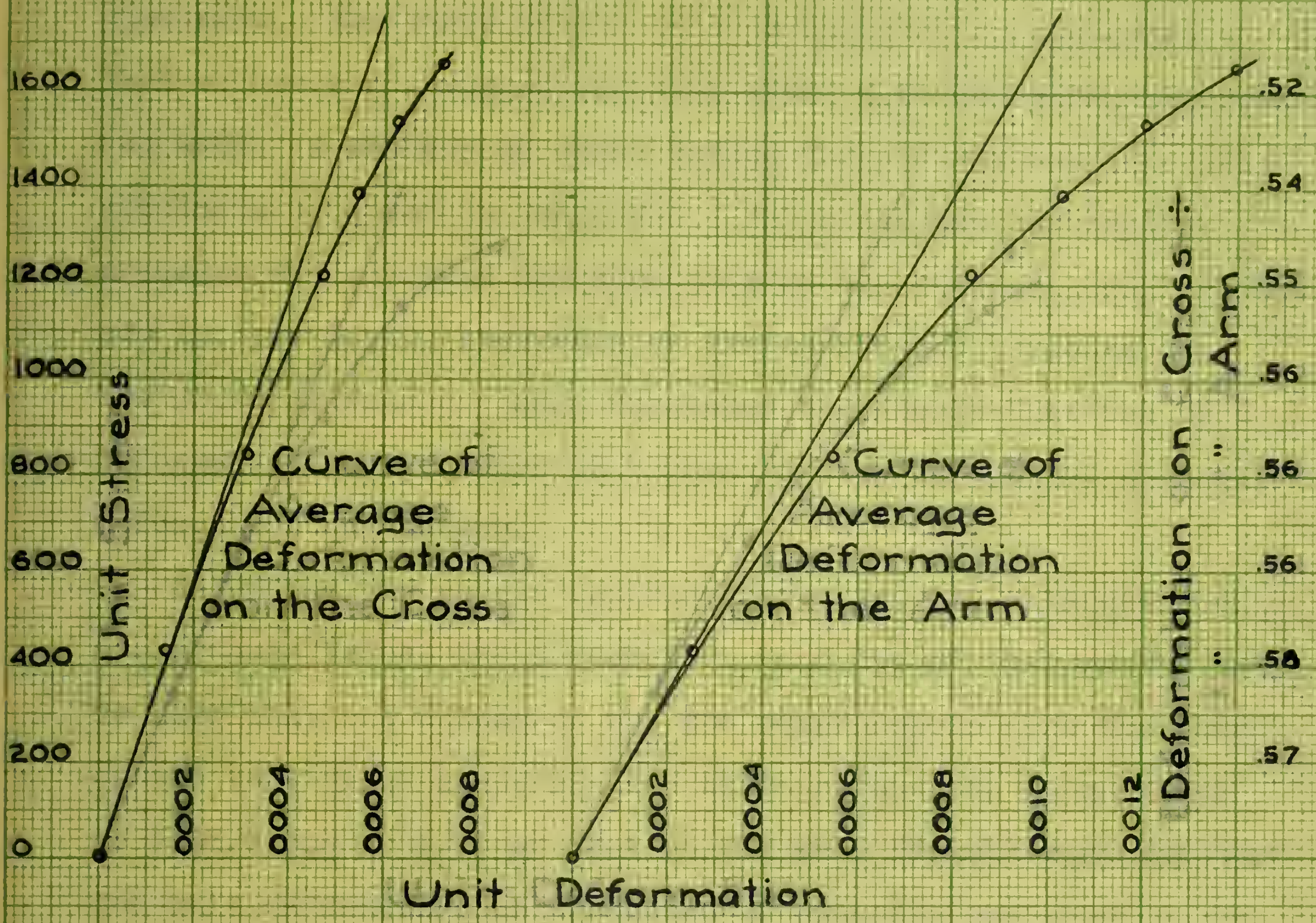
2001

Fig. 42.


Unit Stress
0
200
400
600
800
1000
1200
1400
1600
.0002
.0004
.0006
.0008
.0010
.0012
Unit Deformation
Curve of Average Deformation on the Cross
Curve of Average Deformation on the Arm
Deformation on Cross ÷ Deformation on Arm
.65
.65
.66
.71
.71
.73
.75

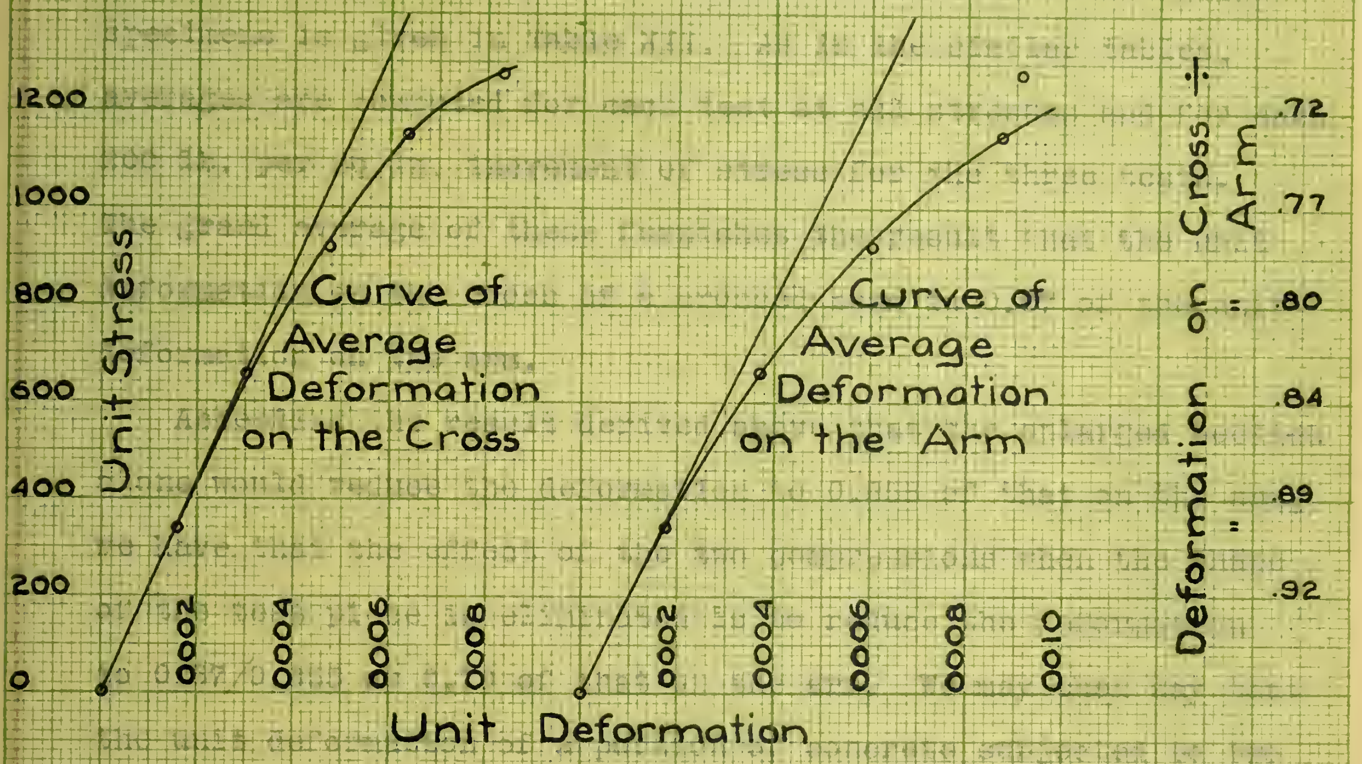
2002

Fig. 43


1600
1400
1200
1000
800
600
400
200
0
Unit Stress
0002
0004
0006
0008
Curve of Average Deformation on the Cross
0002
0004
0006
0008
0010
0012
Curve of Average Deformation on the Arm
Unit Deformation
Deformation on Cross ÷ " " Arm
.52
.54
.55
.56
.56
.56
.58
.57

2003

Fig. 44.


Unit Stress
1200
1000
800
600
400
200
0
.0002
.0004
.0006
.0008
.0002
.0004
.0006
.0008
.0010
Unit Deformation
Curve of Average Deformation on the Cross
Curve of Average Deformation on the Arm
Deformation on Cross ÷ Arm
.72
.77
.80
.84
.89
.92

See these curves for 2001, 2002 and 2003, Fig. 42, 43 and 44. These curves are quite similar in form to those of the compression specimens. The ratio of the unit deformation on the cross to that on the arm averaged 0.69 for 2001, 0.56 for 2002, and 0.82 for 2003. A summary of these ratios for all stresses and all specimens is given in Table XII. As in the similar tables, averages are computed for each test at all stresses and for each 200 lb. per sq.in. increment of stress for the three tests. The grand average of these furnishes the result that the unit deformation on the cross of a crossed beam is 0.67 of the unit deformation on the arm.

Accepting the result derived above that the enlarged section alone would reduce the deformation to 0.855 of that on the arm, we have that the effect of the two compressions when the shape of the test piece is eliminated is to reduce the deformation to 0.67/0.855 or 0.78 of that on the arm. We may then say that the unit deformation of a portion of concrete subjected to two equal bending stresses at right angles is reduced to 78 per cent of the unit deformation which would occur by the action of one of these stresses.

Modulus of Elasticity. The relation of the apparent initial modulus of elasticity on the cross to the modulus of elasticity on the arm is very much the same as the relation between similar quantities found on the compression specimens. See the summary sheet of Table XVI on page 147.

The modulus on the cross of 2001 is 2 760 000, or 1.31 times the modulus of 2 100 000 on the arm. The modulus on the cross of

Table XII.

Crossed Beams 2001, 2002, 2003.

Summary of Ratios of Deformation on the Cross to Deformation on the Arm.

Unit Stress	Deformation on Cross / Deformation on Arm			
	2001	2002	2003	Average
1800				
1600		.52		
1400	.65	.54		.60
1200	.65	.55	.72	.64
1000	.66	.56	.77	.66
800	.71	.56	.80	.69
600	.71	.56	.84	.70
400	.73	.58	.89	.73
200	.75	.57	.92	.75
Average	.69	.56	.82	.67

2002 is 2 920 000, or 1.66 times the modulus of 1 760 000 on the arm. The difference between the two in this test seems large but not unreasonably so when compared with the compression specimens. The modulus on the cross of 2003 is 2 240 000, or 1.11 times the modulus of 2 020 000 found on the arm. The average gives the result that the modulus on the cross of a crossed beam is 1.36 times the modulus on the arm. It will be remembered that the modulus on the cross of a compression specimen is 1.38 times the modulus on the arm. The close agreement between these two results obtained under such widely differing conditions of testing seems noteworthy.

The agreement between the results of the compression specimens and those obtained from crossed beams has been close in each of the several comparisons which have been made. If we may assume that the enlarged section at the cross affects the moduli of elasticity of a specimen approximately the same amount whether the test piece in question is a compression specimen or a crossed beam, an interesting result is deduced. It was found that the enlarged section at the cross of a compression specimen increased the modulus on the cross to 1.21 times the modulus on the arm. It appears then that the action of two equal bending stresses on a portion of concrete increases its apparent initial modulus of elasticity to 1.36/1.21 or 1.12 times what it would be if the same portion were acted upon by one of these bending stresses.

Again it is noticed that the modulus of elasticity is increased, but not as much as the decrease of deformation for the

whole specimen indicates. The decrease of deformation has been computed for the whole test, while the initial modulus of elasticity applies to the first stages of loading. The decrease of deformation at low loads should agree with the increased modulus, and it is found that it does. From Table XII, page 136 we have the result that the deformation on the cross at 200 lb. per sq.in. is 0.75 of that on the arm. From page 131 we get that the effect of increase of section is 0.855. Eliminating the effect of shape of specimen we have the result that the unit deformation of concrete bi-axially loaded with two equal bending stresses perpendicular to each other and at 200 lb. per sq.in. is 0.75/0.855 or 0.88 of the deformation which would occur at this stress under simple loading. We should expect the initial modulus of elasticity to be increased to 1/0.88 or 1.14 times the value obtained under simple loading.

The value of 1.12, obtained by drawing tangents to the stress-deformation curves, agrees with the above conclusion.

The same discrepancy between the values of the modulus of elasticity obtained from the control cylinder and from the arm of a crossed beam is noticed as was noticed with compression specimens. The position in which the specimens were made and the conditions of storage may be significant.

19. Effect of Test Conditions.-The crossed beams were designed to fail in compression, and the deformation indicates that a high compressive stress was developed although the beams actually failed in diagonal tension. The effect of the shape of specimen is not as well established for crossed beams as for compression

specimens because no tests were made on crossed beams resting on two supports. The distribution of deformation over the cross of the specimen was so similar to the distribution on a compression specimen, both in form and in the distance from the cross to which deformation was transferred, and the part of the load carried by the cross, as indicated by the area under the curve showing the distribution of deformation, was so nearly the same on the crossed beam as on the compression specimen that exactly similar methods of eliminating the shape of the specimen itself have been used. The same methods have been applied to eliminate the effect of section on the modulus of elasticity.

As was done in the discussion of compression specimens, the final results have been stated in terms which do not depend at all on the shape of the test piece. The effect of the shape of test piece has been eliminated.

The remarkable agreement of the results obtained under different conditions of testing, has already been pointed out.

20. Comparison of Measured and Computed Results.-The theoretical stresses in the arms of the three beams at each load were computed by the ordinary formulas and summarized in Tables XIII, XIV and XV, pages 140, 141 and 142. It was assumed that one-fourth of the load was carried by each reaction, and the moment was computed for a single arm. From the curves of average deformation on the arm a value of "q" called the "computed value of q" was deduced on the assumption that the ultimate deformation of the concrete in the beam was about the same as that in the control cylinder. The value of "q" used in computing

Load	Mome
9800	605
19900	1229
30000	1851
40000	2470
50000	3088
60000	3705
70000	4323
80000	4940
90000	5550
100000	6160

Computed mon
U

Table XIII.

MEASURED AND COMPUTED QUANTITIES, 2001

Load	Moment	Computed Value of "q"	Value of "q" used in Computations	Computed						Measured				
				k	j	f_s	f_c	v	u	Average Unit Deformation on Arm	on Cross	of Steel	k	f_s
9800	60500	.07	.0	.537	.821	3010	230	25	19	.000094	.000057	.000058	.620	1800
19900	122900	.14	.2	.545	.814	6150	390	51	39	.000198	.000143	.000158	.556	4900
30000	185100	.27	.2	.545	.814	9300	670	67	51	.000380	.000254	.000304	.560	9430
40000	247000	.36	.4	.557	.806	12500	840	103	79	.000508	.000341	.000421	.554	13050
50000	308800	.44	.4	.557	.806	15600	1050	130	100	.000622	.000432	.000552	.540	17100
60000	370500	.58	.6	.573	.797	19000	1180	157	120	.000808	.000538	.000652	.560	20200
70000	432300	.71	.7	.580	.791	22300	1340	184	141	.000992	.000645	.000801	.560	24800
80000	494000	.83	.8	.586	.786	25700	1460	212	161	.001162	.000742	.000904	.565	28000
90000	555000	.98	1.0	.604	.773	29300	1500	243	186	.001369	.000859	.001047	.572	32400
100000	616000	–	1.0	.604	.773	32600	1665	270	207					

Computed moment = Load x 6.16-in. A = 2.45 sq.in. p = .0204 "mo" = 15.7-in. n was taken = 15
Ultimate deformation of control cylinder = .00144, the values of "q" were computed from this.

Loa
1970
3930
5930
6920
7920
8900
9700
7250

Compu
E_s =

Table XIV.

MEASURED AND COMPUTED QUANTITIES, 2002.

Load	Moment	Computed Value of "q"	Value of "q" used in Computations	Computed						Measured				
				k	j	f_s	f_c	v	u	Average Unit Deformation			k	f_s
										on Arm	on Cross	of Steel		
19700	118000	.13	.1	.501	.831	5800	430	49	37	.000255	.000139	.000215	.540	6700
39300	242000	.27	.3	.514	.824	12000	840	100	76	.000544	.000310	.000462	.540	14300
59300	365000	.42	.4	.521	.820	18200	1220	151	115	.000835	.000473	.000662	.558	20500
69200	426000	.51	.5	.528	.815	21400	1390	177	135	.001025	.000544	.000801	.560	24800
79200	487000	.60	.6	.534	.810	24600	1540	204	156	.001203	.000628	.000871	.580	27000
89000	548000	.70	.7	.542	.805	27800	1660	230	176	.001394	.000723	.001015	.580	31500
97000	597000	–	.8	.550	.800	30500	1740	252	193					
72500														
0														

Computed moment = Load x 6.16-in.   A = 2.45 sq.in.   p = .0204   "mo" = 15.7-in.   n was taken as 12

E_s = 31 200 000 E_c = 2 480 000   n = 12.5

Load	M
15000	
29700	1
44000	2
57000	3
66000	4
75000	4

Table XV.

MEASURED AND COMPUTED QUANTITIES, 2003

Load	Moment	Computed Value of "q"	Value of "q" used in Computations	Computed						Measured				
				k	j	f_s	f_c	v	u	Average Unit Deformation			k	f_s
										on Arm	on Cross	Of Steel		
15000	92500	.11	.1	.527	.822	4600	340	38	29	.000169	.000156	.000192	.465	5950
29700	183200	.23	.2	.533	.819	9140	660	75	57	.000364	.000298	.000344	.512	10650
44000	271400	.37	.4	.546	.810	13700	920	113	87	.000599	.000467	.000509	.540	15800
57000	351800	.54	.5	.553	.806	17800	1155	147	112	.000864	.000630	.000656	.570	20400
66000	407000	.57	.6	.560	.802	20700	1280	171	131	.000906	.000829	.000668	.572	20700
75000	462000	–	.7	.567	.798	23600	1410	196	150					

other quantities was taken as the even tenth closest to the computed value. The depth to the neutral surface, arm of resisting couple, tensile and compressive stresses and the bond and shearing stresses were calculated for each load. Some measured quantities are included in the tables for completeness. These are the average deformation on the arm and on the cross, the average steel deformation and the measured steel stress. As a check on the computations, the depth to the neutral surface was obtained graphically from the steel deformation and the deformation on the arm by the usual assumption that a plane section remains plane after bending. There is a very fair agreement between the measured and computed results. The higher measured values of "k" at low loads are undoubtedly influenced by tension in the concrete.

In translating unit deformation of steel to unit stress the value of the modulus of elasticity of steel determined from tests of the steel used in making the specimens, i.e. 31 000 000 lb. per sq.in. was used. The discrepancy among the values of the modulus of elasticity of concrete as determined from control cylinder, on the arm of the crossed beam and on the cross made a translation from unit deformation to unit stress uncertain, hence this was not attempted.

An analysis of the action on the compressive face of a beam of two bending stresses and their relation to deformation can be made. Since the stress between the load points, where all observations were made, is pure bending and not accompanied by shear, the action on the compressive face is one of compression

only. The resulting stress-deformation relations are the same as would be obtained if the acting forces were true compression in place of pure bending, hence the analysis applies to compression specimens as well as to crossed beams. The stresses in this analysis are assumed to be equal.

Let f denote the unit stress,

e denote unit deformation,

E modulus of elasticity,

r Poisson's ratio

$e' = f/E =$ deformation parallel to line of action of stress. This is reduced by $re' = rf/E$ which is produced by the stress perpendicular to the first (assumed to be equal to the other stress). The total deformation is then

$$e = e' - re' = \frac{f}{E}(1 - r) \qquad (1).$$

The experiments show that $(1 - r)$ is 0.78 for crossed beams and 0.80 for compressions. Let f/E be unity in (1) and write 0.80 for $(1 - r)$. It then appears that when the deformation caused by bi-axial loading is 0.80 of that caused by simple loading, the value of "r" is 0.20, or about twice what we should expect from the results of tests on columns.

It seems that the value of Poisson's ratio as determined from tests of columns does not apply to bending action. Poisson's ratio is greater than the value found from column tests. In order to explain the reduction of deformation by the usual method of computation, a value of Poisson's ratio of about 0.2 must be used.

21. Comparison of Results of Crossed Beams and Compression Specimens Loaded Equally on the Two Arms.-A number of comparisons between results obtained from crossed beams and compression specimens loaded equally on the two arms have been drawn in the discussion of stress-deformation relations. These will be briefly summarized here.

It will be remembered that a cross-section of an arm is a square and that the "cross" is a cube in both cases. We should expect quite similar results from the two series, since compressive deformations were measured on the surface of the specimen. The deformation on the cross of a compression specimen was found to be 0.66 of the deformation on the arm and the deformation on the cross of a beam was found to be 0.67 of the deformation on the arm.

The amount of compression carried by the enlargement of section as found from the curves showing the distribution of deformation was 0.145 of the whole on the crossed beams at the highest load and was between 0.16 and 0.13 of the whole on compression specimens for different loads.

The derived results from which the shape of section has been eliminated show that under bi-axial loading with equal loads in two perpendicular directions the unit deformation is reduced to 80 per cent of the deformation under simple loading when determined from compression psecimens and to 78 per cent of the deformation under simple loading when determined from crossed beams.

The modulus of elasticity was found to be increased 14 per cent

by bi-axial compression and 12 per cent by bi-axial bending. These values were determined graphically and checked by a separate computation.

The four agreements mentioned above are in themselves conclusive evidence that the results are not accidental. Such close agreement is quite commonly lacking between series of experiments made under identical conditions.

A summary of the salient points of the investigation has been prepared in Table XVI, page 147. It explains itself.

Table XVI.

SUMMARY OF INVESTIGATION.

Specimen	Age da.	Horizontal		Vertical		Modulus of Elasticity or Concrete			$\frac{E_x}{E_a}$	$\frac{e_x}{e_a}$	Unit Stresses			
		Load	Unit Stress	Load	Unit Stress	Cylinder E_c	Vertical Arm of Specimen E_a	Cross of Specimen E_x			Cylinder	8-in. Cubes Horizontal	8-in. Cubes Vertical	6-in. Cubes
2050	52	110800	1700	103000	1585	2440000	1740000	2140000	(1.23)	(.74)	1995	–	–	2295
2051	73	95000	1440	90000	1365	2460000	1600000	2620000	1.64	.63	1500	(4060)	(5950)	2350
2052	69	113000	1740	120000	1850	2480000	1960000	2550000	1.30	.69	1510	(4100)	(6900)	2755
2053	73	100000	1540	120300	1850	2280000	2360000	2840000	1.20	.68	1550	2800*	2800*	2525
								Average	1.38	.66				
2054°	62	142500	2200	143000	2200									
2055–A	71	124000	1940*	121800	1900*									2640*
2055–B	72	141000	2200*	140500	2200*									2640*
2056–A	60	144000	2250*	140000	2190*									2800*
2056–B	60	175000	2740*	181700	2840*									2800*
2057–A	70	155000	2420*	154000	2410*									2830*
2057–B	70	185000	2890*	185000	2890*									2830*
2058–A	60	228000	3440*	250000	3910*									2805*
2058–B	60	190000	2970*	186000	2900*									2805*
2059°	62	105000	1640	137000	2140									
2061	68	61300	940	120000	1850	2300000	2980000	3900000	1.31	.77	1770	(2970)	(5850)	2475
2062	68	49300	760	98400	1510	2100000	2020000	2240000	1.11	.87	1285	1080*	2050*	1690
2063	69	67400	1040	140000	2150	2590000	2400000	2840000	1.18	.80	1370	(3200)	(6350)	2200
								Average	1.20	.81				
2071	64	–	–	114300	1760	2300000	2080000	2620000	1.26	.80	1770			2475
2072	70	–	–	96600	1490	2100000	2240000	2640000	1.18	(1.07)	1285	0	1100*	1690
2073	71	–	–	127500	1960	2590000	1820000	2170000	1.19	.84	1370			2200
								Average	1.21	.82				
2001	62	–	–	100000	1665	2460000	2100000	2760000	1.31	.69	1500			2350
2002	58	–	–	97000	1740	2480000	1760000	2920000	1.66	.56	1510			2755
2003	70	–	–	74800	1410	2280000	2020000	2240000	1.11	.83	1550			2525
								Average	1.36	.67				

°2054 and 2059 were tested for expansion only.

*Plates greased.

C. 8-in. CUBES.

22. Preparation for Test.- The faces of the cubes were set in a thin bed of plaster a few days before testing. The 8-in. cubes were bedded on the four sides which were vertical in making and the 6-in. cubes were bedded on two of the sides which were vertical in making.

In most cases the maximum loads carried by the cubes were the only data sought but in four cases deformations were measured on the 8-in. cubes along three horizontal and three vertical gauge-lines. Gauge-plugs similar to those used in the compression specimens were set in the cubes while they were being made. Before testing, gauge-holes were drilled in these plugs as described elsewhere.

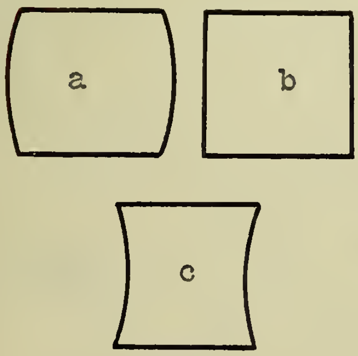
Fourteen 8-in. cubes were tested with two equal loads. The first four, two marked 2051 and two marked 2052, were tested between plates bearing directly on the plaster dressing. The loads carried by these cubes were very high, higher than 6000 lb. per sq.in., while the 6-in. cubes crushed under stresses which were not half as great. Evidently nothing could be learned from further tests of this nature unless something could be done to reduce the friction of the bearing plates. The results of these tests are reported in Table XVI as showing the progress of the tests but they are not used in comparisons.

In the tests of ten other 8-in. cubes loaded with equal loads, the plates were coated with a layer of cup-grease about 1/10 to

1/16-in. thick. The 6-in. cubes of the same number were tested in simple compression with the two bearing plates generously greased, and conclusions as to strength based on tests in which both the one-way and two-way cubes were tested under similar conditions.

23. The Influence of Greased Plates.-It has been generally appreciated that the friction of the plates had an influence in compression tests of short specimens. The strength of a cube is usually much greater than a prism of the same base and twice the height, but a prism three times the height of the cube does not decrease in strength below the prism two diameters high. A research by M. Feret points out that the nature of the bearing plates, or the interposition of various substances between the plates and the compressed faces of the specimen had no influence on the strength developed. The results of Feret's study and of some other studies criticised by him are summarized in the following paragraphs.

Two French engineers, MM. Galy-Aché and Charbonnier had pointed out that when a cylinder of copper is crushed between two plates without placing any material between the plates and the cylinder, it takes a barrel shape, Fig. a, while it remains cylindrical, Fig. b, if the friction of the plates is reduced by plumbago and it could take a form analagous to that of an hyperboloid, Fig. c, if the slipping of the bases caused by the pellicules of lead were



exaggerated. With less ductile materials such as stones and mortars which undergo very small deformations before rupture, these effects are not visible to the eye. It was thought that the strength might be affected by the lubricated plates.

Prof. A. Föppl[x] had broken some cubes of stone and some of mortar both in direct contact with the plates and with the compressed faces lubricated, and he holds that the breaking loads in the second case were reduced half or more.

M. Giovanni Salemi Pace[z] experimented with cubes of stone and found that pasteboard had no effect when placed between the specimen and the plates but that when cork or a mixture of stearine and wax was placed between the plates and the specimen that the breaking load was reduced about half.

(Perhaps the stone and mortar tested by these men had a high Poisson's ratio which increased the deformation perpendicular to the applied load when the restraint of the plates was reduced. and caused failure.)

M. Feret concluded that the results of the men quoted above were too erratic and based on too small a number of experiments to be reliable, and he conducted a few tests on cement mortar prisms and cubes. Five square prisms 2-cm. on a side and 6-cm. high were broken between steel plates and four similar ones between plates coated with 0.5-mm. of parrafine. The

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[x] Mittheilungen d. mech. techn. Labor. d. K. Hochschule, Munchen, 1900.

[z] Atti del Collegio degl'Ingegneri e Architetti in Palermo, 1901- Baumaterialienkunde, 1902.

breaking loads of the first set of prisms averaged 430 kg./cm.^{2} and of the second set 337 kg./cm.^{2}, or 78 per cent of 430. He attributed the reduction to the fact that the parrafine squeezed out at the edges of the loaded faces and therefore that the load was concentrated on the center part of the prism.

All the experiments mentioned above were made on a few specimens and they were far from concordant. Another short set of experiments by Feret on twelve specimens pointed out that the ultimate load carried by a cement mortar cylinder 3-cm. high and 3-cm. in diameter, was the same whether tested with a paste of soap between the specimen and the plates (465 kg. load) or whether tested in direct contact with the steel plates (462 kg. load). The form of the fracture in the two cases was different however. With nothing between the specimen and the plates, fracture occurred as shown by Fig. d, and with soap between the specimen and the plates failure occurred as shown by Fig. e.

d

e

Feret then made a much more complete series of tests on 58 cylinders of neat cement which had hardened a little over six months in moist air. These were tested in sets of six (ten in one case). Various substances were placed between the specimen and the bearing plates. These tests are summarized in Table XVII.

Table XVII.

RESULTS OF FERET'S EXPERIMENTS ON CYLINDERS 3-cm. IN DIAMETER AND 3-cm. HIGH, WITH VARIOUS MATERIALS BETWEEN THE SPECIMEN AND THE BEARING PLATES.

	1	2	3	4	5	6	7	8	9
	Direct Contact	Soap	Grease-Plumbago	Vaseline	Petroleum	Glycerine	Tin	Pasteboard	Emery Cloth
Total Loads for Rupture Kg.	2100 2100 2000 2050 1900 2060 2150 2060 1980 1990	1610 1910 2070 2020 1990 1980	2060 2250 1800 2270 1800 2050	2180 2100 1900 2320 2170 2160	2100 1710 1830 2020 2250 2100	1710 1900 1640 2080 1990 2000	2070 2020 2210 1950 1840 2080	2080 2270 1880 2100 2300 2230	1790 1970 2100 1990 1930 2150
Average	2039	1930	2038	2138	2002	1887	2028	2143	1997
Av. per cm.^{2}	289	273	289	302	283	265	287	304	282
Proportional Numbers	100	95	100	105	98	93	99.5	105	98
Mean Error per cent	2.8	5.9	7.8	4.3	7.7	7.5	4.5	5.8	4.3

Cylinders stored six months in moist air.

The mean of the total loads was calculated and from this the mean unit load. The mean error in per cent gives an idea of the degree of agreement among themselves of each of the six tests entering into an average result. The proportional numbers are computed to show the effect, in per cent, of each substance placed between the specimen and the plates, referred for convenience to the results from cylinders tested in direct bearing against the plates.

Column 1 gives the results obtained with cylinders loaded between the plates of steel, with nothing between the plates and the specimen; columns 2, 3 and 4 give the results of the use of lubricants, soap in fine paste, plumbago-grease and vaseline; the results in columns 5 and 6 were obtained by keeping the bases of the cylinders and the plates immersed in petroleum and glycerine during the test. A greater difficulty was found in keeping the cylinders centered under these conditions, to which the slightly greater mean errors in these two series of tests may be attributed. Finally columns 7, 8 and 9 give the results, respectively, of placing between the compressed faces of the specimen and the plates thin sheets of tin (four thicknesses of tin foil on each base), sheets of pasteboard (two leaves of 0.4 mm. thickness on each base) and of emery cloth (the emery side against the specimen and the cloth against the plates).

The table shows that, in all cases, the ultimate load is sensibly the same, the errors of the means of each being of the same order of magnitude as those obtained among the individual results contributing to each mean.

The tests by direct contact gave slightly more uniform results than the others. Nothing distinctive was noticed as to the character of the fracture.

M. Feret states in conclusion that it is of no consequence to the exactness or regularity of the results if a more or less plastic material is placed between the compressed faces of the specimen and the plates of the machine.

The results obtained in this investigation using greased plates agree with Feret's conclusion. The 6-in. cubes tested between greased plates gave as high strengths as any 1-2-4 cubes tested. The unit stresses of 8-in. cubes tested between greased plates and loaded with equal loads in two directions are more nearly the stresses which could be developed in a structure than the stresses found when plates were not greased. It is thought that, with the greased plates, there was still some friction of the plates left, and that this was great enough to make the strength of the cubes greater than that of the cylinders. With greater reduction in the friction of the plates, cubes might be made to crush under stresses as low as the crushing stresses of cylinders. Perhaps under these conditions bi-axially loaded concrete would be weaker than concrete simply loaded. The fact that the expansion is greater under two loads than under one load points to the same conclusion.

24. Phenomena of Tests and Failure of 8-in. Cubes.-The manner of applying the load was the same for all 8-in. cubes. Increments of load of 5000-lb. were applied to the two faces as nearly at the same time as possible. At each 20000-lb. the machine was

stopped and the specimen inspected. In those cases in which deformations were measured, a series of observations was taken while this stop was made. Load was applied slowly in order to keep the horizontal and vertical stresses in the cube equal at all times. Failure was gradual. Some time before the maximum load was reached, small pieces scaled off the unloaded faces of the cubes near the plates. These were thin and about an inch long. This in itself indicates that there was no concentration of load at the center caused by squeezing out of the grease near the edges of the plates. At failure a slab the full size of the cube and from 0.5 to 1.0-in. thick dropped from each unloaded face and the specimen split in many pieces. The plates were then removed and the cracks sketched to scale. These sketches may be found in the data at the back of the book. The characteristic cone formation in crushed cubes was entirely absent. The cube split in the plane of both loads into several irregular layers or wedges as shown in the photograph of cubes 2055, Fig. 45, and by the sketches. The wedge formation was often more noticeable than in 2055 but the layers, planes of splitting and cracking off of faces were always present.

Squeezing out of the grease was not pronounced. In bedding the cubes in plaster, a sheet of paper was placed on a piece of plate glass, thin plaster poured on the glass and the cube gently lowered in place. In some instances a wrinkle formed in the paper, which made a small groove in the plaster dressing. During a test a small quantity of grease was forced out through these grooves. The general cracking and the fact that the

Fig. 45. 8-in. Cubes 2055 after Failure.

specimen was as much broken in planes near the center of the specimen show that the lozenge of grease mentioned in some of the tests reported by Feret and which he claimed caused concentration of load at the center was not present. The fact that the entire cube was broken indicates that the full strength was developed.

It has been mentioned under "15. Stress-Deformation Relations of Compression Specimens" that the expansion under two loads at right angles was greater than under one load of the same amount. Expansion of the cubes could not be measured, but the character of the fracture indicates that the bi-axially loaded cubes failed by expansion. Expansion (tension) failures would not have a cone formation, but would pull the test piece apart. The cubes shown in Fig. 45 were pulled apart.

The 6-in. cubes tested between greased plates crushed in a way somewhat similar to the way in which the 8-in. cubes failed. The cone formation was not found. Vertical cracks developed at the maximum load on all four unloaded faces. These cracks were as numerous near the corners as near the center and at failure they extended the full height of the cube. Failure was gradual. Some little difficulty was found in keeping the cubes centered until about 10000-lb. load had been applied, after which they remained as placed.

8-in. cube 2072 was tested in simple compression between greased plates and its fracture was in every way similar to the fracture of 6-in. cubes tested between greased plates. The characteristic cracks may be studied from the photograph of this

Fig. 46.

8-in. cube 2072 after Failure

specimen shown in Fig. 46. The bearing plates are still in place. The extent to which grease squeezed out from under the plates may be seen at the top of the cube. The cracks are vertical and they extend the full height of the specimen. Those on the right hand vertical face developed first, followed immediately by the large crack on the left hand vertical face. The specimen was pulled apart after the picture was taken. No cones were formed. The cracks extended through the specimen forming long thin finger-like pieces.

<u>25. Stress-Deformation Relations and Strength of Cubes</u>.- Deformations were measured on four cubes. The individual stress-

deformation lines and the curves of average deformation may be found in the back of the thesis. The curves are similar to those obtained on the cross of compression specimens tested with equal loads on the two arms. The ultimate unit deformation of the cubes was about the same as that on the cross of compression specimens. In tests of cubes and the cross of compression specimens the stress-deformation diagram was not as nearly a parabola as the stress-deformation diagram for the arm or on a cylinder. The moduli of elasticity from cubes 2056-A and 2056-B were 2 520 000 and 3 460 000, values which compare favorably with values obtained on the cross of compression specimens. Cubes 2055-A and 2055-B gave higher values. As was mentioned above, failure of cubes was produced by effect of expansion, and the amount of expansion rather than the amount of compressive deformation is the criterion of strength. That the cubes failed through overcoming the tensile strength of the concrete in the lateral direction is indicated by the form of the broken cube and its planes of cleavage. The powdering and scaling which are usually features of a compressive failure of a cube were not present. The relative strength of the cubes is shown in the summary of unit stresses, Table XVIII.

The average unit stress on the two faces of an 8-in. cube is called its breaking stress. The unit stress of a cube as written in the table is the average breaking stress of the A and B cubes of that number. Hence each value is the average of four. The stresses given for the 6-in. cubes are the average of three cubes.

Table XVIII.

Summary of Unit Stresses of 8-in. and 6-in. Cubes. Plates Greased.

No.	Unit Stress of 8-in. Cube, Bi-axial Compression.	Unit Stress of 6-in. Cube, Simple Compression.	Ratio of Strength of 8-in. Cube to Strength of 6-in. Cube
2053	2800	2525	1.11
2055	2060	2640	.78
2056	2500	2800	.89
2057	2655	2830	.94
2058	3300	2805	1.17
		Average	.98

From the data in the table we may conclude that the compressive strength of concrete under bi-axial loading does not differ materially from the strength under simple compressive loading. As mentioned above this conclusion is based on fifteen 6-in. cube stresses and twenty 8-in. cube stresses.

26. Effect of Test Conditions.-Absolute values of breaking loads are functions of the shape of the specimen, the manner of testing and the speed at which load is applied. Comparisons should not be too freely drawn between results obtained under test conditions. It is believed that the conclusions of the preceding paragraph are not dependent on test conditions for the following reasons. The conclusion applies to relative strength and not to absolute strength. The specimens compared were cubes, made from

the same batch and stored together. The same testing machine, quality of grease and speed of applying the load were employed in tests of bi-axially loaded cubes and simply loaded cubes.

If the greased plates affected the strength of a bi-axially loaded specimen they affected the strength of a simply loaded specimen as well. From these considerations the conclusion that the ultimate unit stress on each loaded face of a bi-axially loaded cube is approximately equal to the ultimate unit stress on the face of a simply loaded cube may be considered general. The effect of test conditions has been eliminated.

IV.

SUMMARY OF CONCLUSIONS.

IV. SUMMARY OF CONCLUSIONS.

27. Permissible Strength for Design.-In the design of reinforced concrete structures in which the concrete is bi-axially loaded, the same working stresses may be permitted as are ordinarily allowed for simple loading. While the working stresses may be as great, it must not be forgotten that an accurate computation of the external forces is implied and if these are not definitely known the working stress must be reduced. A greater working stress for bi-axially loaded concrete should not be permitted.

A statement that, in a bi-axially loaded structure, one load strengthens the material against forces in a perpendicular direction is not true. The deformation is reduced it is true, but these tests show that the strength is not increased. In a material whose tensile and compressive strengths were more nearly equal than in concrete, the strength might be increased by bi-axial loading, but it may be concluded from these tests that this is not the case with concrete.

The effect of decreased deformation has a bearing on the results of tests of structures. Since the modulus is increased and the deformation is reduced by bi-axial loading, this loading brings the neutral surface closer to the compressive face, and reduces the area of concrete which resists compressive forces in structures in which concrete is bi-axially stressed in bending.

The stresses in the concrete are greater than the deformation indicates.

28. Summary. A summary of the conclusions drawn from the tests reported here is given below:

1. When concrete is bi-axially stressed with equal loads at right angles, the unit deformation produced is from 75 to 80 per cent of the deformation which one of these loads would produce on the same portion of concrete. The statement applies to both compressive and bending stresses, and is the average value for all stresses up to the ultimate.

2. The initial modulus of elasticity of concrete bi-axially loaded with equal loads is increased 12 to 14 per cent above the modulus of elasticity of concrete under simple loading. This statement agrees with the unit deformations measured at low loads.

3. Expansion of concrete bi-axially loaded, perpendicular to both loads, is greater than the expansion under one load.

4. The deformation of bi-axially loaded concrete when one load is half as great as the other, measured along the line of action of the greater load, is not affected by the presence of the smaller load. The modulus of elasticity is not affected by the smaller load. The deformation, measured along the line of action of the smaller load, is reduced about two-thirds by the greater load.

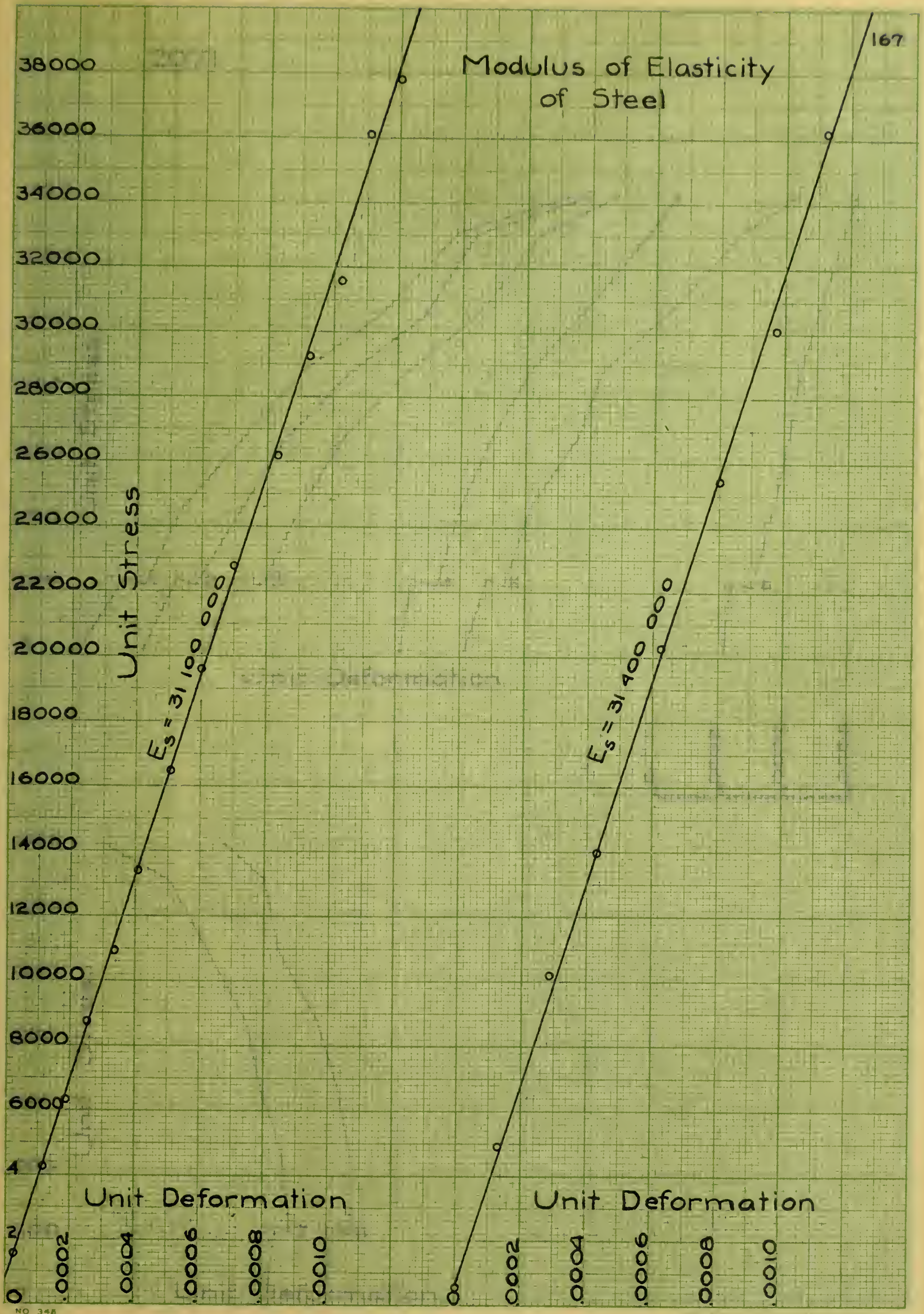
5. The strength of concrete bi-axially loaded with equal loads is approximately equal to the strength of concrete under simple loading.

6. The amount of reduction of deformation stated above

under "1". corresponds to the use of a value of Poisson's ratio of about 0.2 in the ordinary analysis.

V.

DIAGRAMS AND LOG OF TESTS.


