ELECTRIC ARC WELDING
ON A
STEEL COMPRESSION MEMBER

"An Investigation of the Effects Produced by Electric Arc Welding on a Steel Compression Member.

with

An Analysis of the distribution of Welding Stresses in Steel Plates."

Submitted for the degree of Master of Engineering, McGill University, Montreal.

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INTRODUCTION.

Much has been said concerning the value of welded fabrication in structural steel design. In fact, so rapid has been the growth of this method of contruction, that the investigation of its possibilities has been a subject of much research in recent years. Usually when a new method is in its infancy, its limitation and its adaptability are deduced, first, by "trial and error". Tests are carried out to ascertain its properties under certain required conditions, and if the tests prove satisfactory the method is adopted. In due course, by means of mathematical deduction and laboratory research, general laws are formulated to govern, under all practical conditions, the use of the new method.

It has been indicated from time to time that much unexplained phenomena exist in the use of electric arc welding. When a steel plate or other structural shape is electrically welded, it shortens and warps as the deposited weld metal begins to cool. This warping can often be greatly minimized by skillful operation on the part of the welder, but the ultimate contraction of the member, in the direction parallel to the weld, is generally evident. That this shortening is an indication of stresses set up in the member, due to the welding process, is also apparent.

The object of the investigation is twofold. In Part 1 of this paper experiments are conducted on a welded steel column to determine the effects of these residual stresses upon the strength of the member. In Part II an analysis is made of the distribution and magnitudes of the stresses in various sizes of welded plates. The tests will be limited to electric arc welding.

HISTORICAL SKETCH.

One of the first attempts to record the shrinkage in a member, due to electric arc welding, was that carried out in a test at the Dominion Bridge Company, Lachine, P.Q. in 1928. To quote from a paper by A.S. Wall, M.E.I.C., presented before the Montreal Branch of the Engineering Institute of Canada, January 1929: "When members are welded continuously there is apt to be a very positive change in length. An approximate idea of the magnitude of this distortion was obtained by some rough experiments in the shops of the Dominion Bridge Company.

Some box girders were built, each made up of two 15" X 3/8" cover plates, and two 16" X 3/8" web plates, with the webs about ten inches apart. Points 9 feet 8 inches apart were marked on the center lines and near the edges of each plate and the temperature noted. The two webs were then welded to the top cover with continuous 5/16" fillets inside and out. The bottom cover was next attached using 15/16" fillets on the outside only. When the material had cooled the temperature was again taken and the distances between the marked points were measured. The shortening was approximately 1/8 inch in 10 feet.

The axial distortion depends, of course, on the total amount of heat applied relative to the cross-section of the member or perhaps the ratio of weld cross-section to main material cross-section. The total shortening depends also on the length of the member".

This experiment was not carried any further, but from the fact that the parts of the girder remote from the welds had not been raised in temperature sufficiently to change the structure of the metal or even create any marked degree of expansion, it was obvious that high residual stresses must have existed. These stresses, to produce equilibrium, must have been balanced by corresponding stresses of opposite sign in the welds accompanied by some of the parent metal adjacent to the **welds**.

Because of this condition, Mr. R.M. Hardy, Graduate Student in the Department of Civil Engineering, McGill University, was asked to take certain observations on a welded test specimen, in conjunction with an experiment he was carrying out to determine the distribution of stress in parallel weld fillets. Mr. Hardy appended these observations to a thesis entitled "Further Investigation of the Distribution of Stress in Parallel Weld Fillets" submitted in May 1930.

These observations consisted of measurements, before and after welding, of the welded joint fabricated for his own research. The joint was made up of two plates A and B joined together by two channels C1 and C2 back to back and welded to the plates. (see figure 1.)

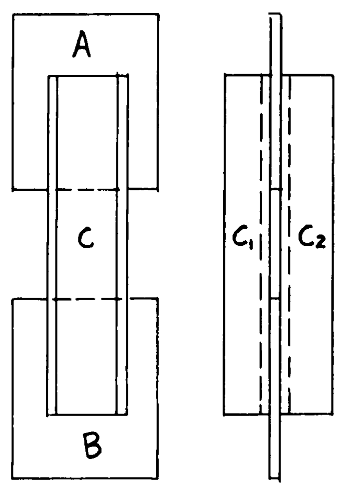


Fig. 1

It was his hope to observe some change in the distribution of stress as the member was put under load. Mr. Hardy's results did not reveal any noticeable redistribution of stress as the joint was loaded, nor did any initial stress in the joint apparently affect the distribution of stress along the weld itself. A definite shortening in the member was the only effect he was able to record.

The next research with regard to this phenomenon was in 1931, at McGill University by Mr. J.F. McDougall, M.Sc. In a paper entitled "The Initial Stress is in Welded Joints" Mr. McDougall gave further evidence of the existance of these residual stresses.

The specimen used in his test was a 7/8-inch steel plate, 6 inches wide by 5 feet long, with a V- groove planed along the longitudinal edges. (see figure 2.) The welding was carried along each groove so that the weld metal completely filled the notch to within one foot six inches of each end. The plate was measued and then welded. Upon remeasurement, the plate was found to have shortened.

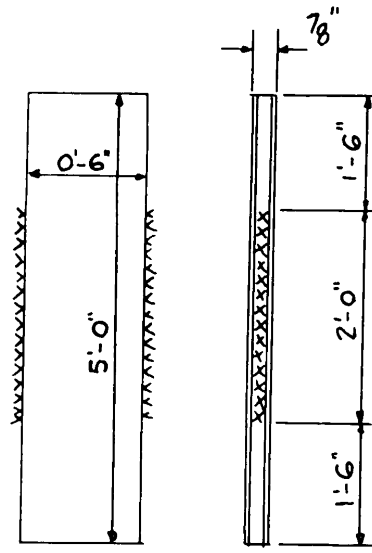


Fig. 2

Mr. McDougall's contention was, in brief, that if the central portion of the plate was initially in compression while the outer portions (including the welds), were in tension, upon submitting the specimen to a tensile pull, that portion of the plate initially in tension would reach its elastic limit before the central portion (initially in compression). Thus the load would be redistributed, with the central portion receiving more and more of the load as the outer parts reached the yield point. If, therefore, a stress-strain diagram were drawn with average deformations plotted against loads, the graph produced would deviate from a straight line at an average stress well within that representing the elastic limit, considering the whole section as acting uniformly. Mr. McDougall's findings showed this to be the case.

Part 1

RESOLUTION

The behaviour of residual stresses in welded members has been investigated so far with specimens submitted to Tensile Loads only. It has been indicated that the ultimate strength of welded tensile members has neither been impaired, nor has any appreciable effect been noticed on the character of the welds themselves, within practical working limits. There remains, however, the examination of the effects these hidden stresses will have on members submitted to Compression Loads. The indications are that while welded structures may be designed in which the tensile members can safely be assumed to be unaffected by the welding process, within the usual factor of safety limits, the same assumption may not be true for members subjected to compression loading.

It is the purpose of this test to investigate the extent to which stresses produced by welding affect the load carrying capacity of compression members, with regard, not only to the ultimate strength of such members, but also to the action of these welding stresses during the loading period.

THEORY

As we have already seen, tests have revealed that there is an internal stress equilibrium in a steel member when electrically welded. If such a member for example, as a steel column H-section, were welded for some distance along the fillets, there would result a setting-up of compression stresses in the parts of the flanges remote from the fillets, and possibly in the center portion of the web. These compression stresses would be balanced by tension stresses in and about the section of the welds.

It is not to be supposed that there is any dividing line between the maximum compression and maximum tension stresses, nor is it thought that the welds themselves resist all the compression..The change from maximum tension in the welds to maximum compression in the edges of the flanges or the center of the web, is necessarily gradual.

Consider one flange of a column that has been welded along the fillets. After welding, the stress distribution would resemble that shown in figure 3, where the initial maximum compression is fc and the initial maximum tension is ft. If the column is submitted to some load W so that the average increment of stress is $\frac{W}{\text{area}}$ equals fx and is distributed uniformly across the section, the maximum compression would equal (fc + fx) and the maximum tension would equal (ft + fx).

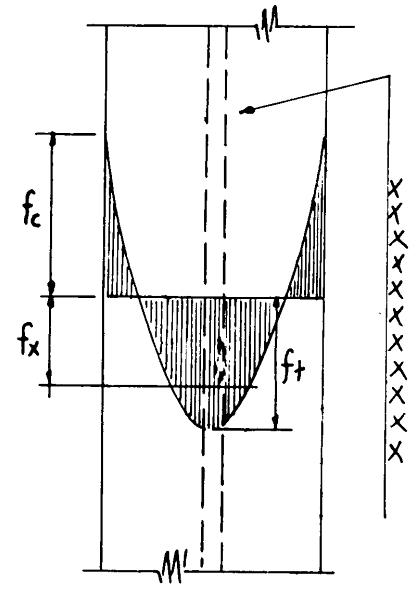


Fig. 3

Provided (fc + fx) is below the yield point of the material, upon lifting the load the column would return to its original length. If, however, the load is increased until (fc + fx) is equal to or greater than the yield point of the material, upon releasing the load there will be found some permanent deformation. Theoretically, failure of the column might be expected to accur soon after any portion of the column has reached the yield point of the material.

THE SPECIMEN

For the purpose of this investigation two columns were chosen. As no theoretical formula can be expected to give the exact strength of such a member under varying conditions of loading, and because so many other factors affect all column tests, one column was taken as a basis of comparison with the one to be welded. The size of this column was governed, of necessity, by the capacity of the machine in which the tests were to be made. Accordingly, two 4 inch C-H-sections at 13.8 #/ ft., cut to a length of 3 feet 3 inches from the same stock, were considered to be most suitable for the investigation. Although the slenderness ratio was not great enough to permit of any appreciable column action, a longer specimen was not used for the reason that it would not fit in the testing machine.

APPARATUS

All loading tests were carried out by means of a Wicksteed testing machine. This is a single lever type of machine and is hydraulically operated. Specimens are tested in the vertical position. It has a capacity of 217,000 lbs. and can be used for both tension and compression tests.