Modulus of Elasticity
of Steel
Unit Stress
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36000
34000
32000
30000
28000
26000
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4
2
0
$E_s = 31\,100\,000$
$E_s = 31\,900\,000$
Unit Deformation
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.0010
Unit Deformation
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.0002
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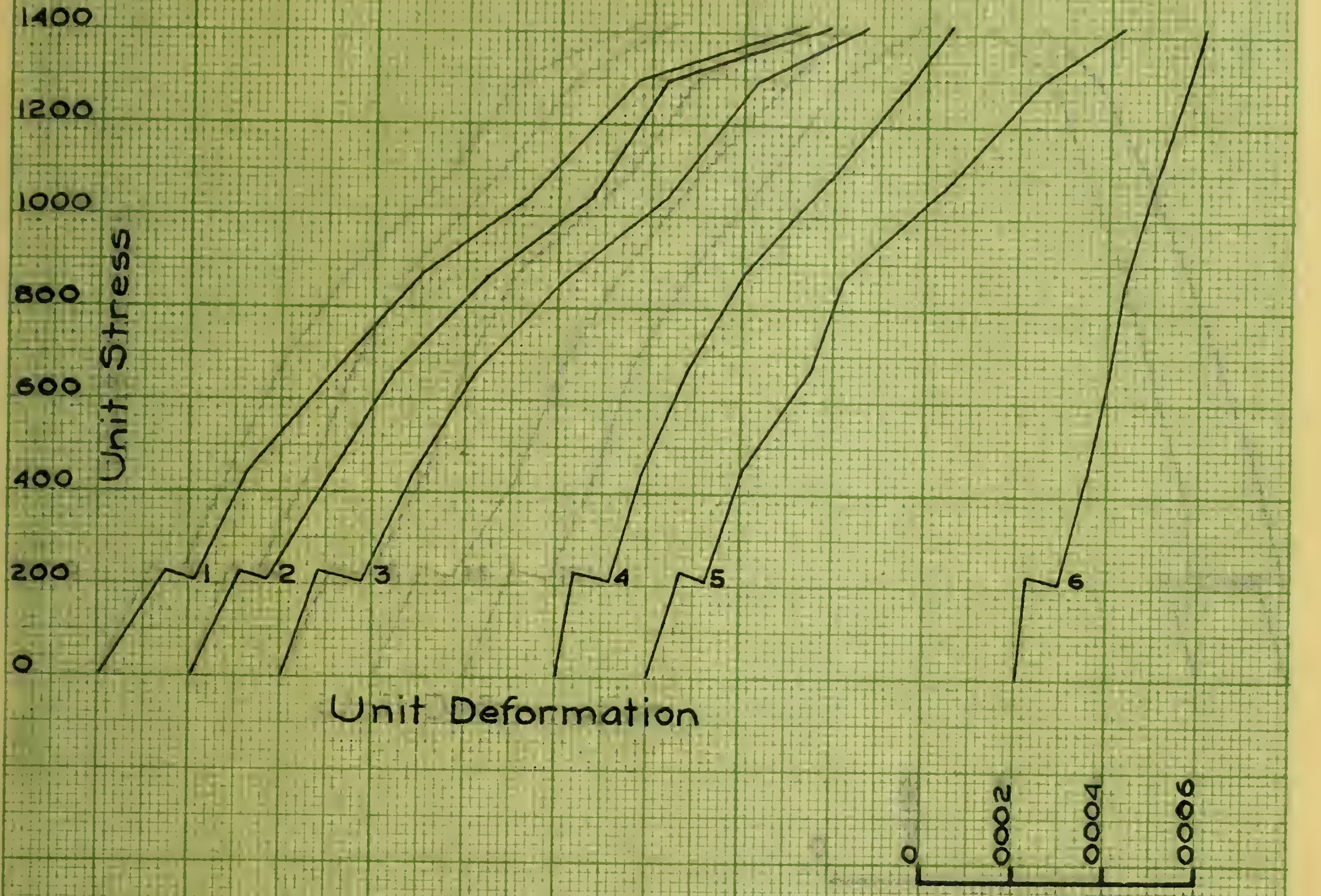
.0006
.0008
.0010

2071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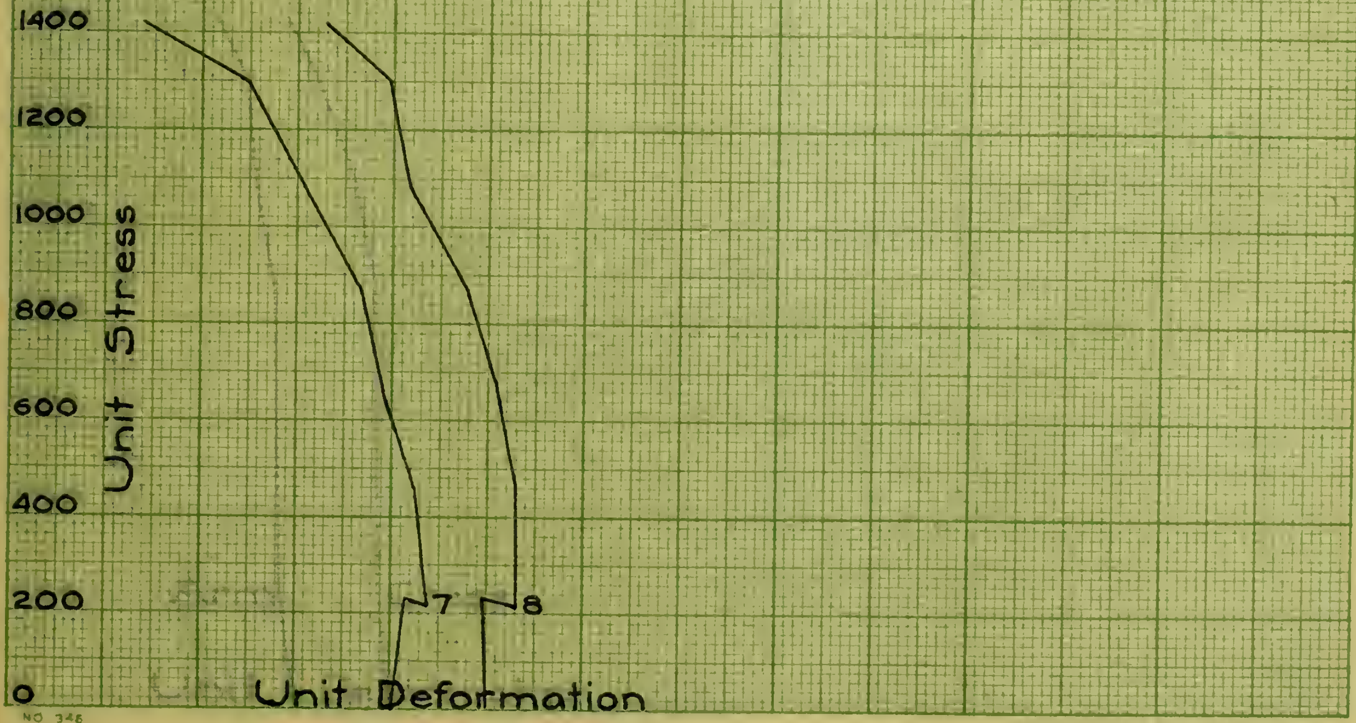
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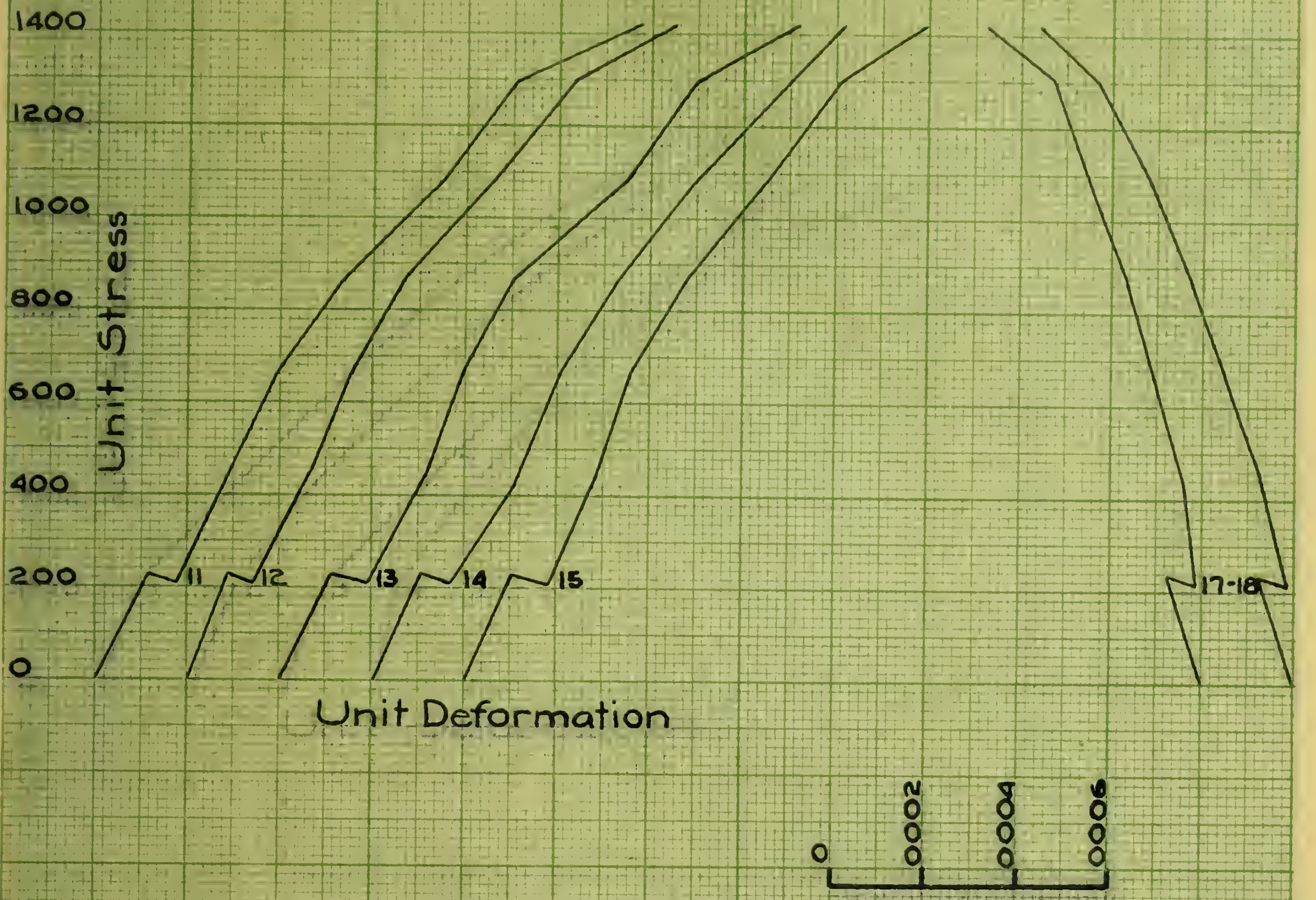
Unit Deformation

2071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17-18
Unit Deformation
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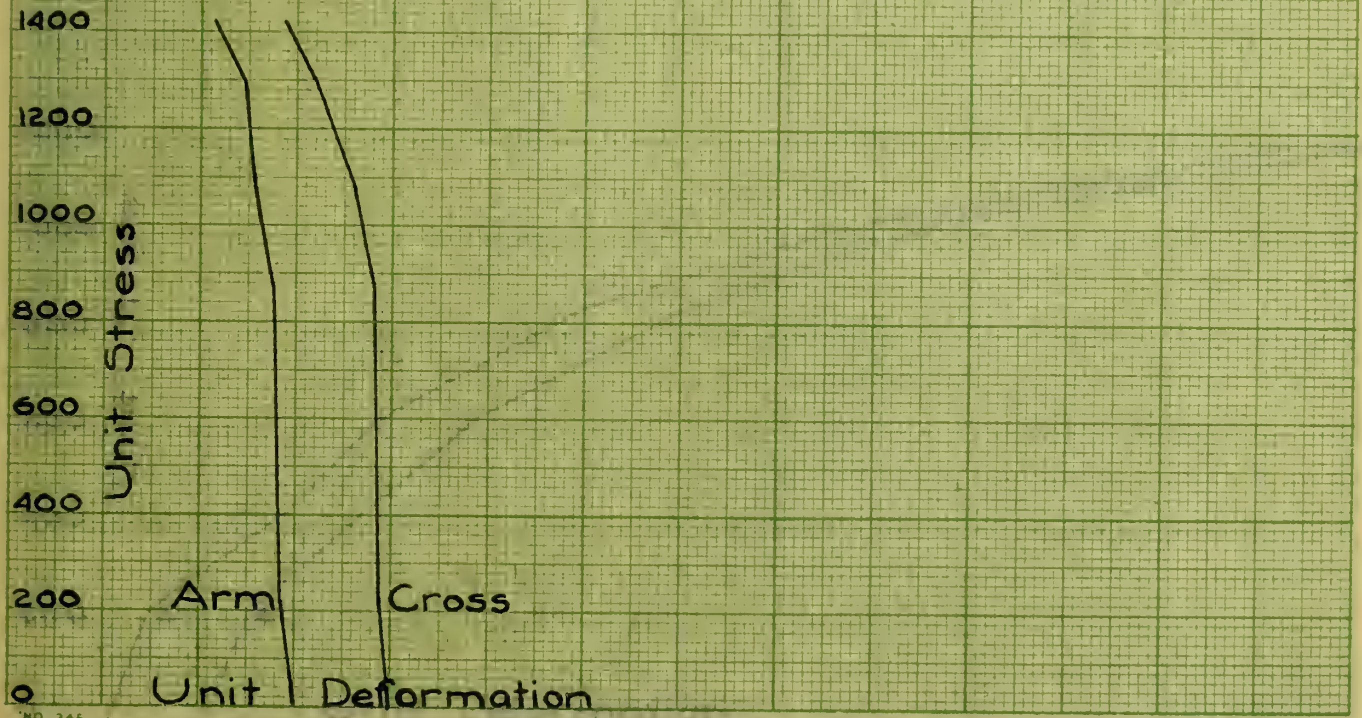
.0004
.0006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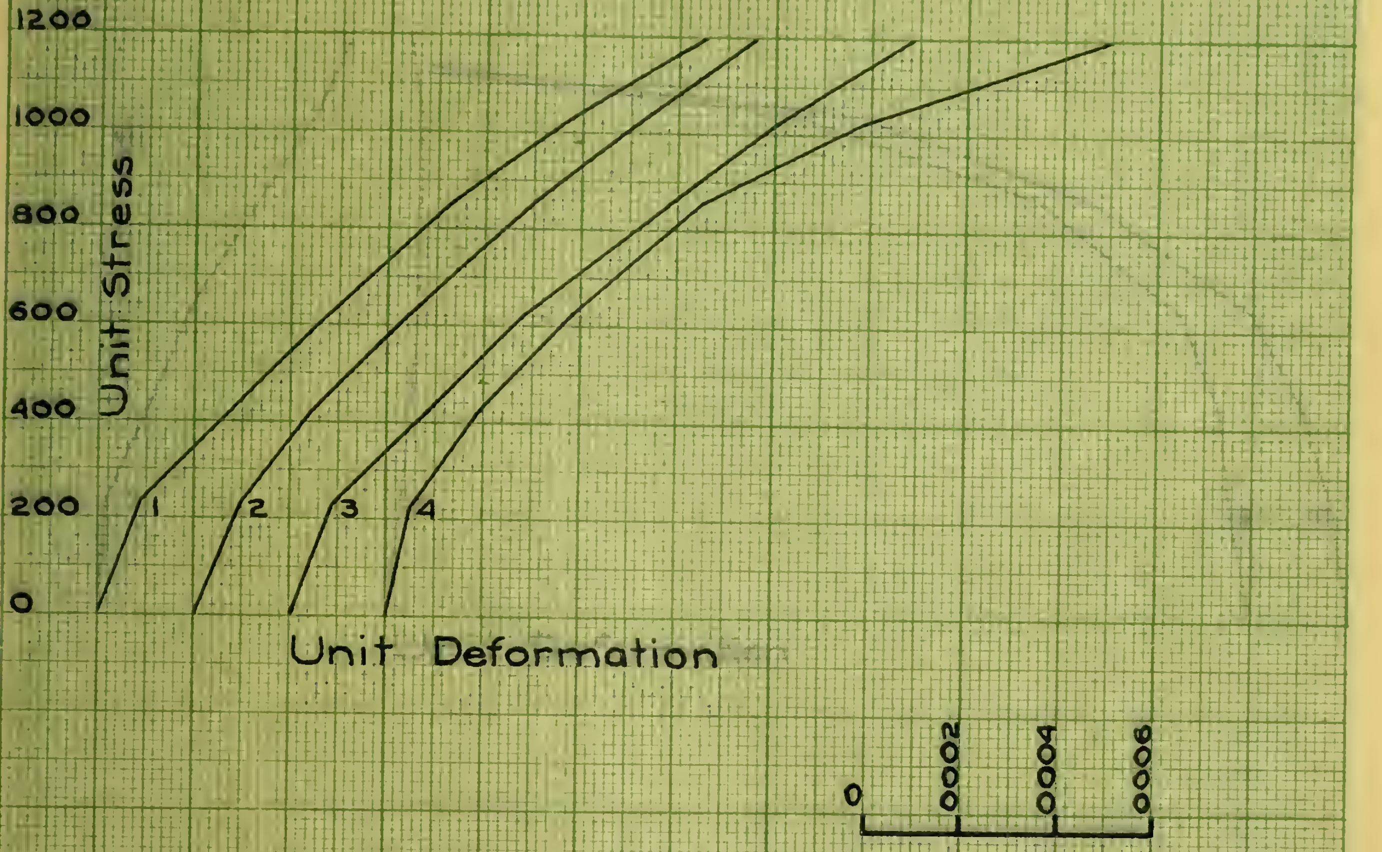
Unit Stress
Arm
Cross
Unit Deformation

2072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Unit Deformation
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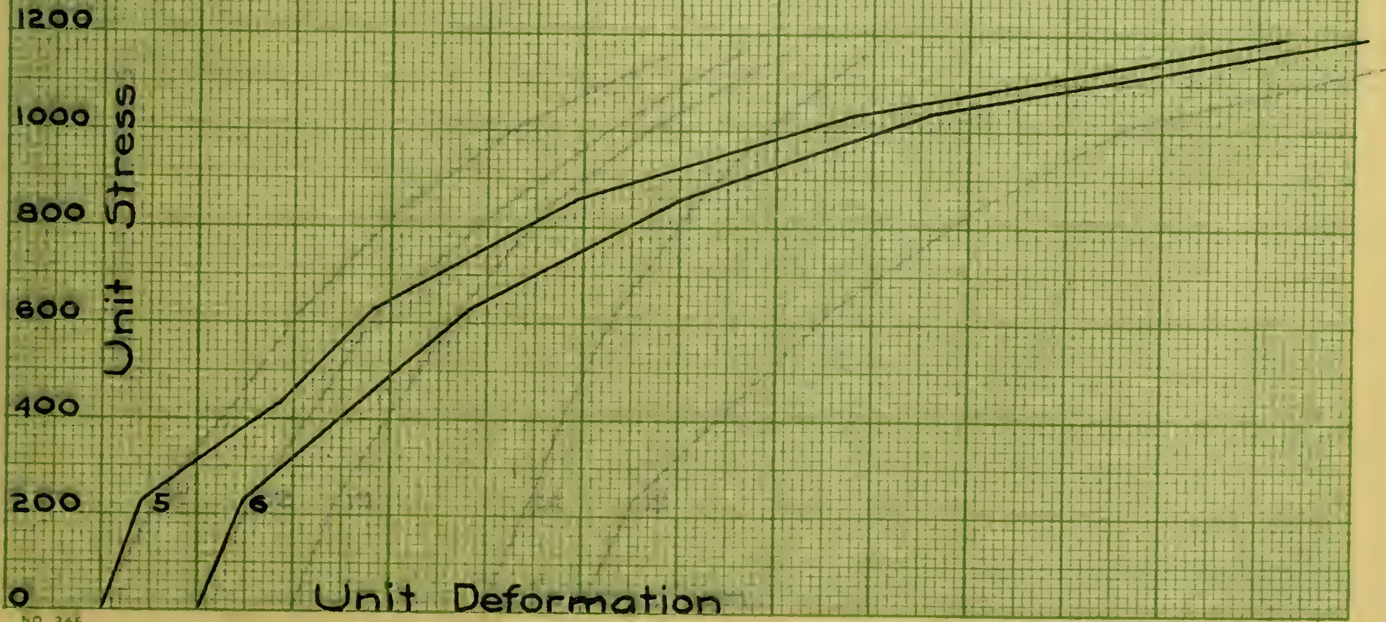
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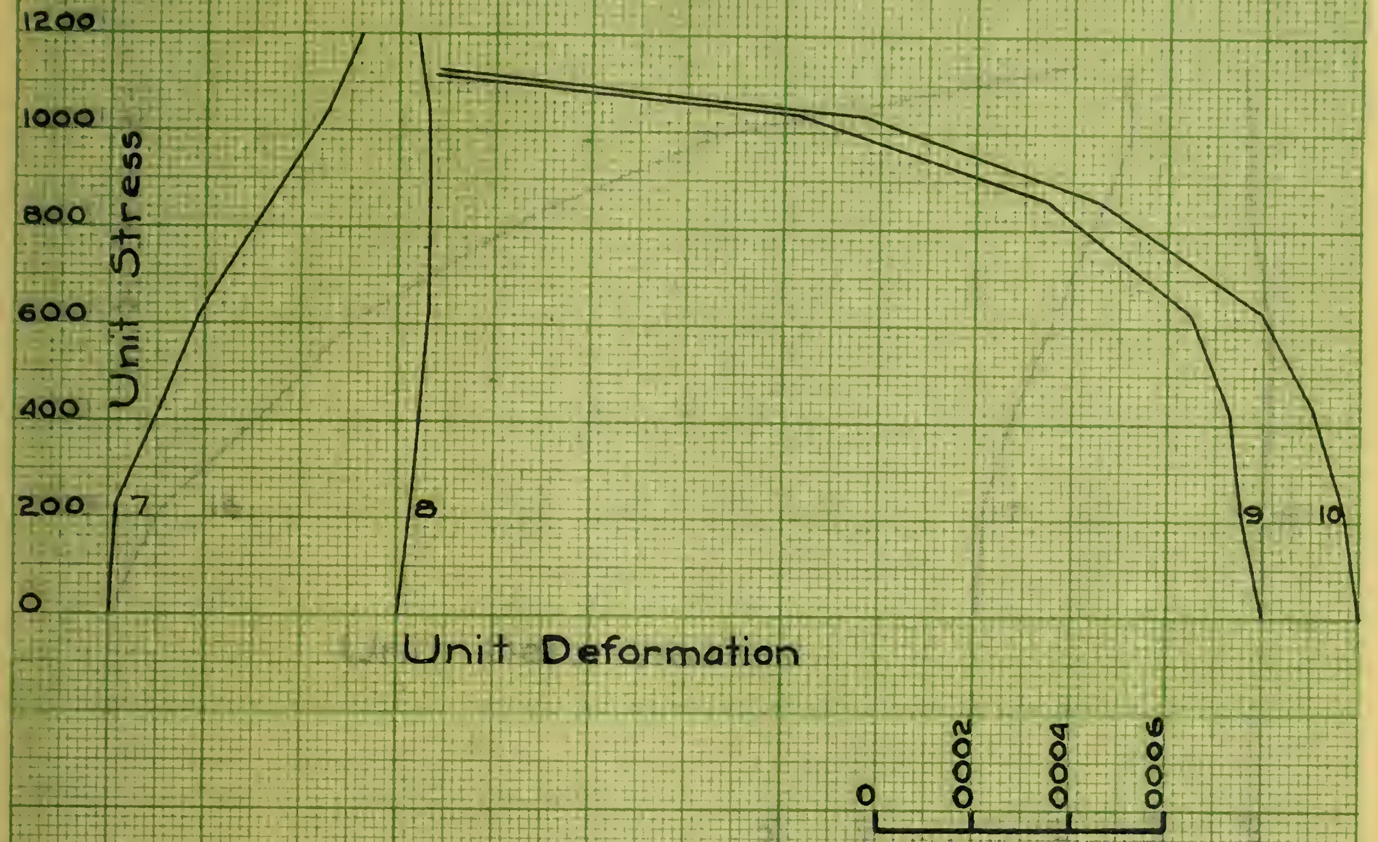
Unit Deformation

2072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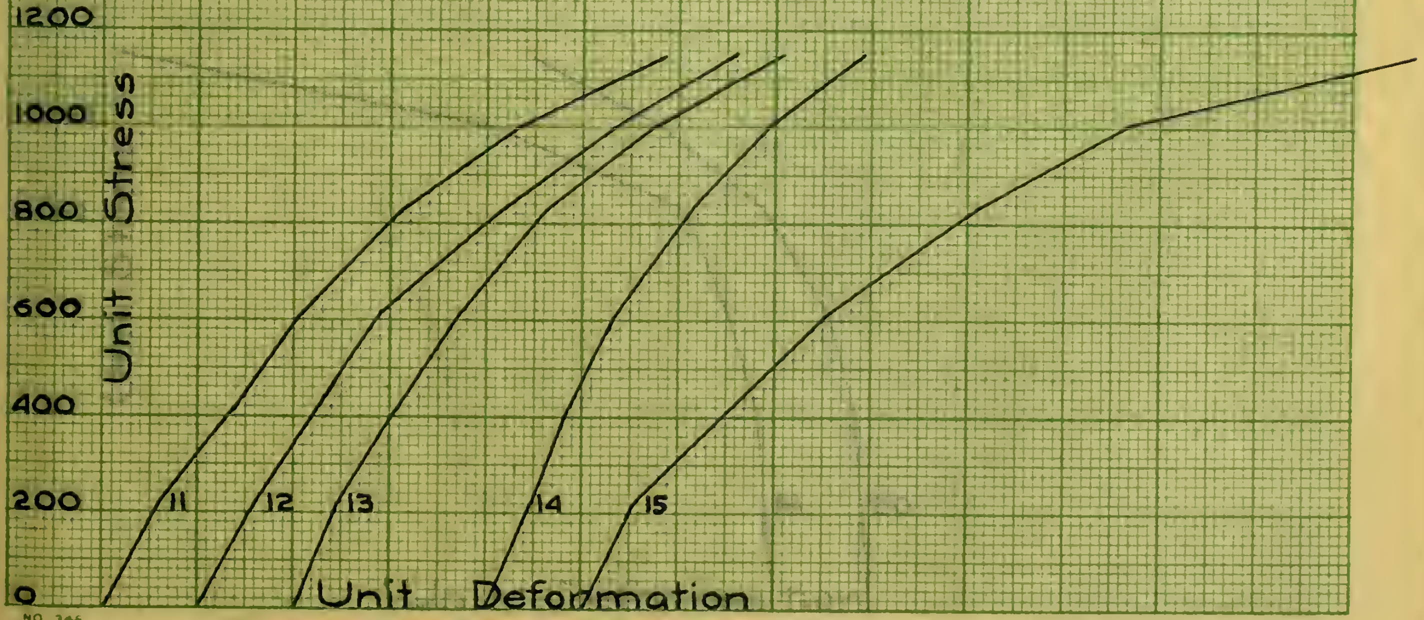
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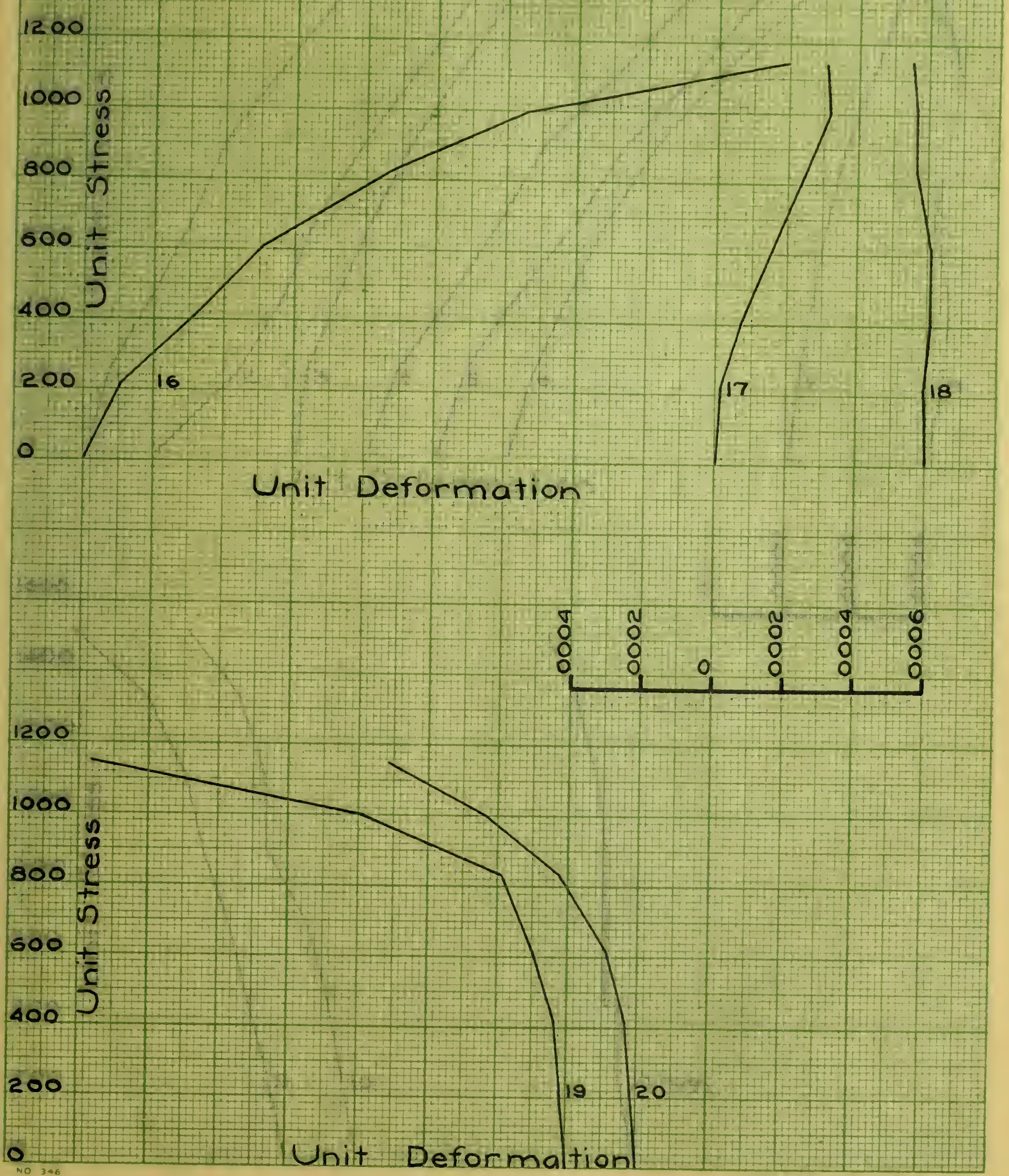
2072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17
18
Unit Deformation
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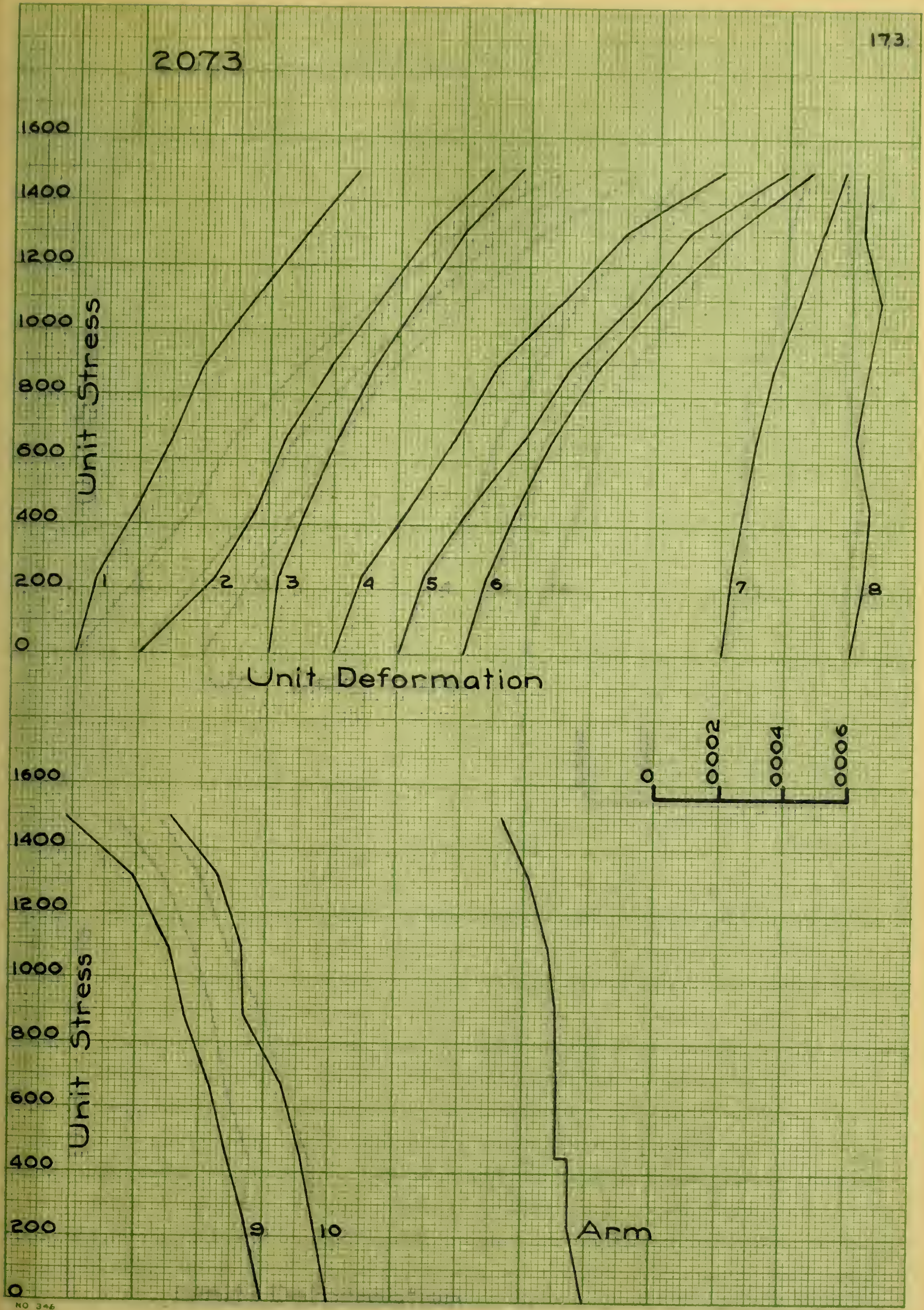
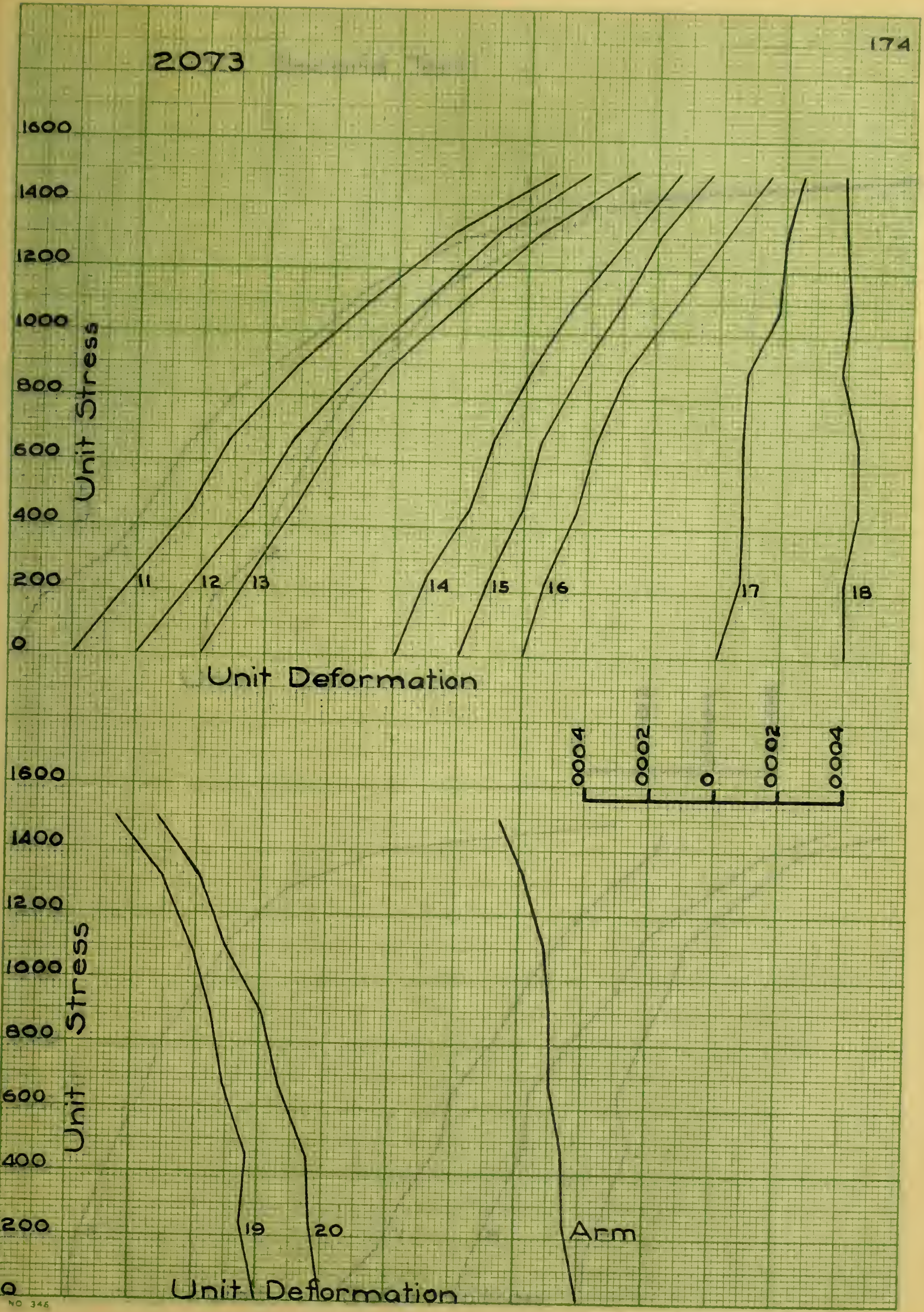
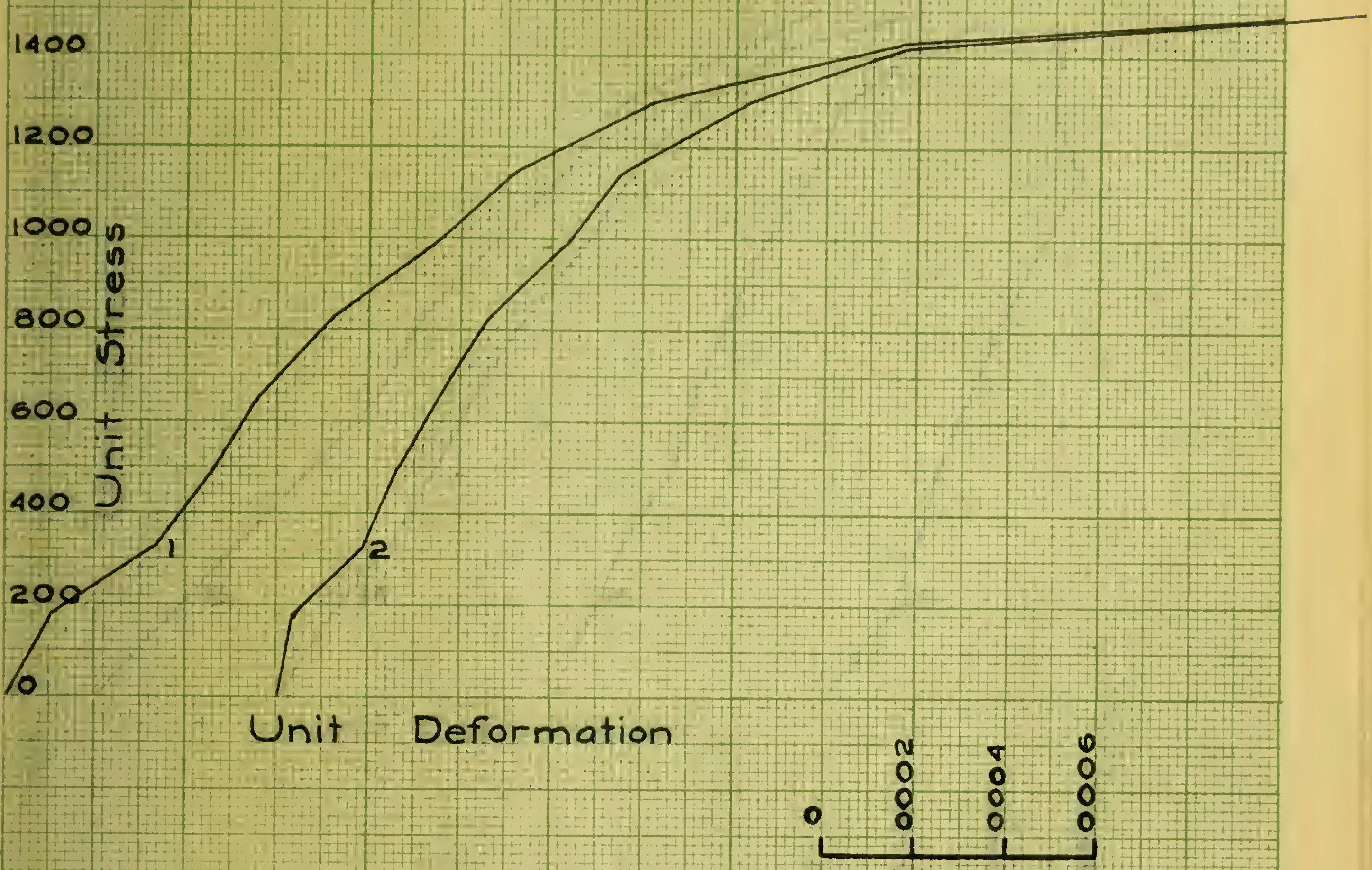
.0002
0
.0002
.0004
.0006
1200
1000
800
600
400
200
0
Unit Stress
19
20
Unit Deformation

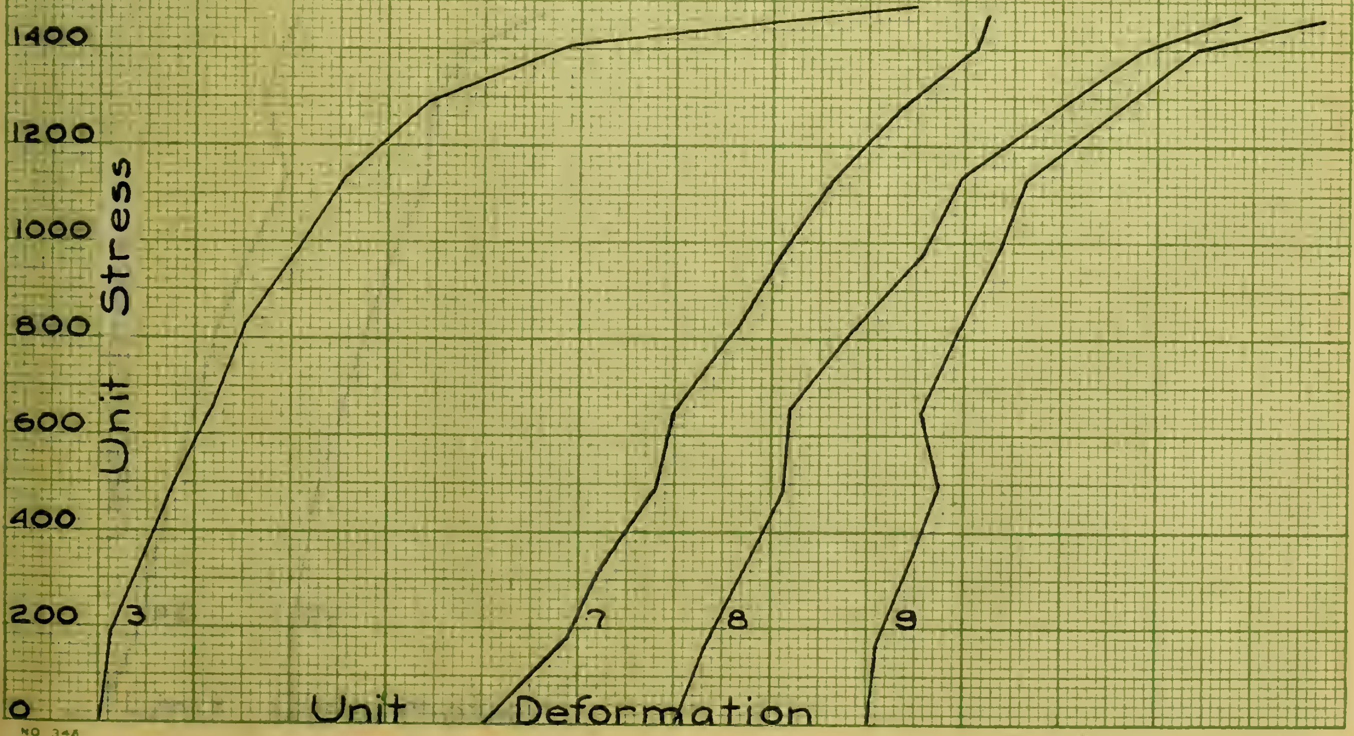

2073
Unit Stress
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
5
6
7
8
Unit Deformation
0
.0002
.0004
.0006
Unit Stress
1600
1400
1200
1000
800
600
400
200
0
9
10
Arm