Marten's mirror extensometers were employed to record the strain in the columns at the various sections when under applied loads. These extensometers are calibrated to read to 0.00001 inches, and when used on a gauge length of 2 inches, record unit stresses to 300 lbs. per square inch. To eliminate errors introduced by any rotation of the specimen, or by the flattening-out of minute indulations on the surface of the steel to which the knife edge of the extensometer might come in contact, it is necessary to reverse the instrument and to repeat the readings. The mean of these readings will be a measure of the actual strain.

In previous tests the Howard gauge has been used to determine the shrinkage due to the welding process. This gauge is a 10-inch micrometer screw gauge designed to read to 0.001 inch on lengths of 10 inches only. To determine the shrinkages over shorter lengths than 10 inches, measurements have to be read beyond the welds, and much interpolation is involved. It is also necessary to drill holes in the specimen in which to rest the gauge points of the instrument. During welding these holes often become distorted or filled with small particles of spattered weld metal. All things taken into consideration, it was decided to adopt a different method for recording these measurements.

The Linear Comparator, an instrument used for comparing standard meter bars, was employed. This instrument was manufactured by The Waterville Iron Works, Waterville, Maine, and has been in McGill University for a number of years. It is set up in the Geodetic Laboratory, where it is protected from rapid changes in temperature. The Comparator consists of a travelling block upon which two micrometer microscopes "A" and "B" are mounted. (see figure 22).
An adjustable platform is provided to receive the specimen to be measured. The movement of the block is parallel to the length of the platform. One microscope "A" is focused on a standard bar, and the other is focused on the specimen to be measured. Fine hair-like scratches on both the standard bar and on the specimen determine the points of measurement. It may readily be seen that one bar or specimen may be measured with reference to another by taking simultaneous readings at each graduation. Of course, the graduations on each

must compare closely enough so that at each interval, the scratches will be within the fields of vision of their respective microscopes. The accuracy of the measurements will depend upon the number of readings taken for each measurement, on the focusing of the micro-copes, and on the character of the scratches. The smallest graduation on microscope "B" equals 0.0001 of a revolution of the micrometer, equivalent to 0.004464 inches.

PREPARATION

The ends of each column were faced in a lathe so that the loads might be applied evenly while the columns were being tested.

The graduations and reference markings may be followed by consulting figure 15. Five longitudinal lines, 7/8-inches apart, were drawn parallel to the axis of the column along the backs of each flange, marked A, B, C, D, E, and I, J, K, L, M, so that C and K were in the centers of their respective flanges. A line G was drawn along the center of one face of the web. The column was then graduated in 2 inch intercepts, to within 4½ inches of each end, by lines drawn at right angles to those already mentioned. Sections 00 and 16 are one inch intervals which were added afterwards. The column to be welded was marked No. 1 and the reference column was marked No. 2.

A fine scratch had to be made at each graduation where a measurement was to be taken with the Comparator. In order that the scratches could be made sufficiently fine, and a bright reflecting plane be obtained enabling them to be easily observed through the microscope, the surface at each point was spot ground with an emery wheel.

Measurements were limited to the flanges only, because it was considered impractical to make measurements on the web. The scratches were made by delicate manipulation of a very sharp scratchall. Each scratch was then surrounded by four heavier scratches making a 1/16-inch square. The width of the fine scratches was on the average less than 0.002 inches.

PROCEDURE

To determine the stress-strain characteristics of the column material, three coupons, nine inches in length, were cut from the same stock as the main test specimens. One of these was taken from the flange and the other two from the web. The flange coupon and one of the web coupons were planed on all surfaces. The rolled surface or skin was left on the other web coupon. These coupons were all of approximately the same dimensions and the tests on them were made in tension. Two extensometers with four inch gauge lengths, placed on opposite faces of the test coupons, recorded the strains at the various applied loads. The mean of the readings at the different loads gave the correct deformations.

No. 1 column was placed in the testing machine and the stress distributions about the sections ΘΘ - 0, 7 - 8 and 15 - 16, were examined for an applied load of 60 kips.

In placing the column between the compression grips of the testing machine, considerable care had to be taken to permit the load to be applied evenly across the section of the column. A ball and socket bearing plate was used to support the column at the base; and at the top, the column was restrained.

The measurement of the column in the Comparator was the next consideration. Readings were taken at every section between 0 and 15 along the fine rows on the backs of each flange, (150 measurements in all).

In making these measurements, three micrometer readings with microscope "B" were recorded for one setting of microscope "A". Microscope "A" being of a much higher power than microscope "B", and the scratches on the **standard** bar being of a much better character than the scratches on the specimen, one setting of "A" was considered to be well within the accuracy of three readings of "B". This procedure greatly simplified the calculations necessary for the reduction of the measurements. It was, therefore, not actually necessary to read the micrometer on "A". This micrometer was fixed, and the block supporting the two microscopes was moved until the fixed hair in the reticule of "A" became tangent to the zero scratch on the standard bar. Three readings with the micrometer on "B" were taken for the corresponding zero scratch on the specimen. The block was then moved until the fine hair in "A" was tangent to the first scratch on the standard bar, and three more corresponding readings were taken. In like manner readings were taken for all other gauge lines.

The scratches having been protected by placing a strip of galvanized iron on the backs of each flange, the column was sent to the Dominion Bridge Company to be welded. The procedure of welding was carried out in such a way that when a tendency for the specimen to go out of alignment was observed, the operator worked at another place on the opposite side in order to compensate for the distortion. The final result was a substantially straight column with a continuous

$\frac{3}{8}$-inch weld along each fillet to within $6\frac{1}{2}$ inches of the ends, i.e. between gauge lines 1 and 14. Bare wire electrodes were used. Upon the return of the specimen to the laboratory, measurements as before were made in the Comparator.

In order to correct for any small amount that the column might have been out of alignment due to the process of welding, the ends were refaced. The specimen was then placed in the testing machine and extensometers placed at A8 -7,E8-7,G7-8,I 7-8,M7-8, and O00-0. The column was gradually loaded from zero to 100 kips, by increments of 10,000 lbs. After each increment the load was taken off the column. The extensometers were read before and after each leading. By this means it was possible to detect, qualitatively, any permanent deformation in the fibres of the column caused by the applied loads.

The specimen was again placed in the Comparator to measure the actual amount it had been shortened by the load of 100 kips. As this was very small, measurements were taken between 0 and 15 only, leaving out all intermediate gauge lines.

This having been completed, the column was placed in the Wicksteed Testing Machine and the stress distribution was examined at sections 00-0, 15-16, and section 1, with one inch gauge extensometers, and at 3-4 and 7-8 with two inch gauge extensometers, for loads of 20, 60, and 100 kips. Care was taken as before to enable the load to be applied uniformly on the specimen, but it so happened that the loads were not evenly applied.

As we are interested in average loads, this, however, did not greatly effect the information to be derived from this examination, but before the column was tested to destruction it was made certain that the loads were applied uniformly across the section. For the final test, extensometers were placed at A8-7, C7-8, E8-7, G7-8, I 7-8, K8-7, and M7-8. (see figure 10). The load was gradually increased until the column buckled and failed. The extensometers were read at each increment.

Column No.2 was then placed in the testing machine and adjustments were made until the loads were being applied uniformly. Distribution of stress about sections 00-0 and 7-8 were examined for a load of 60 kips. Extensometers were arranged as in the final test on column No.1, and column No.2 was then tested to destruction.

NOTE: When it is mentioned that an extensometer was placed at A7-8, it means that the extensometer was placed in row "A" between gauge lines 7 and 8, and that the mirror was at 7. A8-7 would indicate the same except that the mirror would be at 8.

Section 1 is at the extremities of the welds.

RESULTS & DISCUSSION

Young's modulus for the material of the columns was taken as the mean result derived from the three coupons. (see page 10).

Coupon A : (web) $\quad E = \dfrac{\text{Unital Stress}}{\text{Unital Strain}}$

$$= \frac{28640}{0.976}$$

$$= 29.0 \times 10^{6}$$

Coupon B : (flange, planed) $\quad E = \dfrac{21640}{0.747}$

$$= 29.4 \times 10^{6}$$

Coupon C : (web, planed) $\quad E = \dfrac{22020}{0.712}$

$$= 30.9 \times 10^{6}$$

The mean value of $E = 29.7 \times 10^{6}$

The Yield Point was taken as the mean of the values resulting from tests with Coupons C and B. As there is a greater cross-section of flange area than web area, and as it is also doubtful if the rolled surface would act as effectively in raising the yield point in compression as in tension, the mean of Coupons C and B would give the most reasonable value.

Coupon B :- Y.P. =	39900	lbs. per square inch.
Coupon C :- Y.P. =	37000	lbs. per square inch.
Mean Yield Point =	38500	lbs. per square inch.

Ultimate failure :-

Coupon A :	68500	lbs. per square inch.
Coupon B	66800	lbs. per square inch.
Coupon C	65800	lbs. per square inch.
Mean ultimate failure	67000	lbs. per square inch.

Sample observations illustrating the method of reduction to determine the shrinkages in the column due to the process of welding are shown in Table III. In Table IV all shrinkages are tabulated. These results are also shown graphically in figure 6. For the sake of clarity, however, the average shortening over 4 inches has been plotted in some cases instead of the average over 2 inches as shown in Table IV. It will be noticed, in the section just beyond the weld, that the flanges have lengthened, indicating possible initial tension in this section. This is probably compensated for by an equivalent amount of compression in the web at this point, although no measurements were taken for the web. The angular distortion of the column was very slight, due no doubt to the extreme care taken during the welding procedure. The only noticeable distortion other than the recorded shrinkages, was that the flanges from section 1 to 14 (weld section), had been bent towards each other about an eighth of an inch. This small amount would not, however, affect appreciably the moment of inertia.

The following will serve as an indication of the accuracy of the shrinkage measurements.

The probable error of setting microscope "A"	$= \pm 0.02$ revs.of "B".
The probable error of reading microscope "B"	$= \pm 0.03$ revs.of "B".
The probable error due to focusing "B" and direction of light on scratches before welding	$= \pm 0.02$ revs.of "B".
and after welding	$= \pm 0.04$ revs.of "B".