2073

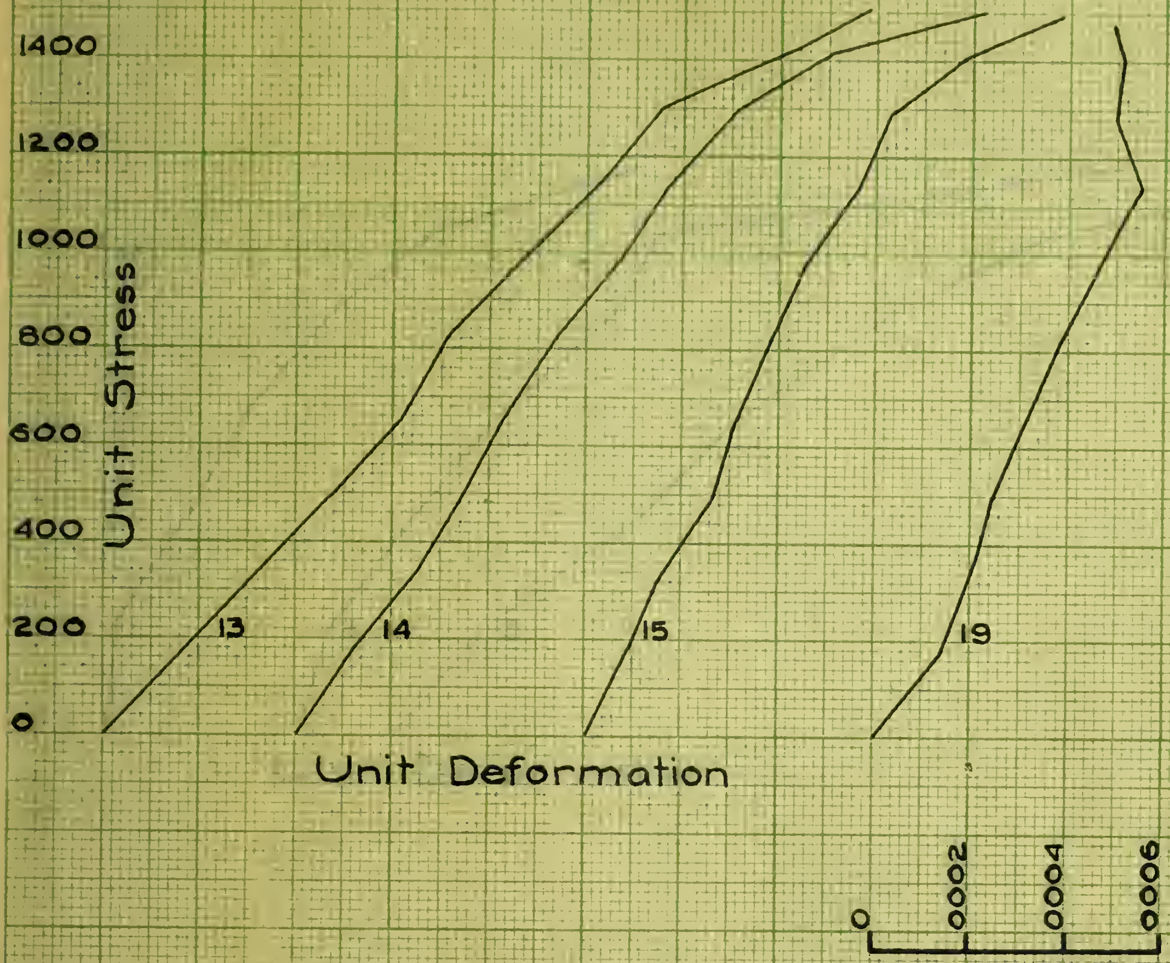

1600
1400
1200
1000
800
600
400
200
0
Unit Stress
11
12
13
14
15
16
17
18
Unit Deformation
.0004
.0002
0
.0002
.0004
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
19
20
Arm
Unit Deformation

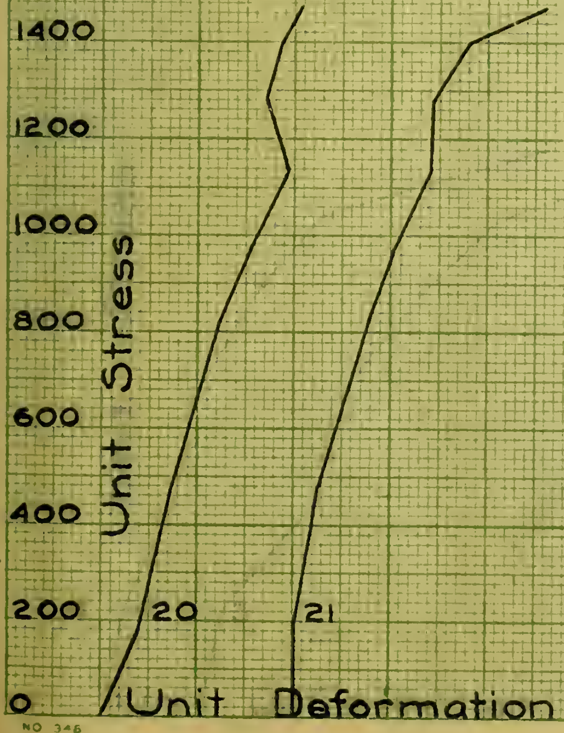
2050 Second Test



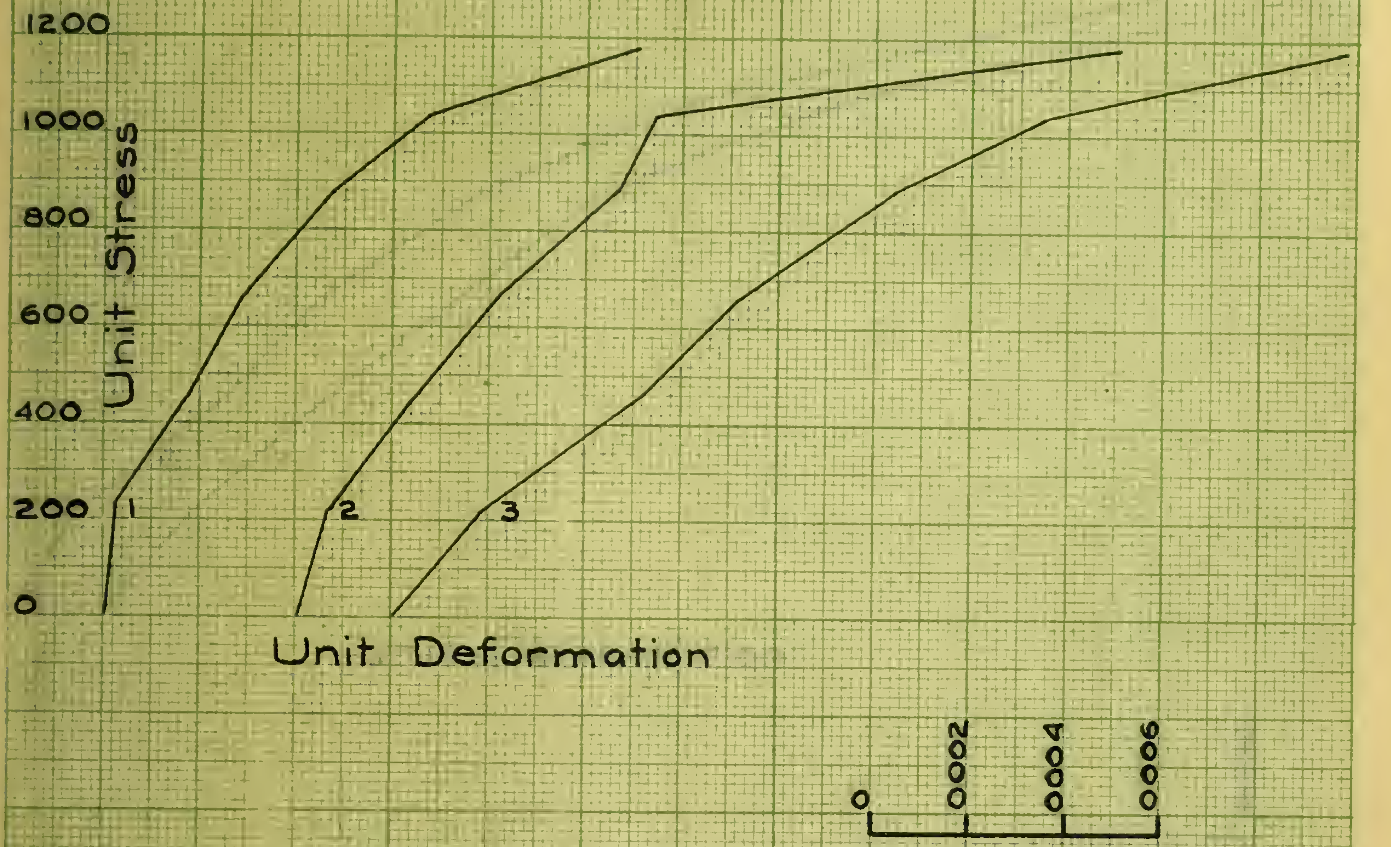


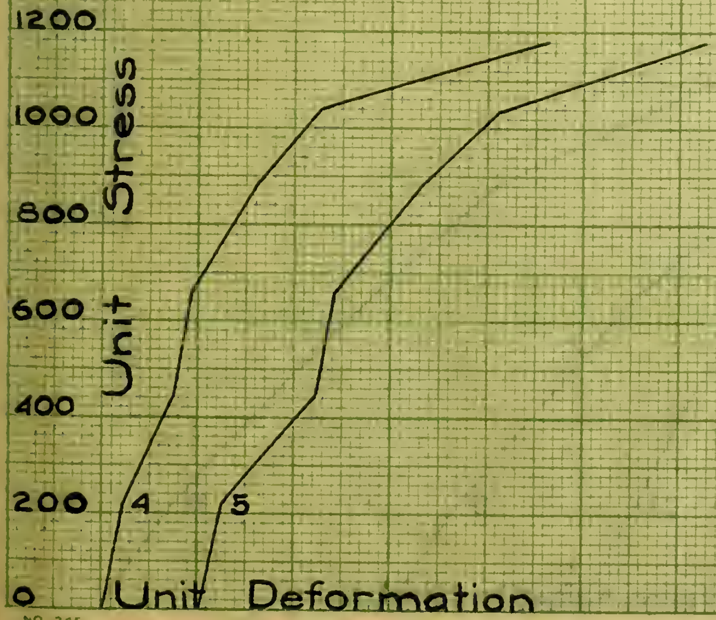
2050 Second Test



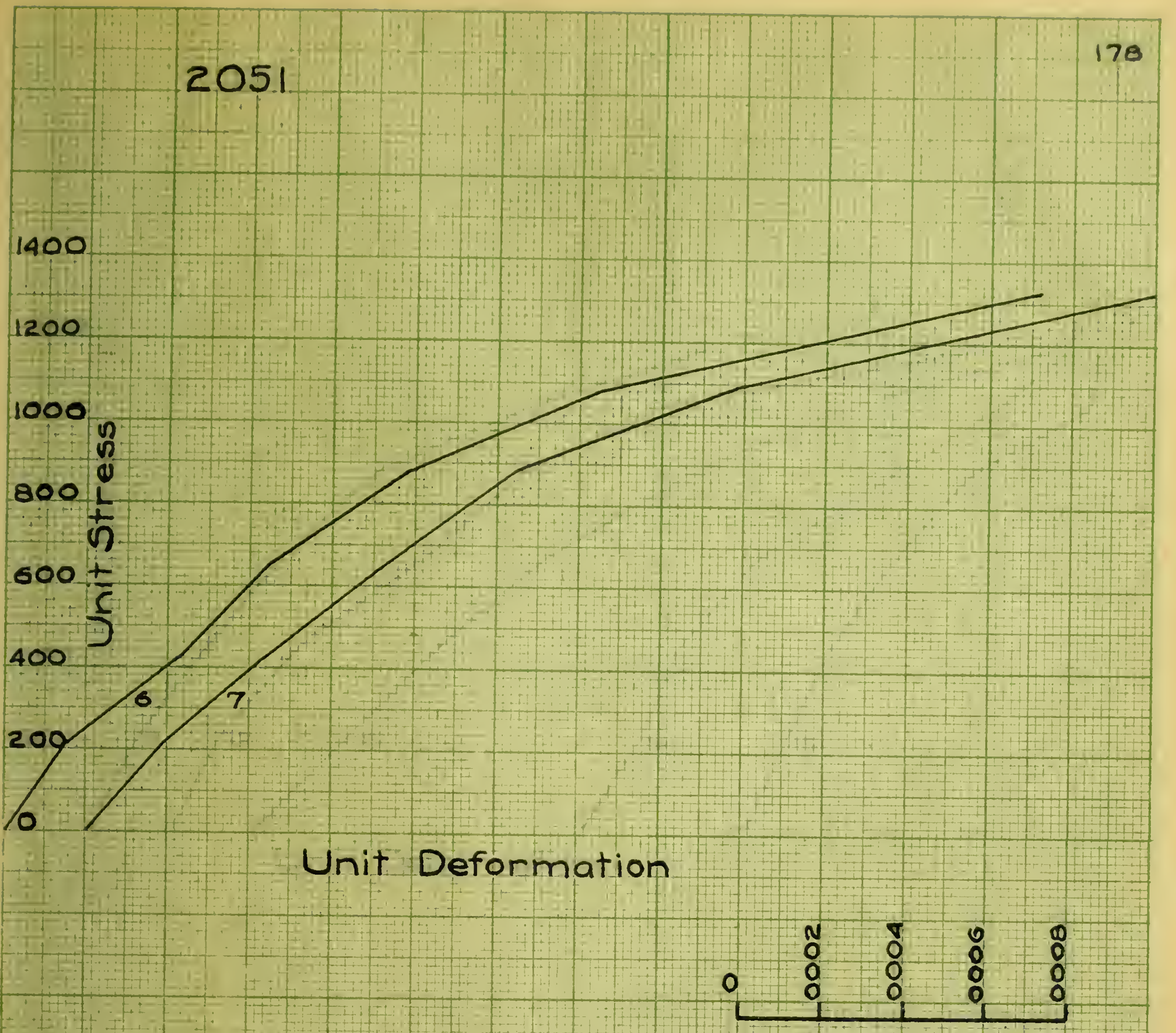


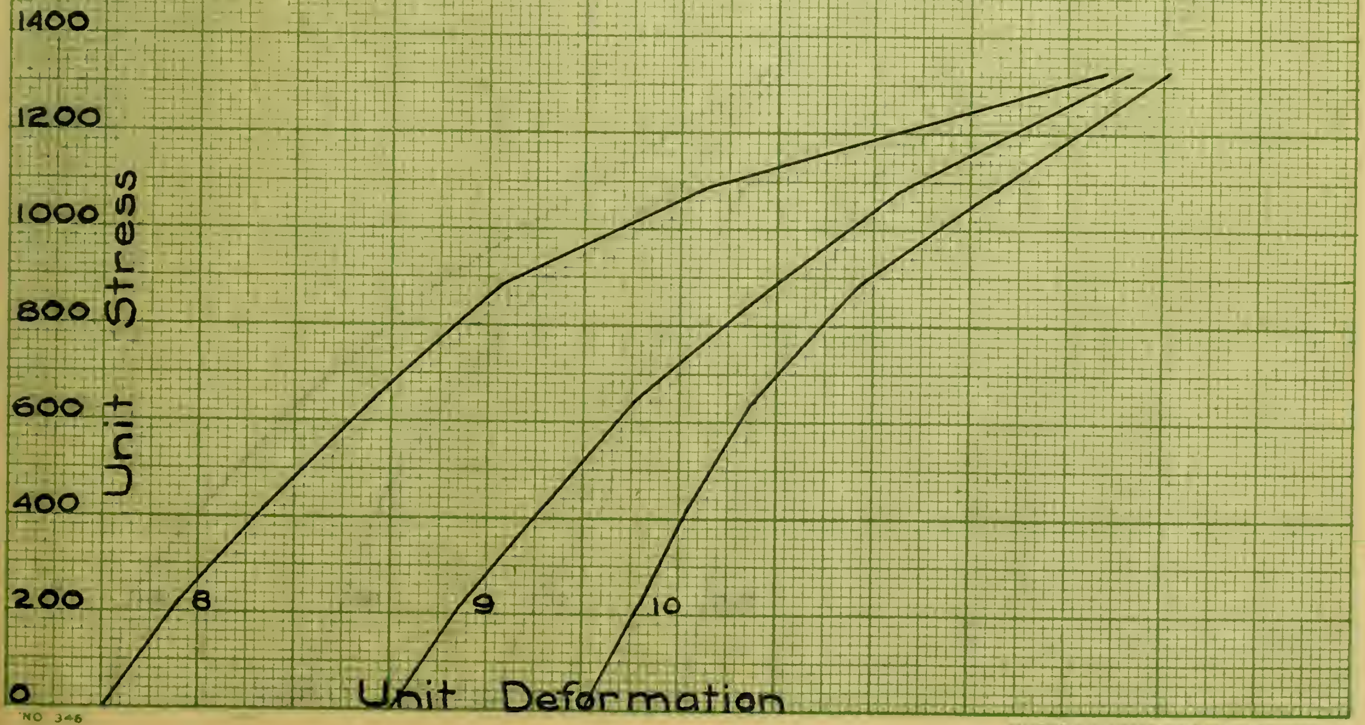
2051


1200
1000
800
600
400
200
0
Unit Stress
1
2
3
Unit Deformation
0
0002
0004
0006

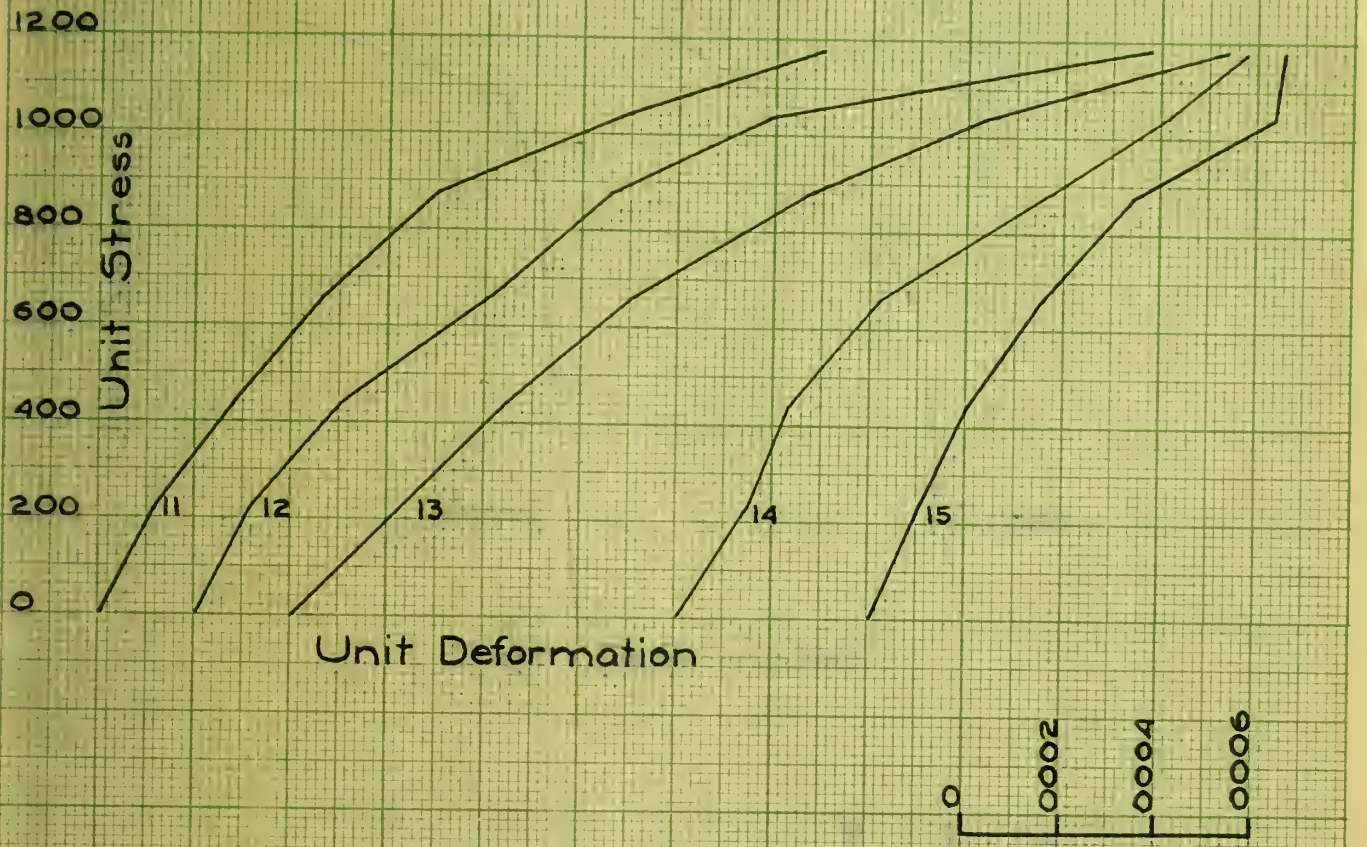

1200
1000
800
600
400
200
0
Unit Stress
4
5
Unit Deformation

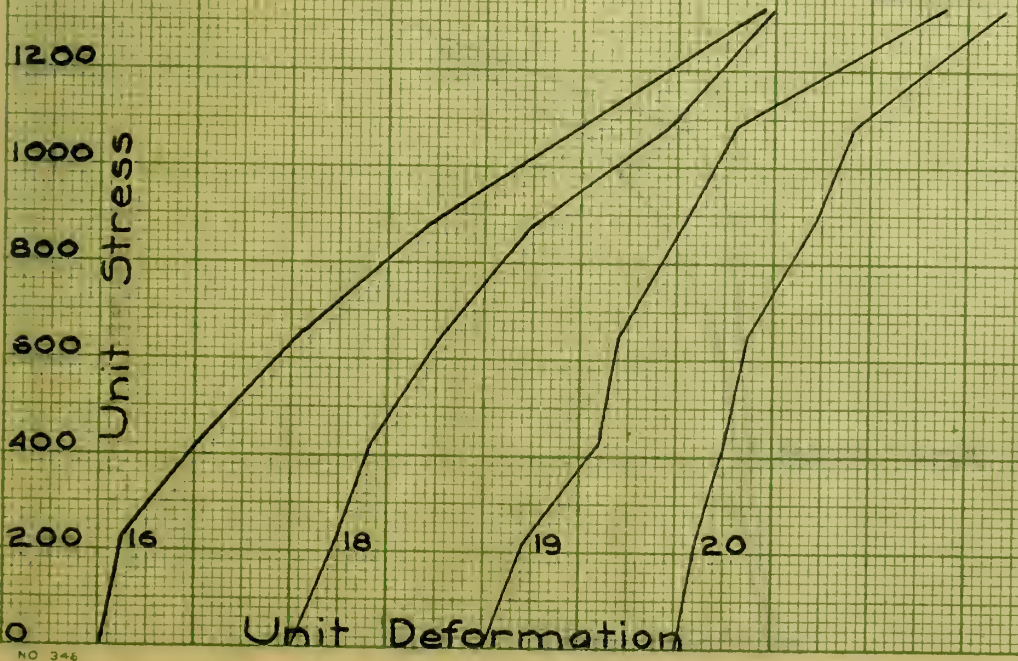
2051


1400
1200
1000
800
600
400
200
0
Unit Stress
6
7
Unit Deformation
0
0002
0004
0006
0008

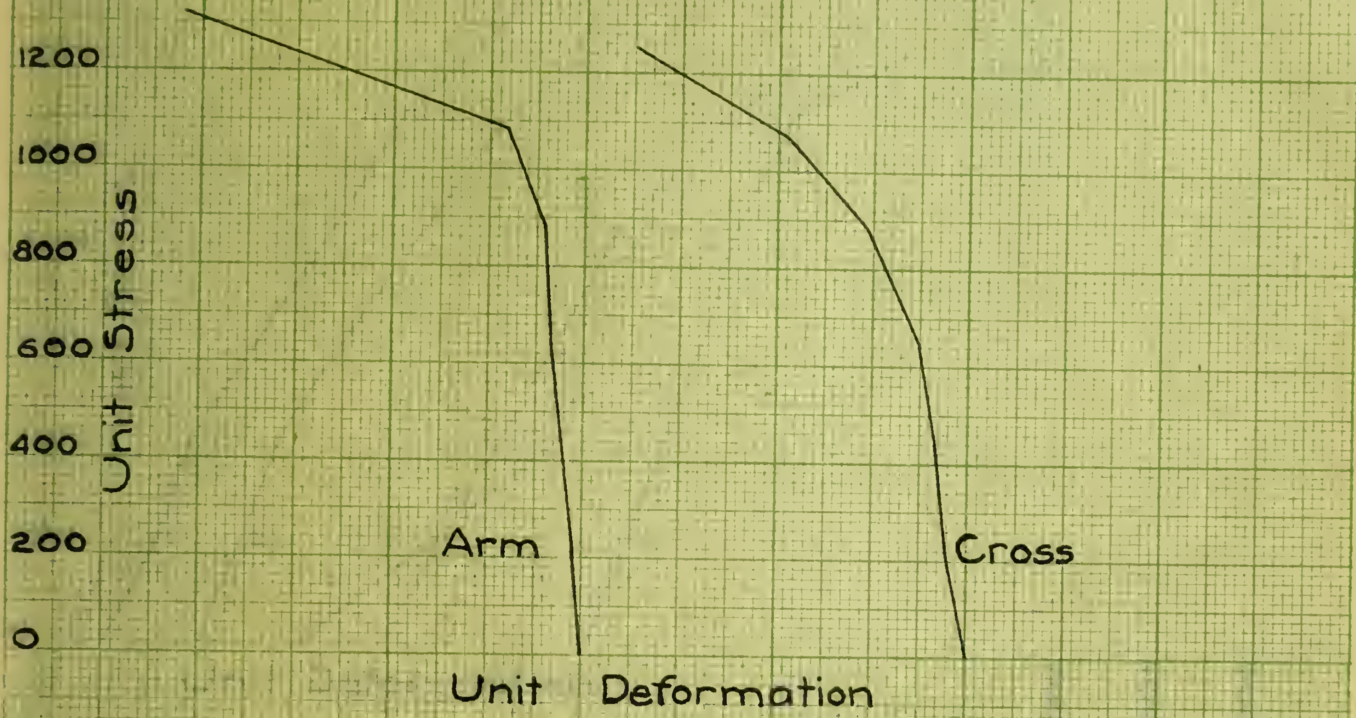

1400
1200
1000
800
600
400
200
0
Unit Stress
8
9
10
Unit Deformation

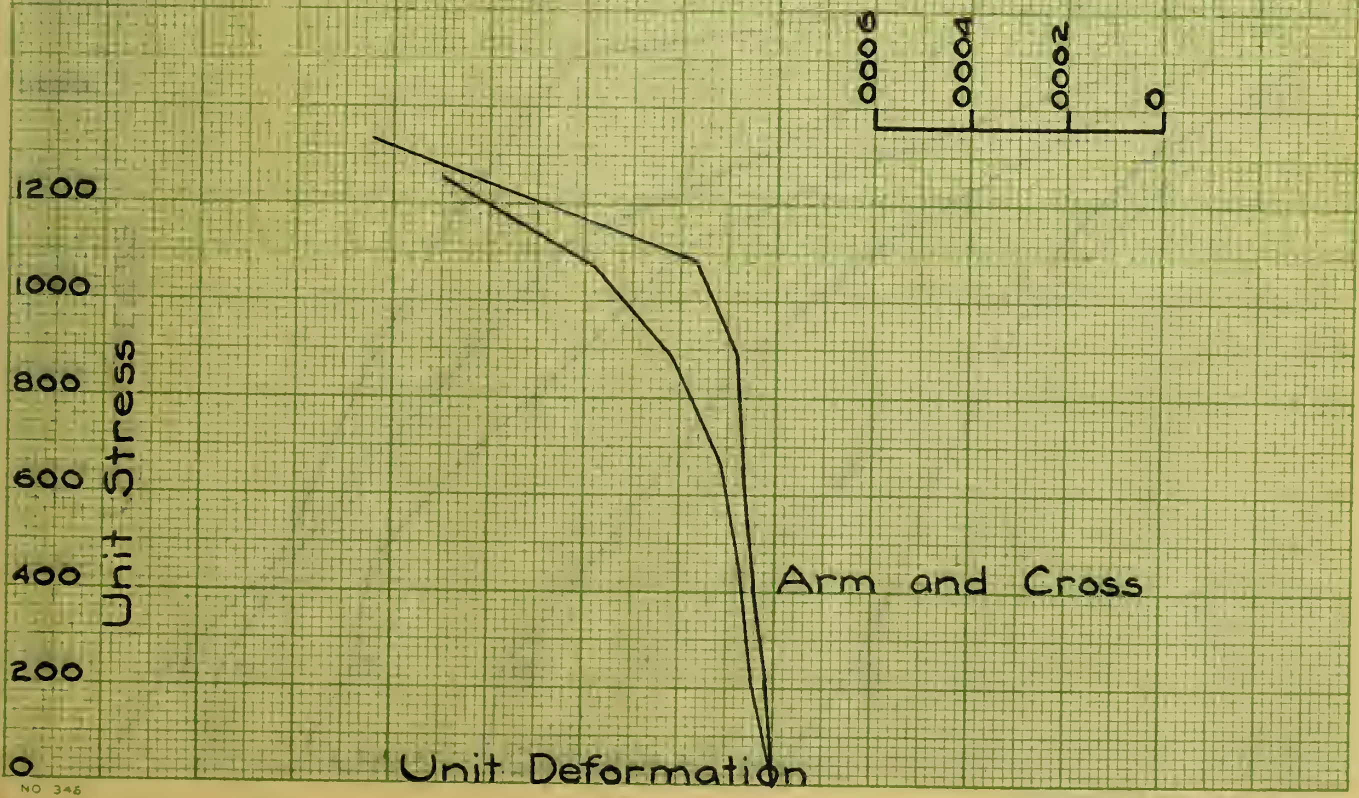
2051


1200
1000
800
600
400
200
0
Unit Stress
11
12
13
14
15
Unit Deformation
0
.0002
.0004
.0006

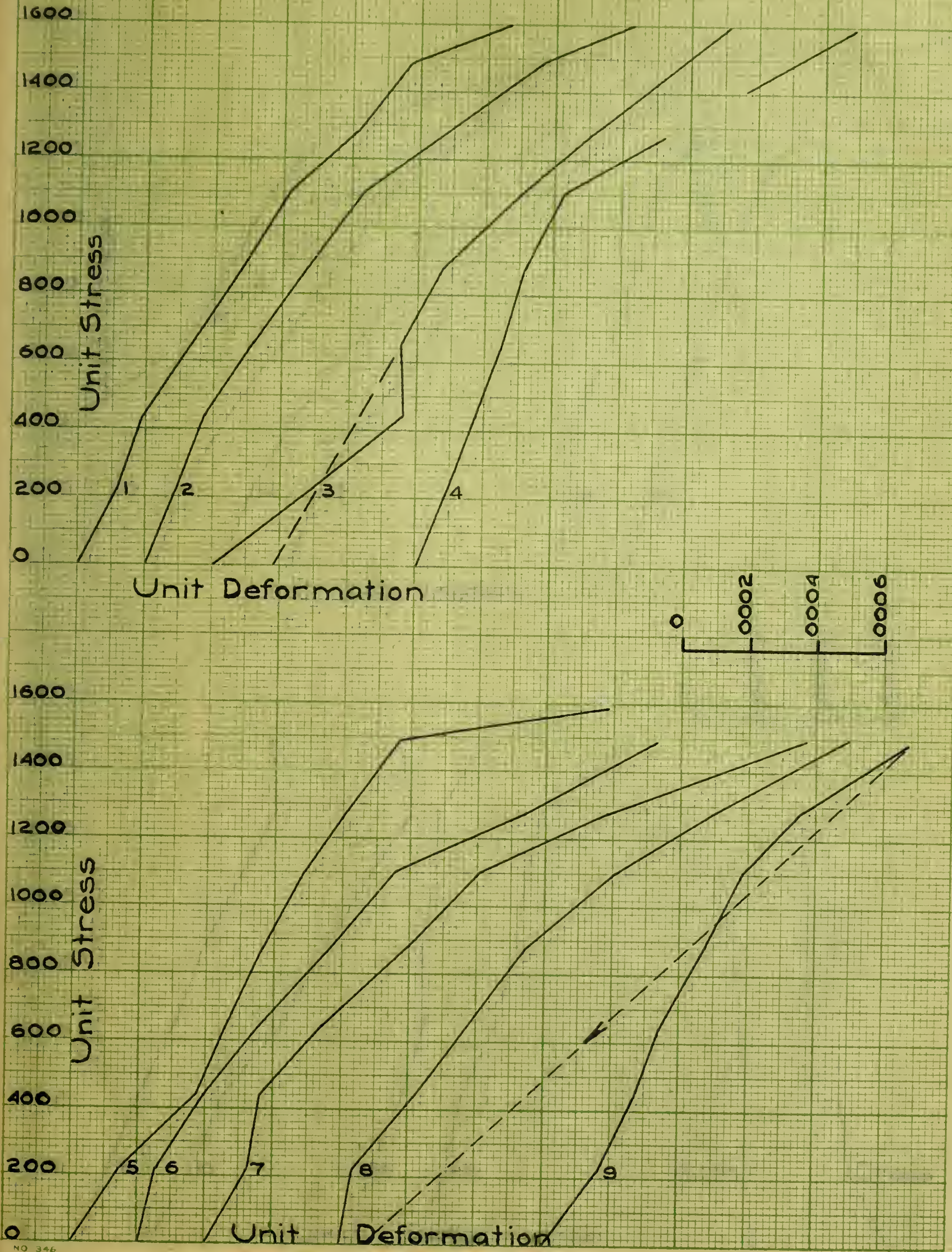

1200
1000
800
600
400
200
0
Unit Stress
16
18
19
20
Unit Deformation

2051

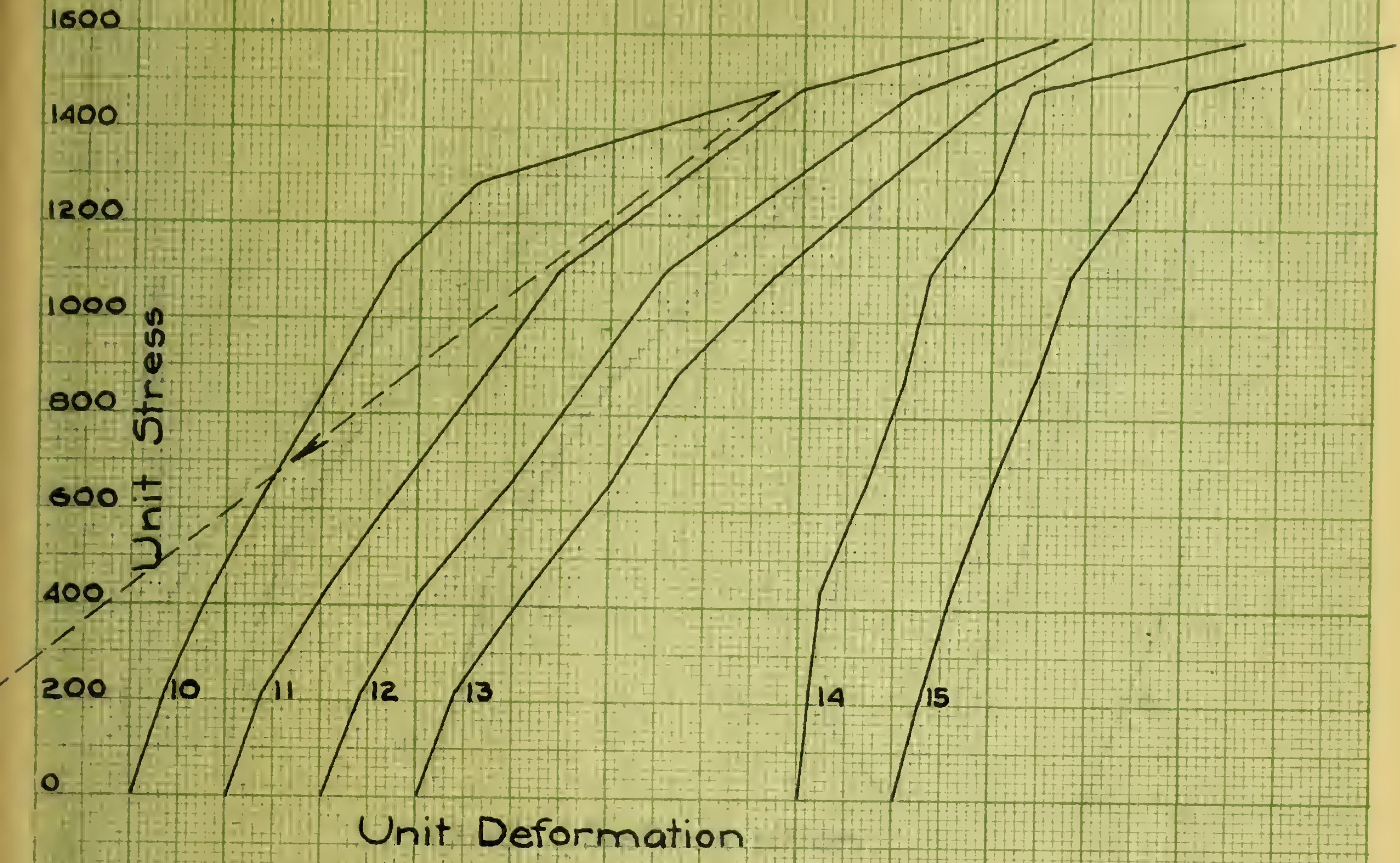

1200
1000
800
600
400
200
0
Unit Stress
Arm
Cross
Unit Deformation

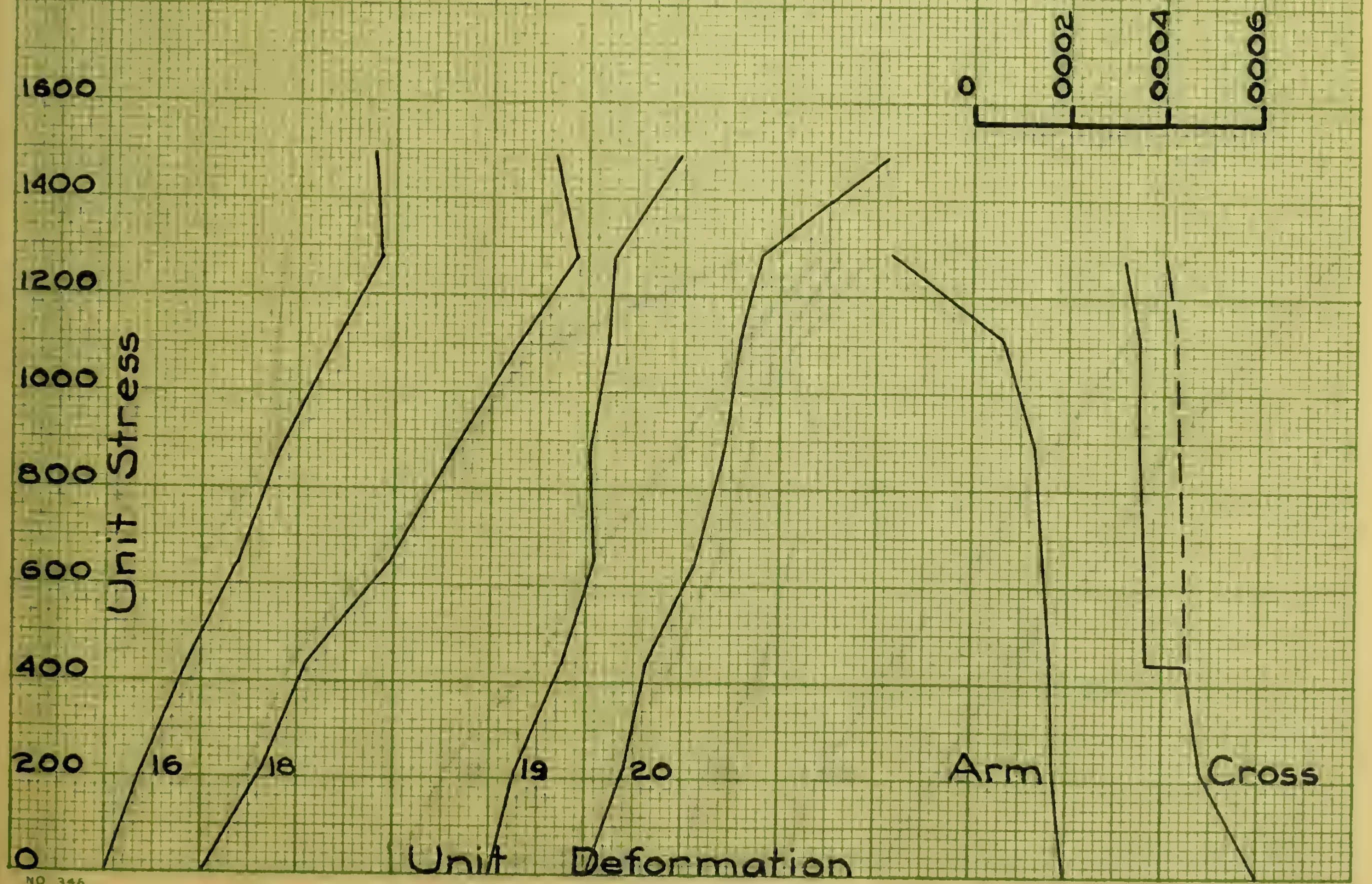

.0006
.0004
.0002
0
1200
1000
800
600
400
200
0
Unit Stress
Arm and Cross
Unit Deformation

2052

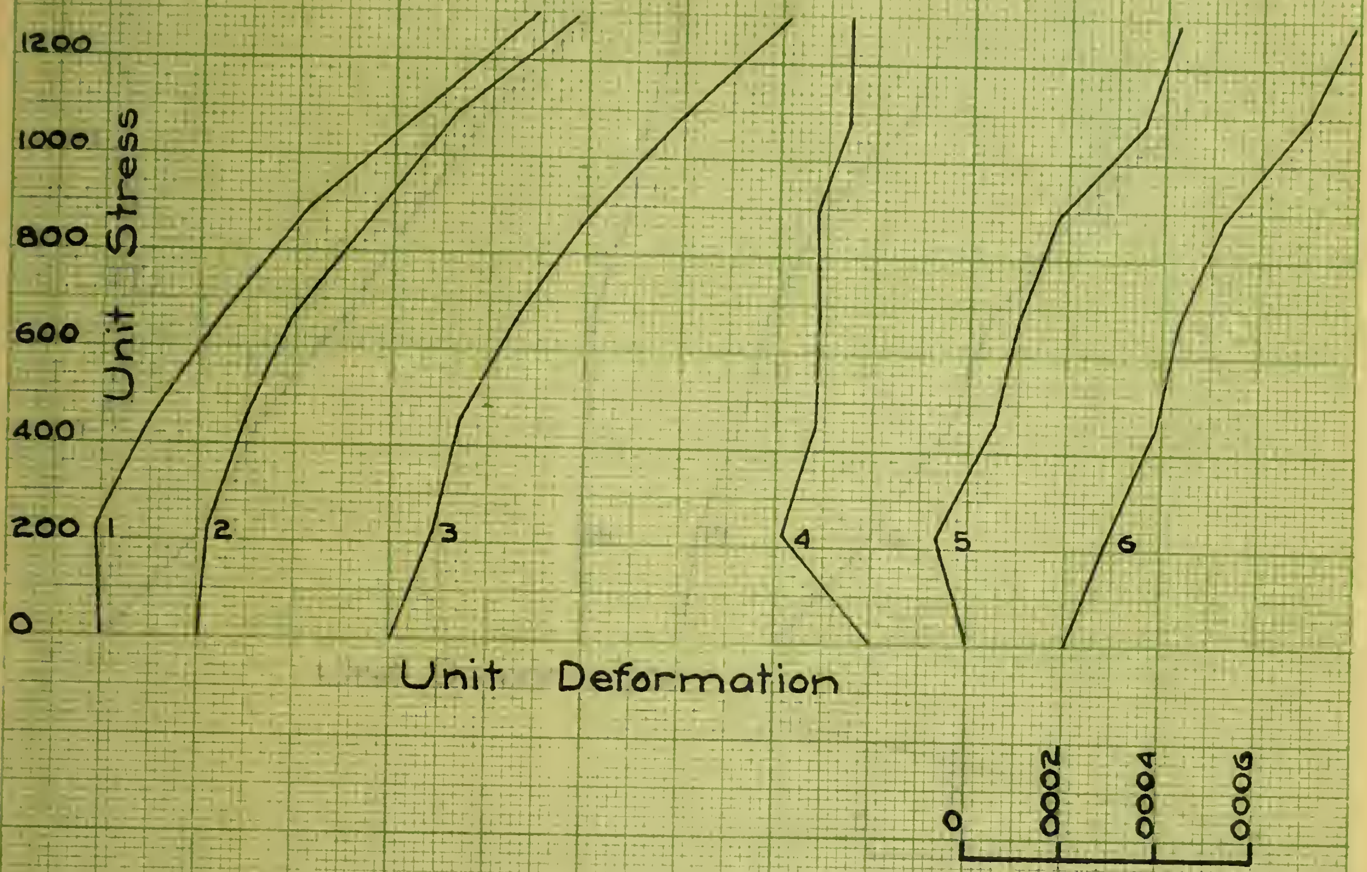

1600
1400
1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
Unit Deformation
0
.0002
.0004
.0006
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
5
6
7
8
9
Unit Deformation

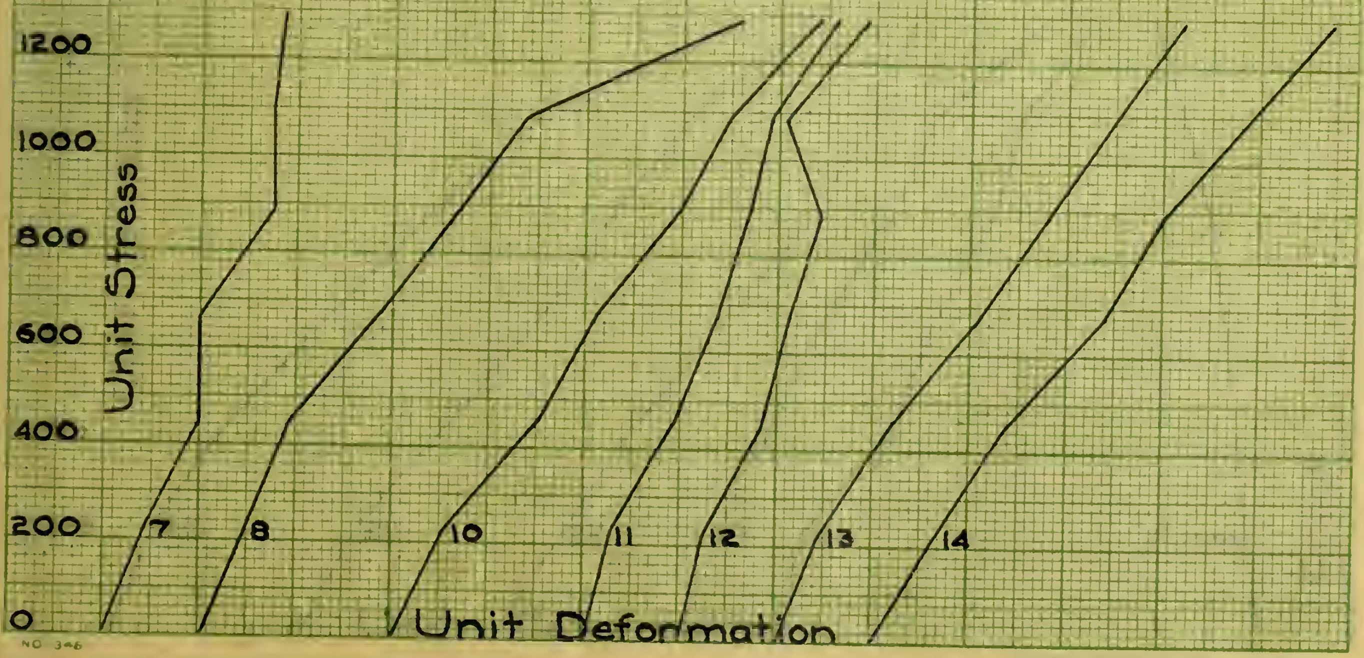
2052


1600
1400
1200
1000
800
600
400
200
0
Unit Stress
10
11
12
13
14
15
Unit Deformation