Let M_1 equal the measurement before welding and M_2 the same measurement after welding.

$$\text{Error in } M_1 = \sqrt{\pm(.02)^2 \pm \left(\frac{.03}{\sqrt{3}}\right)^2 \pm(.02)^2}$$

$$EM_1 = \pm .035 \text{ revs. of "B".}$$

$$\text{Error in } M_2 = \sqrt{\pm(.02)^2 \pm \left(\frac{.03}{\sqrt{3}}\right)^2 \pm(.04)^2}$$

$$EM_1 = \pm .049 \text{ revs. of "B".}$$

If X equals the measure of any one shrinkage

$$X = M_2 - M_1$$

$$\text{Error in } X = \sqrt{\pm(EM_2)^2 \pm (EM_1)^2}$$

$$Ex. = \sqrt{\pm .035^2 \pm .049^2}$$

$$= \pm .06 \text{ revs. of "B".}$$

$$= \pm .06 \times .004464 \text{ in terms of inches.}$$

$$= \pm .00026 \text{ inches.}$$

The extensometer readings from Table V indicate a permanent deformation in the column at all loads above 80 kips. It cannot be said definitely that the yielding took place in the section at which the extensometers were placed, as any slight rotation of the column due to a yielding at some other section would prevent the extensometers from returning to their initial reading. It shows qualitatively, however, that somewhere along the column a yielding took place under the load of 80 kips. If this load were distributed uniformly it would be equivalent to:

$$\frac{80000}{{}^{*}4.48} = 18000 \text{ lbs. per square inch.}$$

If we take 38000 lbs. per square inch as the yield point of the material, it would indicate that there was an initial stress somewhere in the column of

$$38000 - 18000 = 20000 \text{ lbs. per square inch compression.}$$

NOTE: *Including the area of the welds the cross-sectional area equals 4.48 square inches.

The measured permanent deformation in the specimen due to the load of 100 kips (Table Vl), averaged 0.937 revs. of "B" in 30 inches, which is equivalent to:

$$\frac{0.937 \times .004464}{30} = 0.000138 \text{ inches per inch.}$$

If the metal in and about the area of the weld was initially in tension, this tension stress would have been reduced by:

$$0.000138 \times E$$
$$= 0.000138 \times 29.7 \times 10^6$$
$$= 4100 \text{ lbs. per square inch.}$$

But this reduction in stress was influenced by the increment in load from 80 kips to 100 kips, which is equivalent to:

$$\frac{20000}{4.48} = 4460 \text{ lbs. per square inch.}$$

If the yield point in any of the fibres was reached at 80 kips, the additional average stress of 4460 lbs. per square inch would be expected to produce a greater deformation than is indicated by the reduction of 4100 lbs. per square inch, as there would be undoubtedly a shifting of the load from the parts that had reached their yield point to the central area or the section that had not been stressed to the elastic limit. However, as the observations are not representative of every part of the column, the figures provide a qualitative check only on the deduction that an initial compression stress of 20000 lbs. per square inch exists. This figure must be viewed with suspicion. It is a maximum stress and not the average initial compression stress; we can best discount the result by saying that it is probably high.

The examination of the stress distributions is shown in figure 8 . From the average distribution before and after welding, it is observed that the weld has the property of adding to the cross-section of the column. That the weld should resist its share of the load is, of course, obvious from the fact that any reduction in the initial tension in the weld by application of an external load would add an equivalent amount to the capacity of that area of the section initially in compression.

In the tests to destruction, the extensometer readings as shown in Tables IX and X have been plotted against applied loads. (see figure 9, page 25). Although the welded column ultimately withstood a higher load than did the reference column, upon consulting the plotted extensometer readings it appears that the outer fibres in Column No.1 had reached their yield point before any similar yielding was witnessed with Column No.2. Although from the diagram, this difference between the two specimens is not very pronounced, it is to be remembered that Column No.1 had been stressed previously to 100 kips, and yielding was first detected at a load of 80 kips. If failure in a compression member, is considered to be when any of the fibres reach their yield point, then theoretically speaking, the unwelded column exhibited a higher strength than the welded column.

In a short strut, such as the one used in this test, the slenderness ratio is not great enough to encourage the column to buckle at the first signs of yielding of any of the metal, but rather there is a readjustment of the load as the outer fibres reach their load-carrying capacity. The center areas then take a greater share of the burden. It appears that the whole section has to reach its yield point before the column will buckle.

CONCLUSION

We observe from the foregoing results that a compression stress of considerable magnitude is set up in the parts of the web and flanges remote from the weld metal, from which it follows there must be a tensile stress (not necessarily of the same magnitude), in the welds and parent weld metal. It can readily be deduced also that the shortening in the column due to the welding process is not all elastic deformation but that the greater part is permanent. Finally, upon testing the welded column to failure, we find that the initial stresses in the column do not materially affect its ultimate strength, but the weld itself adds to the cross-sectional area.

These results do not tell us what would take place with a long column in which the buckling load is the governing factor of strength. In such cases, the maximum allowable fibre stress is sufficiently low so that any initial stresses of the nature indicated by this experiment would not, it is thought, reduce the load-carrying capacity of the column. Nevertheless, it is quite conceivable to understand where a column in practice might be subjected to a load, which, when coupled with the initial residual stress, would stress parts of the column to approximately the Yield Point. It would be difficult to state what effect these high stresses would have over long periods of time without further knowledge with regard to "long time creep"; but the writer believes that time would add to, rather than deduct from, the strength of such a member.

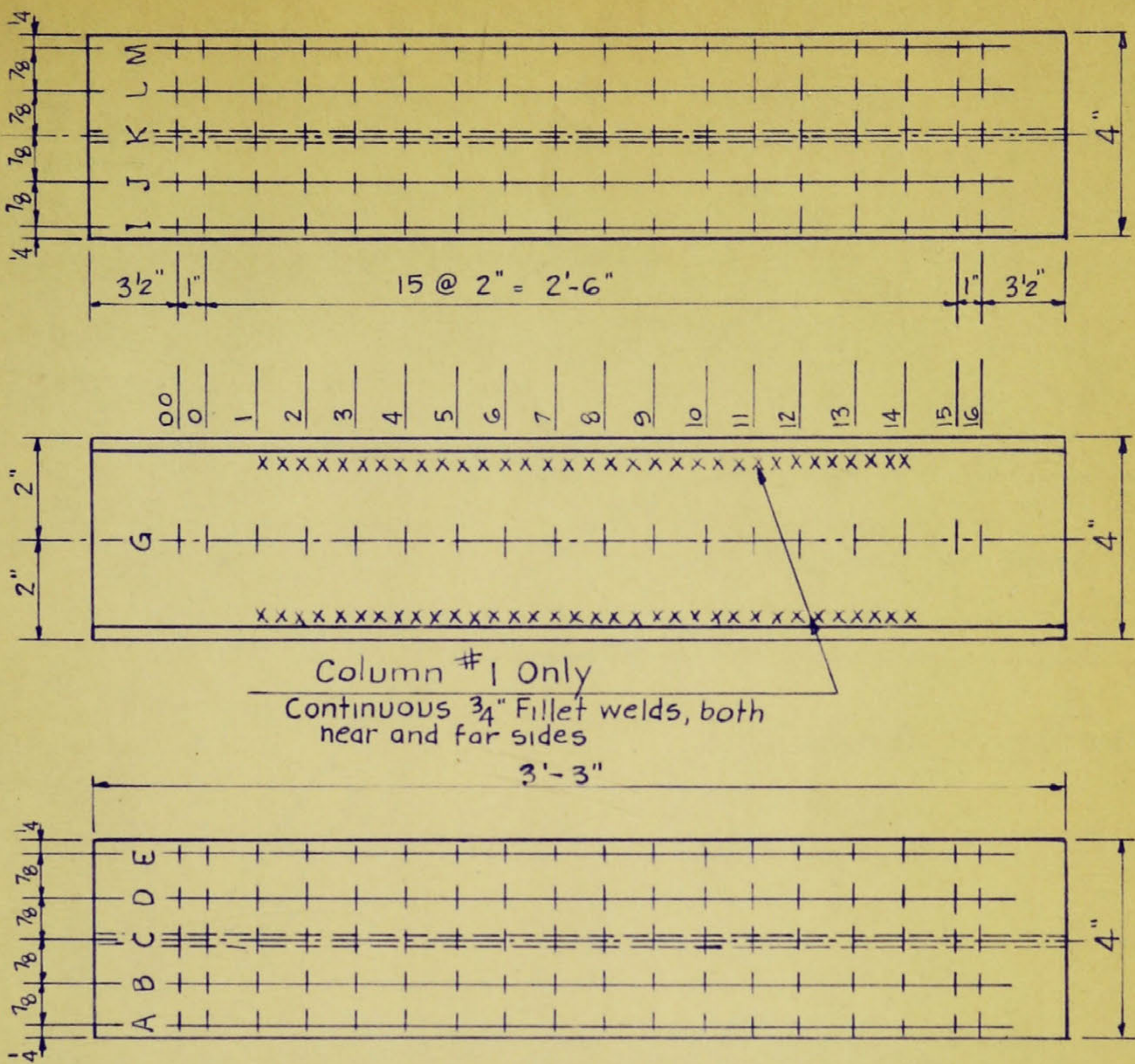
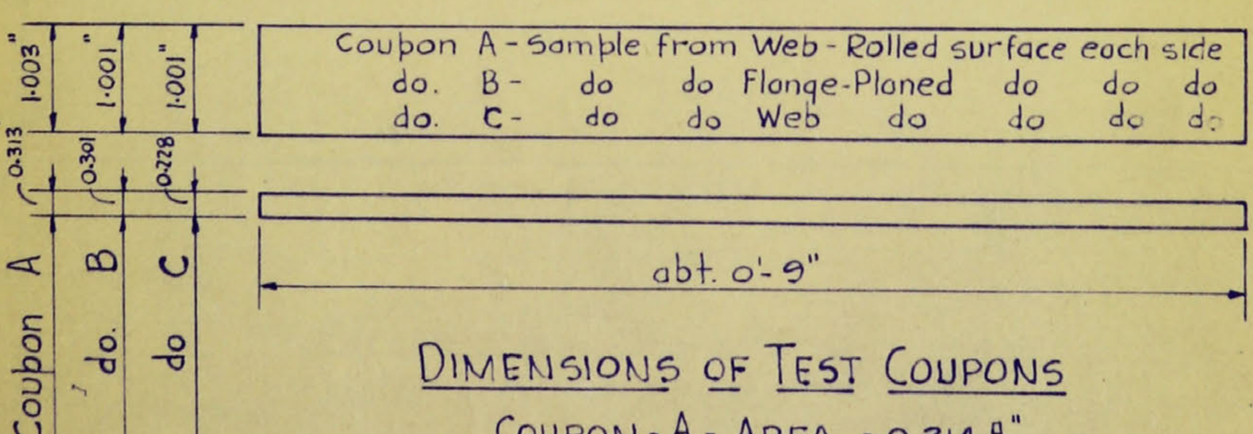