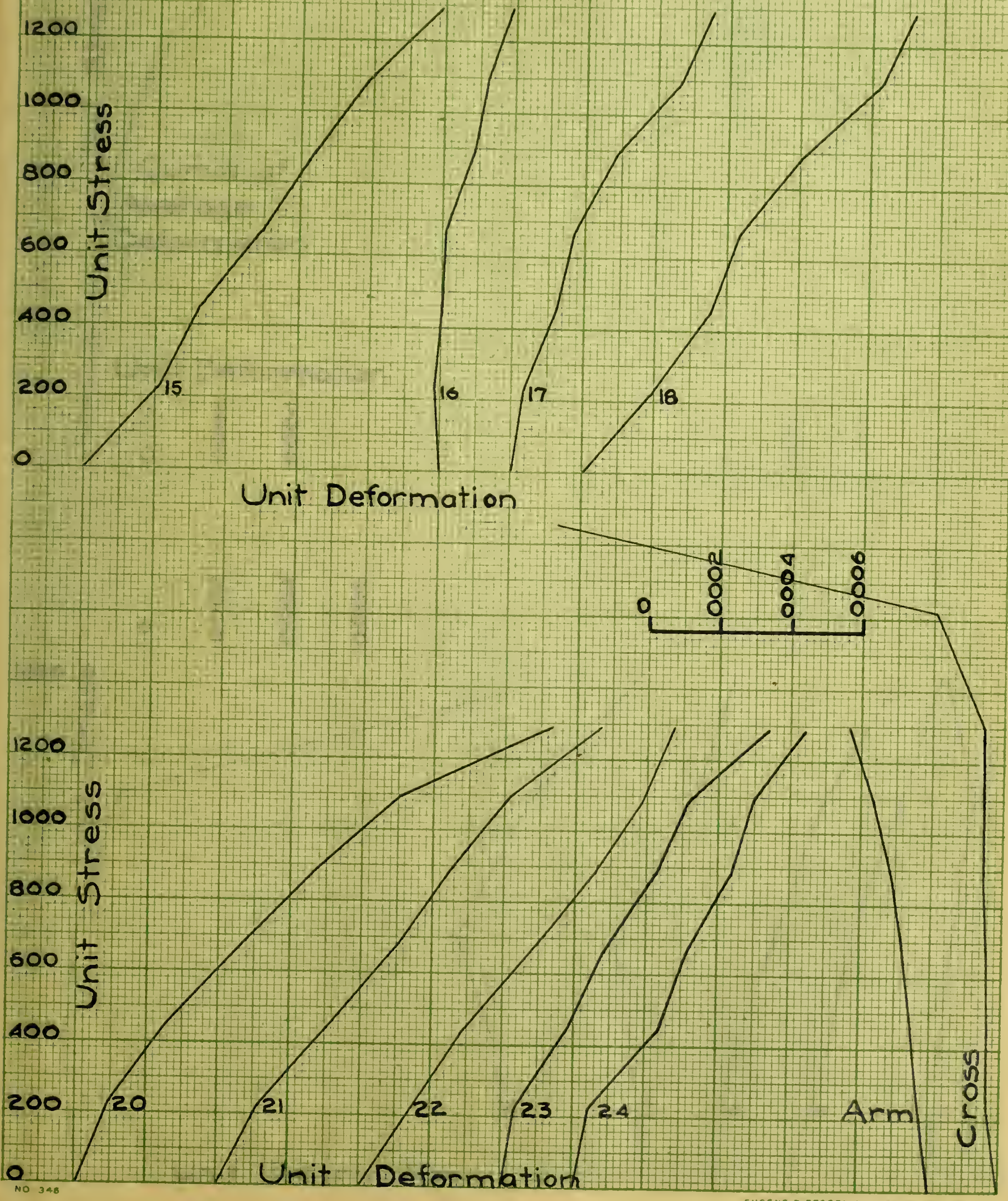

0
.0002
.0004
.0006
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
16
18
19
20
Arm
Cross
Unit Deformation

2053

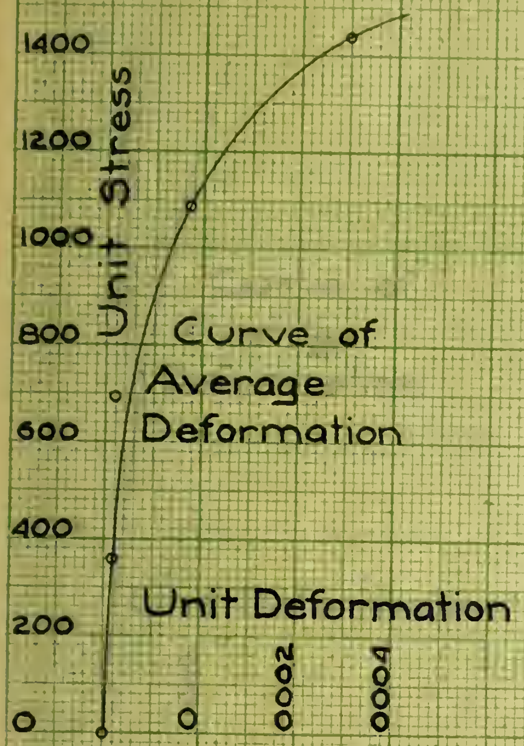

1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
5
6
Unit Deformation
0
.0002
.0004
.0006

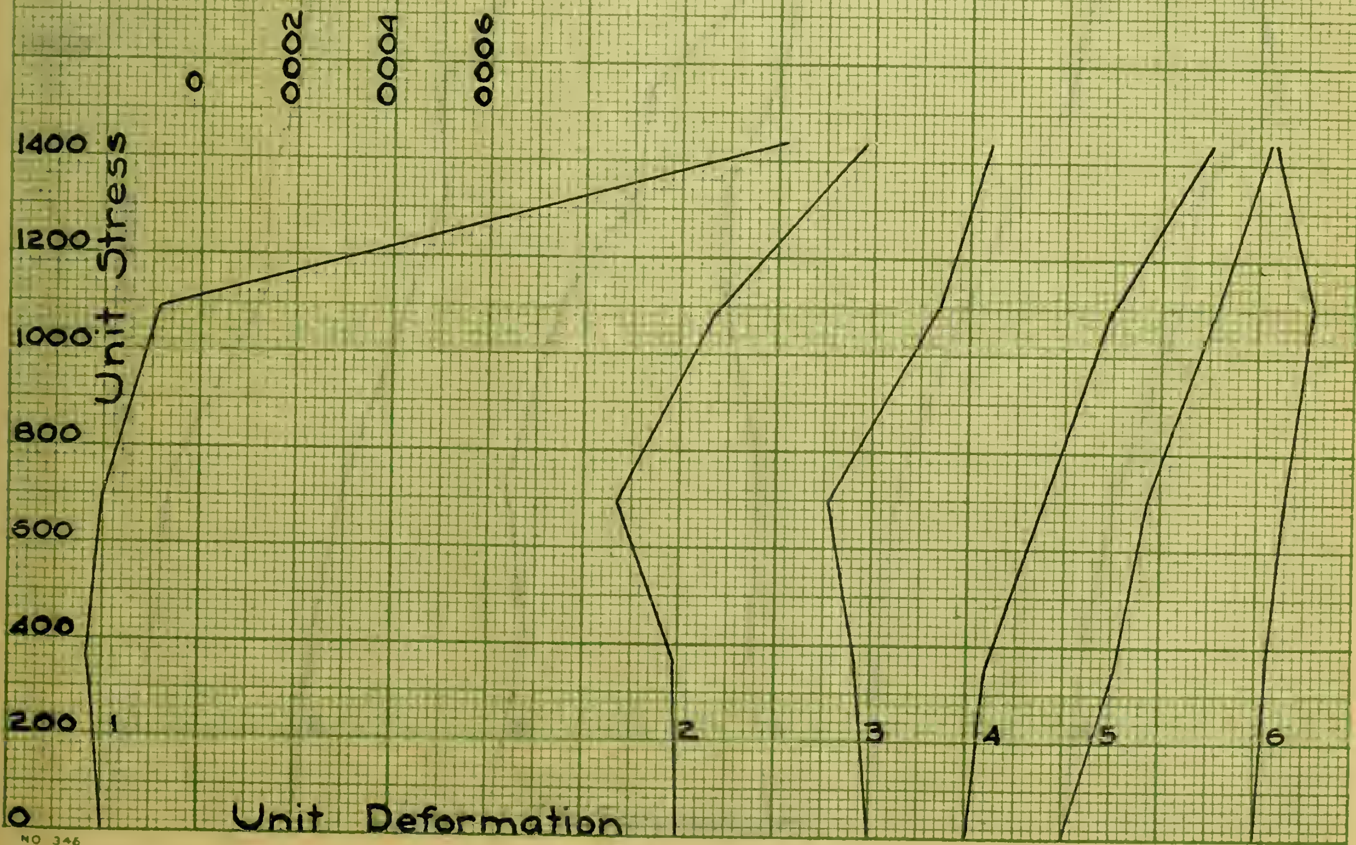

1200
1000
800
600
400
200
0
Unit Stress
7
8
10
11
12
13
14
Unit Deformation

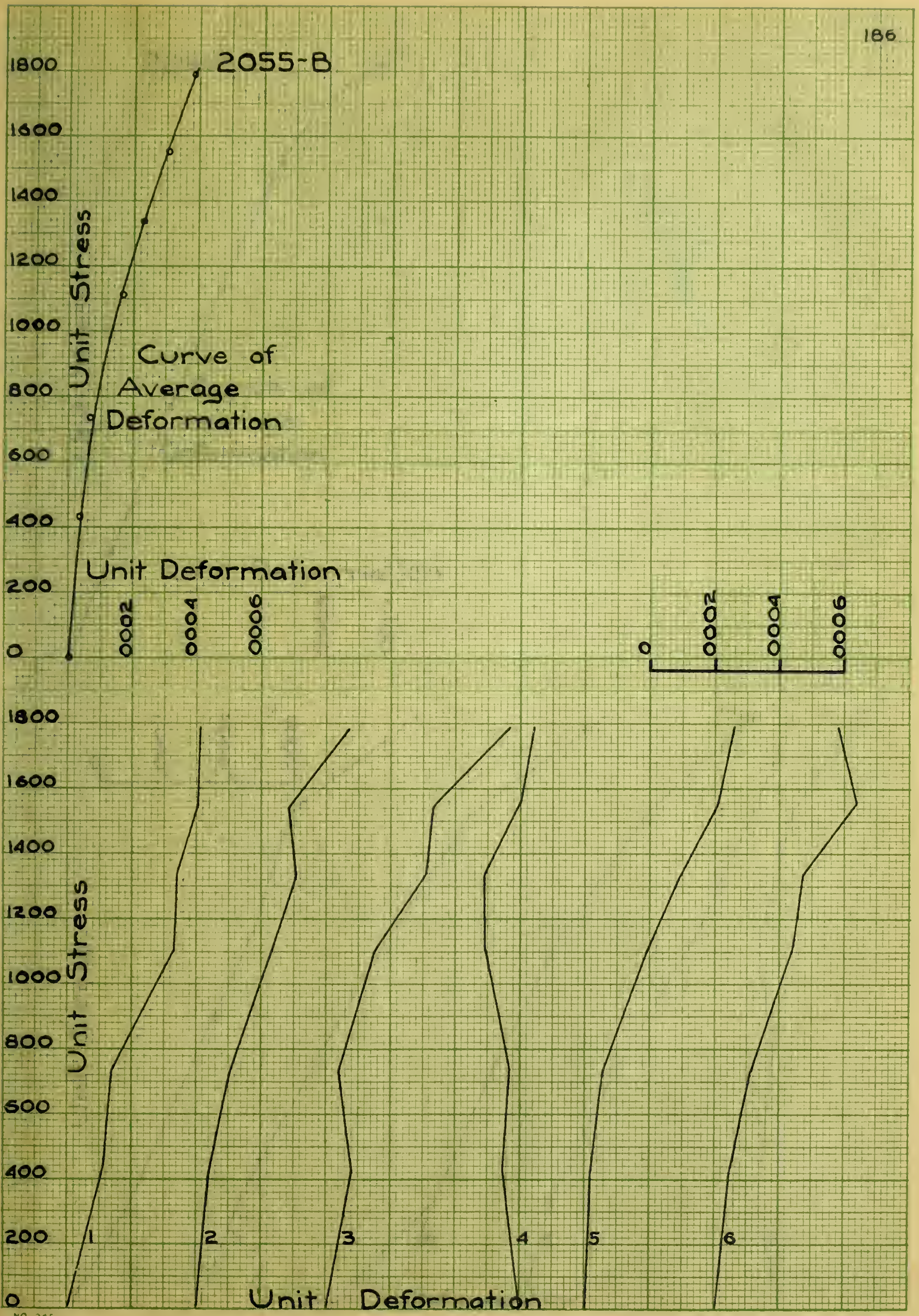
2053

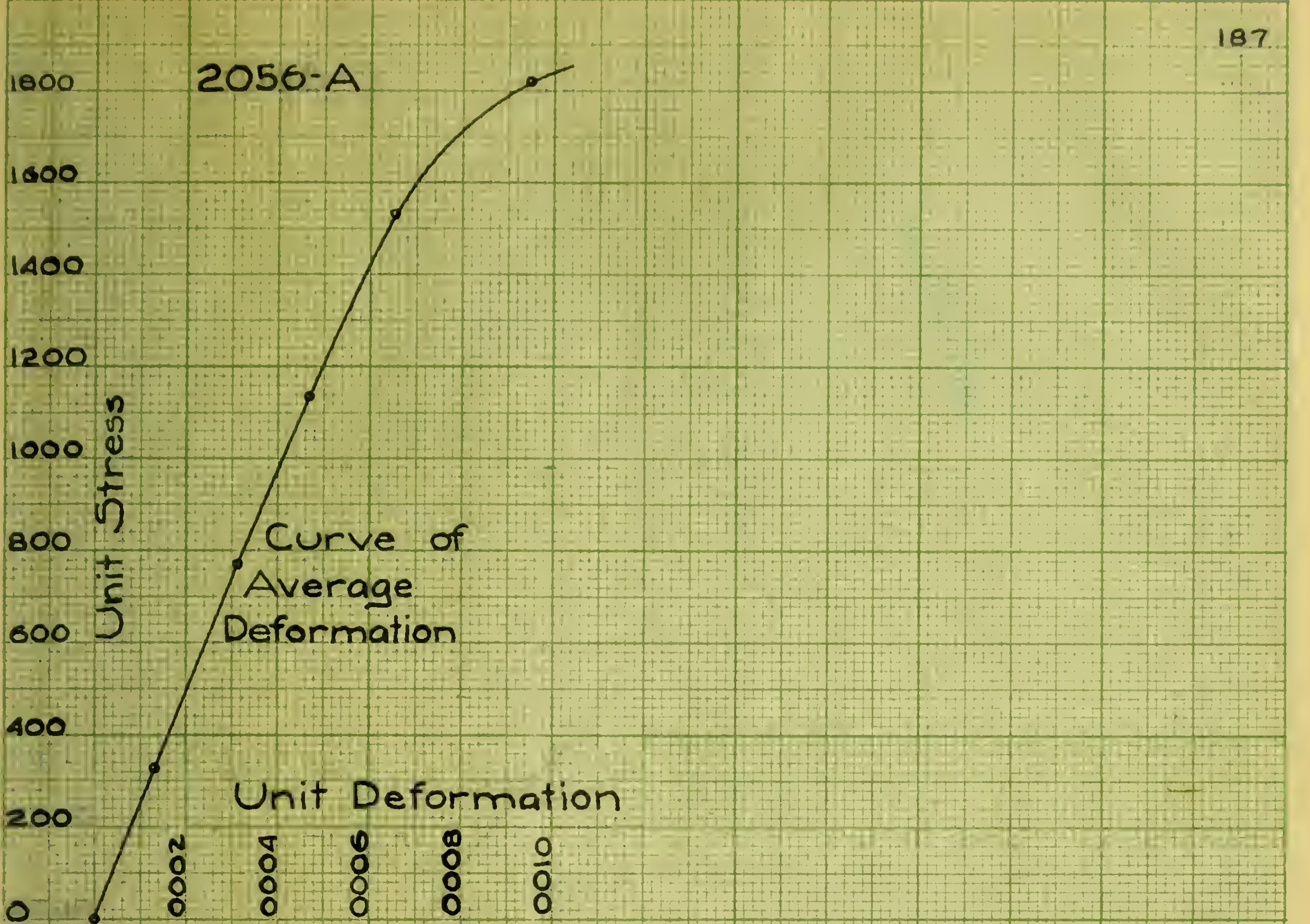

1200
1000
800
600
400
200
0
Unit Stress
15
16
17
18
Unit Deformation
0
.0002
.0004
.0006
1200
1000
800
600
400
200
0
Unit Stress
20
21
22
23
24
Arm
Cross
Unit Deformation

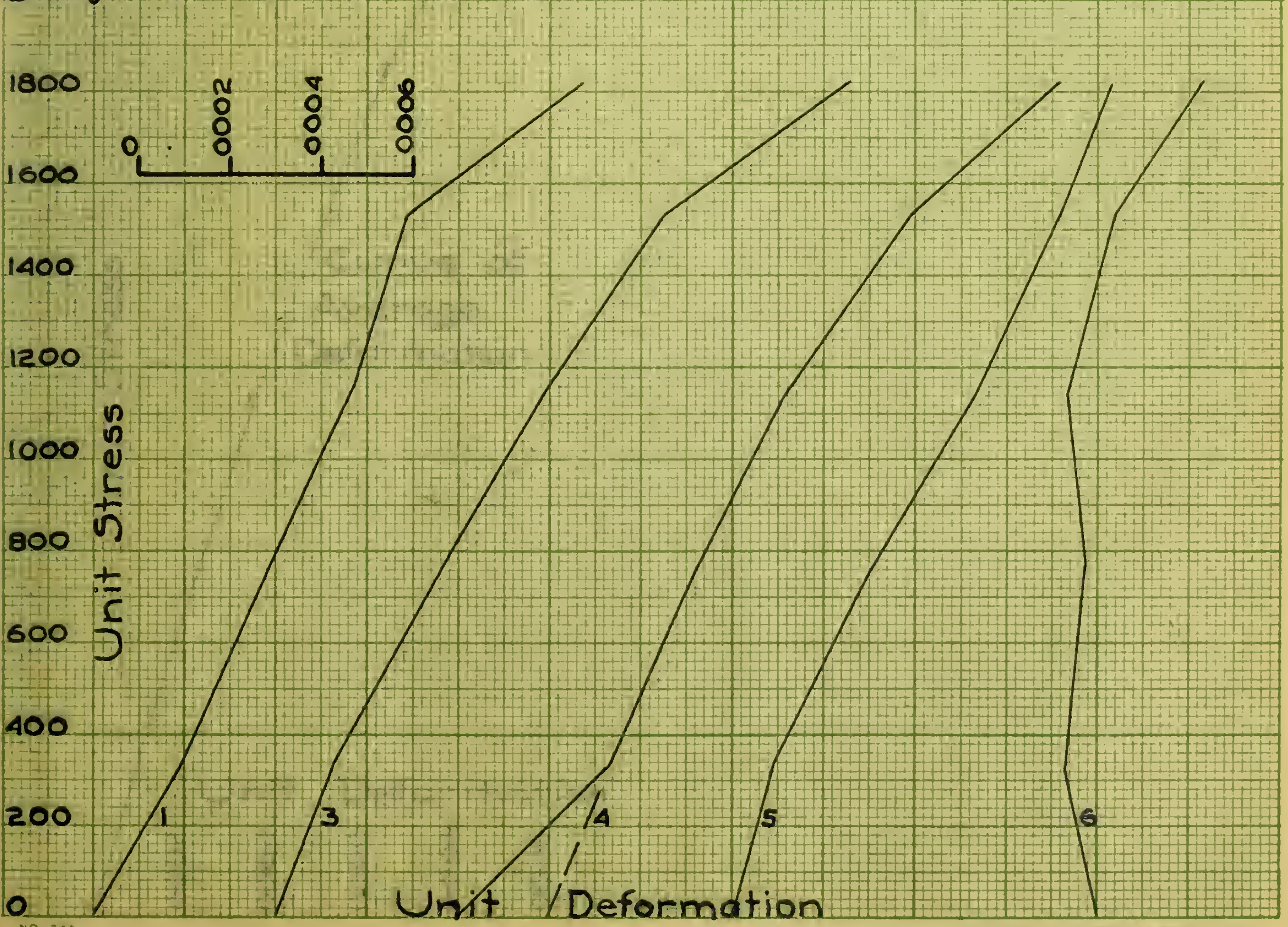
2055-A


1400
1200
1000
800
600
400
200
0
Unit Stress
Curve of Average Deformation
Unit Deformation
0
0002
0004

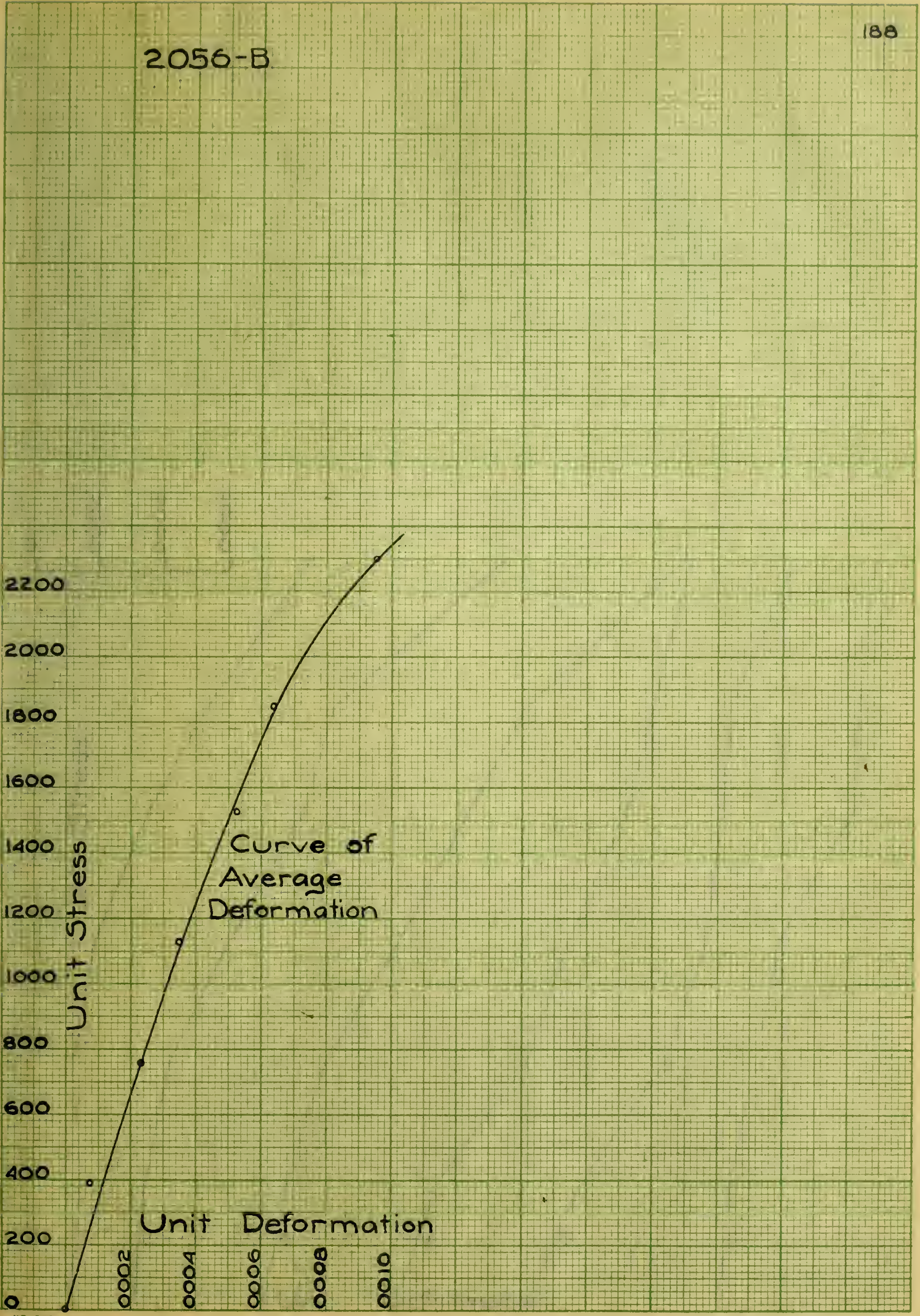

0
0002
0004
0006
1400
1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
5
6
Unit Deformation

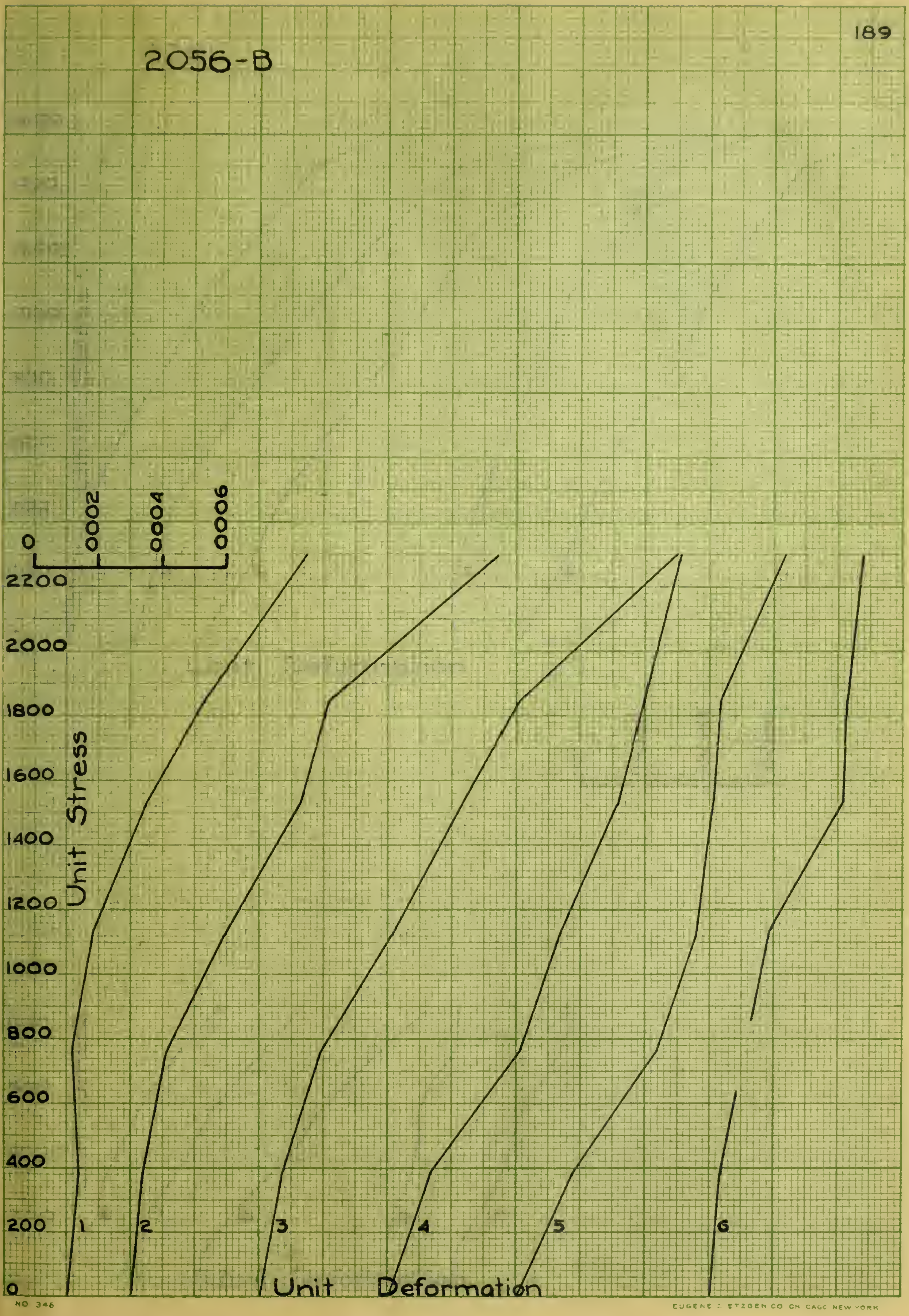

2055-B
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
Curve of Average Deformation
Unit Deformation
0002
0004
0006
0
0002
0004
0006
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
5
6
Unit Deformation

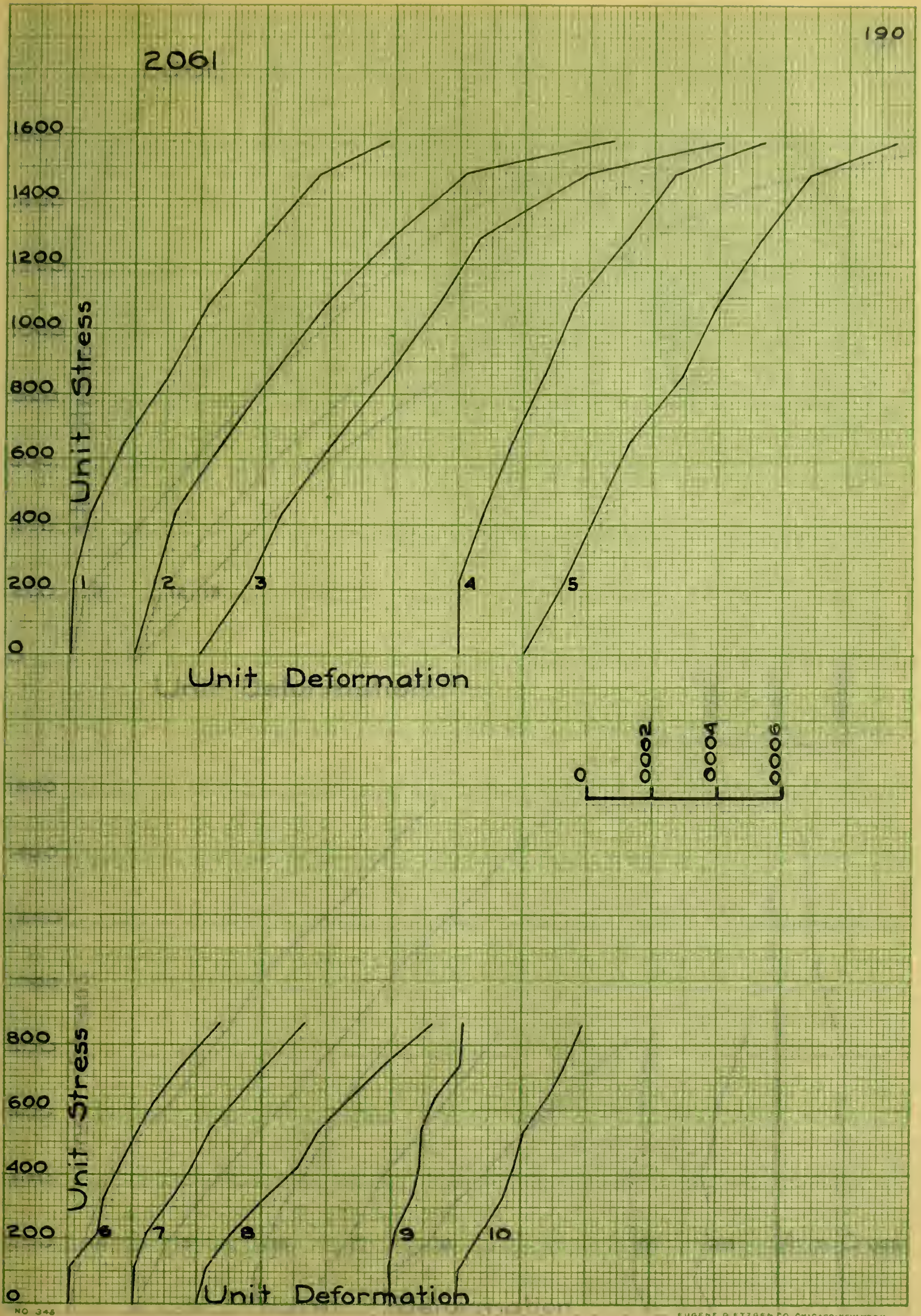

2056-A
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
Curve of Average Deformation
Unit Deformation
0002
0004
0006
0008
0010


1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
0
0002
0004
0006
1
3
4
5
6
Unit Deformation

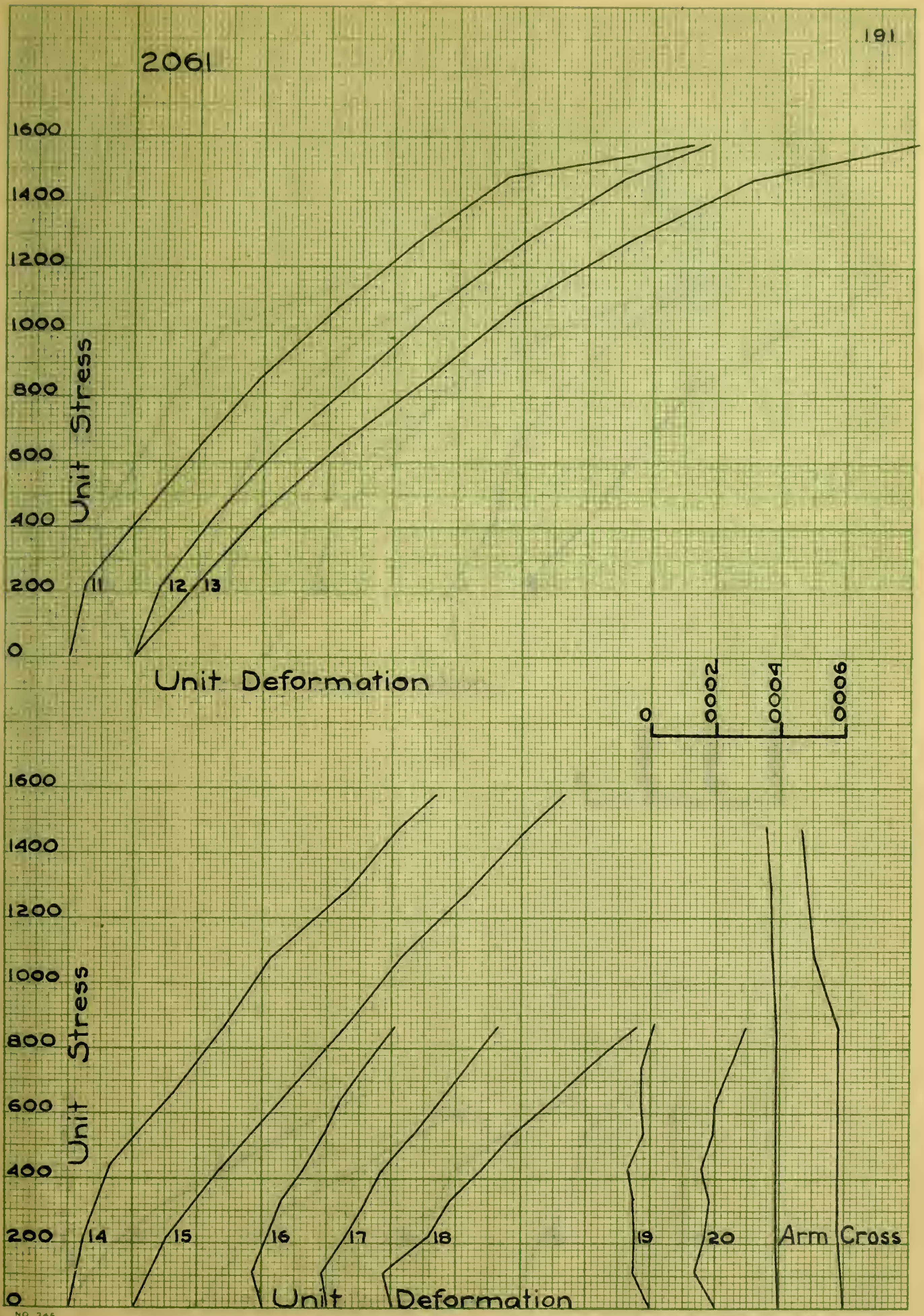
2056-B


Curve of
Average
Deformation
Unit Stress
Unit Deformation
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
0002
0004
0006
0008
0010

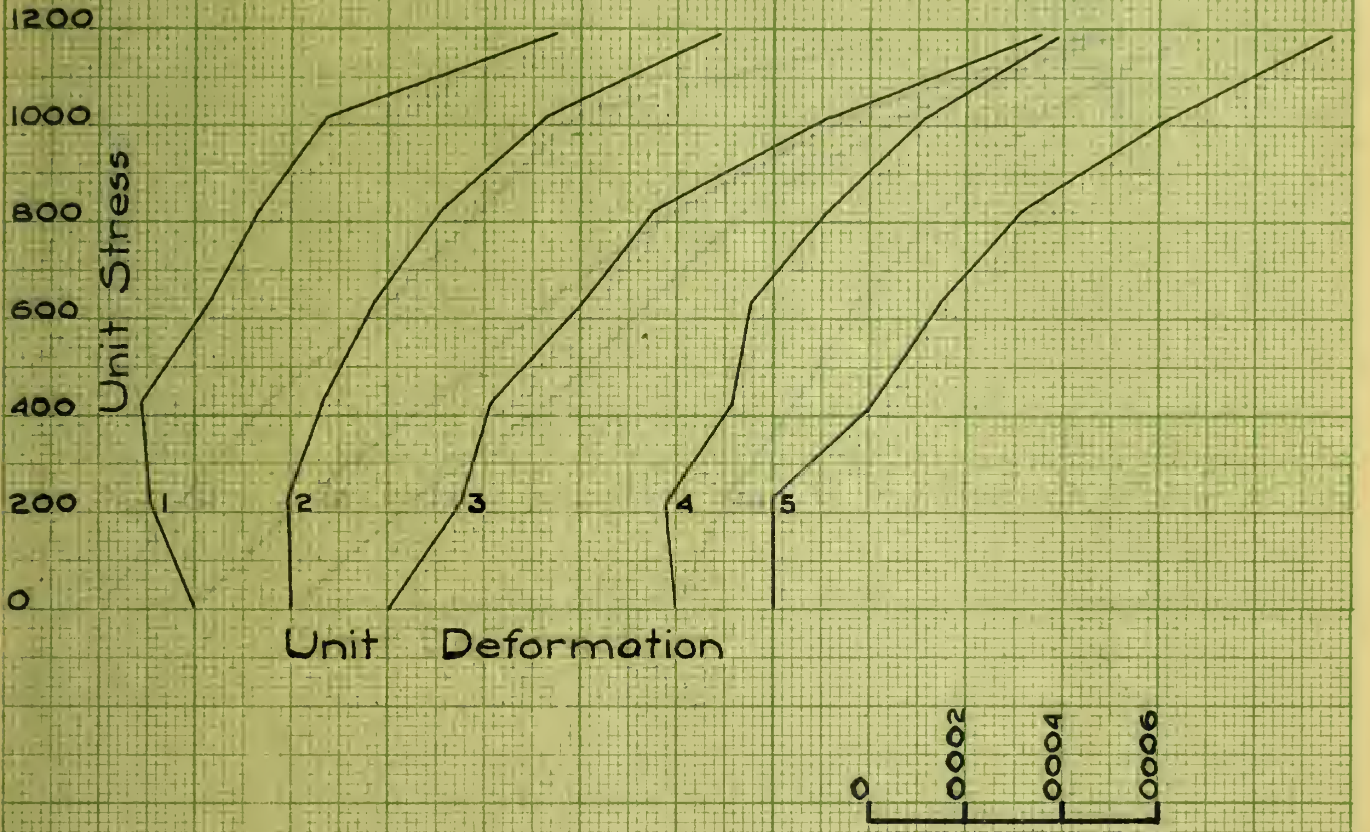

2056-B
0
.0002
.0004
.0006
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
5
6
Unit Deformation
NO 346
EUGENE DIETZGEN CO CHICAGO NEW YORK

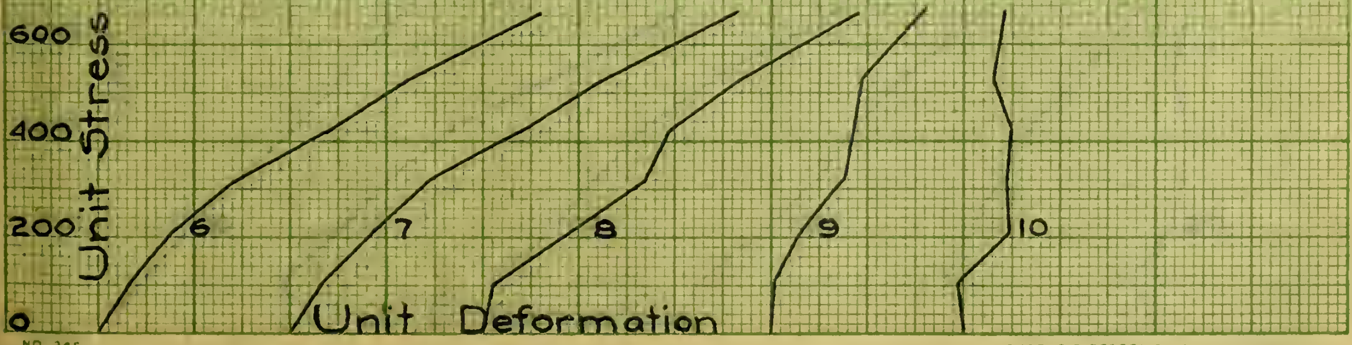

2061
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
5
Unit Deformation
0
.0002
.0004
.0006
800
600
400
200
0
Unit Stress
6
7
8
9
10
Unit Deformation

2061

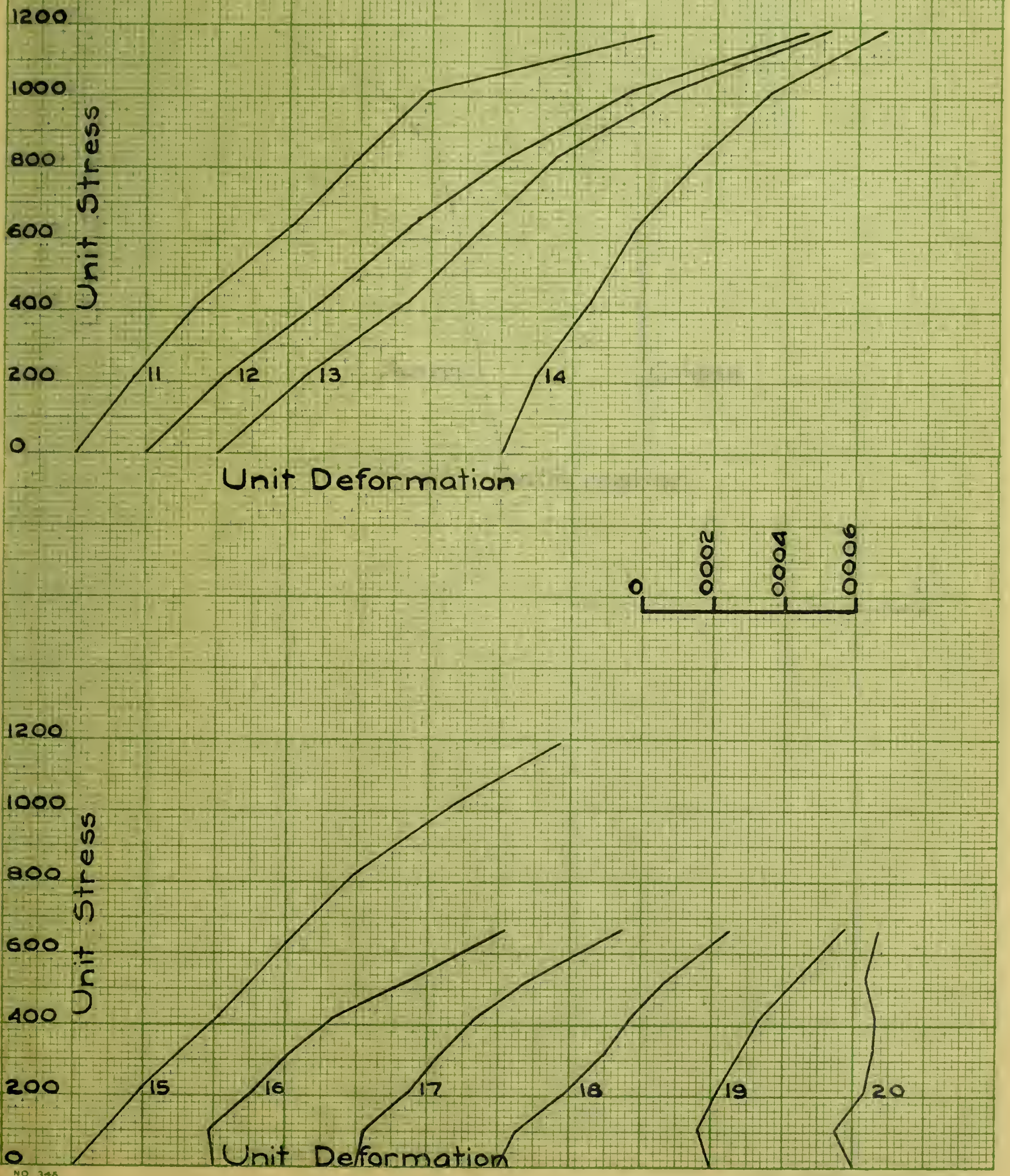

1600
1400
1200
1000
800
600
400
200
0
Unit Stress
11
12
13
Unit Deformation
0
.0002
.0004
.0006
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
14
15
16
17
18
19
20
Arm
Cross
Unit Deformation