DIAGRAM SHOWING DIMENSIONS AND REFERENCE MARKINGS OF THE 4"-H COLUMNS

– Not to scale –



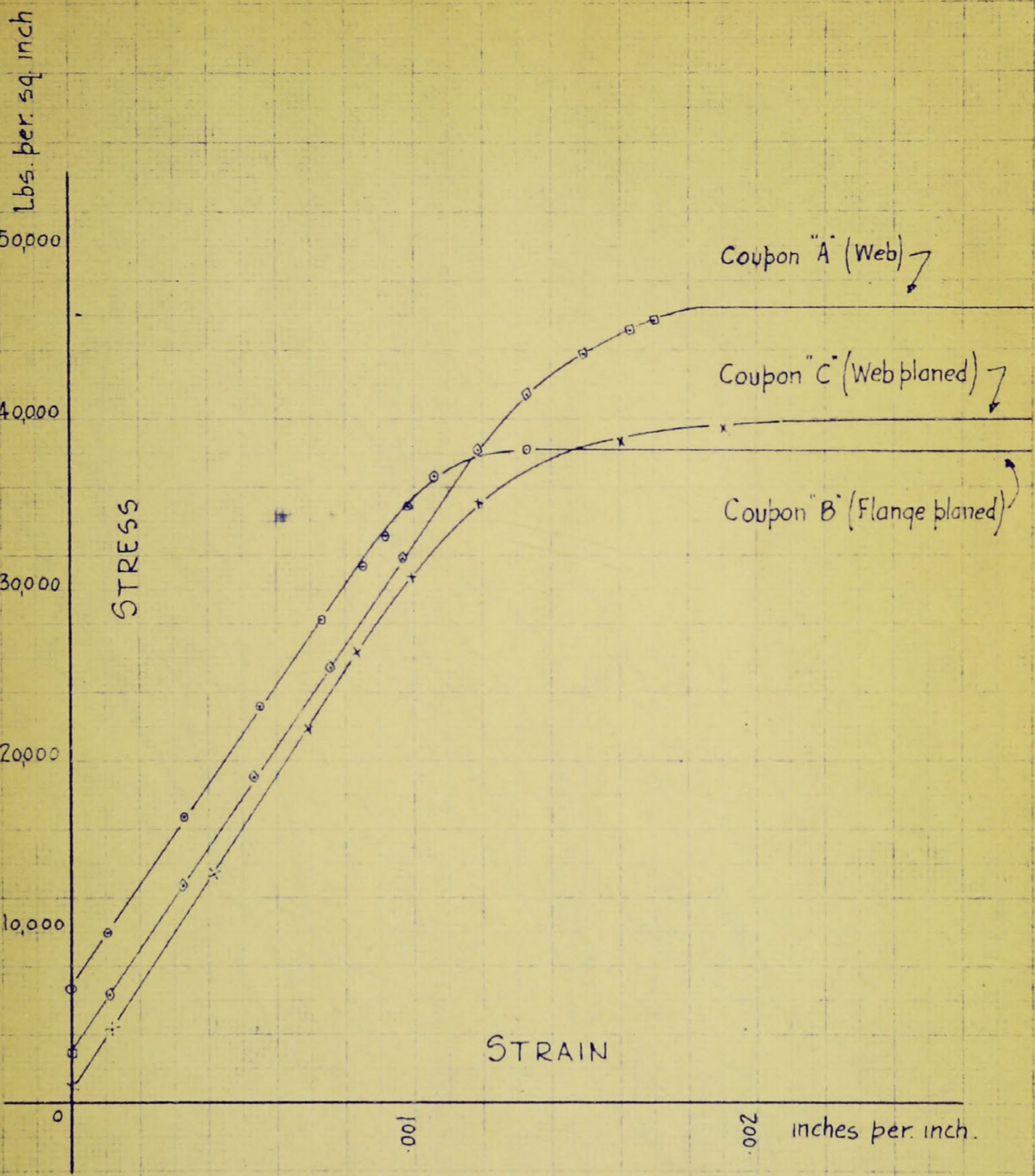
DIMENSIONS OF TEST COUPONS

COUPON - A - AREA = 0.314 □"

do B do = 0.301 □"

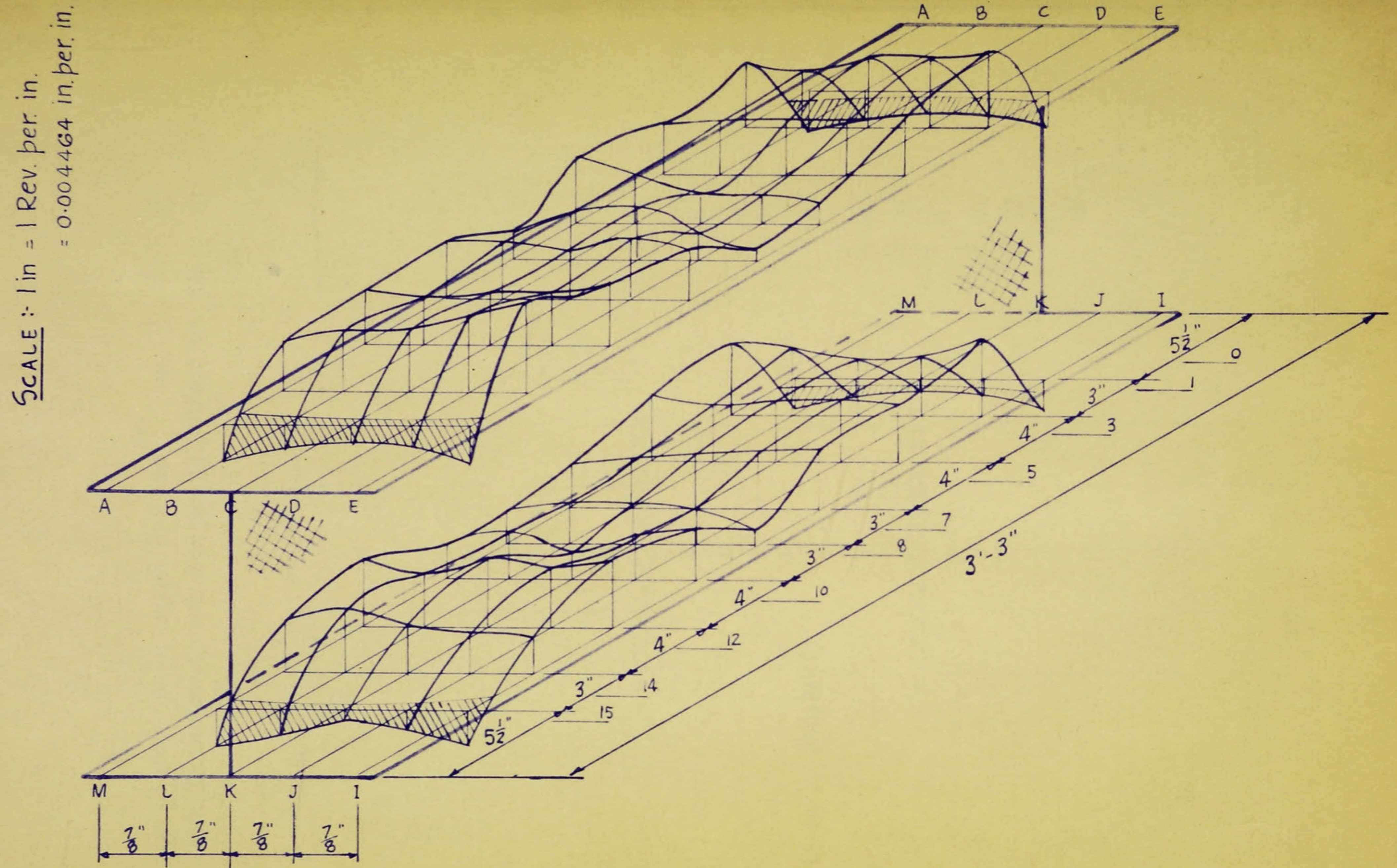
do C do = 0.228 □"

FIGURE-4-



Stress-strain Characteristics of the Material of the Columns ——

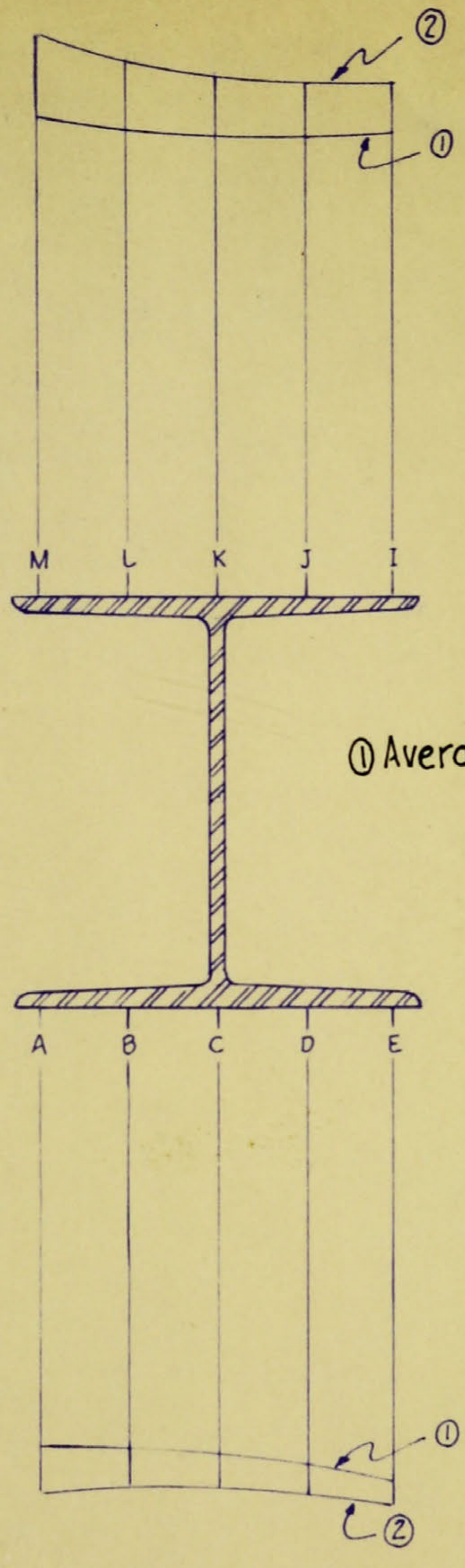
FIGURE - 5 -



AXOMETRIC DIAGRAM SHOWING THE SHRINKAGE OF THE 4"-H SPECIMEN DUE TO THE WELDING PROCESS

FIGURE-6

Scale:- 1 in = 4 Revs. of Mic. "B"
= 0.0178 in



① Average = ·00133 in. per in.

① Total shrinkage in 30 ins. due to welding process
② do do do do after initial load of 100 kips

FIGURE -7-

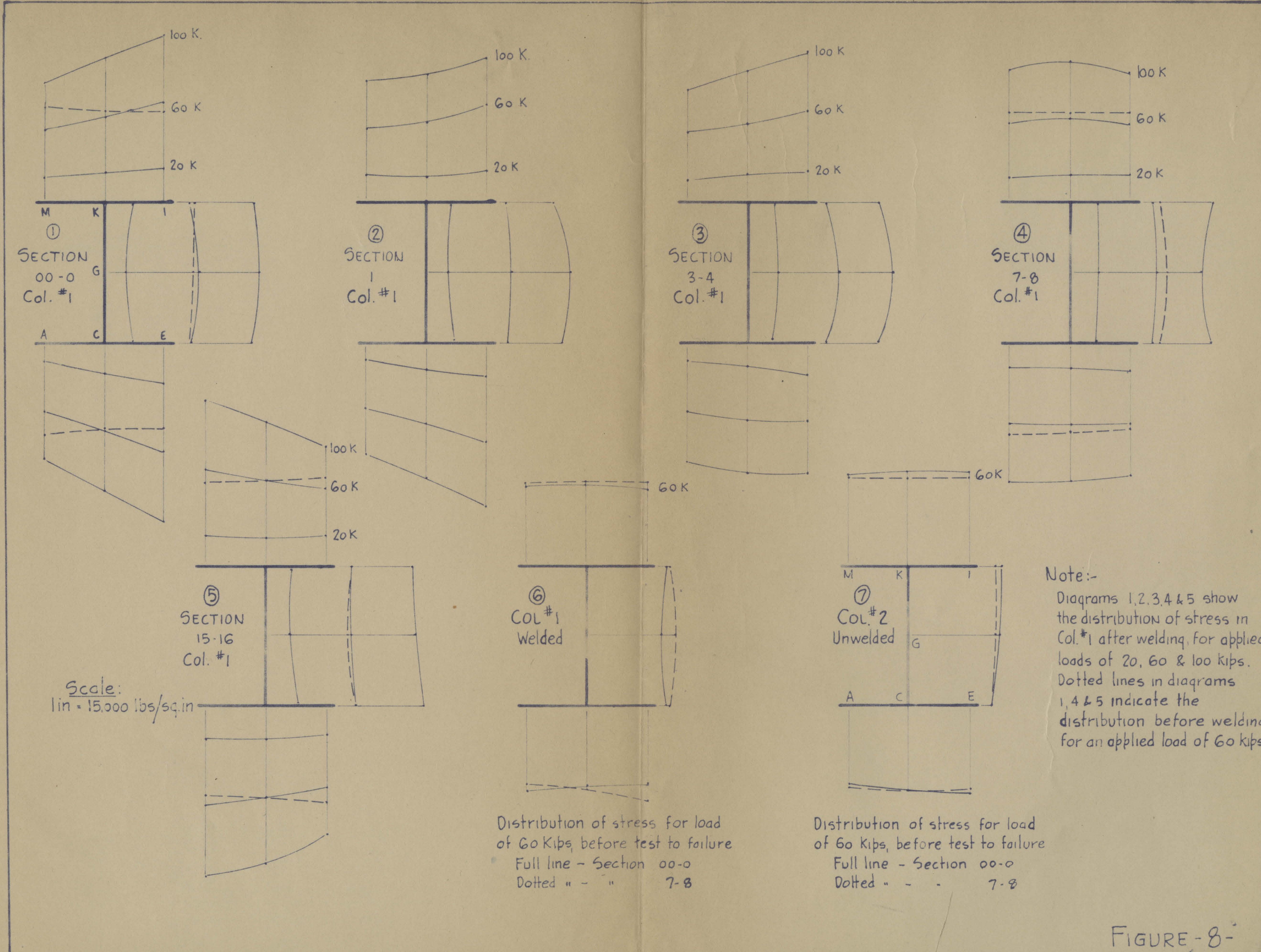

100 K.
60 K
20 K
M
K
I
① SECTION 00-0 Col. #1
G
A
C
E
② SECTION 1 Col. #1
③ SECTION 3-4 Col. #1
④ SECTION 7-8 Col. #1
100 K
60 K
20 K
⑤ SECTION 15-16 Col. #1
⑥ COL #1 Welded
⑦ COL. #2 Unwelded
Scale: 1 in = 15,000 lbs/sq.in
Distribution of stress for load of 60 Kips, before test to failure
Full line - Section 00-0
Dotted " - " 7-8
Distribution of stress for load of 60 Kips, before test to failure
Full line - Section 00-0
Dotted " - " 7-8
Note:-
Diagrams 1,2,3,4 & 5 show the distribution of stress in Col. #1 after welding, for applied loads of 20, 60 & 100 kips. Dotted lines in diagrams 1,4 & 5 indicate the distribution before welding for an applied load of 60 kips.

FIGURE - 8 -

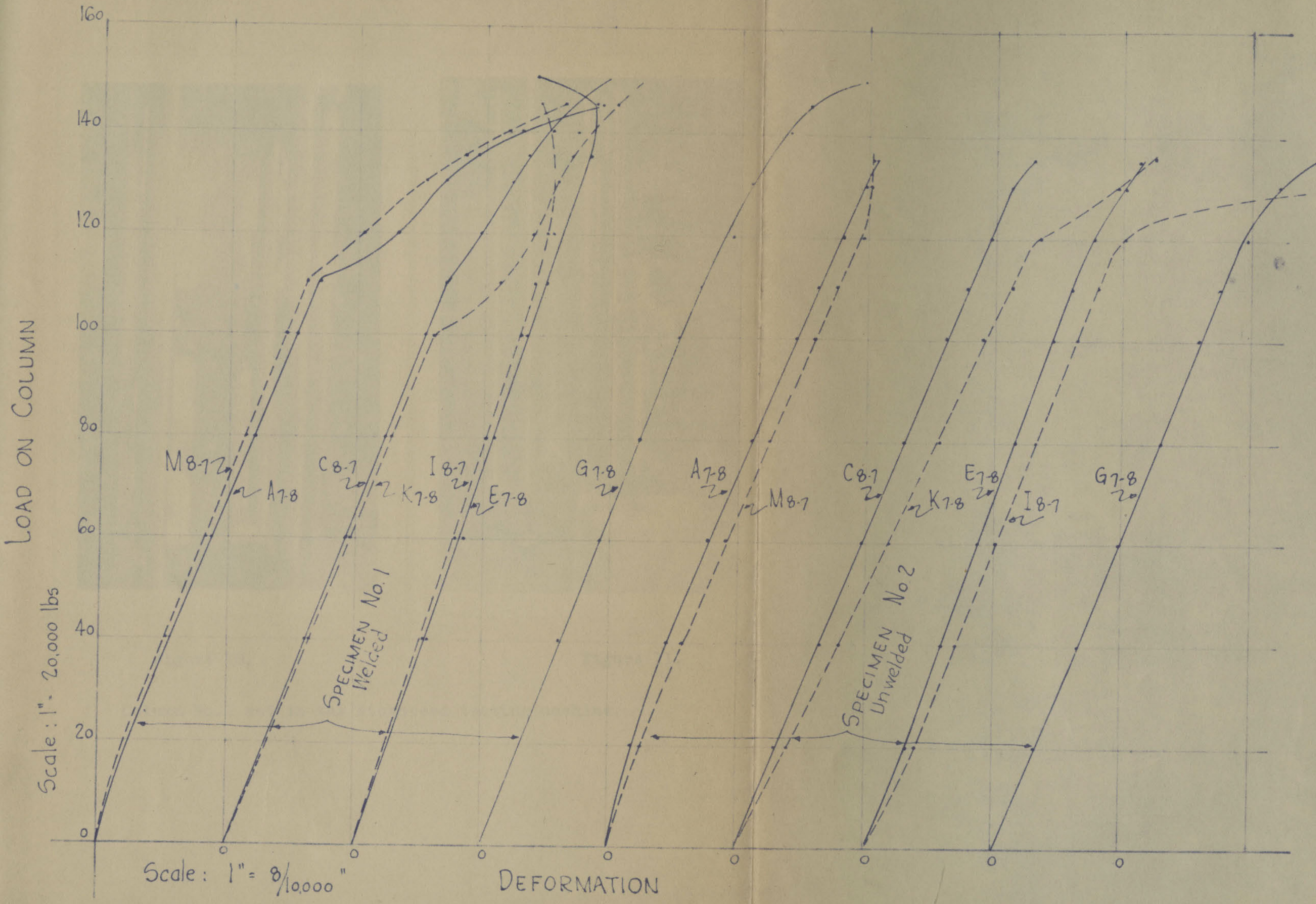
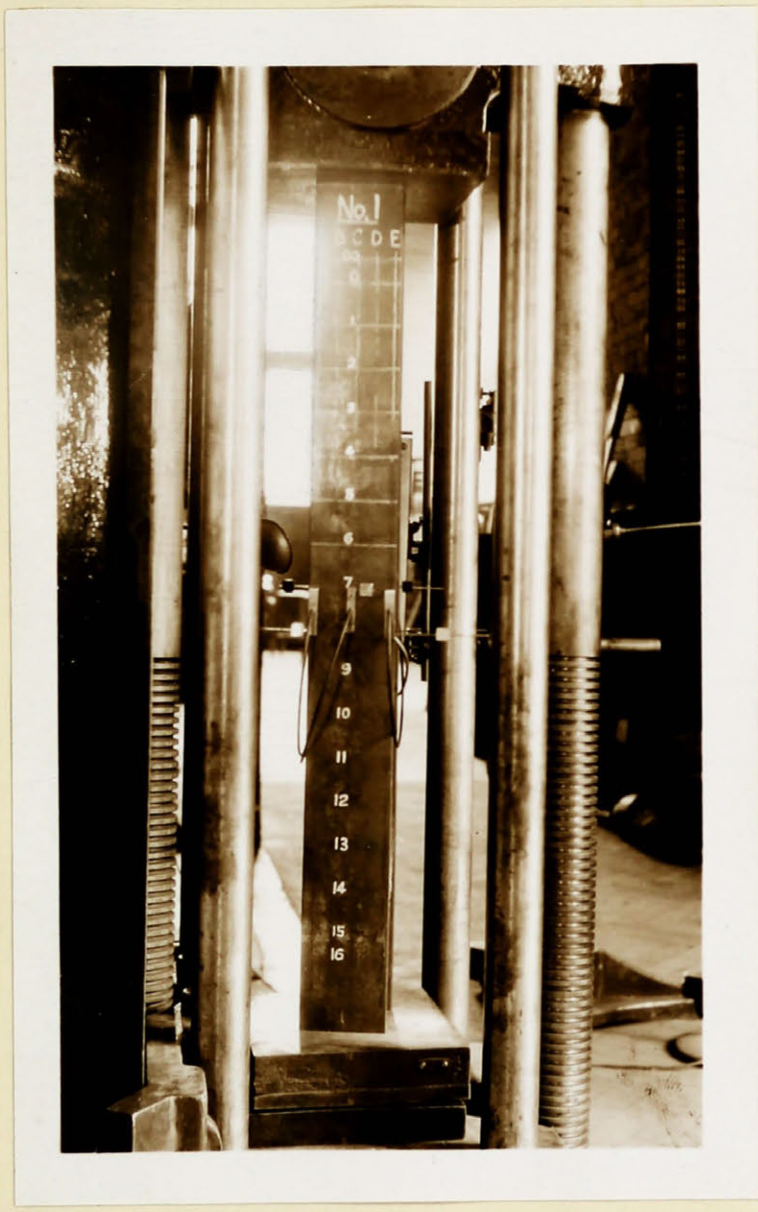