2062

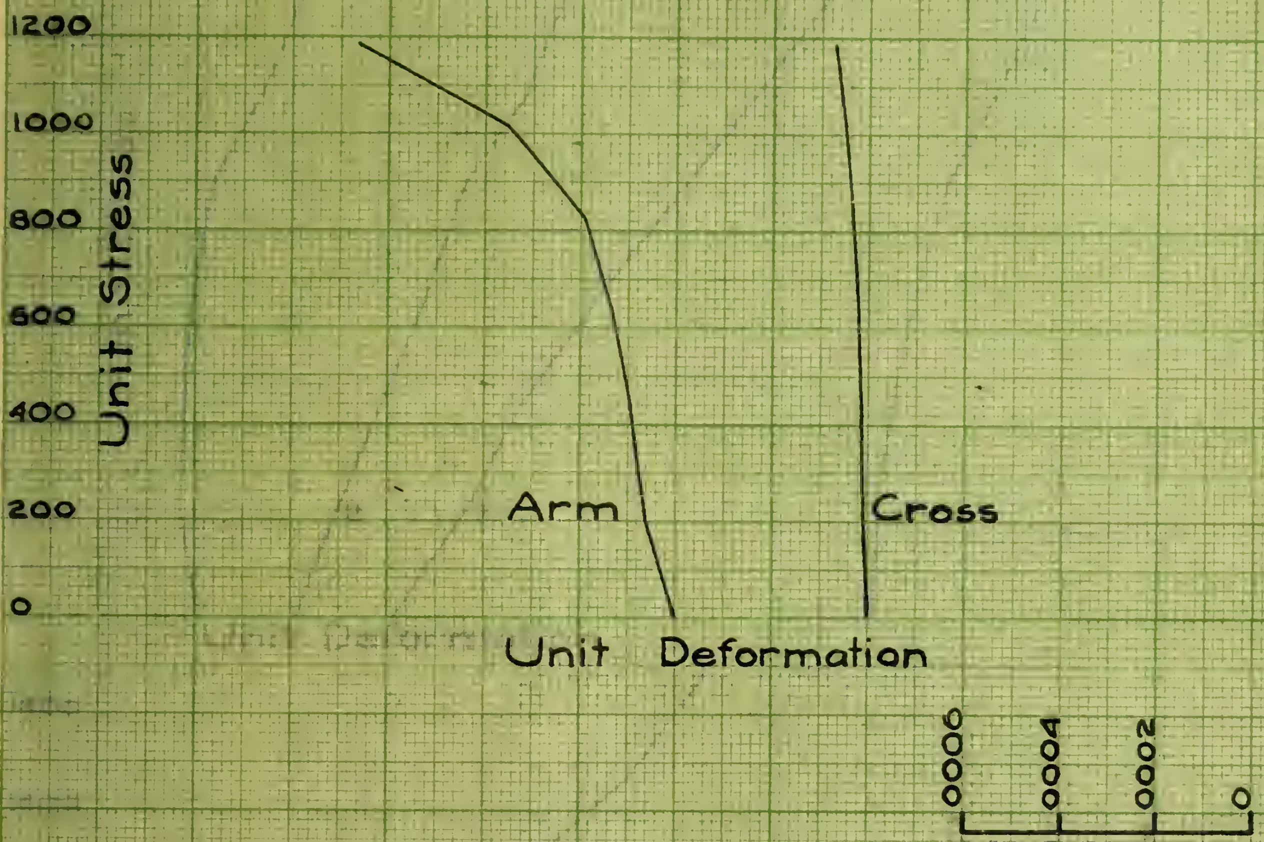

1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
5
Unit Deformation
0
.0002
.0004
.0006

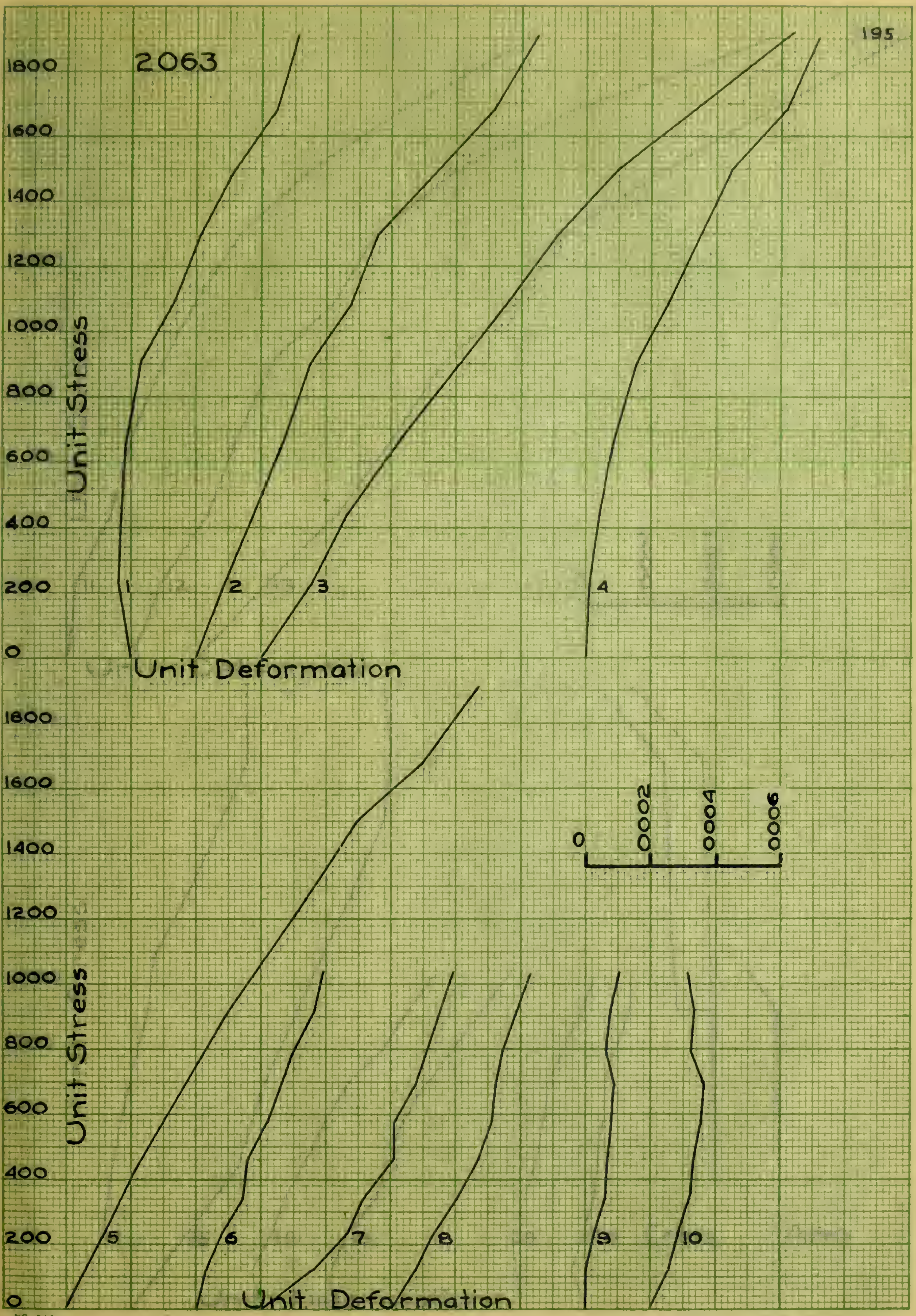

600
400
200
0
Unit Stress
6
7
8
9
10
Unit Deformation

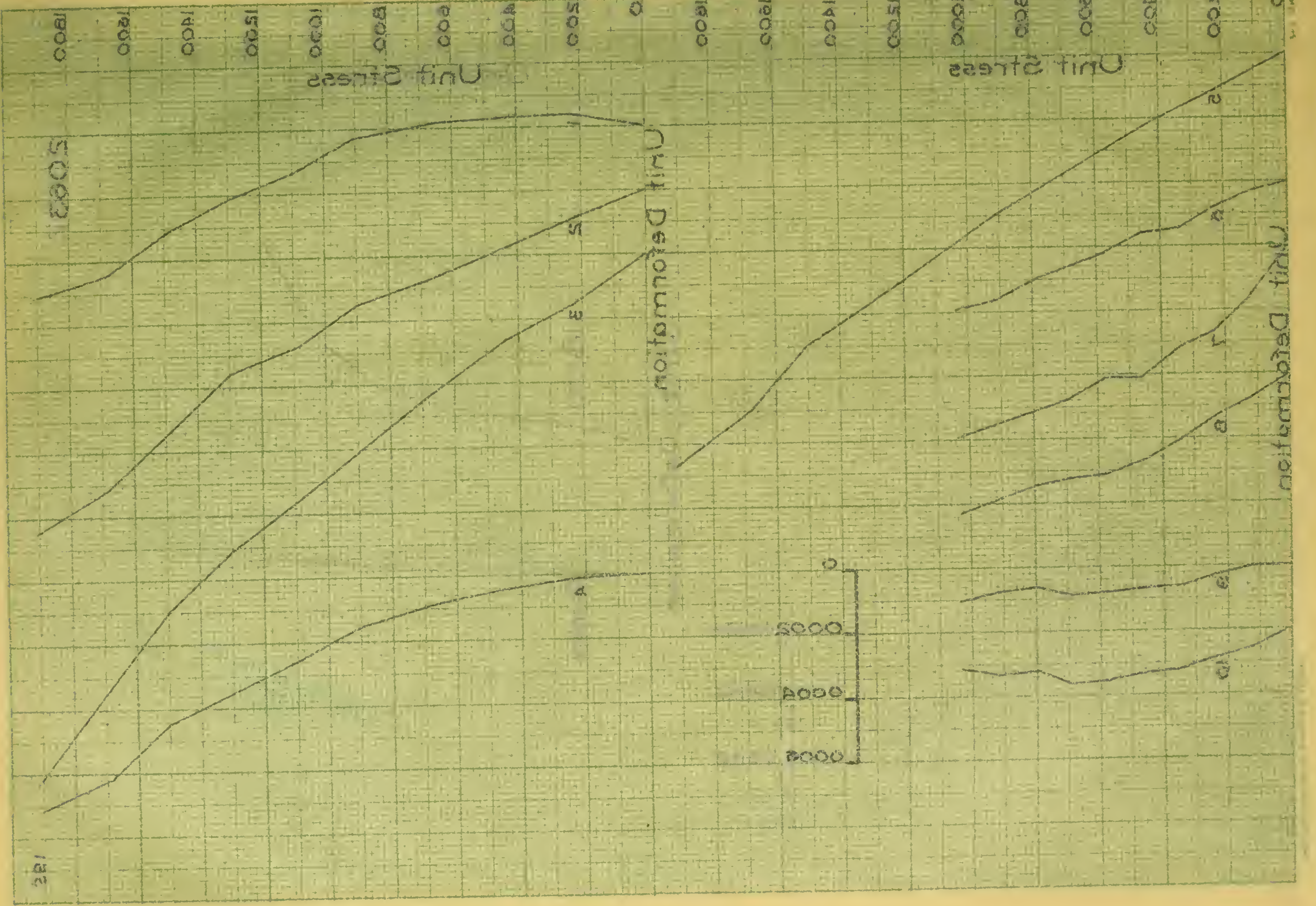
2062

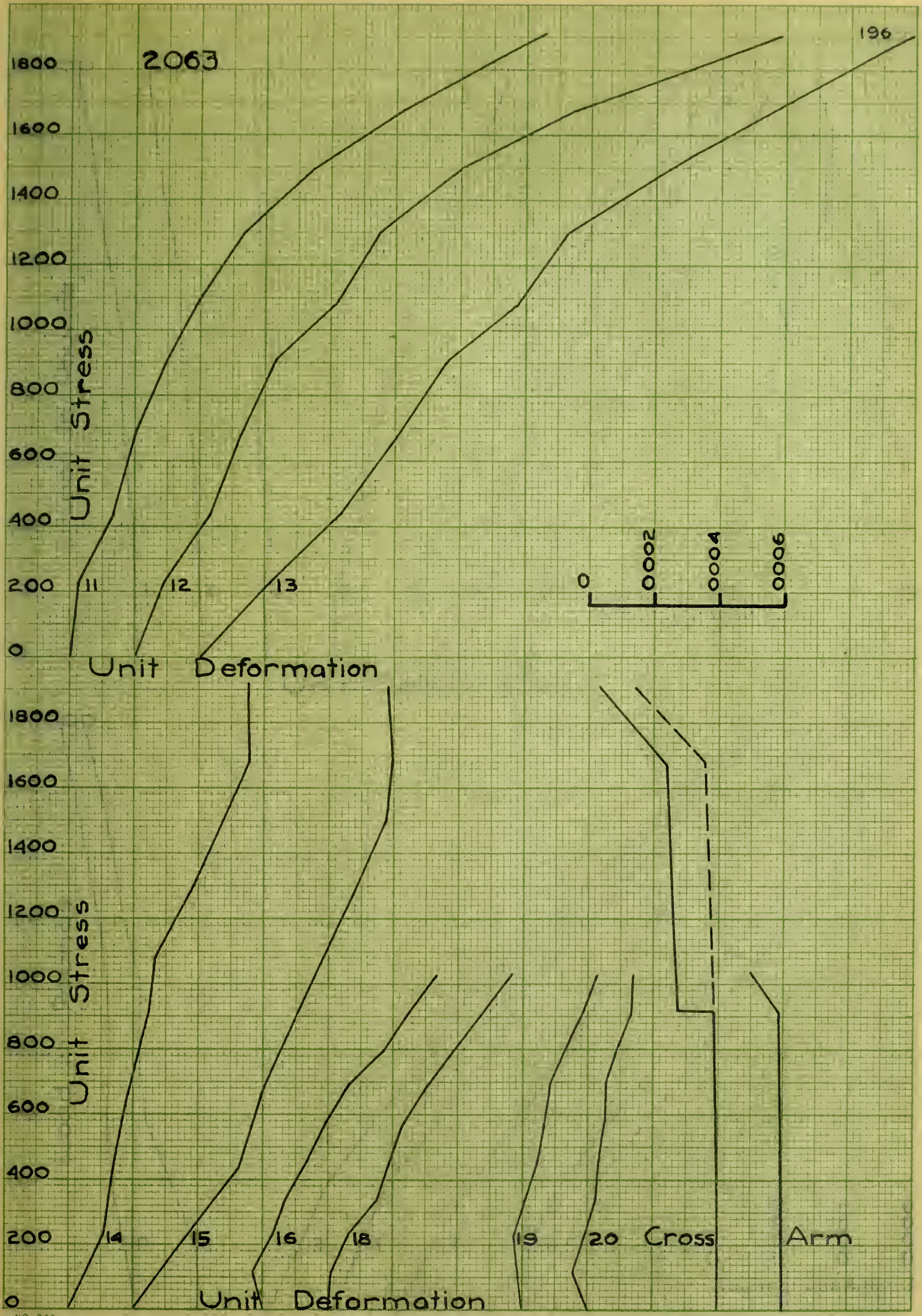

1200
1000
800
600
400
200
0
Unit Stress
11
12
13
14
Unit Deformation
0
.0002
.0004
.0006
1200
1000
800
600
400
200
0
Unit Stress
15
16
17
18
19
20
Unit Deformation

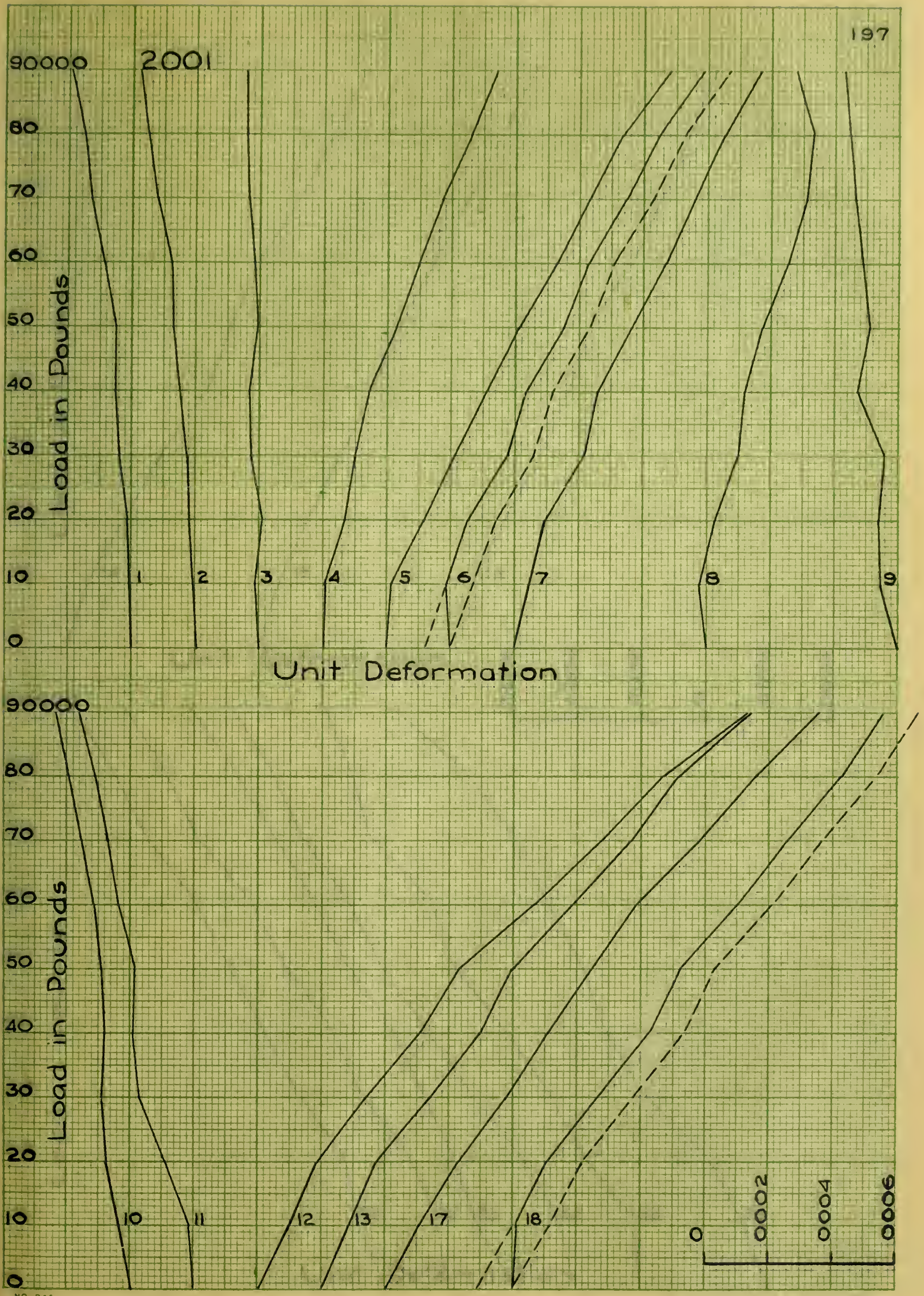
2062


1200
1000
800
600
400
200
0
Unit Stress
Arm
Cross
Unit Deformation
0006
0004
0002
0

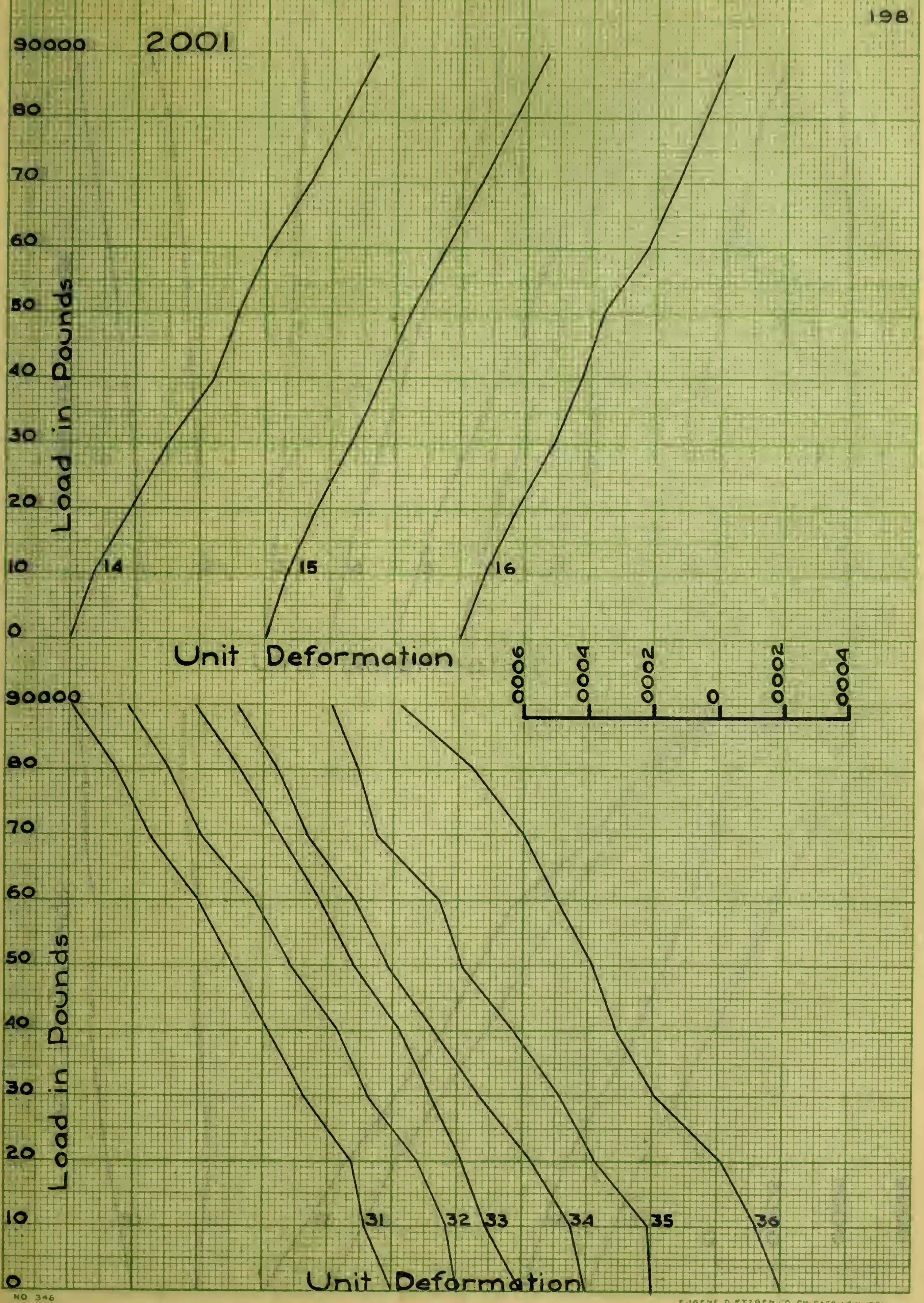

2063
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
1
2
3
4
Unit Deformation
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
0
.0002
.0004
.0006
5
6
7
8
9
10
Unit Deformation

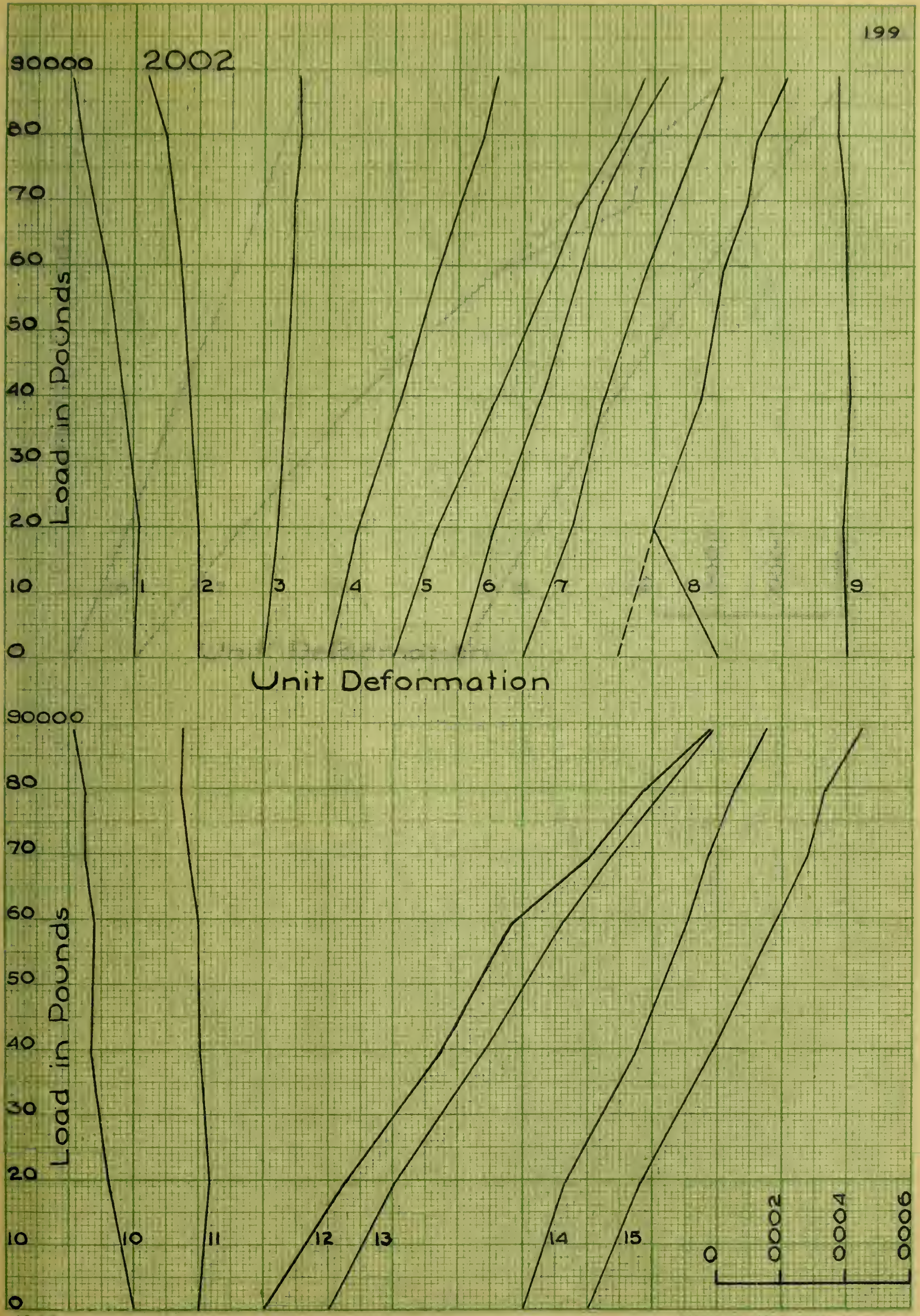


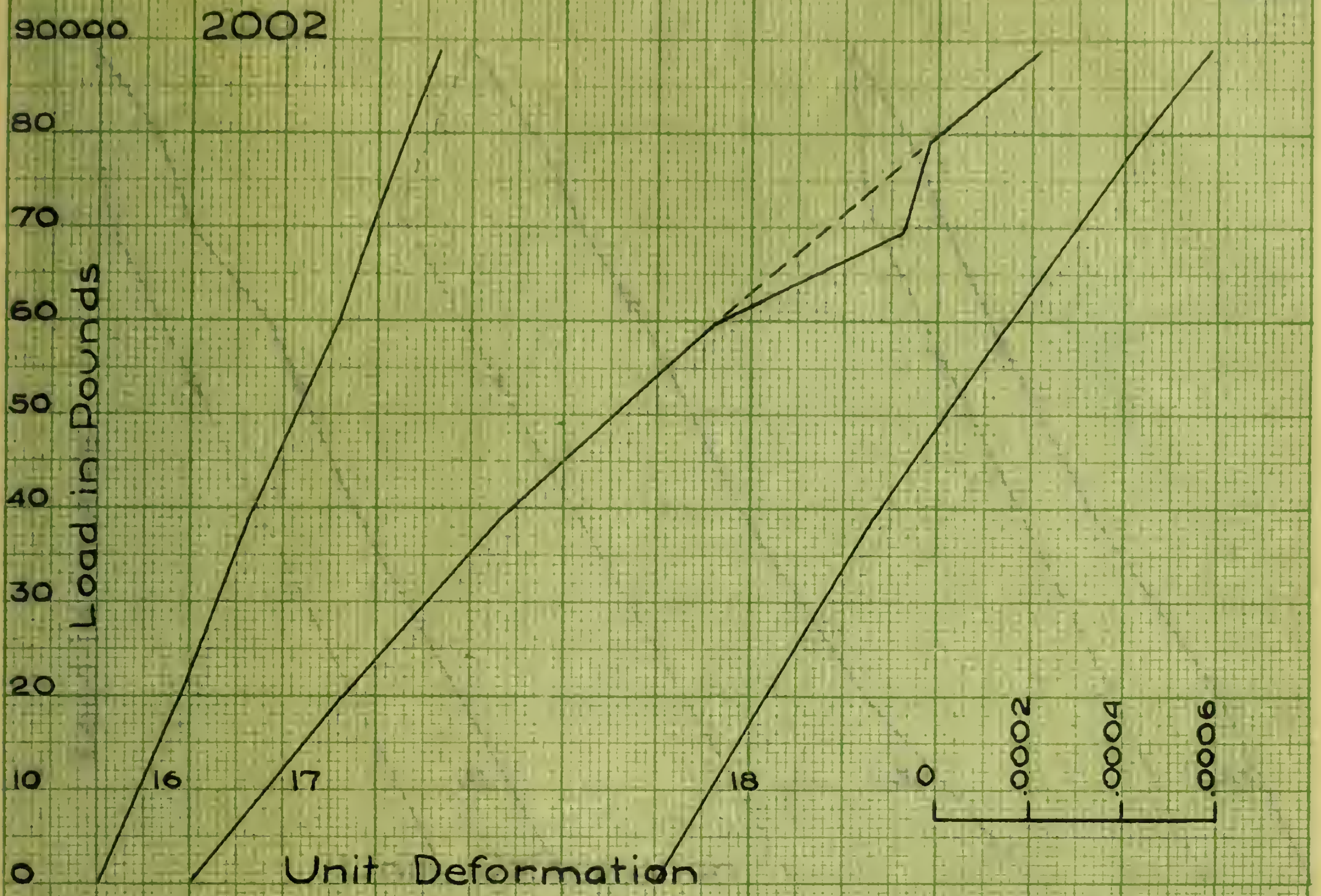

2063
196
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
11
12
13
0
.0002
.0004
.0006
Unit Deformation
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Stress
14
15
16
18
19
20
Cross Arm
Unit Deformation

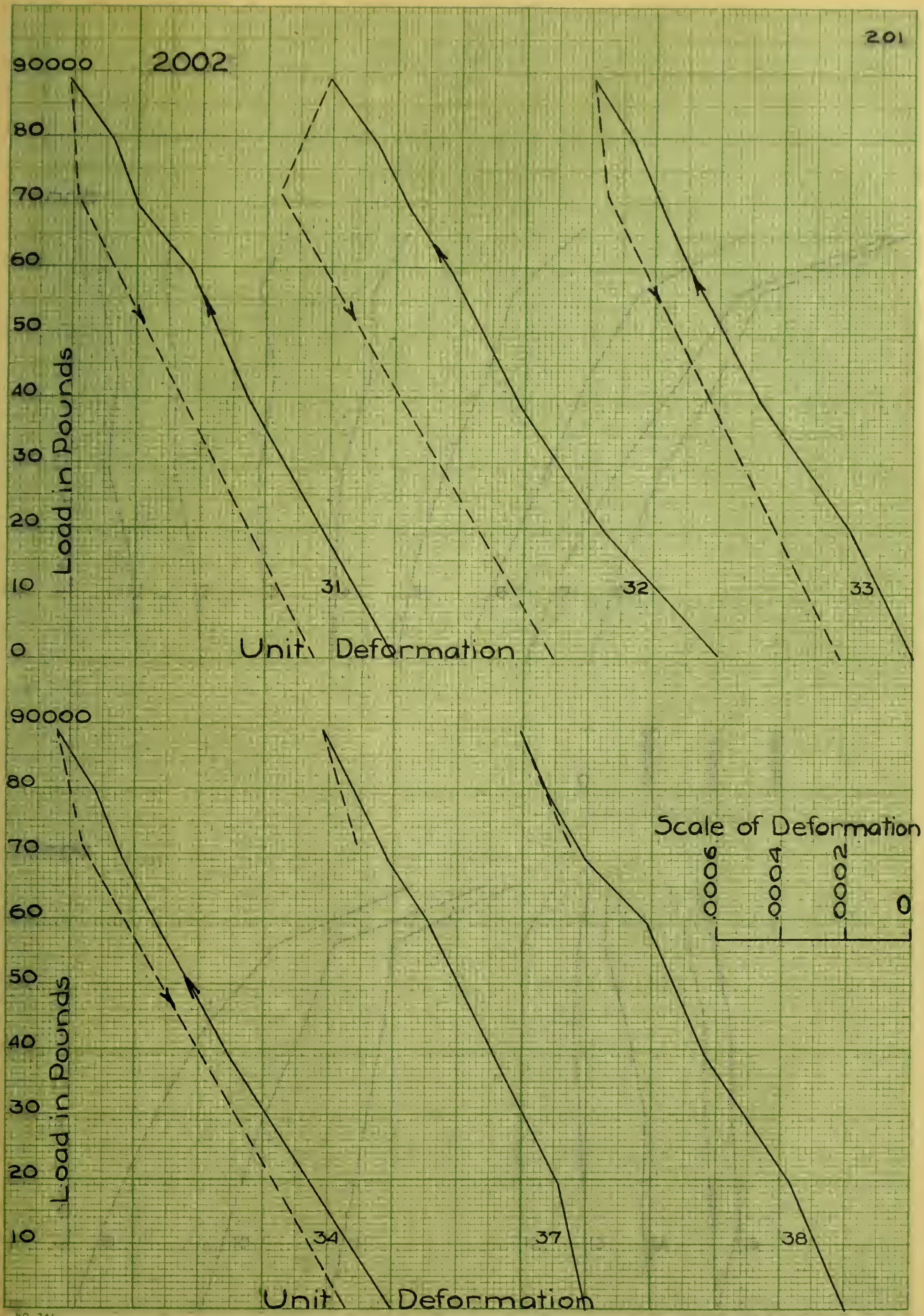

2001
90000
80
70
60
50
40
30
20
10
0
Load in Pounds
1
2
3
4
5
6
7
8
9
Unit Deformation
90000
80
70
60
50
40
30
20
10
0
Load in Pounds
10
11
12
13
17
18
0
0002
0004
0006

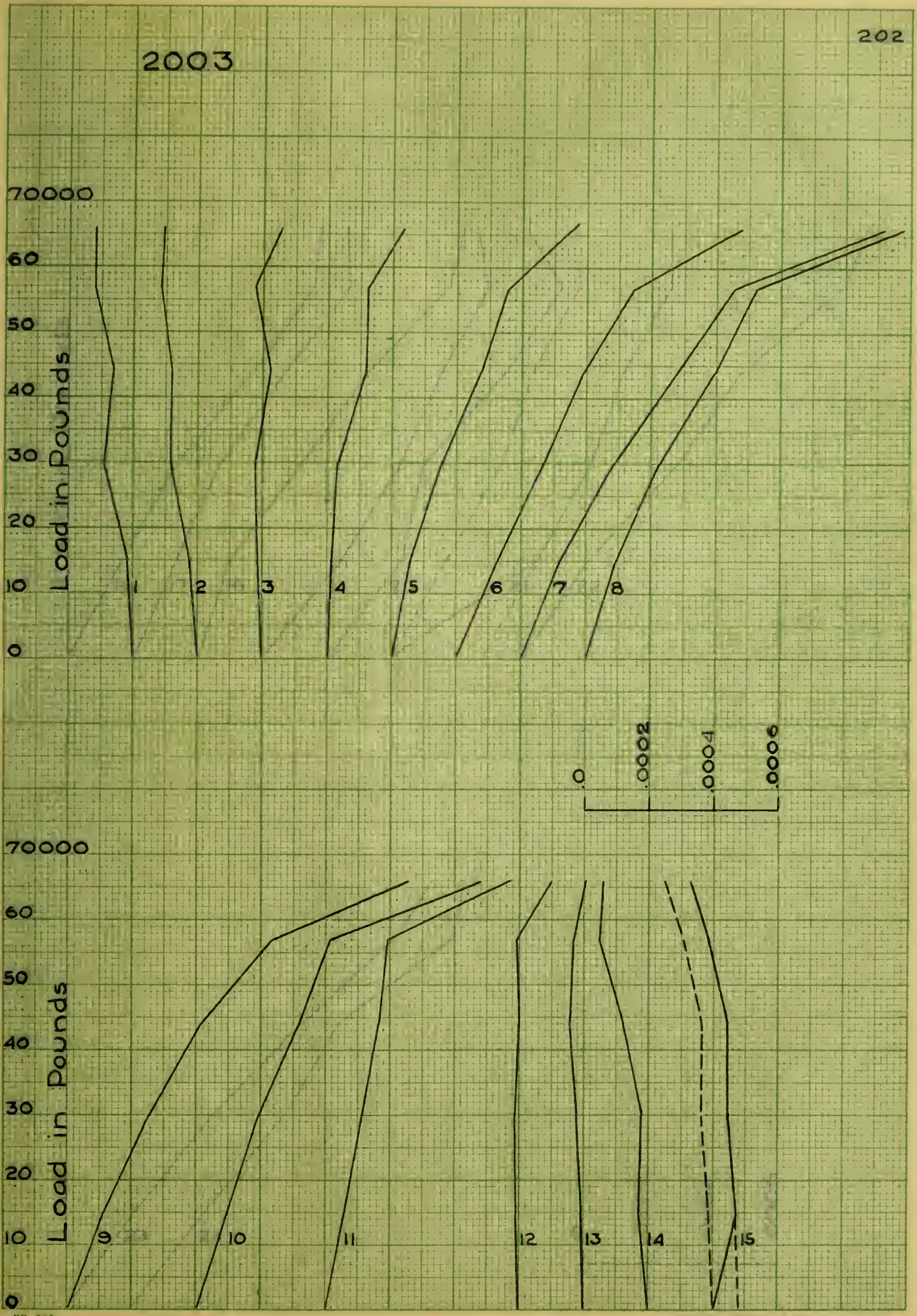
2001


90000
80
70
60
50
40
30
20
10
0
Load in Pounds
14
15
16
Unit Deformation
.0006
.0004
.0002
0
.0002
.0004
90000
80
70
60
50
40
30
20
10
0
Load in Pounds
31
32
33
34
35
36
Unit Deformation

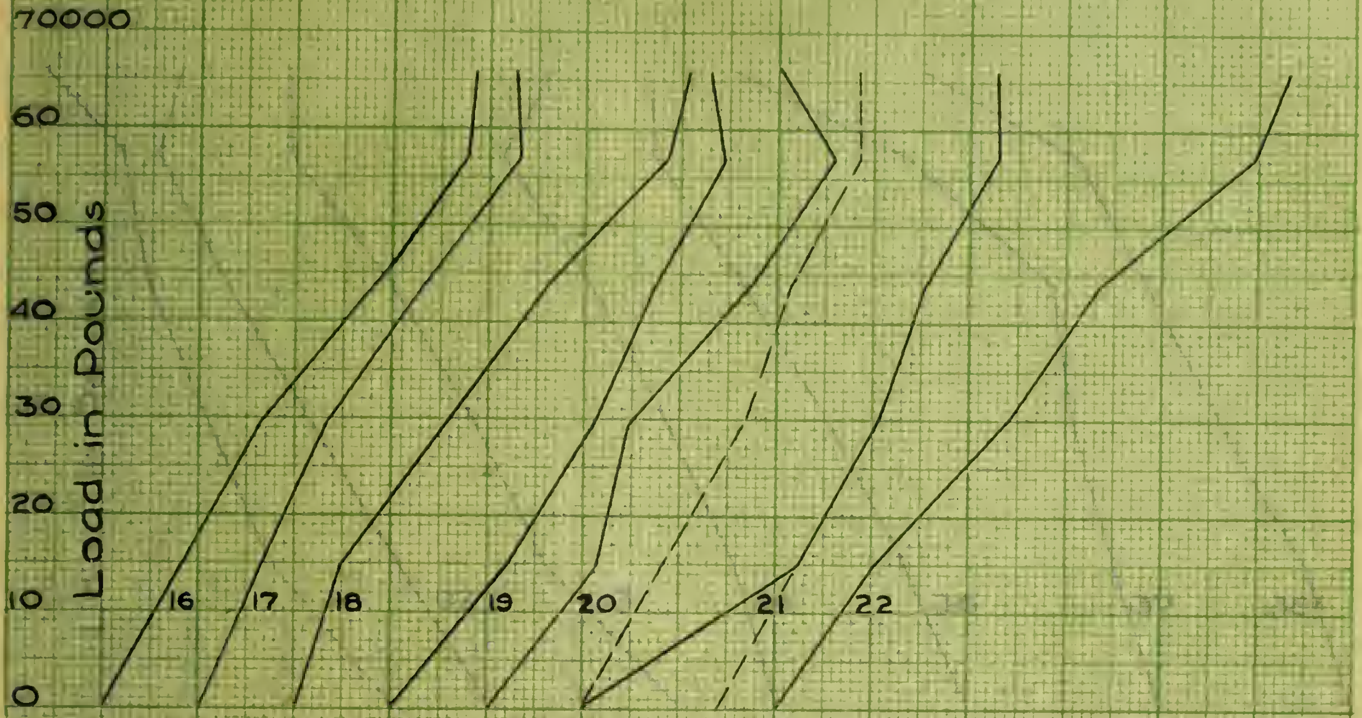

2002
90000
80
70
60
50
40
30
20
10
0
Load in Pounds
1
2
3
4
5
6
7
8
9
Unit Deformation
90000
80
70
60
50
40
30
20
10
0
Load in Pounds
10
11
12
13
14
15
0
.0002
.0004
.0006

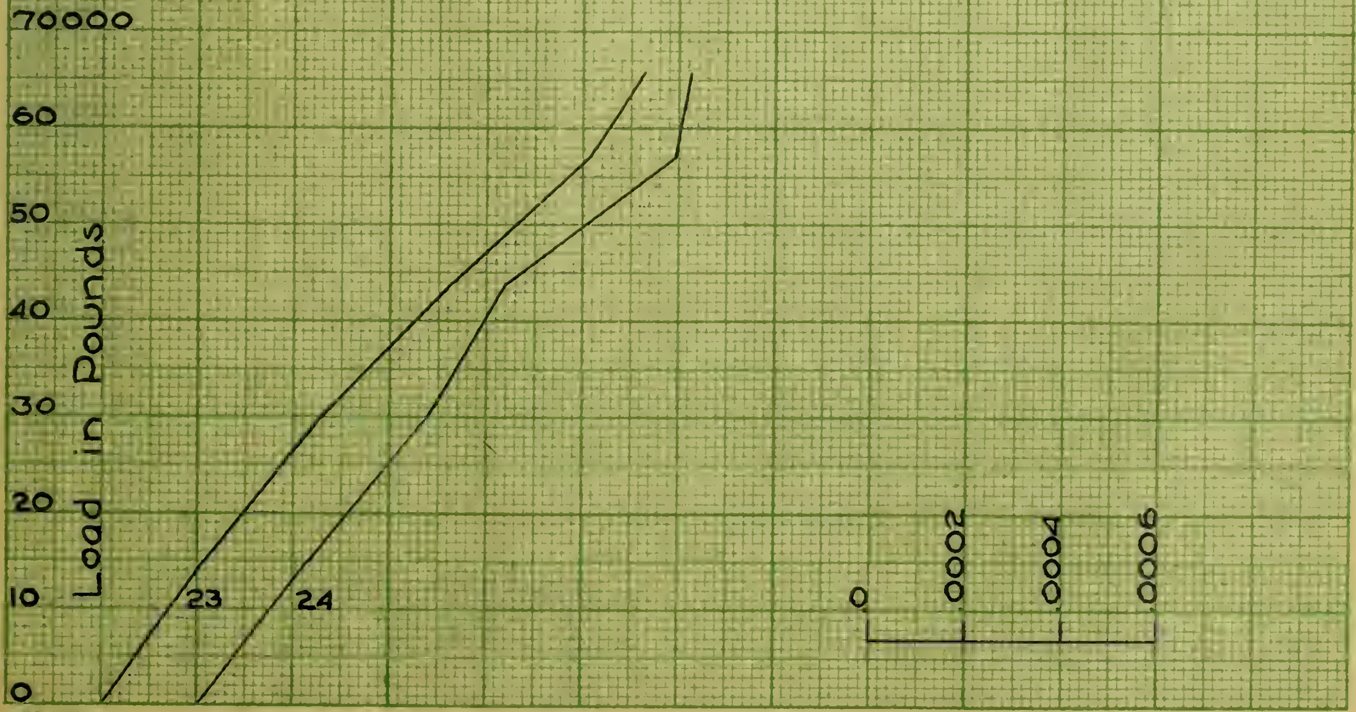

90000
2002
80
70
60
50
40
30
20
10
0
Load in Pounds
16
17
18
Unit Deformation
0
.0002
.0004
.0006