160
140
120
100
80
60
40
20
0
LOAD ON COLUMN
Scale: 1" = 20,000 lbs
M8-7
A7-8
C8-7
K7-8
I8-7
E7-8
G7-8
A7-8
M8-7
C8-7
K7-8
E7-8
I8-7
G7-8
SPECIMEN No. 1
Welded
SPECIMEN No 2
Unwelded
Scale: 1" = 8/10,000"
DEFORMATION

FIGURE-9-



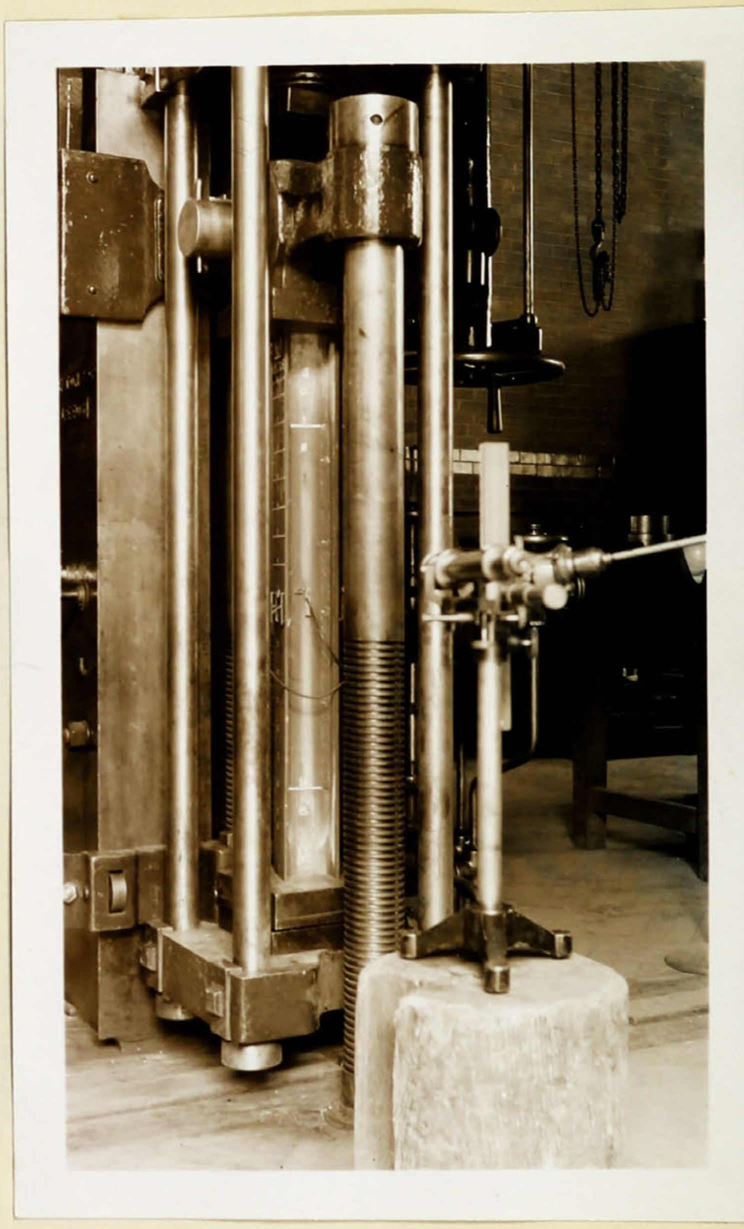


Figure 10.

Figure 11.

Column No.1 set in the Wicksteed testing machine.

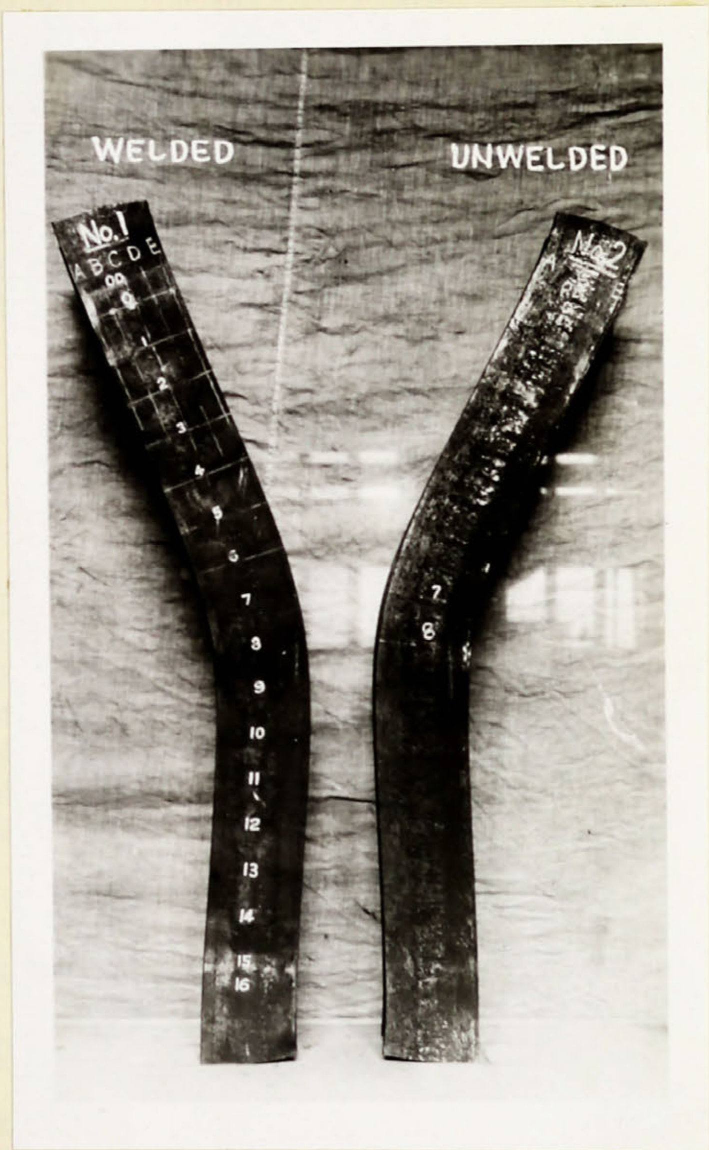


Figure 12.

Columns 1 and 2, after failure.

OBSERVATIONS.

TABLE 1.