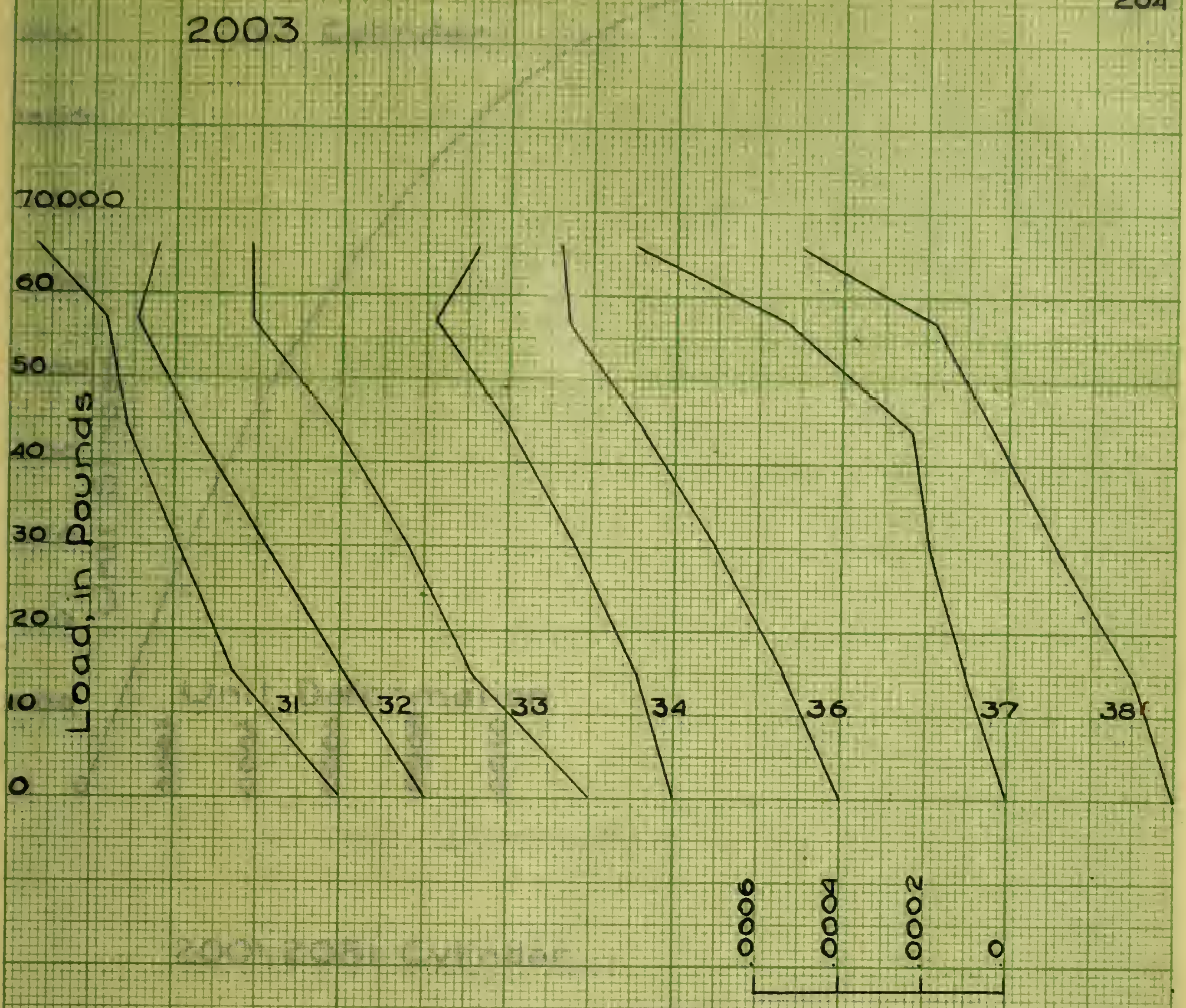

2002
90000
80
70
60
50
40
30
20
10
0
Load in Pounds
Unit Deformation
31
32
33
90000
80
70
60
50
40
30
20
10
Load in Pounds
Unit Deformation
34
37
38
Scale of Deformation
.0006
.0004
.0002
0

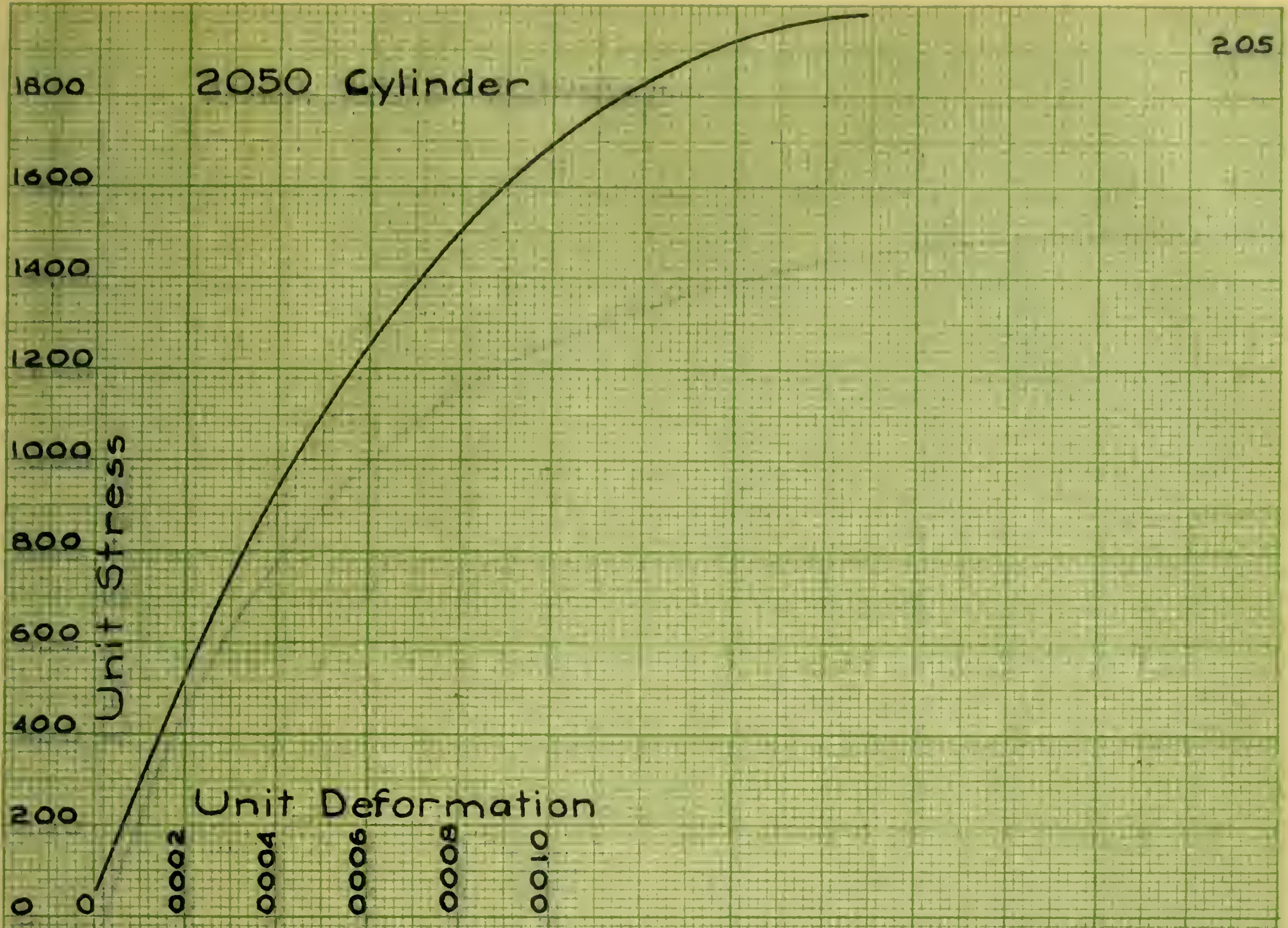

2003
70000
60
50
40
30
20
10
0
Load in Pounds
1
2
3
4
5
6
7
8
0
.0002
.0004
.0006
70000
60
50
40
30
20
10
0
Load in Pounds
9
10
11
12
13
14
15

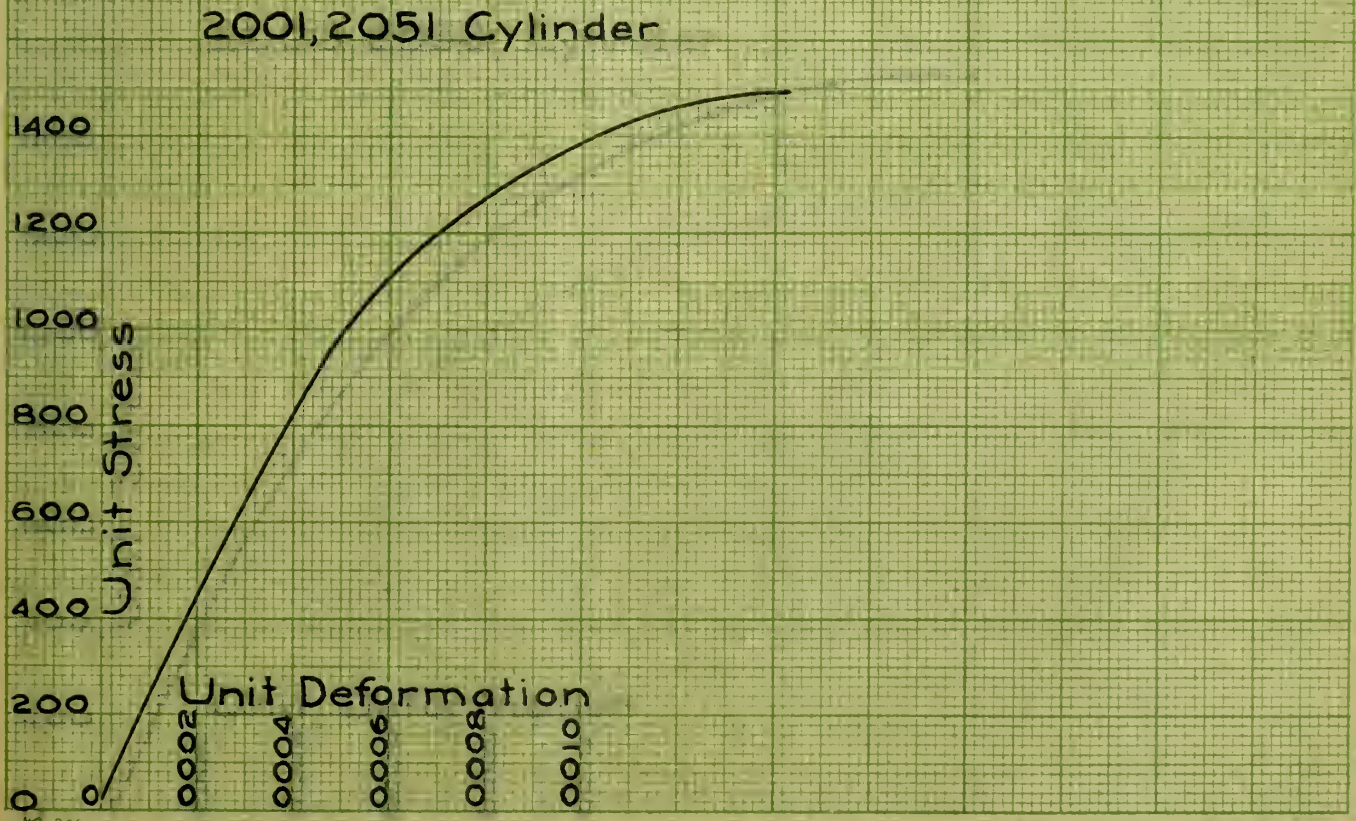
2003


Load in Pounds
70000
60
50
40
30
20
10
0
16
17
18
19
20
21
22

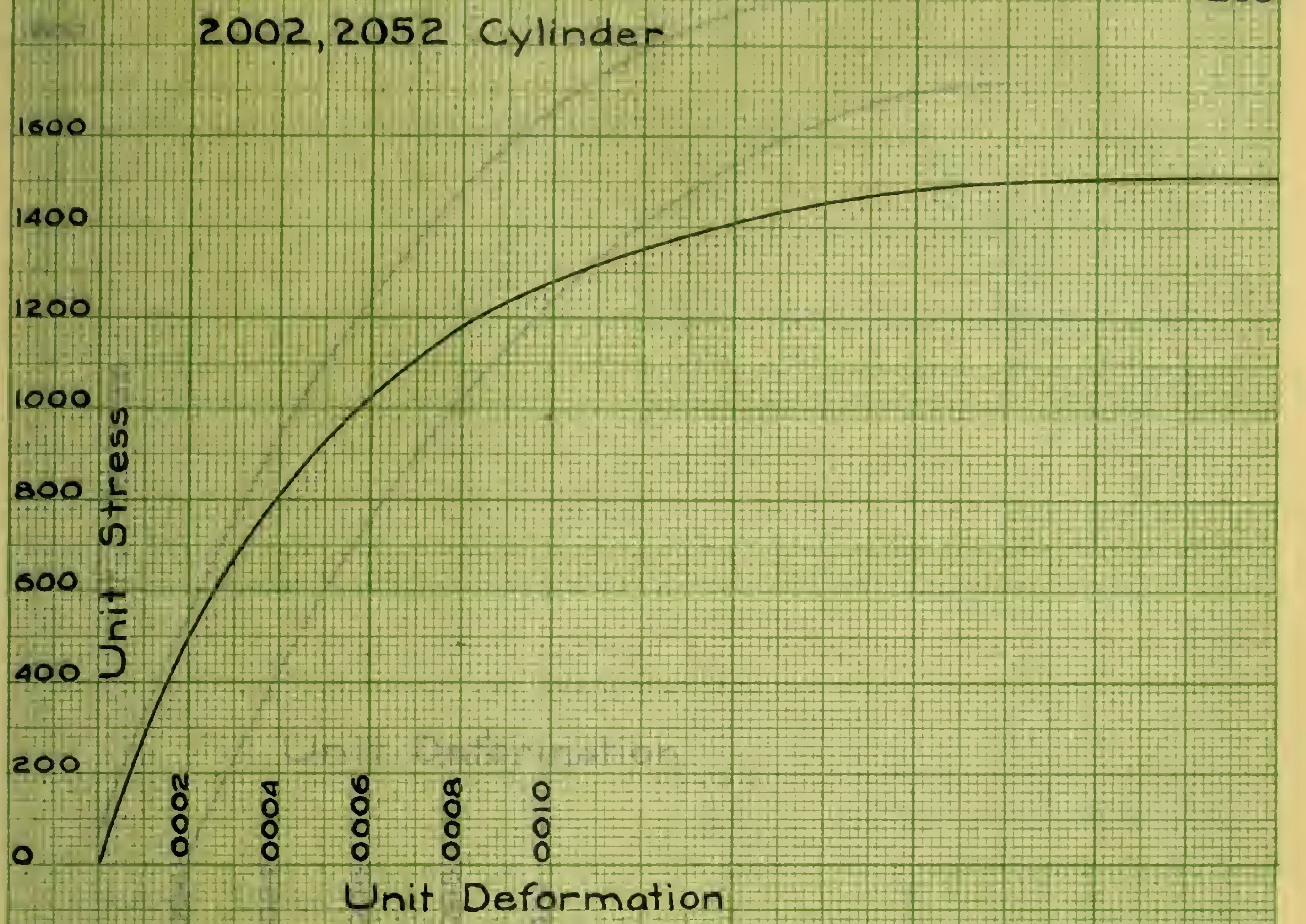

Load in Pounds
70000
60
50
40
30
20
10
0
23
24
0
.0002
.0004
.0006


2003
70000
60
50
40
30
20
10
0
Load, in Pounds
31
32
33
34
36
37
38
.0006
.0004
.0002
0

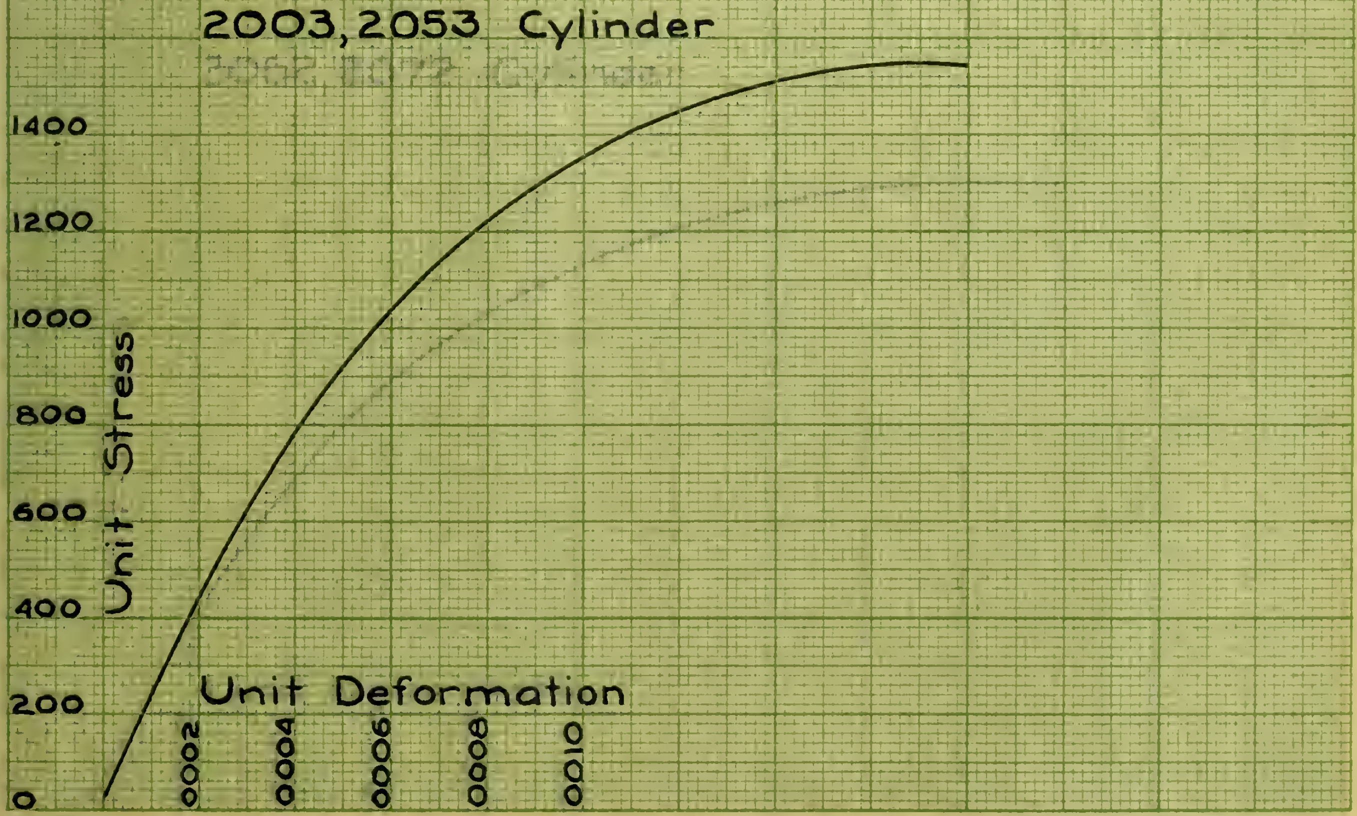

2050 Cylinder
Unit Stress
1800
1600
1400
1200
1000
800
600
400
200
0
Unit Deformation
0
0.002
0.004
0.006
0.008
0.010

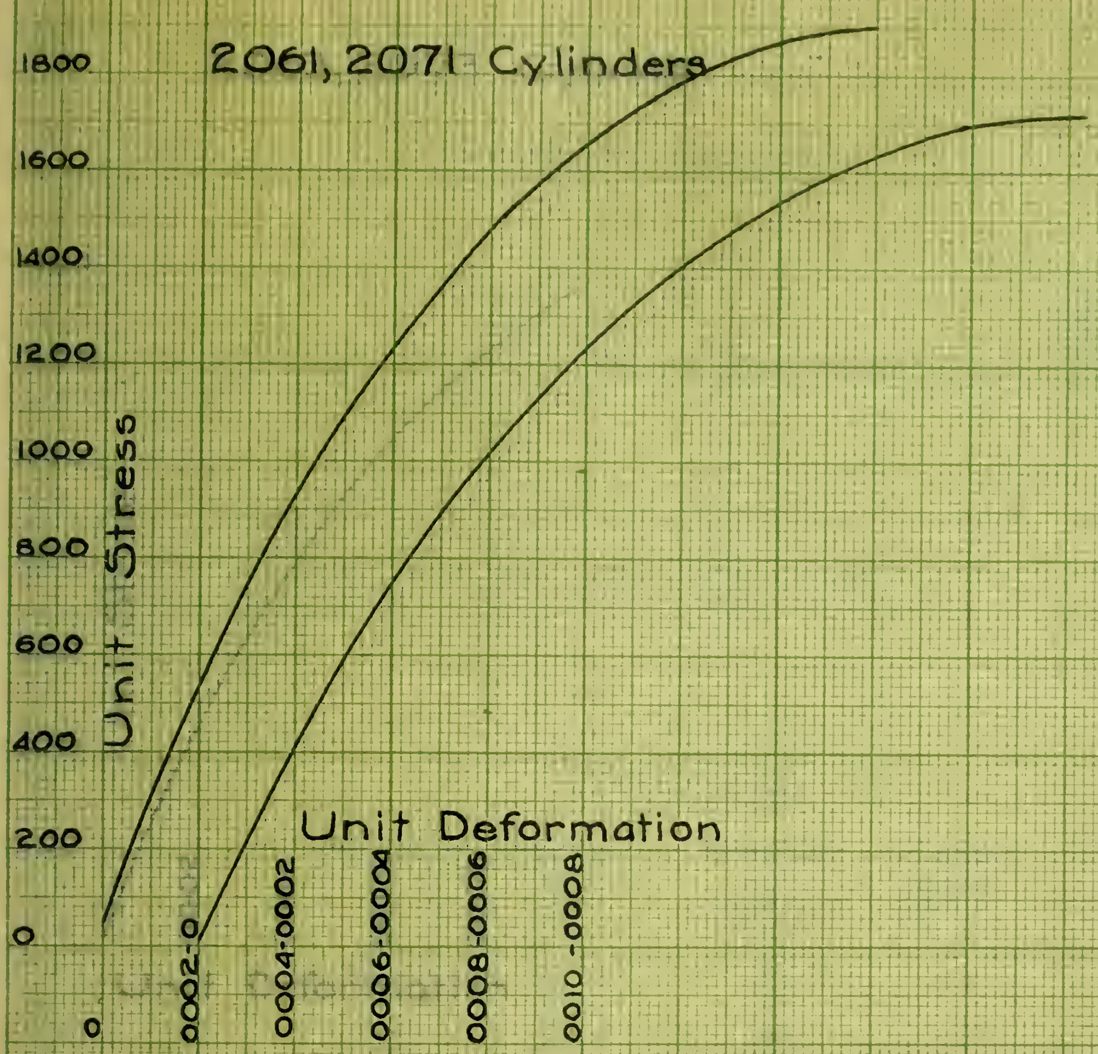

2001, 2051 Cylinder
Unit Stress
1400
1200
1000
800
600
400
200
0
Unit Deformation
0
0.002
0.004
0.006
0.008
0.010

2002, 2052 Cylinder

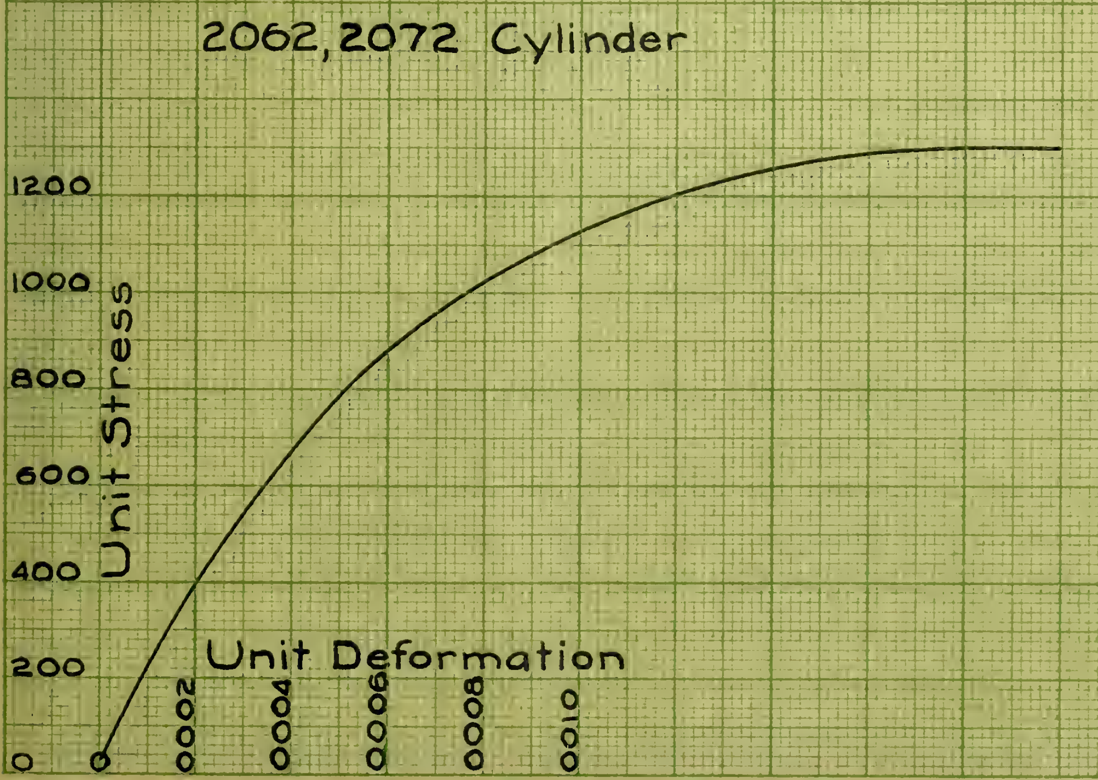


2003, 2053 Cylinder



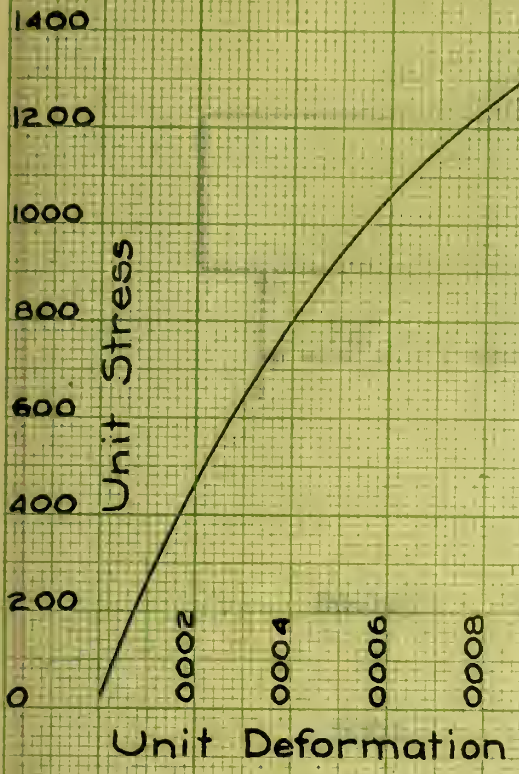


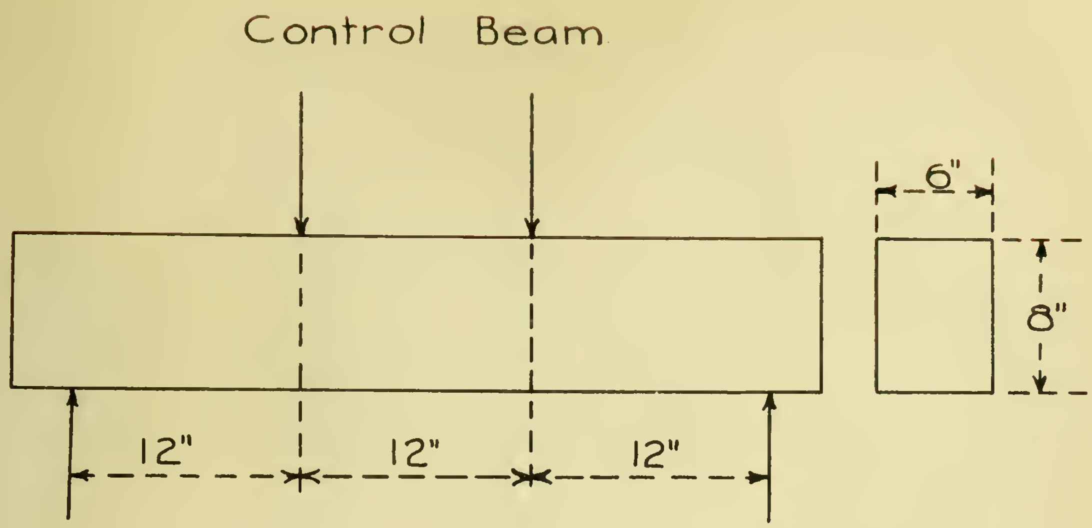
2061, 2071 Cylinders



2062, 2072 Cylinder

2063, 2073 Cylinder





CONTROL BEAMS.

Number	Load lb.	Modulus of Rupture	Age, days.
2001	3000	280	60
2002	4100	385	59
2003	2670	259	68

TESTS OF STEEL IN BEAMS.

Load	Reading	Unit Deformation	Unit Stress	
0	10.0	0	0	
470	11.0	.000025	1510	
1310	14.7	117	4220	
1960	17.3	182	6320	
2710	20.1	252	8740	
3400	23.5	337	10960	
4150	26.1	402	13400	
5120	30.2	505	16500	
6070	34.0	600	19600	
7060	38.0	700	22800	
8120	43.5	837	26200	
9070	47.2	930	29250	
9800	50.9	1022	31600	
11200	54.3	1108	36100	
11730	58	120	37800	Drop of Beam
18550			59800	

Diameter
.6311
.6281
.6310
.6273
.6304
.6285

Av. .6294
Area .310 sq.in.

# # # # #

Load	Reading	Unit Deformation	Unit Stress
160	10.0	.000000	520
1470	15.0	125	4860
3070	21.3	282	10200
4220	27.1	427	13980
6120	34.8	620	20280
7680	42.0	800	25400
9290	49.0	975	30800
10940	55.0	1125	36200
11450	Drop of Beam		37900
17070			56500

Diameter
.6218
.6201
.6209
.6187

Av. .6201
Area .302 sq.in.

CALIBRATION OF GAUGE 1355 WITH JACK B-2161

Gauge Reading	Load in Pounds	Time
220	6450	
300	8200	
400	10400	
500	12550	
600	15000	
650	15200	
760	17950	
850	19800	4:00
970	22300	
1130	26300	
1160	26800	
1260	28800	
1350	30800	
1430	32750	
1530	34900	4:03
1450°	34000	4:12
1630	36900	
1750	39050	
1830	41000	
1910	43250	
2050	45950	
2150	47800	
2250	50250	4:18
2340	52350	
2460	55350	
2560	57900	
2700	60600	
2800	63300	
2900	65050	
3000	67350	4:23
2500°	52800	4:25
2430°	52500	
2320°	51400	4:34
2300°	50400	4:44
2290°	49800	4:50
2270°	49100	5:00
2250°	47050	5:27

° Not plotted

CALIBRATION OF GAUGE 849 WITH JACK B-2161

Gauge Reading	Load in Pounds
10	18300
20	38700
25	48400
30	57700
35	68300
40	78000
45.5	87900
49.7	96600
58	115000

CALIBRATION OF DYNAMOMETER NO. 1

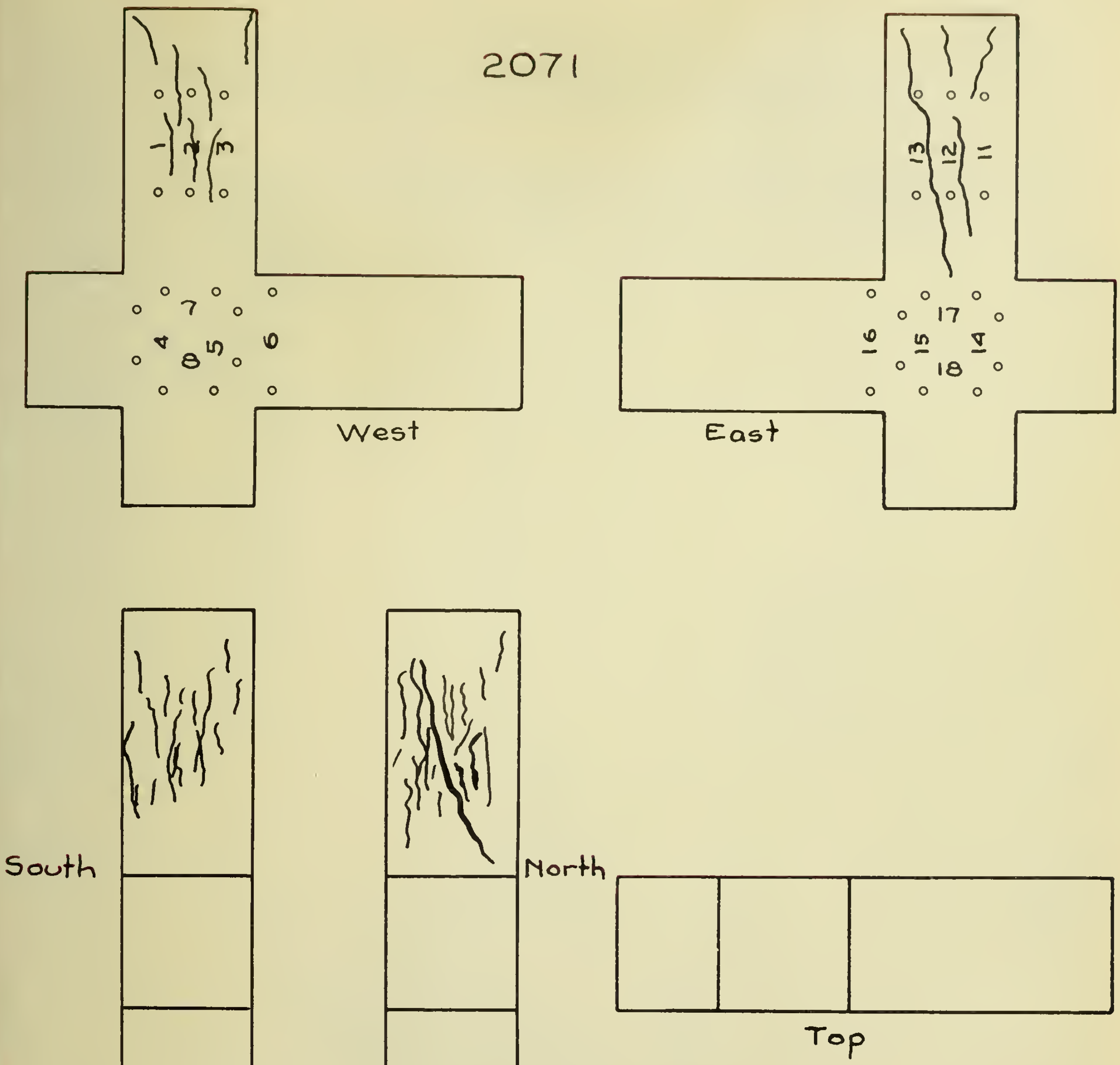
Reading	Load in Pounds
.0022	3000
38	5000
72	10000
105	15000
140	20000
170	25000
200	30000
229	35000
251	40000
280	45000
305	50000
330	55000
360	60000
390	65000
412	70000
435	75000
462	80000
488	85000
515	90000
540	95000
570	100000

SECOND CALIBRATION OF DYNAMOMETER NO. 1.
Made after the Series of Tests.

Load in Pounds.	Reading.	
0	.0000	
3900	28	
10300	70	
21000	135	
32900	198	
40800	237	
50000	287	
59100	335	
68100	380	
78100	429	
87700	479	
99100	537	
110100	592	
119600	644	
128600	689	
137600	736	
124800	687	
99000	572	
68800	429	
50300	333	
26000	189	
0	1	
120000	665	
130000	714	
139500	762	
0	1	
12200	88	
32300	203	
44600	268	
60800	352	
74100	422	
90800	511	
107000	594	
123300	680	
139200	762	
0	1	
0	0	Reset
11700	82	
31100	194	
45900	270	
60100	348	
77200	439	
90500	509	
106100	590	
121000	670	
139300	764	

CALIBRATION OF DYNAMOMETER NO. 2.

Load in Pounds.	Reading.	
0	.0000	
4500	.0021	
12200	60	
21600	100	
33200	150	
46000	197	
63200	249	
75100	288	
92000	338	
105400	373	
120900	413	
134800	454	
153000	504	
165900	534	
181600	575	
196300	622	
210200	658	
225000	700	
192600	637	Down
148400	537	
97900	403	
47300	230	
0	0000	


2071
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West
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11
17
16
15
14
18
East
South
North
Top

AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2071.

Average Unit Stress	Average Deformation on the Arm 1, 2, 3, 11, 12, 13.	Average Deformation on the Cross 4, 5, 14, 15.
230	.000105c	.000080c
210	178c	147c
445	299c	245c
665	421c	348c
870	576c	456c
1080	794c	640c
1300	978c	837c
1420	1256c	976c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2071.

Unit Stress	Gauge Line 1	2	3	4	5	6
230	.000143c	.000110c	.000080c	,000043c	.000070c	.000023c
210	210c	170c	177c	117c	123c	93c
445	323c	310c	287c	187c	200c	157c
665	513c	450c	427c	280c	353c	200c
870	693c	643c	617c	397c	420c	233c
1080	923c	863c	823c	583c	650c	297c
1300	1163c	1033c	1030c	770c	857c	370c
1420	1540c	1383c	1267c	857c	1023c	400c

Gauge Line

7	8	11	12	13	14	15
.000007t	.000027c	.000113c	.000083c	.000103c	.000107c	.000100c
73c	67c	177c	143c	190c	170c	180c
47c	60c	290c	263c	320c	317c	277c
23t	17c	393c	353c	393c	403c	357c
70t	47t	533c	467c	503c	530c	477c
190t	167t	750c	660c	743c	677c	650c
307t	203t	907c	833c	900c	907c	813c
530t	363t	1177c	1050c	1120c	1020c	1003c

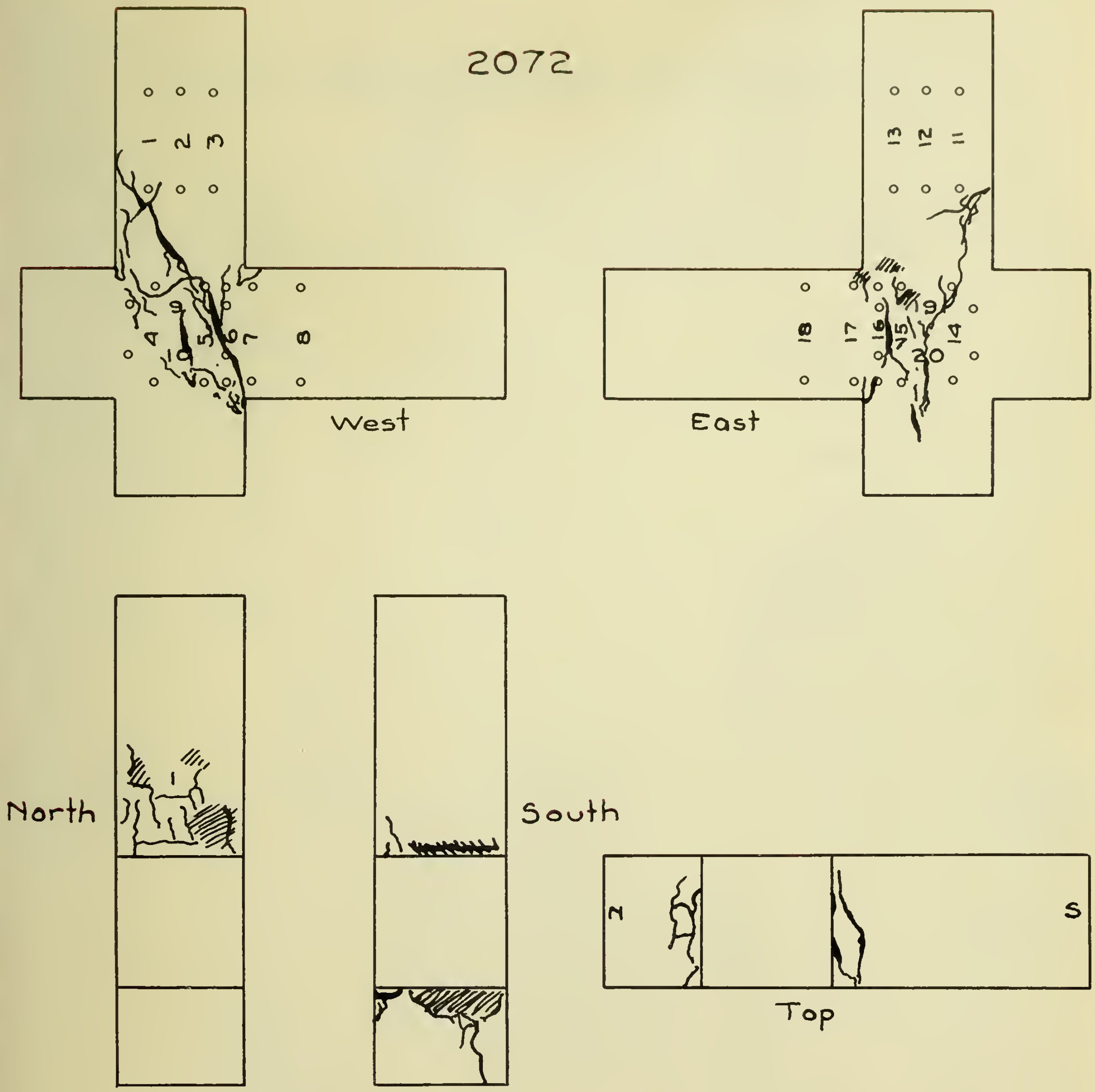
"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2071.

Unit Stress	Gauge Line 17	Gauge Line 18	Expansometers Arm	Expansometers Cross
230	.000077t	.000070t	.000025t	.000017t
210	13t	17t	27t	19t
445	43t	73t	29t	21t
665	110t	150t	35t	22t
870	163t	227t	50t	24t
1080	250t	317t	88t	79t
1300	323t	430t	112t	144t
1420	467t	560t	190t	219t

"t" denotes tension.

2072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17
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West
East
North
South
Top
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S

AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2072

Average Unit Stress	Average Deformation on the Arm 1, 2, 3, 11, 12, 13.	Average Deformation on the Cross 4, 5, 14, 15
220	.000100c	.000085c
420	257c	256c
620	427c	428c
850	668c	720c
1020	895c	1062c
1180	1167c	1614c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2072.

Unit Stress	Gauge Line									
	1	2	3	4	5	6	7	8	9	10
225	.000083c	.000097c	.000090c	.000053c	.000080c	.000093c	.000017c	.000027c	.000043t	.000033t
425	277c	247c	283c	190c	363c	323c	103c	47c	67t	90t
630	483c	450c	487c	383c	563c	563c	190c	63c	157t	200t
860	737c	700c	780c	650c	990c	1000c	340c	63c	457t	543t
1035	973c	927c	1003c	983c	1553c	1507c	450c	60c	977t	1023t
1200	1257c	1150c	1280c	1483c	2460c	2427c	520c	40c	2413t	2220t
1465										

"c" denotes compression, "t" denotes tension.

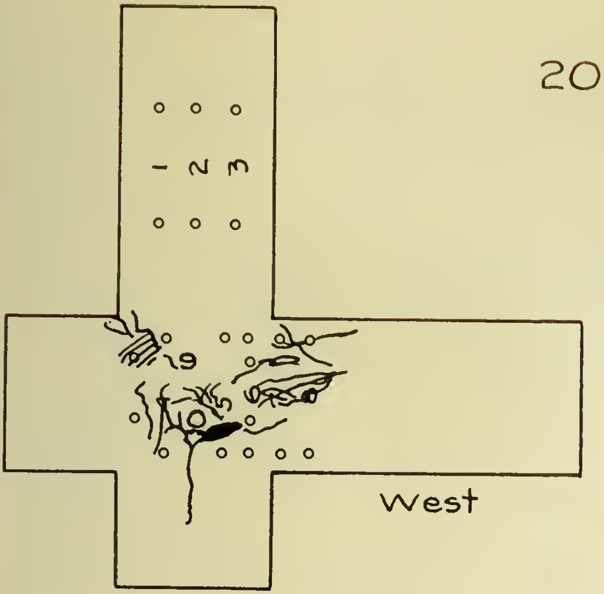
UNIT STRESSES AND UNIT DEFORMATIONS, 2072

Unit Stress	Gauge Line					
	11	12	13	14	15	16
220	.000117c	.000120c	.000093c	.000097c	.000110c	.000103c
410	277c	243c	213c	167c	303c	310c
610	410c	387c	347c	263c	503c	503c
830	627c	637c	527c	423c	817c	870c
1000	867c	863c	747c	587c	1123c	1253
1150	1177c	1120c	1020c	783c	1730c	2000c
1465						

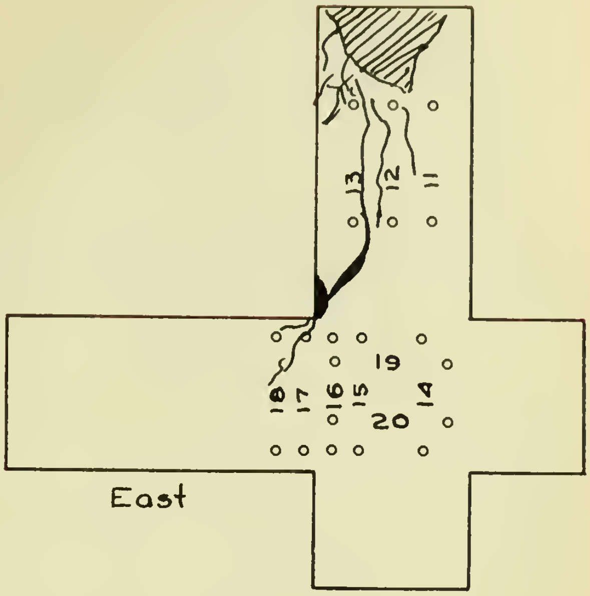
Gauge Line			
17	18	19	20
.000010c	.000003t	.000007t	.000007t
74c	03c	33t	37t
157c	07c	97t	90t
243c	33t	190t	223t
317c	37t	587t	433t
307c	47t	1363t	713t

"c" denotes compression, "t" denotes tension.