Test of Coupon "A" (Web)

Total load in kips	Ext. Front	Ext. Back	Front Diff.	Back Diff.	Mean Diff.	Unit Strain	Unit Stress
1.0	35.93	5.35	0	0	0	0	3180
2.0	35.70	5.98	0.23	0.63	0.43	0.108	6360
4.0	35.22	7.25	0.71	1.90	1.305	0.326	12720
6.0	34.48	8.21	1.45	2.86	2.155	0.539	19100
8.0	33.69	9.18	2.24	3.83	3.035	0.759	25400
10.0	32.90	10.11	3.03	4.75	3.89	0.972	31800
12.0	32.12	11.12	3.81	5.77	4.79	1.197	38200
13.0	31.70	11.80	4.23	6.45	5.34	1.335	41400
13.8	31.28	12.68	4.65	7.33	5.99	1.498	43900
14.2	30.90	13.38	5.03	8.03	6.53	1.630	45200
14.4	30.70	13.80	5.23	8.45	6.84	1.710	45800
14.6	Yield Point						46500
21.5	Failure						68500

Test of Coupon "B" (Flange planed)

Total load in kips	Ext. Front	Ext. Back	Front Diff.	Back Diff.	Mean Diff.	Unit Strain	Unit Stress
2.0	32.00	13.30	0	0	0	0	6750
3.0	31.49	13.63	.5	.33	.42	0.105	9960
5.0	30.38	14.30	1.62	1.00	1.31	0.327	16600
7.0	29.30	15.02	2.70	1.72	2.21	0.553	23200
8.5	28.47	15.60	3.53	2.30	2.92	0.729	28200
9.5	27.91	16.03	4.09	2.73	3.41	0.852	31500
10.0	27.65	16.31	4.35	3.01	3.68	0.920	33200
10.5	27.42	16.62	4.58	3.32	3.95	0.988	34900
11.0	27.09	16.91	4.91	3.61	4.26	1.065	36600
11.2	Yield Point						37200
20.1	Failure						66800

Test of Coupon "C" (Web planed)

Total load in kips	Ext. Front	Ext. Back	Front Diff.	Back Diff.	Mean Diff.	Unit Strain	Unit Stress
0.2	27.00	6.00	0	0	0	0	880
1.0	26.25	6.18	.75	.18	0.465	0.116	4280
3.0	24.79	7.11	2.21	1.11	1.66	0.415	13150
5.0	23.39	7.90	3.61	1.90	2.755	0.689	21900
6.0	22.55	8.18	4.45	2.18	3.315	0.829	26300
7.0	21.88	8.86	5.12	2.86	3.99	0.998	30700
8.0	21.60	10.13	5.40	4.13	3.765	1.191	35100
8.8	19.95	11.81	7.05	5.81	6.43	1.608	38600
9.0	19.20	13.45	7.80	7.45	7.625	1.906	39400
9.1	Yield Point						39900
15.0	Failure						65800

TABLE II

Stress distribution for load of 60 kips in Col.No.1.(before welding).

	Load kips	A	C	E	G	I	K	M
	0	19.00	12.00	18.00	28.00	14.00	17.00	14.00
Mirror at top	60	19.52	12.49	18.50	28.49	14.45	17.47	14.45
	0	19.00	12.00	18.00	28.00	14.00	17.00	14.00
Section 00-0	0	16.00	15.00	20.00	25.00	10.00	13.00	12.00
	60	15.53	14.55	19.55	24.52	9.49	12.48	11.42
Mirror at bottom	0	16.00	15.00	20.00	25.00	10.00	13.00	12.00
	0	14.00	21.00	30.00	31.00	17.00	18.00	15.00
Mirror at top	60	15.00	22.00	30.98	31.98	17.95	18.97	15.95
	0	14.00	21.00	30.00	31.00	17.00	18.00	15.00
Section 7 - 8	0	13.00	13.00	32.00	21.00	10.00	16.00	14.00
	60	12.00	12.02	31.07	19.91	9.01	15.00	12.99
Mirror at bottom	0	13.00	13.02	32.00	21.00	10.00	16.00	14.00
	0	14.00	25.00	27.00	20.00	11.00	16.00	14.00
Mirror at top	60	14.52	25.52	27.54	20.41	11.45	16.44	14.42
	0	14.00	25.00	27.00	20.00	11.45	16.00	14.00
Section 15 - 16	0	14.00	22.00	19.00	20.00	11.00	15.00	21.00
	60	13.53	21.51	18.50	19.50	10.47	14.50	20.50
Mirror at bottom	0	14.00	22.00	19.00	20.00	11.00	15.00	21.00

TABLE III

Sample observations showing the method of reduction to determine the shrinkage due to the welding process. (observations for row "C")

Gauge Line	Read. Micr. "B"	Mean before welding	Read. Micr. "B"	Mean after welding	Diff. before welding	Diff. after welding	Change in length
0	16.69		24.46				
	.70	16.70	.46	24.46			
	.70		.46		-6.03	-5.73	+0.30

TABLE III (continued)

Gauge Line	Read. Micr. "B"	Mean before welding	Read. Micr. "B"	Mean after welding	Diff. before welding	Diff. after welding	Change in length
1	10.66 .67 .68	10.67	18.74 .73 .73	18.73	+0.23	-0.84	-1.07
2	10.91 .90 .90	10.90	17.88 .89 .89	17.89	+1.71	+0.95	-0.76
3	12.61 .61 .60	12.61	18.84 .84 .85	18.84	-3.58	-3.74	-0.16
4	9.02 .02 .04	9.03	15.09 .09 .11	15.10	+3.78	+2.41	-1.37
5	12.82 .82 .80	12.81	17.52 .50 .51	17.51	-1.73	-1.61	+0.12
6	11.09 .09 .07	11.08	15.90 .90 .90	15.90	-1.40	-2.04	-0.64
7	9.68 .68 .68	9.68	13.86 .87 .86	13.86	+1.82	+1.10	-0.72
8	11.49 .50 .50	11.50	14.95 .97 .97	14.96	-0.29	-1.42	-1.13
9	11.20 .22 .21	11.21	13.54 .55 .54	13.54	-3.87	-4.06	-0.19
10	7.34 .34 .34	7.34	9.48 .48 .48	9.48	+4.80	+3.56	-1.24
11	12.13 .14 .15	12.14	13.05 .03 .05	13.04	-2.88	-3.16	-0.28

TABLE III (continued)

Gauge Line	Read. Micr. "B"	Mean before welding	Read. Micr. "B"	Mean after welding	Diff. before welding	Diff. after welding	Change in length
12	9.27 .27 .25	9.26	9.88 .87 .88	9.88	-0.65	-0.87	-0.22
13	8.60 .61 .62	8.61	9.02 .01 .00	9.01	+0.71	-0.86	-1.57
14	9.31 .32 .33	9.32	8.14 .15 .16	8.15	-2.90	-2.69	+0.21
15	6.42 .43 .41	6.42	5.46 .46 .46	5.46	-10.28	-19.01	-8.72
0	16.70 .71 .70	16.70	24.47 .47 .47	24.47			

NOTE: A minus sign in the column headed "Change in length" denotes contraction, a plus sign + expansion.

TABLE IV

Tabulation of All Shrinkage Measurements.

Gauge Line	A	B	C	D	E	I	J	K	L	M
0										
	+0.53	+0.37	+0.30	+0.37	+0.50	+0.42	+0.24	+0.12	+0.23	+0.43
1										
	0.78	0.80	1.07	+1.09	1.49	1.05	0.96	1.12	1.08	1.14
2										
	0.91	0.69	0.76	0.89	0.63	1.11	0.69	0.36	0.80	0.87
3										
	0.58	0.65	0.16	0.84	1.29	1.06	1.01	0.52	0.56	0.64
4										
	0.72	0.78	1.37	0.58	0.31	0.53	0.64	1.17	0.92	0.98
5										
	1.01	0.71	+0.12	0.22	0.40	1.30	1.04	0.86	0.91	0.99
6										
	0.85	0.46	0.64	0.52	0.20	0.39	0.52	0.72	0.44	0.19
7										
	0.31	0.66	0.72	0.35	0.09	0.14	0.48	0.54	0.58	0.43
8										
	1.62	1.21	1.13	1.12	1.45	1.30	0.84	0.68	0.92	1.08

TABLE IV (continued)

Gauge Line	A	B	C	D	E	I	J	K	L	M
9–10	+0.04	0.38	0.19	0.56	0.08	0.19	0.45	0.11	0.32	+0.06
10–11	0.03	0.48	1.24	0.76	0.89	0.62	0.86	1.09	0.28	0.48
11–12	1.46	0.87	0.28	0.68	0.94	1.29	0.83	0.79	1.19	1.42
12–13	0.68	0.72	0.22	0.46	0.91	0.35	0.48	0.16	0.64	1.14
13–14	0.72	0.97	1.57	1.60	1.63	0.56	0.66	1.10	1.16	.29
14–15	+0.51	+0.38	+0.21	+0.31	+0.53	+0.47	+0.26	+0.11	+0.31	+0.50
0–15	8.59	8.63	8.72	8.99	9.28	9.00	8.96	8.98	9.04	9.29
15–14	9.63	9.38	9.23	9.67	10.31	9.89	9.46	9.21	9.58	10.22

NOTE: Figures marked plus denote expansion, all others denote contraction. These figures are in terms of revolutions of micrometer "B". To reduce to inches, multiply by 0.004464.

TABLE V

Initial Loading test after welding, to detect the presence of Residual Stresses in Column No. 1.

Load kips	EXTENSOMETER READINGS A8 - 7	E8 - 7	G7 - 8	I7 - 8	M7 - 8	C 00-0
0	14.00	21.00	14.00	14.00	25.00	9.00
5	13.95	20.95	14.02	14.05	25.05	9.02
0	.00	.00	.00	.00	.00	.00
10	13.89	20.89	14.07	14.11	25.10	9.08
0	.00	.00	13.99	.00	.00	.00
20	13.76	20.71	14.22	14.28	25.23	9.17
0	.00	.00	.00	.00	.00	.00
30	13.60	20.58	14.39	14.40	25.37	9.26
0	.00	.00	.00	.00	.00	.00
40	13.45	20.44	14.58	14.52	25.50	9.35
0	.00	.00	.00	.00	.00	.00
50	13.31	20.30	14.75	14.67	25.66	9.43
0	.00	.00	14.02	.00	.00	.00
60	13.18	20.18	14.96	14.79	25.80	9.53
0	.00	.00	14.06	.00	.00	.00
70	13.02	20.02	15.10	14.94	25.94	9.62
0	.00	.00	.00	.00	.00	.00
80	12.89	19.90	15.43	15.06	26.03	9.71
0	14.03	21.08	14.15	13.96	24.90	.00
80	12.87	19.87	15.30	15.08	26.10	9.20
0	.00	.00	.00	.00	.00	.00

TABLE V (continued)

Load kips	EXTENSOMETER READINGS A8 - 7	E8 - 7	G7 - 8	I7 - 8	M7 - 8	C 00-0
90	12.72	19.73	15.62	15.18	26.20	9.80
0	14.03	21.06	14.13	13.94	24.99	9.01
90	21.71	19.71	15.51	15.22	26.23	9.79
0	.00	.00	.00	.00	.00	.00
100	12.32	19.62	15.80	15.30	26.48	9.89
0	13.71	21.08	14.12	13.90	25.12	.00
100	12.52	21.08	15.72	15.36	26.40	9.89
0	13.97	21.01	14.02	13.99	25.10	.00
100	12.54	19.56	15.71	15.36	26.40	9.89
0	13.98	21.00	14.01	14.00	25.00	9.00

TABLE VI

Tabulation of Permanent Longitudinal Contractions Caused by Initial Load of 100 kips on Column No. 1, after Welding.