2073

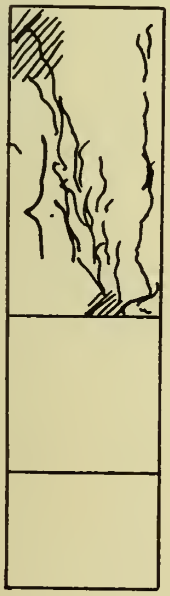


West

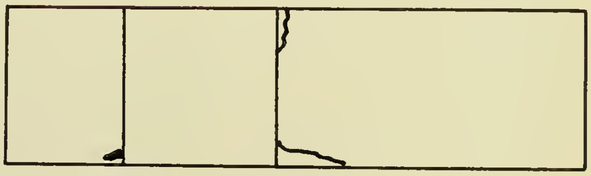


East

North



South



Top

AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2073

Average Unit Stress	Average Deformation on the Arm 1, 2, 3, 11, 12, 13.	Average Deformation on the Cross 4, 5, 14, 15
240	.000145c	.000088c
450	279c	221c
670	390c	330c
890	539c	454c
1095	716c	612c
1315	924c	782c
1500	1155c	1009c
1960		

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2073.

Unit Stress	Gauge Line									
	1	2	3	4	5	6	7	8	9	10
240	.000063c	.000237c	.000030c	.000083c	.000080c	.000073c	.000027c	.000047c	.000050t	.000047t
450	190c	360c	117c	237c	230c	163c	63c	60c	110t	83t
670	300c	450c	210c	377c	390c	273c	103c	17c	163t	143t
890	390c	587c	320c	500c	527c	417c	150c	57c	243t	267t
1095	550c	733c	453c	697c	720c	590c	230c	93c	297t	270t
1315	720c	893c	600c	900c	897c	823c	303c	37c	407t	343t
1500	867c	1073c	780c	1203c	1193c	1070c	373c	43c	620t	493t
1960										

"c" denotes compression, "t" denotes tension.

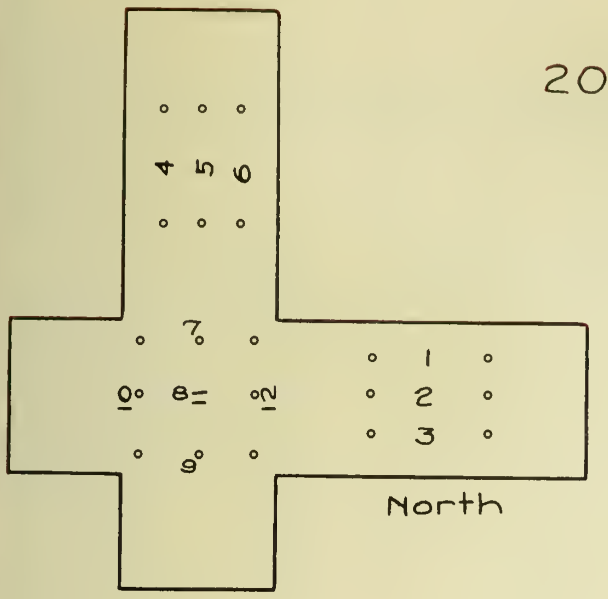
UNIT STRESSES AND UNIT DEFORMATIONS, 2073.

Unit Stress	Gauge Line 11	12	13	14	15	16
240	.000200c	.000193c	.000147c	.000097c	.000093c	.000073c
450	367c	357c	287c	230c	197c	167c
670	490c	483c	410c	300c	253c	220c
890	693c	673c	573c	417c	370c	330c
1095	903c	873c	787c	540c	493c	460c
1315	1177c	1117c	1040c	720c	610c	613c
1500	1493c	1387c	1333c	867c	773c	750c
1960						

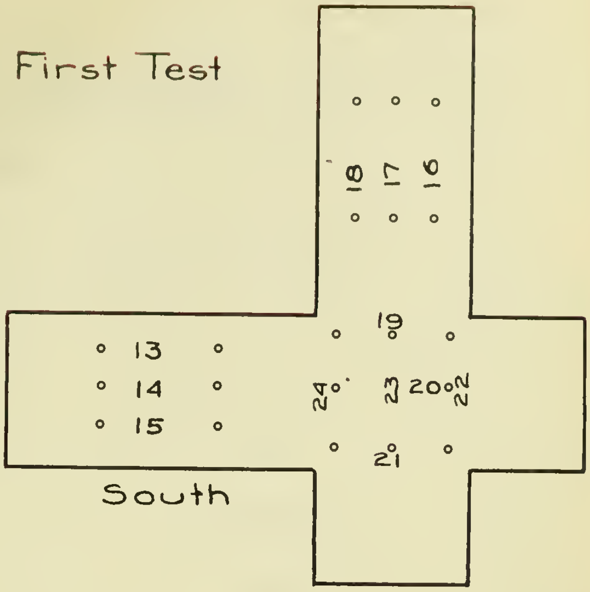
Gauge Line 17	18	19	20	Expansometer on Arm
.000070c	.000003t	.000050t	.000037t	.000052t
73c	37c	37t	43t	55t
70c	30c	113t	140t	98t
90c	20t	153t	193t	100t
183c	03c	213t	303t	120t
197c	07t	310t	383t	181t
253c	17t	457t	530t	262t

"c" denotes compression, "t" denotes tension.

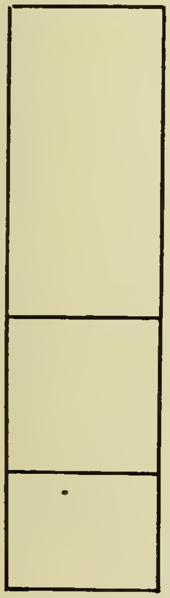
2050 First Test

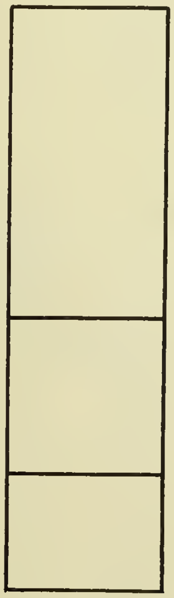


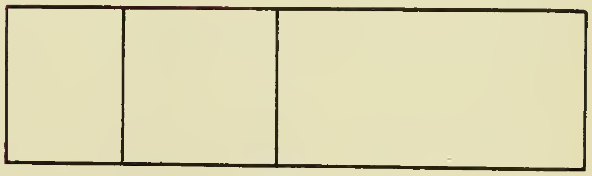
North



South







AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2050.

FIRST TEST

Average Unit Stress	Average Deformation on the Arm. 1, 2, 3, 13, 14, 15.	Average Deformation on the Cross. 7, 8, 9, 19, 20, 21.
130	.000063c	.000017c
270	148c	82c
470	299c	156c
630	415c	238c
675	488c	256c
795	585c	297c
950	735c	417c

SECOND TEST

180	.000090c	.000079c
330	202c	152c
490	324c	198c
650	416c	229c
830	521c	316c
980	636c	395c
1140	791c	477c
1285	978c	550c
1405	1278c	652c
1480	2087	765c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2050, FIRST TEST

Unit Stress	Gauge Line					
	1	2	3	4	6	7
130	.000097c	.000067c	.000073c	.000073c	.000040c	.000043c
270	213c	153c	153c	183c	167c	120c
470	407c	330c	330c	307c	270c	227c
630	487c	473c	450c	493c	410c	337c
675	650c	593c	590c	623c	517c	333c
810	760c	710c	687c	753c	640c	453c
965	933c	823c	817c	940c	837c	563c

Gauge Line						
8	9	10	12	10'	12'	13
.000070c	.000003c	.000027c	.000013c	.000017c	.000023t	.000073c
140c	87c	110c	97c	53c	60t	123c
230c	200c	183c	123c	160c	50c	230c
313c	250c	273c	177c	224c	110c	346c
313c	277c	370c	217c	304c	153c	333c
370c	280c	413c	233c	410c	177c	446c
470c	317c	637c	307c	580c	177c	633c

"c" denotes compression

UNIT STRESSES AND UNIT DEFORMATIONS, 2050, FIRST TEST

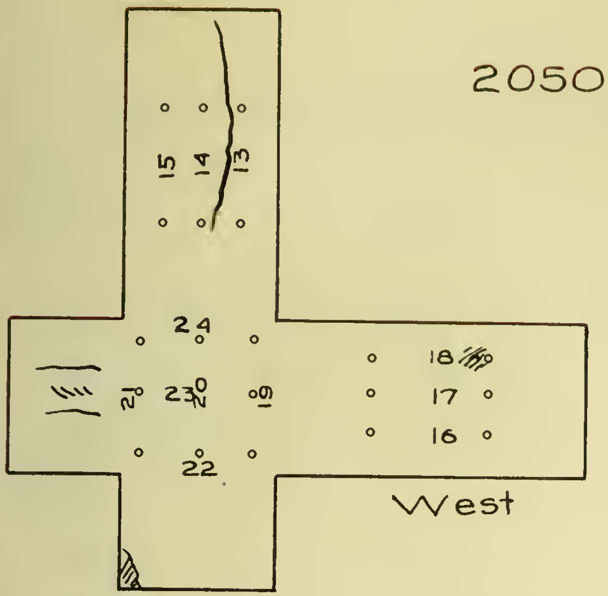
Gauge Line						
14	15	16	18	19	20	21
.000097c	.000040c	.000050c	.000027c	.000003c	.000017c	.000007t
153c	113c	150c	113c	40c	73c	50c
274c	240c	230c	204c	83c	117c	97c
390c	366c	363c	310c	193c	193c	160c
410c	377c	450c	353c	210c	214c	214c
490c	446c	486c	430c	314c	130c	264c
643c	560c	666c	487c	437c	390c	320c

Gauge Line		
22	24	Expansometer on Arm
.000023c	.000053c	.000000
83c	93c	04t
117c	143c	10t
203c	220c	27t
280c	250c	40t
356c	270c	40t
453c	277c	43t

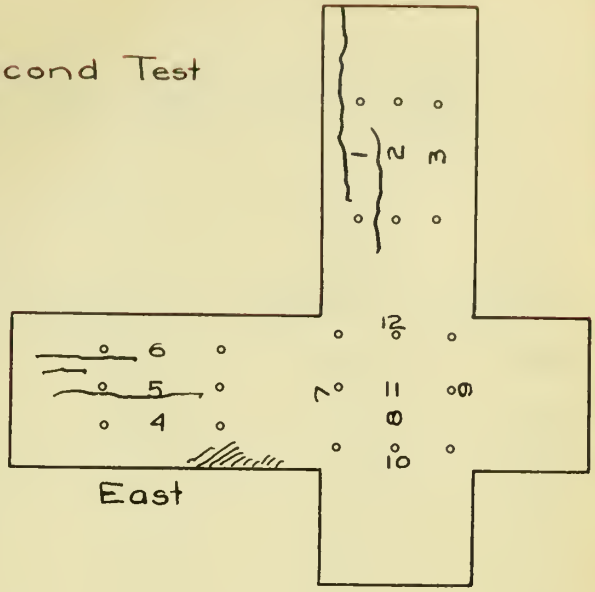
"c" denotes compression,

"t" denotes tension.

2050 Second Test

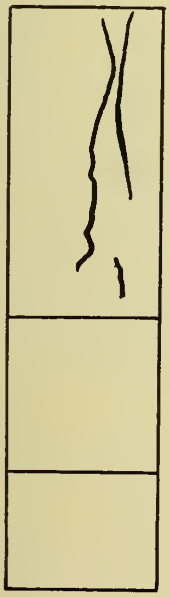


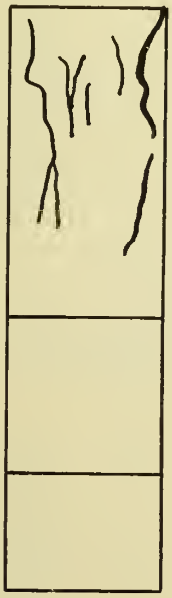
West



East

North





South

Top

UNIT STRESSES AND UNIT DEFORMATIONS, 2050, SECOND TEST

Unit Stress	Gauge Line					
	1	2	3	7	8	9
180	.000103c	.000033c	.000020c	.000173c	.000063c	.000020c
330	333c	183c	87c	347c	143c	83c
490	453c	260c	157c	360c	230c	150c
650	533c	353c	237c	397c	240c	113c
830	723c	460c	307c	537c	380c	187c
980	940c	633c	413c	620c	510c	263c
1140	1120c	747c	513c	727c	590c	330c
1285	1440c	1017c	683c	863c	797c	520c
1405	1960c	1390c	980c	1027c	967c	683c
1480	3960c	2740c	1700c	1043c	1177c	943c

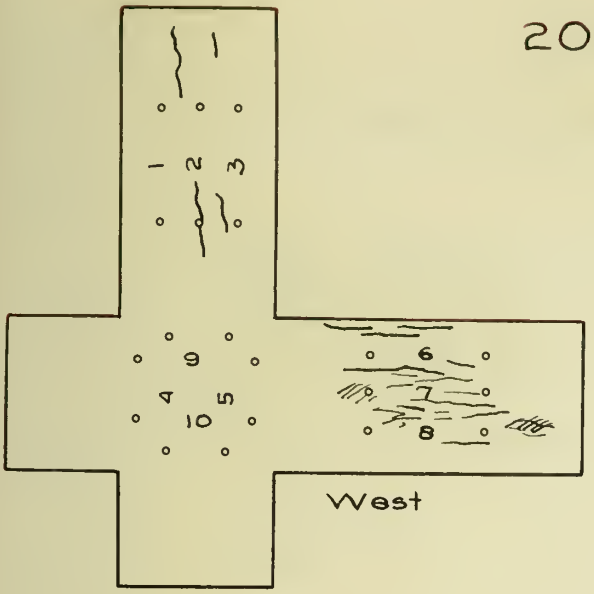
"c" denotes compression

UNIT STRESSES AND UNIT DEFORMATIONS, 2050, SECOND TEST

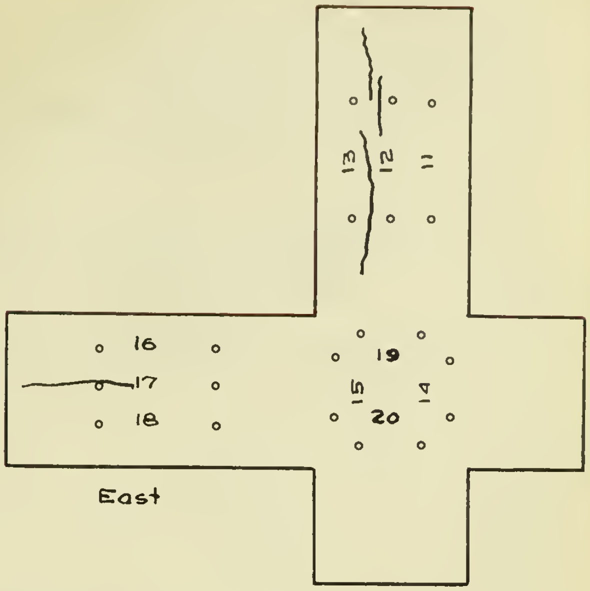
Gauge Line					
13	14	15	19	20	21
.000177c	.000113c	.000093c	.000140c	.000077c	.000000
213c	243c	153c	200c	113c	23c
473c	340c	263c	240c	153c	57c
617c	423c	313c	317c	197c	110c
713c	540c	383c	390c	250c	153c
707c	670c	453c	467c	307c	203c
1023c	773c	570c	553c	383c	280c
1160c	913c	633c	497c	340c	283c
1440c	1113c	787c	507c	370c	357c
1583c	1530c	987c	497c	407c	520c

"c" denotes compression

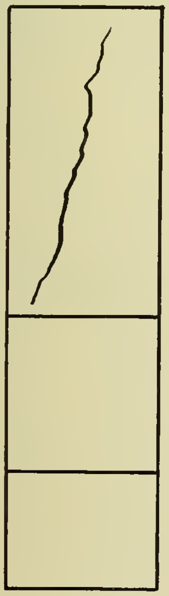
2051



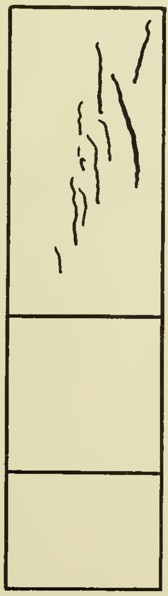
West



East



North



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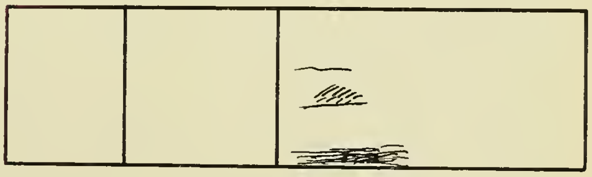


Top

AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2051.

Average Unit Stress	Average Deformation on the Arm. 1, 2, 3, 6, 7, 8, 11, 12, 13, 16, 18.	Average Deformation on the Cross. 4, 5, 9, 10, 14, 15, 19, 20.
220	.000124c	.000091c
440	322c	212c
660	535c	318c
885	810c	523c
1065	1143c	717c
1255	1734c	1047c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2051

Unit Stress	Gauge Line					
	1	2	3	4	5	6
225	.000030c	.000070c	.000183c	.000040c	.000050c	.000150c
440	177c	233c	503c	147c	243c	423c
660	293c	420c	720c	187c	290c	640c
885	480c	663c	1043c	327c	470c	990c
1040	683c	750c	1357c	457c	630c	
1085						1457c
1180	1110c	1710c	2097c	913c	1050c	
1330						2523c

Unit Stress	Gauge Line					
	7	8	9	10	11	12
225	.000193c	.000157c	.000150c	.000117c	.000117c	.000117c
440	440c	353c	323c	220c	280c	307c
660	723c	573c	513c	353c	467c	617c
885	1053c	837c	793c	570c	707c	867c
1040					1080c	1207c
1085	1563c	1257c	1057c	857c		
1180					1503c	1977c
1330	2763c	2083c	1530c	1213c		

"c" denotes compression

UNIT STRESSES AND UNIT DEFORMATIONS, 2051

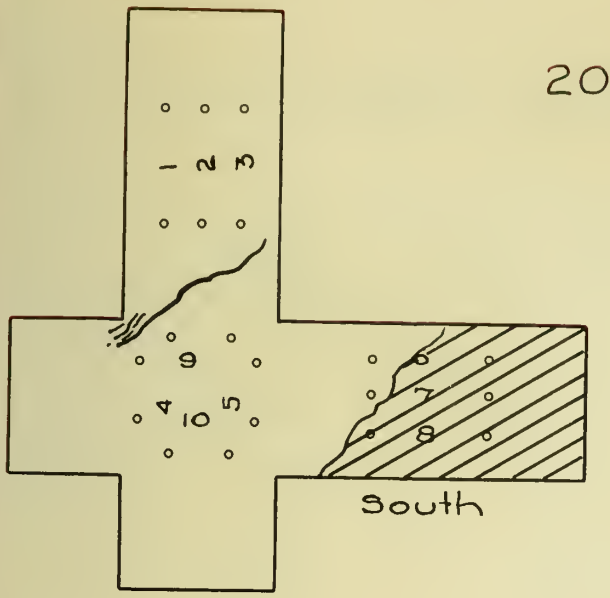
Unit Stress	Gauge Line					
	13	14	15	16	18	19
225	.000223c	.000147c	.000103c	.000040c	.000083c	.000080c
440	447c	227c	200c	207c	167c	240c
660	703c	423c	353c	417c	313c	280c
885	1073c	773c	543c	690c	507c	423c
1040	1440c	1010c	830c			
1085				1000c	783c	527c
1180	1917c	1180c	853c			
				1377c	1010c	953c

Unit Stress	Gauge Line	Expansometer	
	20	Arm	Cross
225	.000037c	.000011t	.000042t
440	97c	38t	65t
660	143c	61t	105t
885	287c	79t	209t
1085	367c	161t	370t
1330	683c	842t	695t

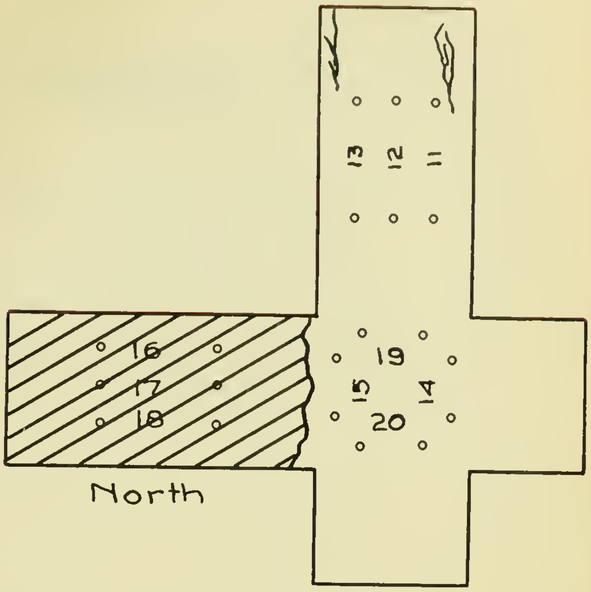
"c" denotes compression,

"t" denotes tension.

2052

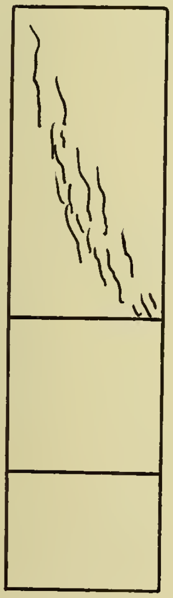


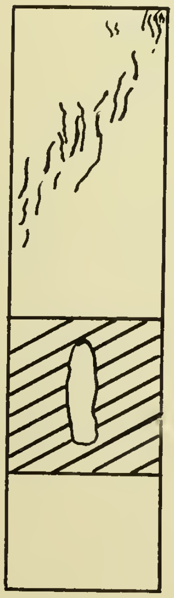
South



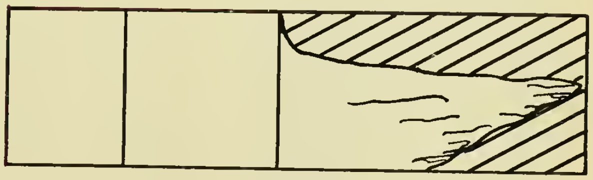
North

West





East



Top

AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2052.

Average Unit Stress	Average Deformation on the Arm. 1, 2, 3, 6, 7, 8, 11, 12, 13, 16, 18.	Average Deformation on the Cross 4, 5, 9, 10, 14, 15, 19, 20.
220	.000105c	.000086c
440	231c	177c
650	371c	263c
880	536c	344c
1105	711c	430c
1280	944c	541c
1490	1211c	685c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2052

Unit Stress	Gauge Line 1	2	3	4	5	6
225	.000117c	.000097c	.000293c	.000087c	.000143c	.000050c
435	190c	177c	560c	166c	370c	193c
650	337c	317c	547c	243c	460c	360c
880	490c	480c	677c	303c	567c	563c
1105	627c	640c	907c	430c	690c	757c
1280	820c	883c	1117c	550c	807c	1137c
1490	1080c	1170c	1380c	-	970c	1523c
1590	1260c	1440c	1520c	1277c	1580c	-
1720	-	1550c	-	1390c	1927c	-

Gauge Line 7	8	9	10	11	12	13
.000120c	.000037c	.000167c	.000077c	.000077c	.000080c	.000080c
153c	220c	273c	173c	213c	207c	237c
340c	377c	347c	293c	363c	383c	400c
597c	547c	473c	417c	537c	553c	573c
803c	807c	583c	543c	697c	720c	753c
1190c	1097c	750c	720c	927c	950c	950c
1777c	1493c	1063c	1347c	1197c	1230c	1210c
-	-	527t[z]	593t[z]	1567c	1533c	1403c
-	-	1127t[z]	1177c[z]	-	1760c	-

[z] No horizontal load

"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2052

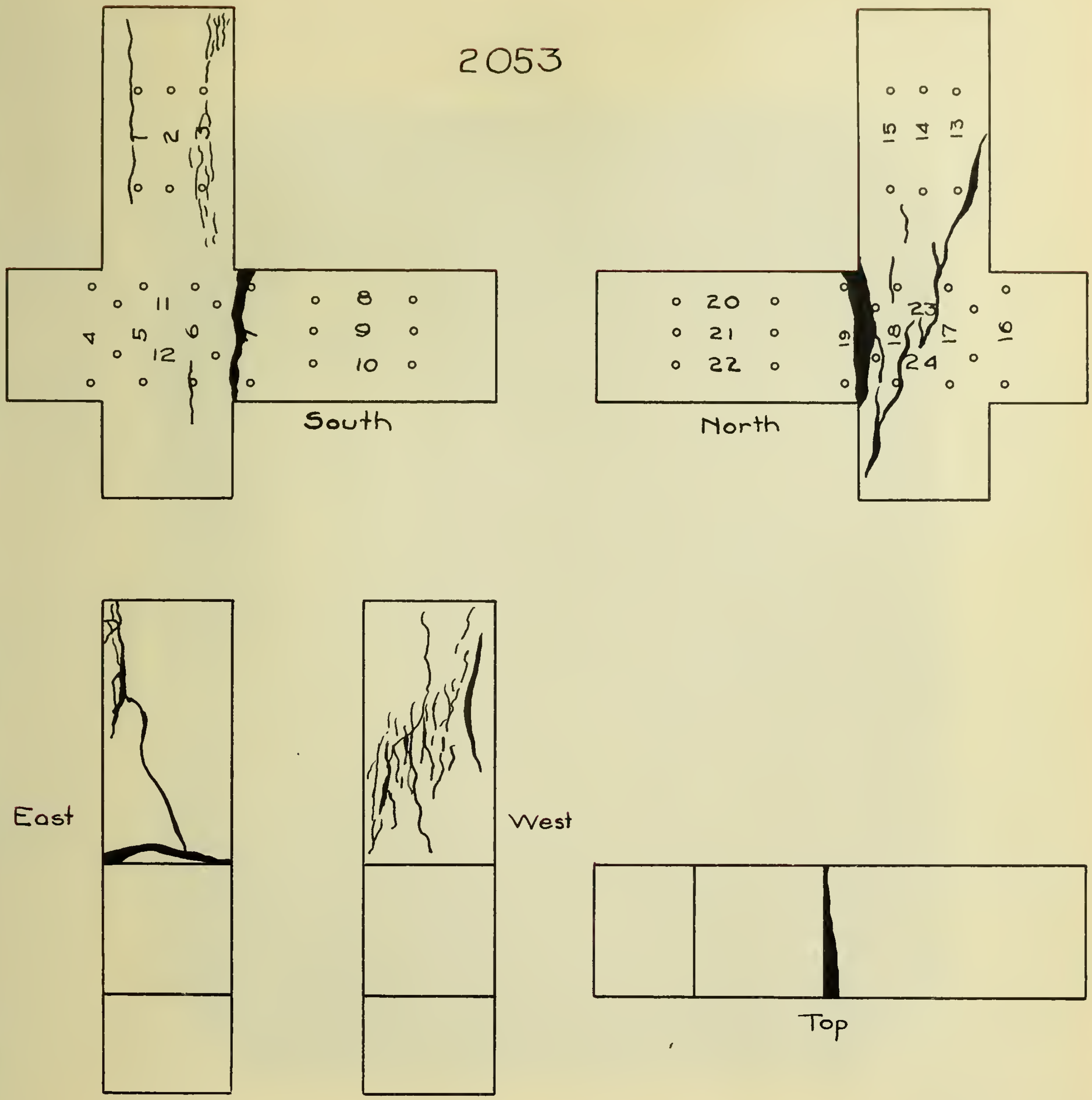
Gauge Line					
14	15	16	18	19	20
.000020c	.000057c	.000080c	.000127c	.000057c	.000080c
43c	120c	170c	217c	150c	123c
133c	197c	273c	387c	207c	223c
217c	290c	360c	517c	203c	283c
263c	367c	457c	653c	247c	317c
390c	497c	570c	763c	257c	360c
480c	607c	543c	723c	393c	623c
923c	1037c	-	-	53c[z]	93t[z]
960c	1123c	-	-	-	-

Expansometers

Arm		Cross	
Before	After	Before	After
.000022t	.000023t	.000117t	.000120t
34t	34t	144t	230t
50t	50t	234t	235t
65t	71t	237t	249t
130t	140t	251t	251t
375t	-	282t	287t
-	-	-	-
-	-	-	-
-	-	-	-

"c" denotes compression, "t" denotes tension

2053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Compression Specimen 2053 after Failure.

AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2053.

Average Unit Stress	Average Deformation on the Arm 1, 2, 3, 8, 9, 10, 13, 14, 15, 20, 21, 22.	Average Deformation on the Cross 5, 6, 11, 12, 17, 18, 23, 24.
225	.000095c	.000052c
450	227c	182c
670	392c	250c
890	556c	358c
1095	719c	467c
1290	957c	593c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2053

Unit Stress	Gauge Line 1	2	3	4	5	6
225	.000010t	000020c	.000083c	.000183t	.000067t	.000083c
450	100c	90c	140c	120t	47c	183c
670	247c	200c	253c	117t	100c	233c
890	427c	363c	417c	127t	177c	327c
825[z]	-	-	-	123t[z]	343c[z]	460c[z]
1095	653c	530c	600c	60t	357c	493c
1290	887c	770c	817c	60t	423c	587c

Unit Stress	Gauge Line 7	8	10	11	12	13
225	.000083c	.000083c	.000103c	.000053c	.000043c	.000090c
450	200c	183c	300c	183c	163c	240c
670	200c	367c	420c	270c	217c	420c
890	347c	530c	593c	333c	280c	570c
825[z]	310c[z]					507c[z]
0		143c[z]	260c[z]	10c[z]	27t[z]	
1095	343c	677c	697c	380c	210c	707c
1290	370c	1120c	883c	517c	380c	850c

[z] Series of observations taken while horizontal load was removed for change of gauges.

"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2053

Unit Stress	Gauge Line 14	15	16	17	18	20
225	.000133c	.000213c	.000017t	.000030c	.000197c	.000083c
450	273c	320c	00	120c	357c	250c
670	473c	497c	03c	163c	437c	453c
890	600c	640c	87c	283c	607c	670c
825[z]	577c[z]	637c[z]	107c[z]	467c[z]	790c[z]	
0[z]						97c[z]
1095	777c	783c	120c	460c	830c	903c
1290	947c	987c	187c	550c	917c	1333c

Unit Stress	Gauge Line 21	22	23	24
225	.000107c	.000143c	.000037c	.000040c
450	307c	293c	180c	223c
670	497c	480c	280c	303c
890	647c	653c	427c	433c
0[z]	113c[z]	147c[z]	53t[z]	10t[z]
1095	807c	783c	513c	490c
1290	1063c	870c	737c	633c

[z] Series of observations taken while horizontal load was removed for change of gauges.

"c" denotes compression, "t" denotes tension.

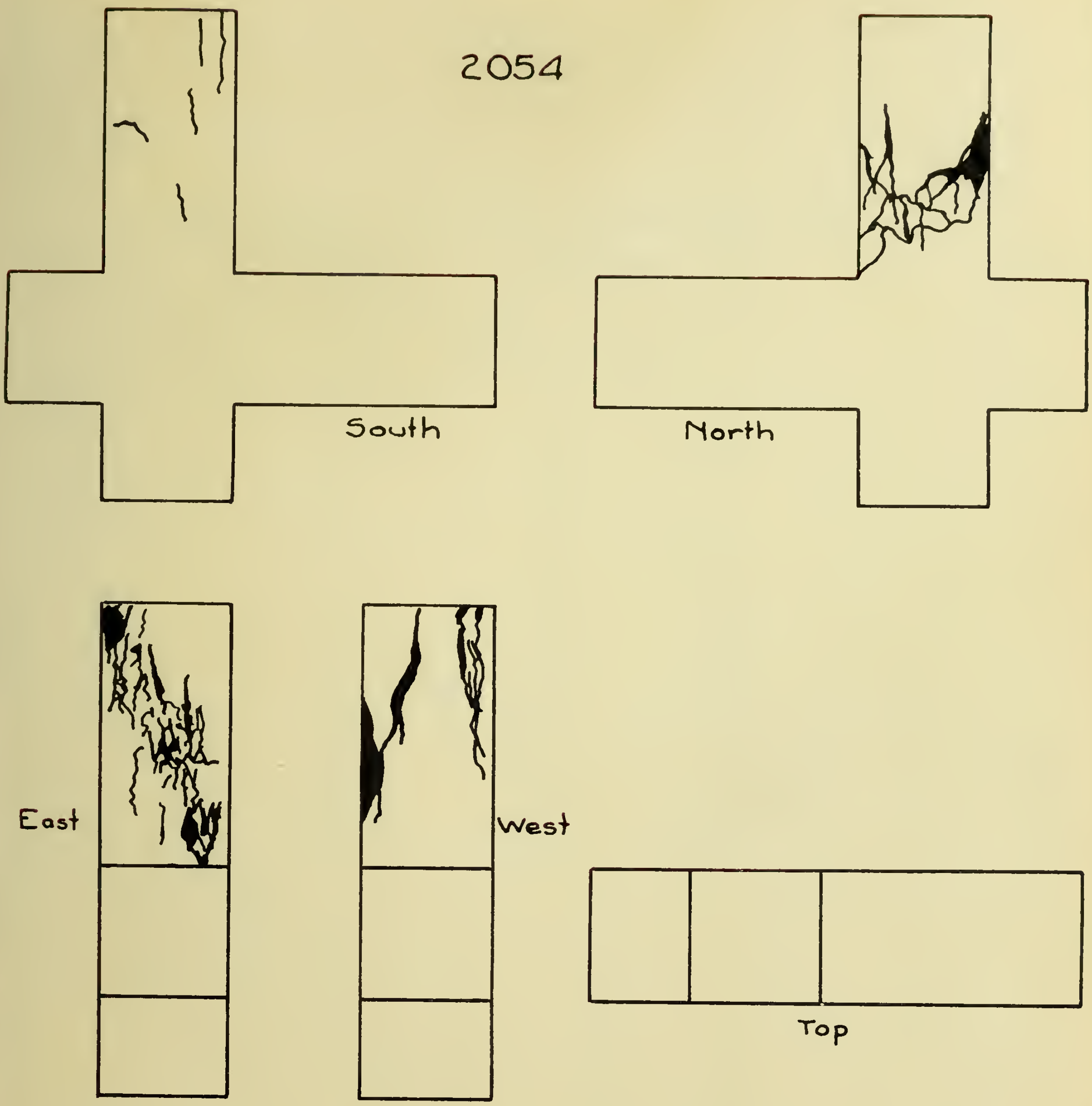
UNIT STRESSES AND UNIT DEFORMATIONS, 2053

Unit Stress	Expansometers			
	Arm		Cross	
	Before	After	Before	After
225	.000021t	.000040t	.000029t	.000031t
450	51t	51t	35t	35t
670	75t	93t	37t	47t
890	114t	-	50t	-
825[z]	-	114t[z]	-	50t[z]
1095	162t	163t	51t	51t
1290	237t	247t	54t	61t

[z] Series of observations taken while horizontal load was removed for change of gauges.

"t" denotes tension.

2054



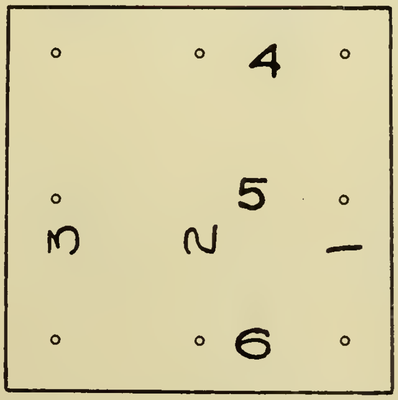
UNIT STRESSES AND UNIT DEFORMATIONS, 2054

Unit Stress	Expansion Arm	Expansion Cross
115	.000001t	.000001t
240	1t	3t
470	4t	10t
710	13t	18t
940	23t	25t
1175	31t	25t
1400	40t	36t
1640	120t	93t
1880	275t	105t
2080	850t	218t

[illegible]

[illegible]

2055-A



Gauge-Holes for 2055-A, 2055-B, 2056-A, 2056-B.

UNIT STRESSES AND UNIT DEFORMATIONS, 2055

Cube 2055-A

Unit Stress	Gauge Line						
	1	2	3	4	5	6	Average
356	.000040t	.000007t	.000033t	.000037c	.000077c	.000020c	.000014c
695	3t	133t	90t	157c	167c	53c	20c
1090	110c	77c	137c	293c	313c	110c	173c
1440	1413c	387c	240c	500c	420c	37c	500c
1920							

Cube 2055-B

Unit Stress	Gauge Line						
	1	2	3	4	5	6	Average
430	.000110c	.000040c	.000077c	.000053t	.000017c	.000043c	.000040c
735	137c	100c	40c	30t	53c	110c	70c
1110	330c	233c	150c	110t	193c	240c	173c
1340	340c	303c	303c	113t	293c	273c	233c
1550	400c	283c	323c	0	403c	437c	307c
1790	403c	470c	570c	40c	460c	380c	387c
2200							

UNIT STRESSES AND UNIT DEFORMATIONS, 2056

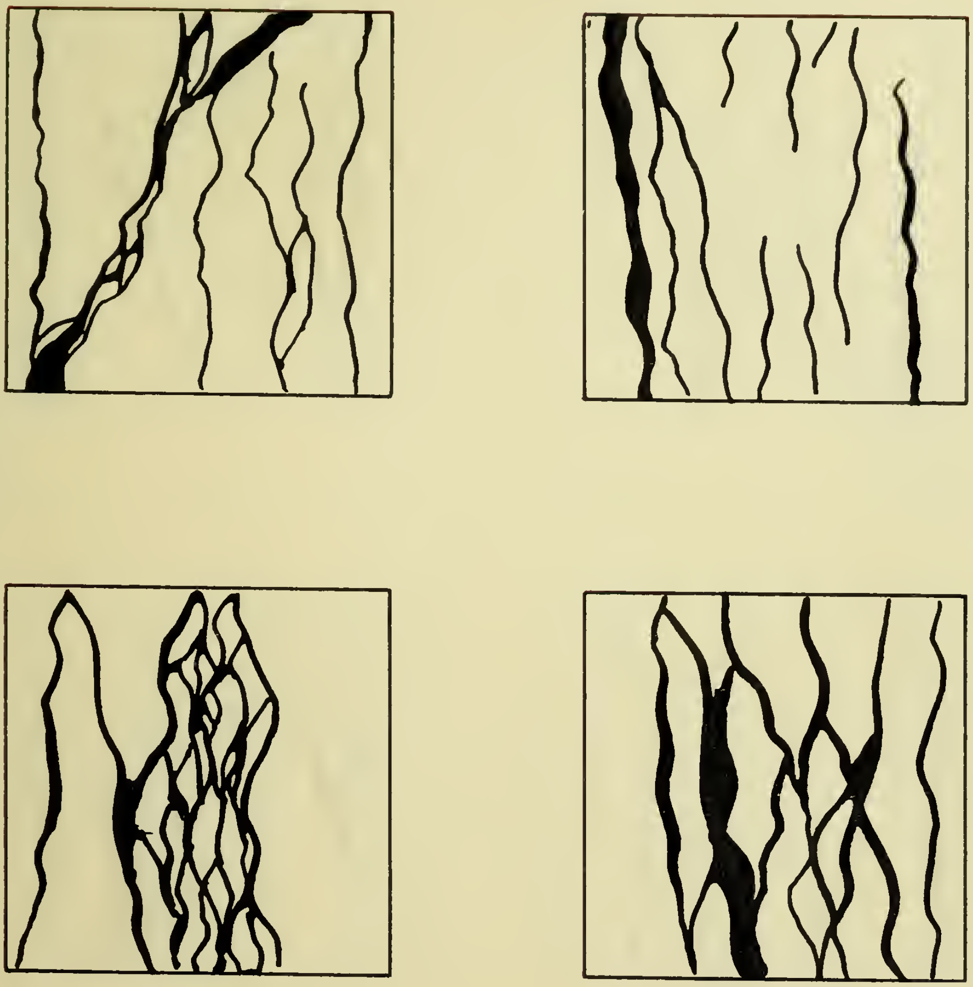
Cube 2056-A

Unit Stress	Gauge Line					
	1	3	4	5	6	Average
325	.000193c	.000123c	.000333c	.000087c	.000067t	.000133c
770	393c	370c	523c	310c	37t	313c
1140	563c	587c	717c	533c	67t	467c
1530	693c	853c	990c	717c	37c	657c
1820	1073c	1260c	1320c	830c	233c	943c
2220						

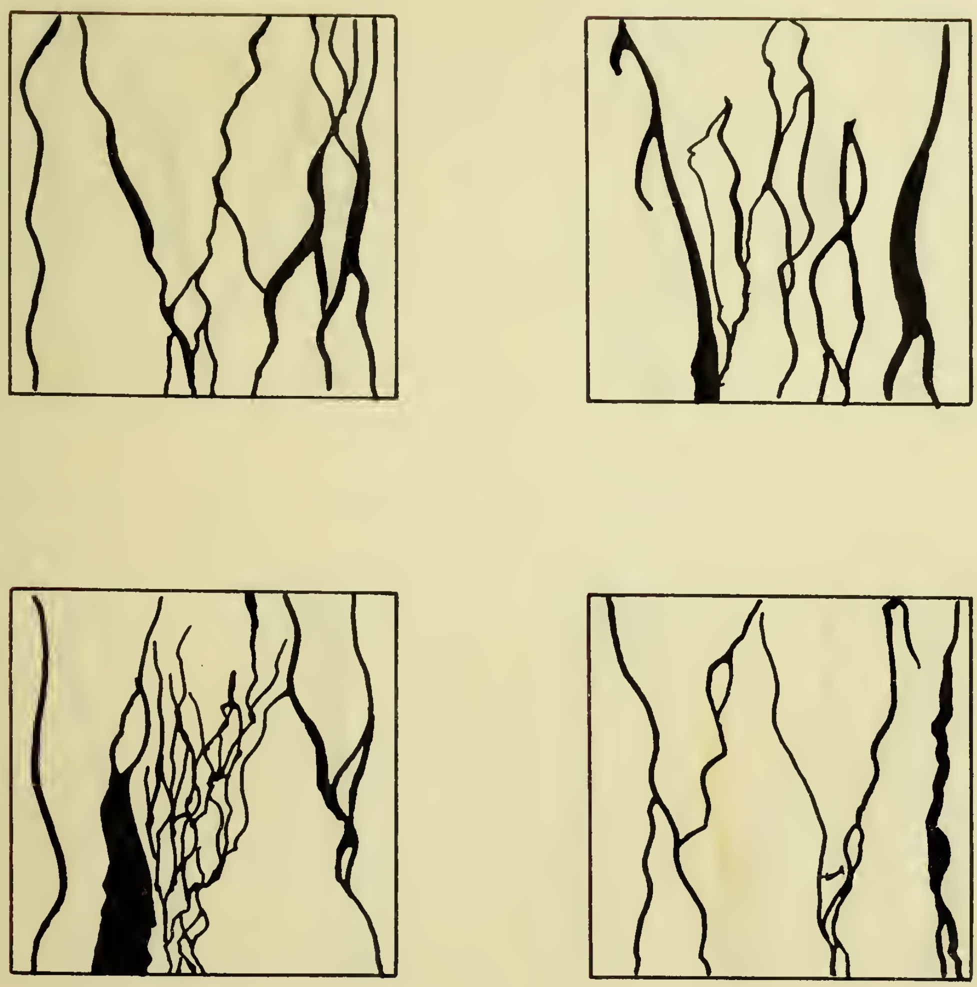
Cube 2056-B

Unit Stress	Gauge Line						
	1	2	3	4	5	6	Average
386	.000037c	.000037c	.000070c	.000130c	.000170c	.000027c	.000077c
760	17c	103c	187c	407c	437c	-	230c
1130	80c	293c	413c	537c	553c	180c	343c
1530	247c	527c	633c	713c	603c	410c	523c
1850	430c	713c	810c	797c	637c	423c	637c
2300	753c	1147c	1297c	903c	827c	457c	953c
2790							

2057-A



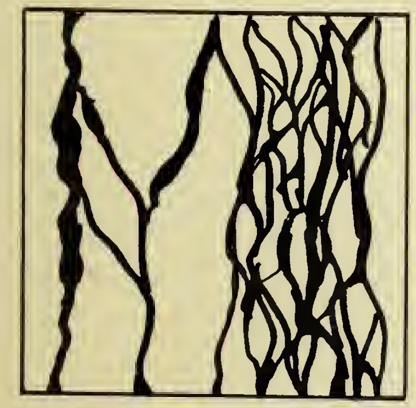
2057-B






2058-A

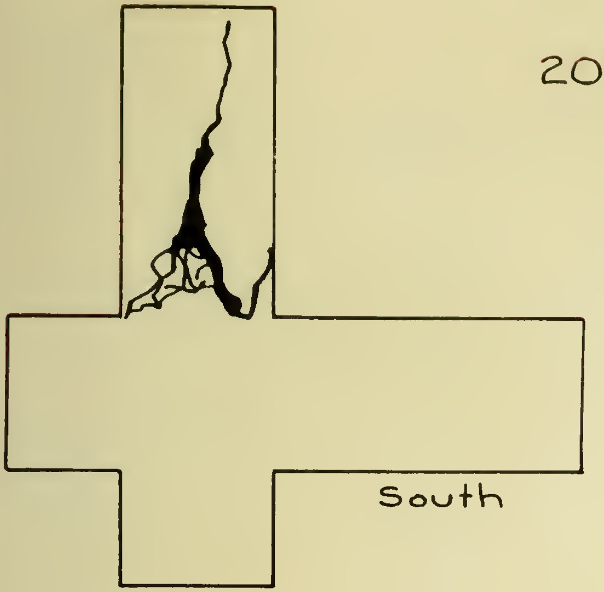
2058-B



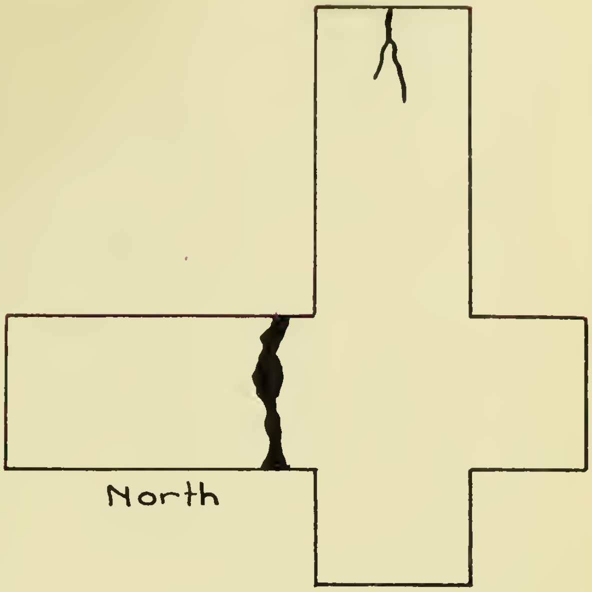
UNIT STRESSES, 2057 AND 2058

Cube	Unit Stress
2057-A	2420
2057-B	2890
2058-A	3680
2058-B	2940

2059



South



North

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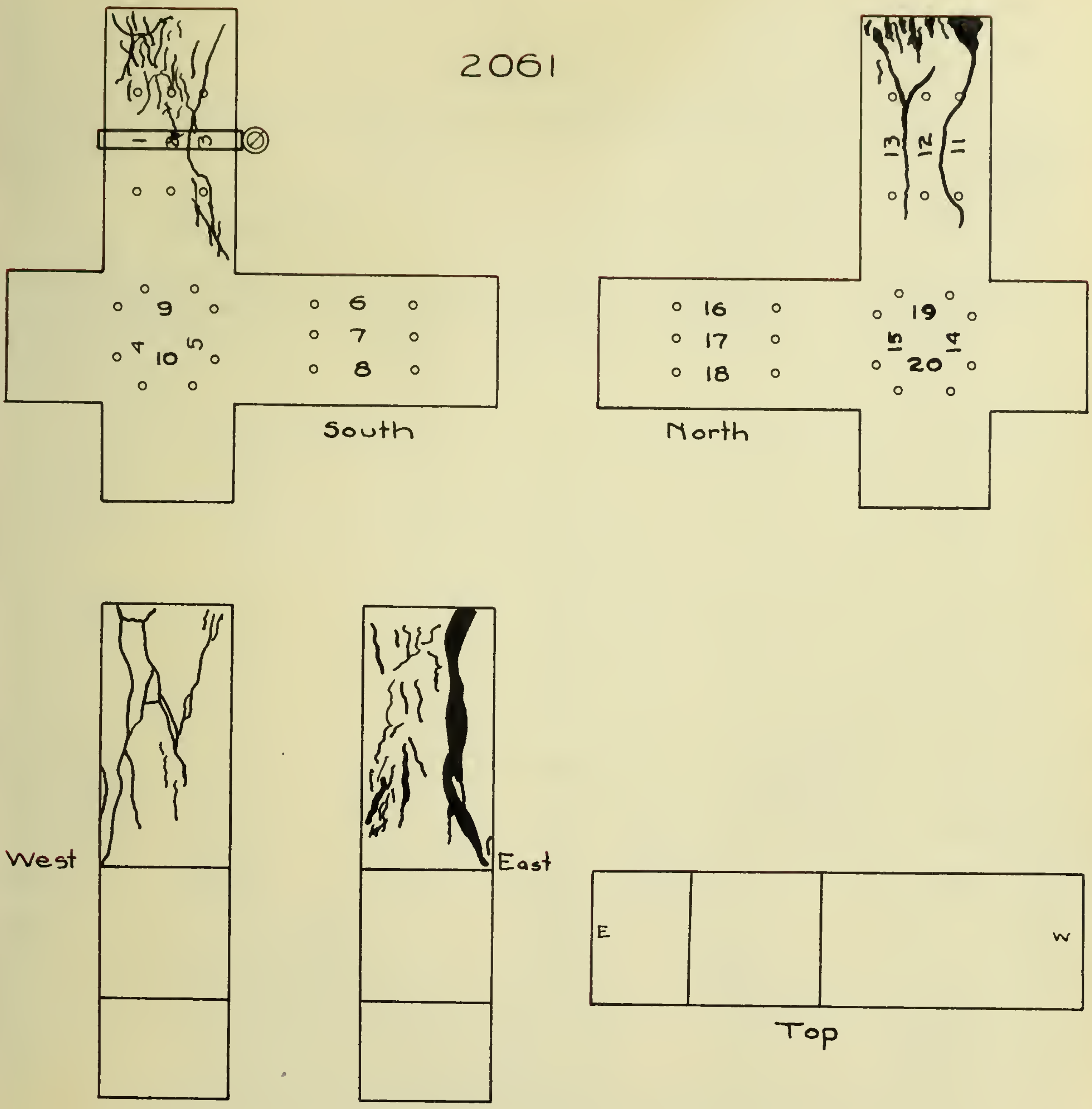
Top

UNIT STRESSES AND UNIT DEFORMATIONS, 2059.

Unit Stress	Expansion	
	Arm	Cross
255	.000011t	.000001t
480	.000022t	.000003t
705	29t	5t
920	43t	11t
980	47t	14t
1160	49t	19t
1375	58t	21t
1590	110t	24t
1840	124t	30t
2050	293t	38t
2200		

2061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Average Stresses and Average Deformations, 2061.

	Vertical Arm.			Horizontal Arm.	
Average Unit Stress	Average Deformation on the Arm	Average Deformation on the Cross	Average Unit Stress	Average Deformation on the Arm	Average Deformation on the Cross
	1, 2, 3, 11, 12, 13.	4, 5, 14, 15.		6, 7, 8, 16, 17, 18.	9, 10, 19, 20.
225	.000091c	.000068c	110	.000007t	.000028t
440	219c	178c	220	71c	01t
655	394c	318c	330	133c	32c
860	582c	466c	425	203c	37c
1080	779c	599c	535	275c	66c
1280	1021c	778c	635	356c	93c
1475	1291c	943c	745	448c	139c
1580	1693c	1139c	865	570c	174c
1820			930		
			2020		

"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2061.

Unit Stress	Gauge Line					
	1	2	3	11	12	13
225	.000007c	.000063c	.000153c	.000047c	.000083c	.000193c
440	67c	133c	257c	223c	253c	383c
655	173c	280c	413c	410c	457c	633c
860	310c	423c	577c	590c	687c	907c
1080	430c	590c	733c	823c	923c	1177c
1280	597c	787c	953c	1070c	1200c	1520c
1475	770c	1023c	1183c	1357c	1507c	1903c
1580	987c	1470c	1610c	1920c	1770c	2403c

Unit Stress	Gauge Line			
	4	5	14	15
225	.000000	.000127c	.000043c	.000103c
440	77c	223c	137c	277c
655	160c	327c	320c	467c
860	260c	483c	480c	643c
1080	350c	590c	627c	827c
1280	513c	723c	853c	1023c
1475	660c	880c	1020c	1213c
1580	940c	1147c	1137c	1333c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2061.

Unit Stress	Gauge Line					
	6	7	8	16	17	18
110	.000000	.000007c	.000027c	.000030t	.000020t	.000027t
220	87c	47c	107c	13c	57c	113c
330	110c	130c	210c	53c	120c	177c
425	160c	183c	310c	123c	167c	277c
535	217c	240c	373c	187c	263c	373c
635	273c	323c	473c	237c	343c	487c
745	353c	403c	573c	317c	437c	603c
865	477c	530c	727c	403c	527c	757c

Unit Stress	Gauge Line			
	9	10	19	20
110	.000003t	.000003c	.000050t	.000063t
220	07c	73c	53t	33t
330	63c	143c	53t	23t
425	83c	177c	70t	43t
535	90c	203c	20t	10t
635	133c	280c	37t	03t
745	213c	330c	30t	43c
865	217c	383c	07c	90c

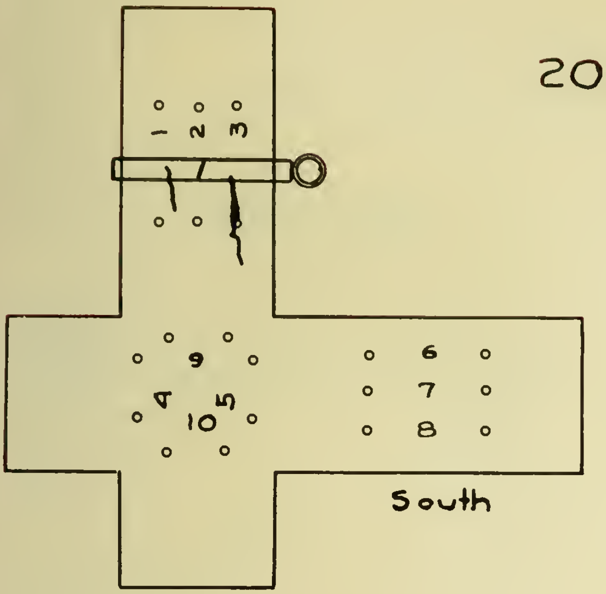
"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT EXPANSIONS, 2061

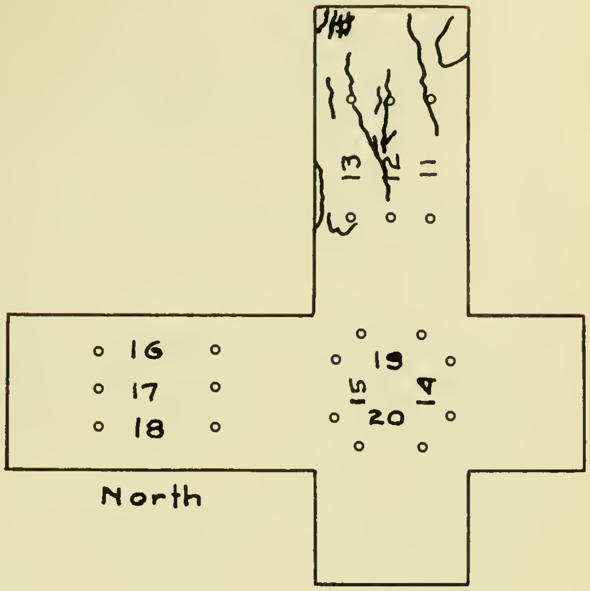
Unit Stress	Expansometers	
	Arm	Cross
225	.000011t	.000017t
440	11t	17t
655	11t	17t
860	11t	17t
1080	24t	94t
1280	29t	112t
1475	41t	128t
1580	-	-

"t" denotes tension.

2062

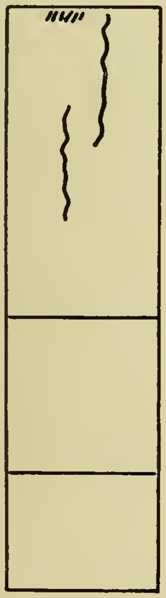


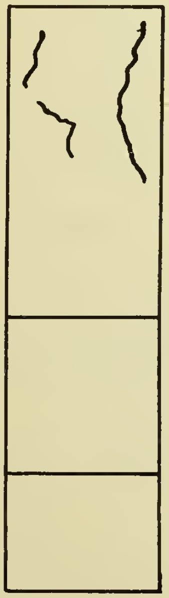
South



North

West





East

Top

Average Stresses and Average Deformations, 2062.

Vertical Arm			Horizontal Arm		
Average Unit Stress	Average Deformation on the Arm	Average Deformation on the Cross	Average Unit Stress	Average Deformation on the Arm	Average Deformation on the Cross
	1, 2, 3, 11, 12, 13.	4, 5, 14, 15.		6, 7, 8, 16, 17, 18.	9, 10, 19, 20.
225	.000119c	.000068c	105	.000037c	.000020c
425	255c	243c	210	159c	50c
640	450c	370c	320	277c	93c
830	622c	543c	420	399c	115c
1020	909c	786c	525	555c	131c
1190	1403c	1097c	665	810c	212c

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2062

Unit Stress	Gauge Line					
	1	2	3	11	12	13
225	.000097t	.000003t	.000157c	.000177c	.000223c	.000257c
425	113t	60c	210c	347c	490c	537c
640	27c	170c	403c	607c	740c	753c
830	130c	313c	550c	790c	1003c	947c
1020	377c	537c	910c	997c	1360c	1277c
1190	747c	887c	1350c	1660c	2057c	1717c
1510						

Unit Stress	Gauge Line			
	4	5	14	15
225	.000020t	.000000	.000097c	.000197c
425	117c	203c	243c	410c
640	157c	343c	377c	603c
830	307c	517c	550c	797c
1020	513c	813c	757c	1063c
1190	790c	1160c	1073c	1363c
1510				

"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2062

Unit Stress	Gauge Line 6	7	8	16	17	18
105	.000067c	.000070c	.000023c	.000010t	.000023c	.000050c
210	157c	177c	183c	110c	147c	183c
320	283c	297c	340c	213c	237c	293c
420	480c	483c	387c	340c	337c	367c
525	650c	647c	537c	543c	480c	473c
665	930c	933c	787c	817c	747c	647c

Unit Stress	Gauge Line 9	10	19	20
105	.000010c	.000007t	.000033t	.000050t
210	60c	97c	13c	30c
320	153c	97c	73c	50c
420	173c	100c	133c	53c
525	190c	63c	237c	33c
665	323c	83c	373c	67c

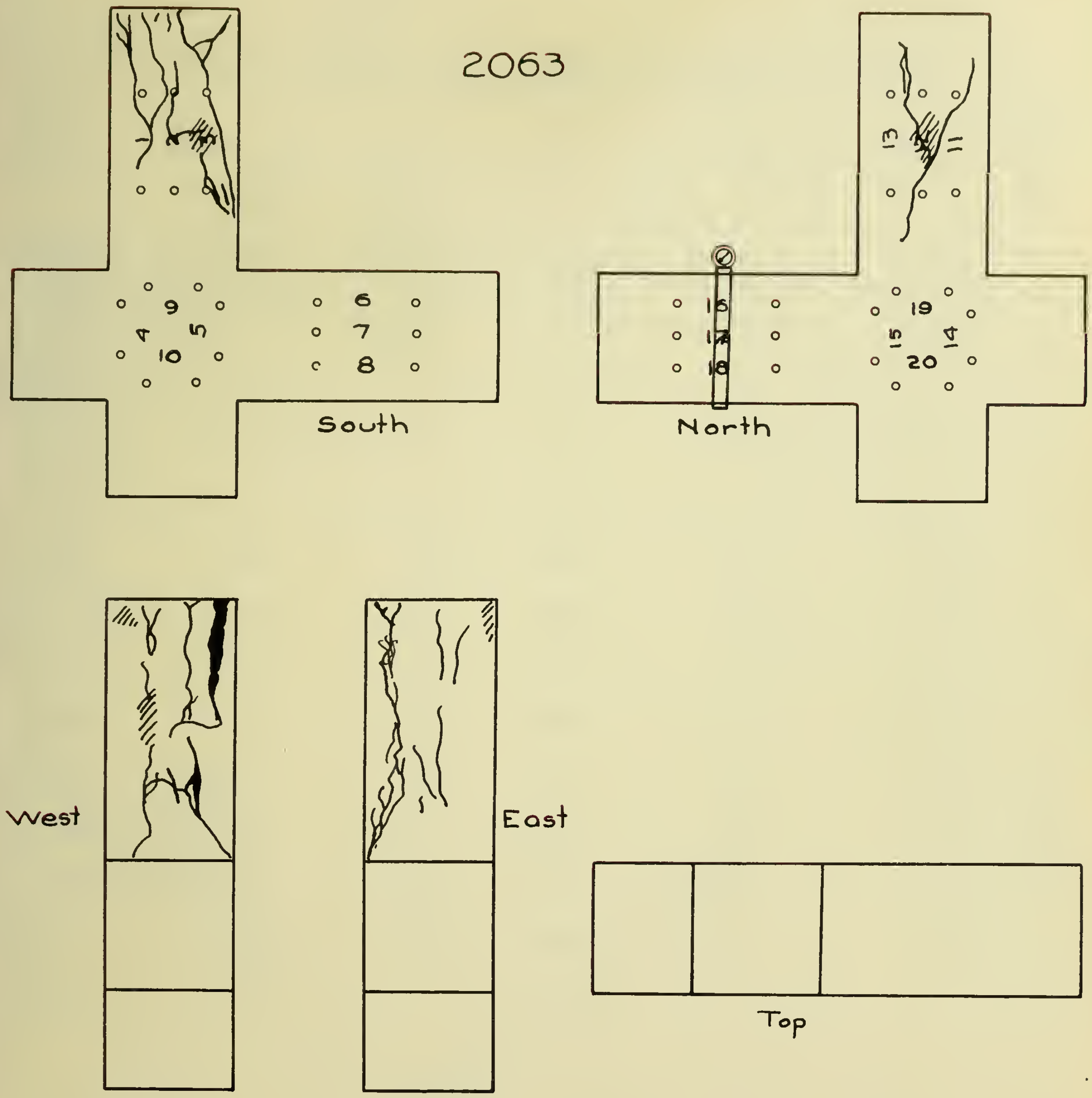
"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT EXPANSIONS, 2062

Vertical Arm		Cross	
Unit Stress	Unit Deformation	Unit Stress	Unit Deformation
105	.000061t	105 and 225	.000012t
210	87t	210 and 425	12t
320	135t	320 and 640	18t
420	190t	420 and 830	29t
525	350t	525 and 1020	46t
665	661t	665 and 1190	65t
775	2690	775 and 1510	89t

"t" denotes tension.

2063



AVERAGE STRESSES AND AVERAGE DEFORMATIONS, 2063.

Horizontal Arm			Vertical Arm		
Average Unit Stress	Average Deformation on the Arm	Average Deformation on the Cross	Average Unit Stress	Average Deformation on the Arm	Average Deformation on the Cross
	6, 7, 8, 16, 17, 18.	9, 10, 19 20.		1, 2, 3, 11, 12, 13.	4, 5, 14, 15.
115	.000040c	.000000	225	.000090c	.000099c
230	107c	19c	435	199c	178c
340	175c	56c	660	294c	252c
460	233c	70c	910	381c	353c
570	271c	88c	1080	553c	429c
685	325c	96c	1300	678c	548c
790	377c	99c	1500	892c	648c
910	443c	132c	1680	1143c	764c
1030	501c	146c	1915	1474c	826c
1040			2160		

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2063.

Unit Stress	Gauge Line					
	1	2	3	11	12	13
225	.000040t	.000087c	.000157c	.000027c	.000097c	.000213c
435	33t	173c	260c	133c	233c	430c
660	20t	263c	420c	193c	313c	597c
910	30c	353c	410c	293c	437c	760c
1080	123c	477c	750c	383c	617c	967c
1300	207c	560c	903c	533c	743c	1123c
1500	317c	750c	1100c	743c	1000c	1440c
1680	443c	913c	1347c	1030c	1350c	1773c
1915	513c	1053c	1633c	1463c	1983c	2200c
2160						

"c" denotes compression, "t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2063

Unit Stress	Gauge Line			
	4	5	14	15
225	.000007c	.000120c	.000103c	.000167c
435	33c	217c	137c	327c
660	80c	350c	187c	390c
910	157c	500c	250c	507c
1080	247c	617c	267c	587c
1300	357c	763c	383c	690c
1500	443c	897c	473c	780c
1680	613c	1097c	553c	793c
1915	703c	1263c	557c	780c
2160				

"c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2063

Unit Stress	Gauge Line					
	6	7	8	16	17	18
115	.000027c	.000160c	.000077c	.000030t	.000003c	.000003c
230	80c	270c	130c	30c	73c	60c
340	143c	317c	200c	63c	-	153c
460	160c	410c	267c	140c	-	190c
570	220c	410c	307c	187c	-	230c
685	260c	480c	320c	260c	-	307c
790	297c	507c	340c	363c	-	380c
910	363c	550c	383c	443c	-	477c
1030	393c	587c	427c	533c	-	563c
1040						

"t" denotes tension, "c" denotes compression.

UNIT STRESSES AND UNIT DEFORMATIONS, 2063.

Unit Stress	Gauge Lines			
	9	10	19	20
115	.000000	.000060c	.000017t	.000043t
230	27c	83c	23t	10t
340	60c	130c	07c	27c
460	67c	133c	43c	37c
570	77c	157c	63c	53c
685	83c	163c	80c	57c
790	60c	127c	127c	83c
910	73c	137c	187c	133c
1030	100c	117c	230c	137c
1040				

"t" denotes tension, "c" denotes compression.

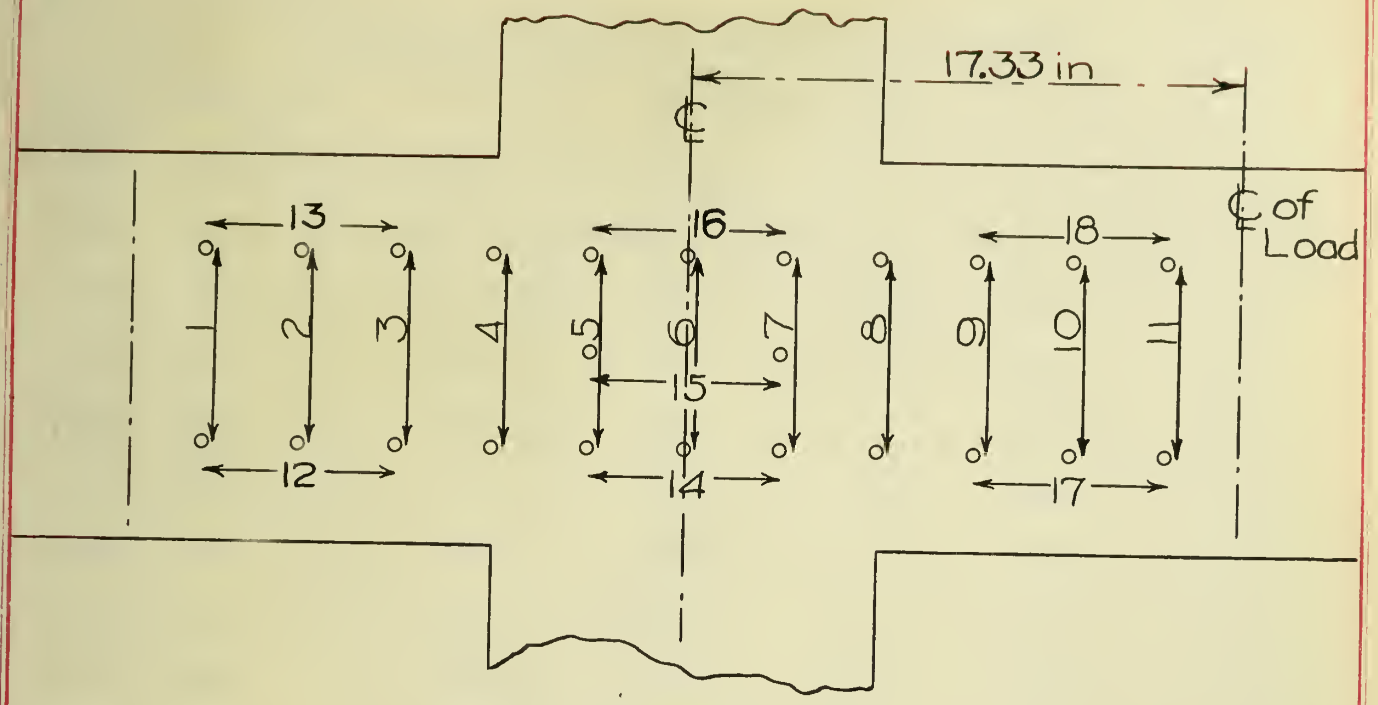
UNIT STRESSES AND UNIT EXPANSIONS, 2063.

Horizontal Arm			Cross		
Unit Stress	Expansion		Unit Stress	Expansion	
	Before	After		Before	After
115	.000000	.000000			
230	01t	01t	115 and 225	.000002t	.000002t
340	01t	01t			
460	04t	04t	230 and 435	06t	06t
570	04t	04t			
685	06t	06t	340 and 660	12t	14t
790	10t	10t			
910	11t	11t 101t[z]	460 and 910	17t	138t[z]
1030	100t	-			
			570 and 1080	140t	140t
			685 and 1300	144t	145t
			790 and 1500	154t	155t
			910 and 1680	161t	161t 372t[z]
			1030 and 1915	374t	-

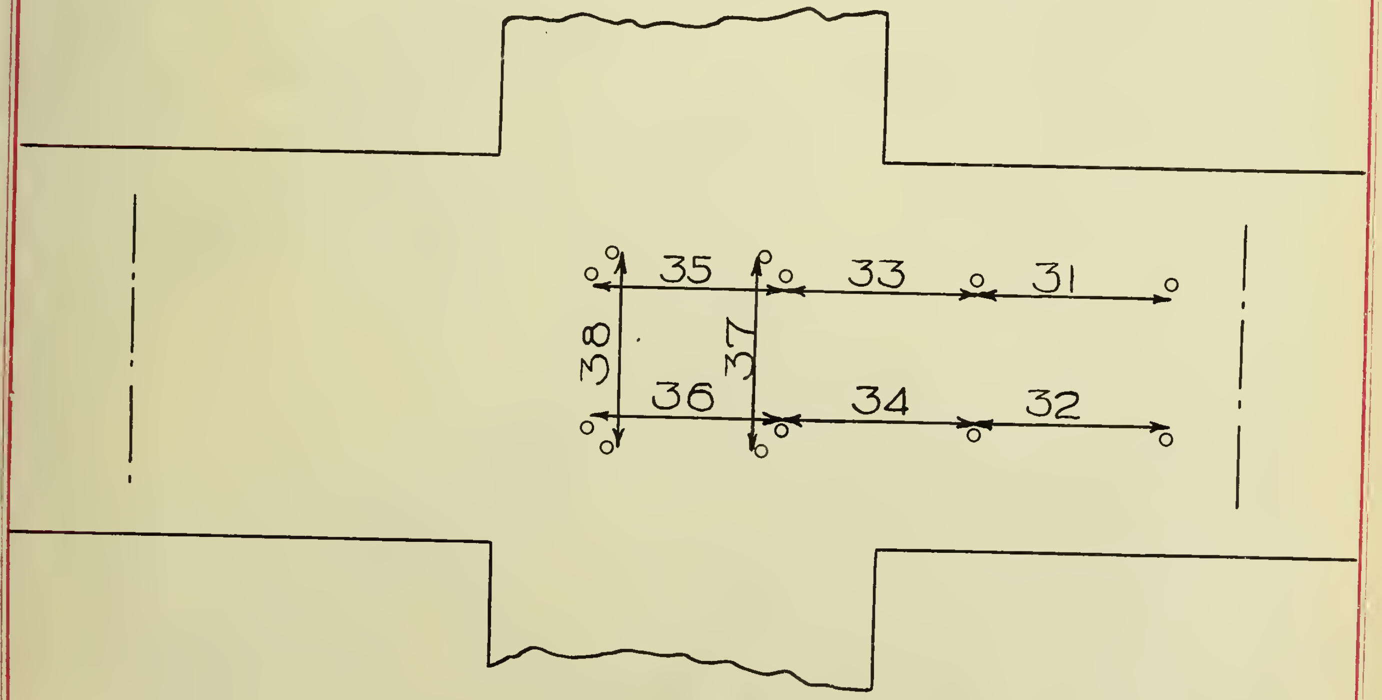
[z] Instrument disturbed, readings taken afterward .

"t" denotes tension.

2001



Compression Face



Tension Face

UNIT STRESSES AND UNIT DEFORMATIONS, 2001

Total Load lb.	Computed Unit Stress, f_c	Gauge Line				
		1	2	3	4	5
9800	230	.000007t	.000007t	.000010t	.000010c	.000017c
19900	390	10t	20t	10c	63c	117c
30000	670	40t	27t	23t	100c	210c
40000	840	50t	50t	30t	143c	313c
50000	1050	47t	74t	7t	230c	410c
60000	1180	83t	80t	13t	300c	533c
70000	1340	127t	123t	30t	377c	637c
80000	1460	147t	150t	40t	463c	740c
90000	1500	190t	180t	40t	540c	890c
100000	1665					

"c" denotes compression

"t" denotes tension

UNIT STRESSES AND UNIT DEFORMATIONS, 2001

Gauge Line

6	7	8	9	10	11	12
.000070c	.000043c	.000020t	.000057t	.000037t	.000017t	.000100c
133c	97c	23c	60t	77t	87t	183c
253c	217c	97c	40t	97t	170t	340c
310c	257c	120c	123t	87t	190t	510c
433c	363c	170c	93t	90t	183t	633c
503c	473c	250c	117t	117t	240t	870c
633c	560c	307c	140t	157t	270t	1067c
720c	653c	327c	157t	197t	307t	1267c
870c	770c	277c	173t	237t	360t	1537c

UNIT STRESSES AND UNIT DEFORMATIONS, 2001

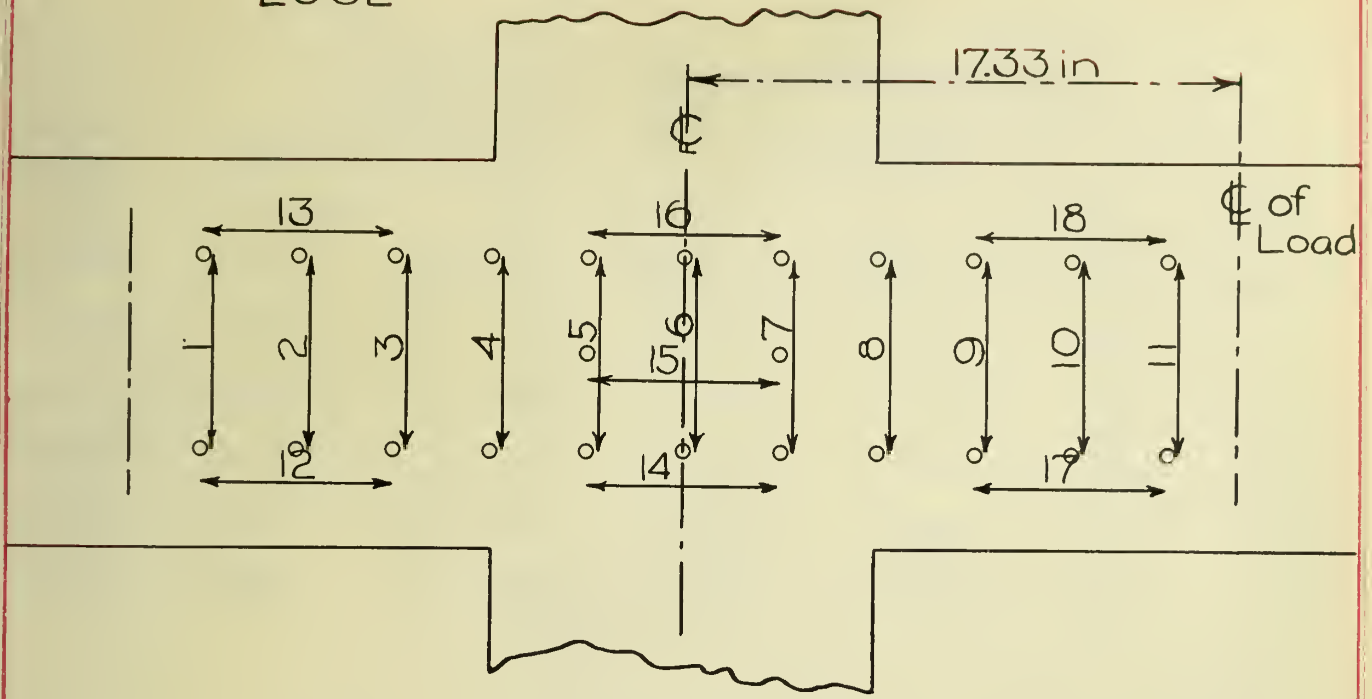
Gauge Line

13	14	15	16	17	18
.000087c	.000073c	.000063c	.000077c	.000100c	.000007t
170c	187c	153c	173c	233c	107c
340c	297c	260c	287c	380c	263c
497c	440c	353c	370c	503c	427c
600c	510c	440c	433c	643c	517c
783c	600c	547c	573c	787c	697c
970c	723c	657c	660c	983c	850c
1113c	830c	760c	743c	1150c	1020c
1333c	933c	863c	833c	1357c	1153c

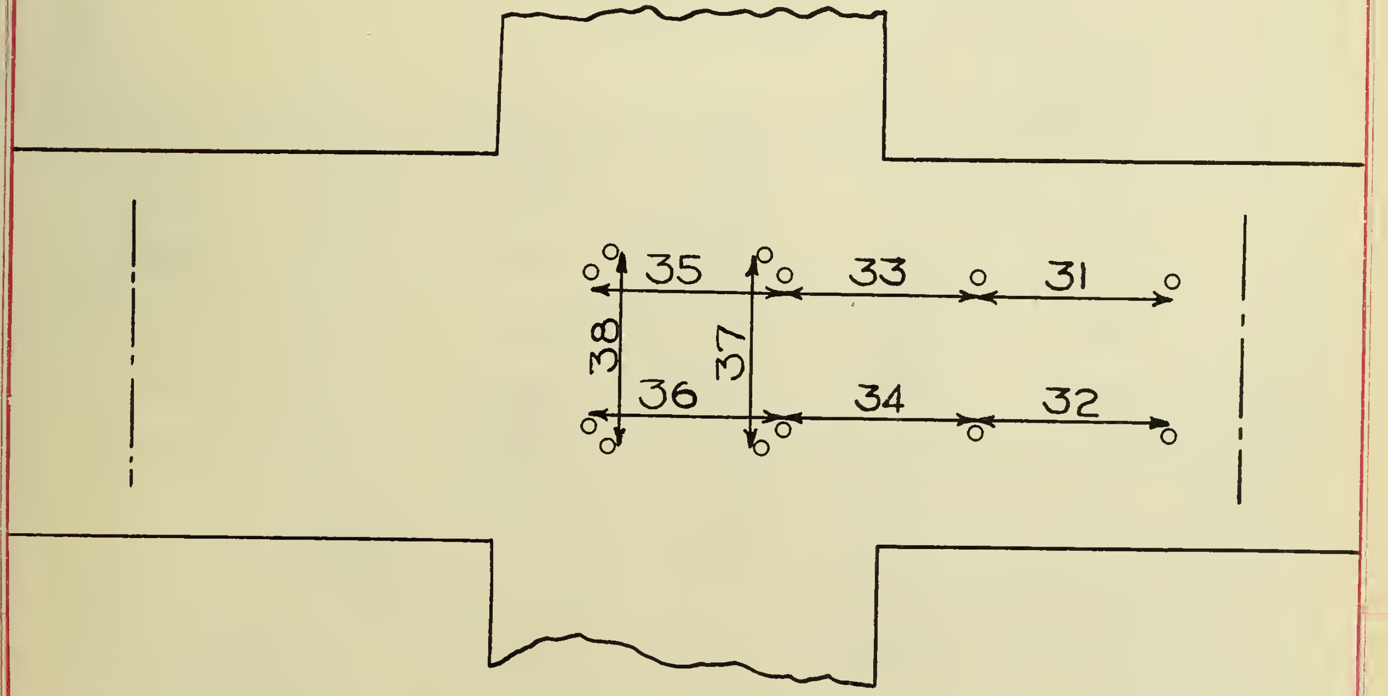
UNIT STRESSES AND UNIT DEFORMATIONS, 2001

Gauge Line					
31	32	33	34	35	36
.000080t	.000037t	.000107t	.000043t	.000003t	.000077t
123t	123t	183t	163t	170t	187t
270t	277t	277t	323t	280t	397t
380t	367t	373t	463t	427t	513t
493t	520t	517t	613t	583t	583t
600t	623t	620t	713t	657t	700t
753t	797t	747t	860t	850t	800t
853t	893t	873t	950t	903t	953t
997t	1023t	1013t	1080t	983t	1183t

2002



Compression Face



Tension Face

UNIT STRESSES AND UNIT DEFORMATIONS, 2002

Total Load, lb.	Computed Unit Stress, f_c	Gauge Line 1	2	3	4	5
19700	430	.000013 c	.000000	.000043 c	.000093 c	.000123 c
39300	840	30 t	30 t	63 c	220 c	307 c
59300	1220	87 t	57 t	83 c	333 c	493 c
69200	1390	130 t	80 t	83 c	400 c	567 c
79200	1540	163 t	103 t	107 c	473 c	683 c
89000	1660	193 t	160 t	103 c	513 c	767 c

Gauge Line 6	7	8	9	10	11	12
.000103c	.000150c	.000100c	.000017t	.000080t	.000037c	.000257c
253c	243c	247c	03c	137t	03c	547c
377c	373c	307c	07t	123t	00	763c
430c	450c	383c	10t	153t	27t	1000c
533c	530c	417c	30t	153t	53t	1167c
643c	603c	517c	27t	190t	43t	1380c

"c" denotes compression,

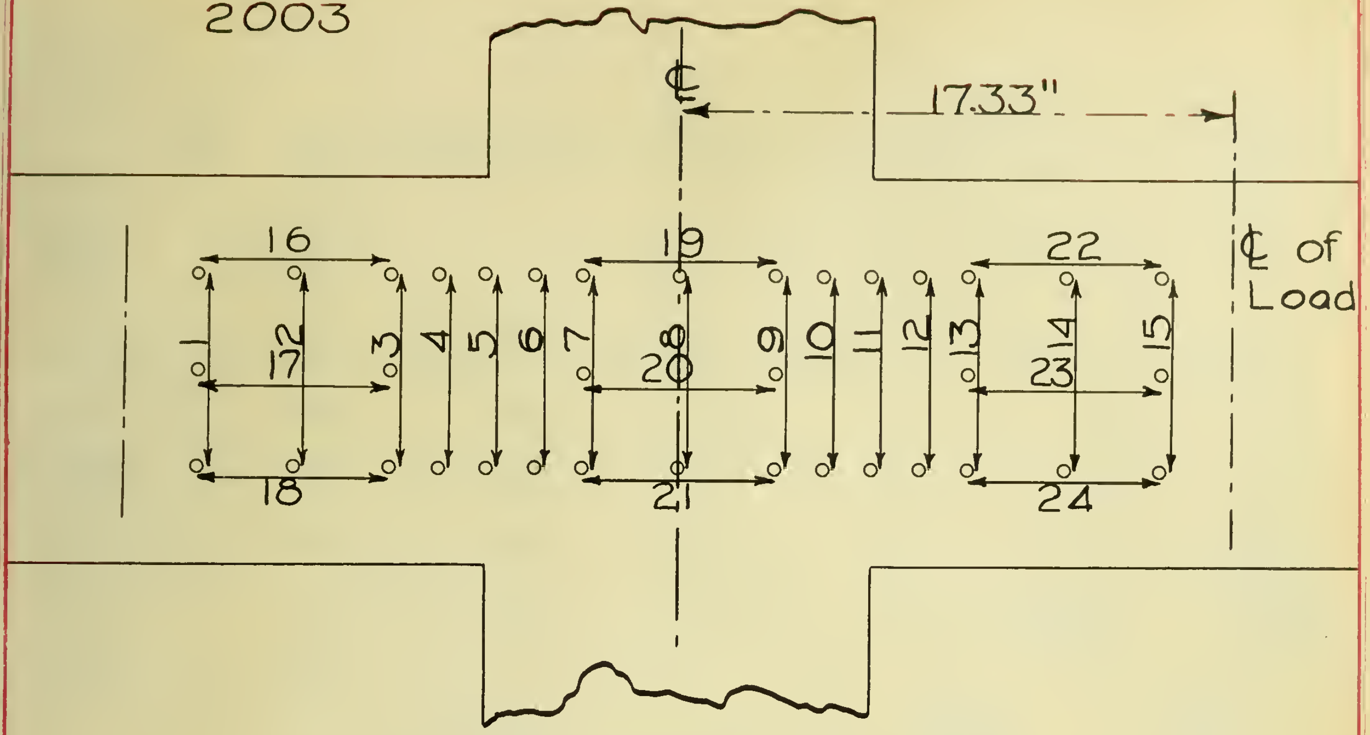
"t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2002

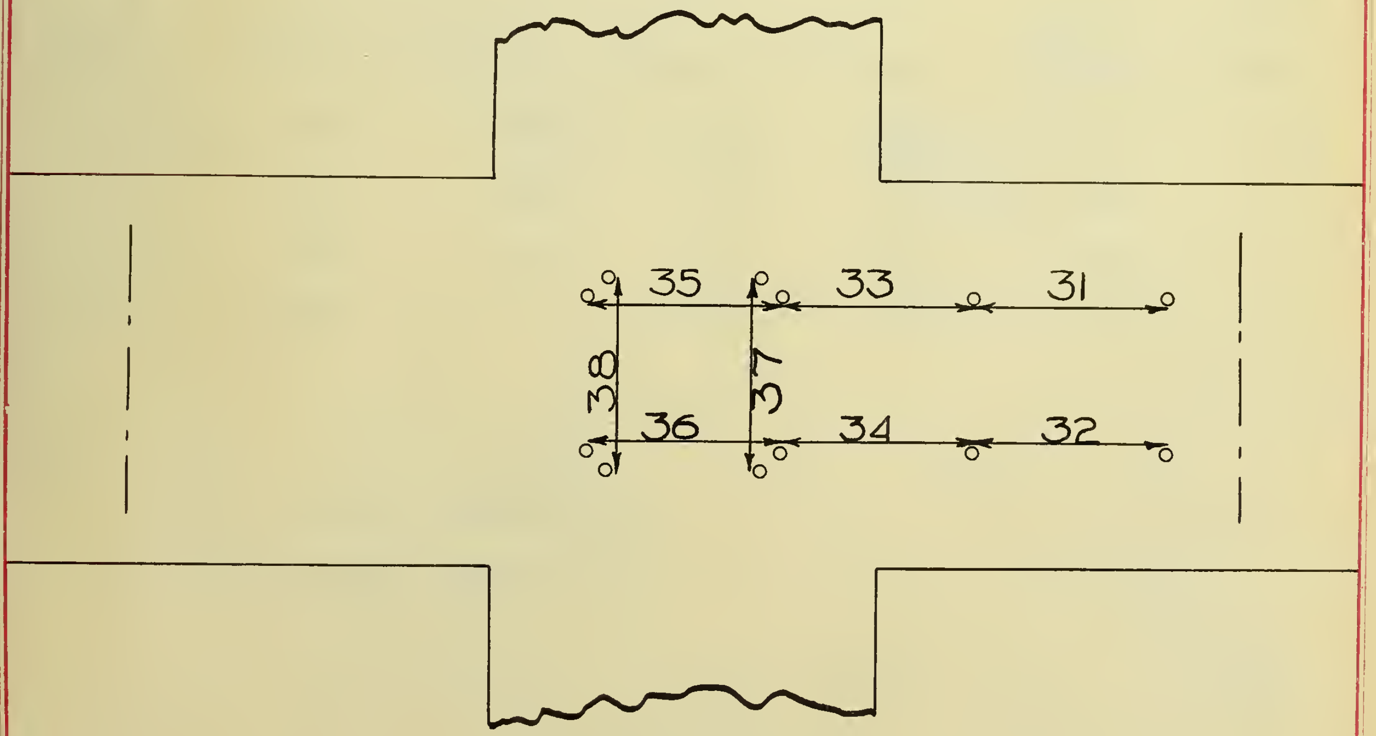
Gauge Line					
13	14	15	16	17	18
.000210c	.000130c	.000160c	.000173c	.000323c	.000230c
480c	347c	380c	330c	677c	473c
723c	503c	580c	510c	1110c	743c
873c	570c	673c	577c	1530c	890c
1033c	647c	727c	650c	1580c	1033c
1193c	750c	843c	733c	1813c	1187c

Load lb.	Gauge Line					
	31	32	33	34	37	38
19700	.000220t	.000357t	.000193t	.000260t	.000087t	.000170t
39300	447t	617t	470t	510t	290t	440t
59300	633t	823t	693t	727t	483t	613t
69200	800t	963t	783t	833t	620t	807t
79200	873t	1063t	867t	917t	717t	927t
89000	1017t	1207t	993t	1040t	820t	1013t
72500	983t	1357t	943t	960t	713t	850t
0	243t	507t	230t	143t		

2003



Compression Face



Tension Face

UNIT STRESSES AND UNIT DEFORMATIONS, 2003

Total Load lb.	Computed Unit Stress, f_c	Gauge Line 1	2	3	4	5
15000	340	.000017t	.000030t	.000017t	.000010c	.000057c
29700	660	87t	83t	23t	30c	147c
44000	920	60t	80t	23c	113c	270c
57000	1155	120t	117t	27t	117c	357c
66000	1280	120t	113t	53c	230c	553c
75000	1410					

Gauge Line 6	7	8	9	10	11	12
.000127c	.000117c	.000083c	.000110c	.000100c	.000060c	.000007t
270c	280c	220c	250c	187c	110c	17t
397c	473c	397c	413c	317c	163c	00
547c	653c	520c	630c	407c	190c	10t
873c	1117c	973c	1047c	857c	567c	100c

"c" denotes compression,

"t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2003

Gauge Line

13	14	15	16	17	18	19
.000007t	.000027t	.000067c	.000103c	.000127c	.000093c	.000240c
23t	20t	47c	330c	267c	313c	420c
43t	80t	47c	567c	470c	523c	543c
37t	153t	13t	757c	667c	777c	683c
00	143t	73t	770c	653c	807c	660c

Gauge Line

20	21	22	23	24	(21)
.000223c	.000443c	.000200c	.000213c	.000223c	(.000163c
290c	607c	473c	447c	473c	327c
547c	707c	673c	723c	640c	427c
717c	857c	983c	1013c	990c	577c
600c	857c	1067c	1123c	1017c	577c)

"c" denotes compression,

"t" denotes tension.

UNIT STRESSES AND UNIT DEFORMATIONS, 2003

Gauge Line

31	32	33	34	36	37	38
.000253t	.000197t	.000283t	.000097t	.000130t	.000100t	.000100t
390t	380t	430t	233t	293t	187t	277t
517t	550t	607t	397t	473t	337t	437t
567t	683t	807t	573t	650t	533t	573t
740t	640t	813t	477t	670t	897t	887t

"t" denotes tension.


Monastery Hill