	A	B	C	D	E	I	J	K	L	M
0 - 15	0.89	0.73	0.65	0.59	0.41	0.93	1.07	1.18	1.37	1.54
	0.86	0.71	0.58	0.58	0.52	0.92	0.99	1.22	1.29	1.67
Mean.	0.88	0.72	0.62	0.59	0.47	0.93	1.03	1.20	1.33	1.60

NOTE: Figures are in terms of revolutions of micrometer "B". To reduce to inches multiply by 0.004464.

TABLE VII

Analysis of the stress distribution in Col.No.1.(after welding).

	Load kips	A	C	E	G	I	K	M
	0	20.00	21.00	9.00	15.00	13.00	17.00	26.00
Mirror at top	20	20.11	21.18	9.25	15.05	13.12	17.12	26.12
	60	20.43	21.53	9.65	15.48	13.47	17.42	26.35
	100	20.72	21.88	10.08	15.91	13.82	17.72	26.59
Section 00 - 0	0	20.00	21.00	9.00	15.00	13.00	17.00	26.00
	0	18.00	19.00	13.00	13.00	10.00	17.00	29.00
	20	17.92	18.86	12.81	12.72	9.78	16.81	28.86
Mirror at bottom	60	17.69	18.57	12.46	12.45	9.40	16.48	28.55
	100	17.45	18.24	12.11	12.19	9.01	16.13	28.28
	0	18.00	19.00	13.00	13.00	10.00	17.00	29.00

TABLE VII (continued)

	Load kips	A	C	E	G	I	K	M
Mirror at top	0	14.00	18.00	23.00	11.00	16.00	16.00	28.00
	20	14.10	18.17	23.18	11.08	16.14	16.10	28.10
	60	14.39	18.49	23.55	11.46	16.48	16.38	28.35
	100	14.66	18.80	23.90	11.88	16.82	16.64	28.60
	0	14.00	18.00	23.00	11.00	16.00	16.00	28.00
Section 1								
Mirror at bottom	0	23.00	21.00	19.00	12.00	15.00	19.00	27.00
	20	22.92	20.86	18.80	11.78	14.80	18.83	26.87
	60	22.67	20.57	18.46	11.51	14.42	18.50	26.55
	100	22.42	20.28	18.09	11.27	14.04	18.13	26.26
Mirror at top	0	22.00	15.00	20.00	16.00	21.00	27.00	29.00
	20	22.22	15.28	20.36	16.28	21.32	27.28	29.22
	60	20.80	15.92	21.06	17.10	21.99	27.81	29.78
	100	23.36	16.52	21.72	17.82	22.63	28.39	30.23
	0	14.00	26.00	27.00	12.00	17.00	21.00	28.00
Section 3 - 4								
Mirror at bottom	0	14.00	26.00	27.00	12.00	17.00	21.00	28.00
	20	13.81	25.74	26.66	11.63	16.65	27.70	27.78
	60	13.27	25.19	26.07	11.11	15.99	20.10	27.21
	100	12.73	24.62	25.43	10.60	15.31	19.50	26.78
	0	22.00	15.00	20.00	16.00	21.00	27.00	29.00
Mirror at top	0	17.00	18.00	14.00	14.00	14.00	24.00	25.00
	20	17.28	18.31	14.32	14.22	14.28	24.26	25.22
	60	17.92	17.92	14.92	14.93	14.81	24.88	25.80
	100	18.55	19.54	15.51	15.70	15.37	25.51	26.40
	0	17.00	18.00	14.00	14.00	14.00	24.00	25.00
Section 7 - 8								
Mirrors at bottom	0	14.00	11.00	14.00	12.00	18.00	24.00	27.00
	20	13.78	10.74	18.31	11.62	17.68	23.68	26.72
	60	13.18	10.14	14.92	11.04	17.10	23.04	26.12
	100	12.56	9.55	15.51	10.50	16.51	22.38	25.51

TABLE VII (continued)

	Load kips	A	C	E	G	I	K	M
Mirrors at top	0	17.00	20.00	22.00	17.00	14.00	14.00	25.00
	20	17.19	20.18	22.16	17.10	14.15	14.14	25.12
	60	17.59	20.51	22.47	17.49	14.40	14.44	25.46
	100	17.98	20.85	22.72	17.93	14.63	14.80	25.80
	0	17.00	20.00	22.00	17.00	14.00	14.00	25.00
Section 15 - 16	0	21.00	18.00	21.00	12.00	22.00	20.00	25.00
	20	20.83	17.82	20.84	11.84	21.82	19.85	24.80
Mirrors at bottom	60	20.49	17.50	20.58	11.56	21.54	19.50	24.40
	100	21.10	17.11	20.30	11.28	21.30	19.19	23.98
	0	17.00	20.00	22.00	17.00	14.00	14.00	25.00

TABLE VIII

Distribution of Stress in Column No.1, before test to destruction.

	Load	EXTENSOMETER READINGS A	C	E	G	I	K	M
Mirrors at top	0	17.00	22.00	22.00	17.00	14.00	16.00	27.00
	60	19.47	17.50	23.58	17.50	14.42	16.42	27.42
	0	17.00	22.00	22.00	17.00	14.00	16.00	27.00
Section 00 - 0	0	19.00	17.00	23.00	14.00	14.00	16.00	30.00
	60	16.61	21.58	21.51	13.50	13.49	15.49	29.51
Mirrors at bottom	0	19.00	17.00	23.00	14.00	14.00	16.00	30.00
Mirrors at top	0	14.00	21.00	20.00	19.00	16.00	20.00	30.00
	60	14.96	21.91	20.91	19.80	16.83	20.83	30.83
	0	14.00	21.00	20.00	19.00	16.00	20.00	30.00
Section 7 - 8	0	15.00	17.00	24.00	20.00	19.00	17.00	29.00
	60	14.10	16.13	23.18	19.14	18.16	16.08	28.10
Mirrors at bottom	0	15.00	17.00	24.00	20.00	19.00	17.00	29.00

TABLE IX

Failure test of Column No.1. (welded)

Load kips	ESTENSOMETER READINGS A8 - 7	C7 - 8	E8 - 7	G7 - 8	I7 - 8	K8 - 7	M7 - 8
0	19.00	21.00	22.00	10.00	15.00	21.00	24.00
40	18.43	21.61	21.43	10.60	15.52	20.38	24.54
60	18.12	21.92	21.18	10.92	15.78	20.07	24.88
80	17.79	22.23	20.92	11.23	16.02	19.73	25.15
100	17.47	22.54	20.68	11.52	16.28	19.42	25.45
0	19.00	21.00	22.00	10.00	15.00	21.00	24.00
100	17.47	22.53	20.68	11.51	16.28	19.43	25.47
110	17.34	22.70	20.52	11.70	16.38	19.19	25.62
120	16.68	22.95	20.48	11.97	16.47	18.89	26.05
125	16.49	23.07	20.36	12.01	16.52	18.78	26.20
130	16.32	23.20	20.26	12.08	16.53	18.62	26.49
135	16.08	23.32	20.20	12.22	16.52	18.47	26.82
140	15.72	23.51	20.18	12.38	16.48	18.32	27.18
145	15.10	23.68	20.13	12.53	16.42	18.30	27.61
150	13.58	23.95	20.62	12.98	15.98	17.98	28.68
155	12.75	24.12	20.63	13.25	15.92	17.82	29.18
160	10.60	24.58	20.83	14.10	15.54	17.50	30.42
165	Failure by Buckling						

TABLE X

Distribution of Stress in Column No.2. (before test to destruction)

	Load kips	EXTENSOMETER READINGS A	C	E	G	I	K	M
	0	16.00	20.00	20.00	11.00	17.00	20.00	26.00
Mirrors at top	60	16.58	20.58	20.55	11.45	17.39	20.38	26.36
	0	16.00	20.00	20.00	11.00	17.00	20.00	26.00
Section 00 - 0	0	16.00	18.00	21.00	17.00	16.00	17.00	27.00
Mirrors at bottom	60	15.68	17.65	20.64	16.48	15.42	16.42	26.40
	0	16.00	18.00	21.00	17.00	16.00	17.00	27.00
	0	16.00	23.00	23.00	15.00	20.00	16.00	29.00
Mirrors at top	60	16.90	23.98	24.03	15.98	21.03	16.94	29.92
	0	16.00	23.00	23.00	15.00	20.00	16.00	29.00
Section 7 - 8	0	22.00	25.00	24.00	17.00	16.00	20.00	28.00
	60	21.19	24.14	23.11	16.00	14.88	18.90	26.97
Mirrors at bottom	0	22.00	25.00	24.00	17.00	16.00	20.00	28.00

TABLE XI

Failure test of Column No.2. (unwelded)

	EXTENSOMETER READINGS						
Load	A8 - 7	C7 - 8	E8 - 7	G7 - 8	I7 - 8	K8 - 7	M7 - 8
0	23.00	22.00	19.00	15.00	11.00	19.00	23.00
40	22.54	22.65	18.40	15.67	11.71	18.18	23.15
60	22.23	22.98	18.12	15.99	12.01	17.80	23.92
80	21.88	23.30	17.84	16.30	12.32	17.43	24.25
100	21.55	23.62	17.56	16.60	12.63	17.09	24.60
0	23.00	22.00	19.00	15.00	11.00	19.00	23.00
100	21.56	23.61	21.57	16.60	12.62	17.08	24.60
110	21.39	23.78	17.41	16.76	12.80	16.88	24.76
115	21.30	23.87	17.33	16.83	12.88	16.78	24.86
120	21.70	23.96	17.23	16.92	13.00	16.66	24.97
125	21.10	24.02	17.10	17.08	14.24	16.30	24.96
130	21.01	24.13	17.00	17.22	14.91	16.04	25.00
135	20.94	24.30	16.89	17.48	15.86	15.77	25.04
140	20.90	24.55	16.57	17.90	17.60	15.53	25.07
145	Failure by Buckling.						

Part 2

RESOLUTION

Although it appears from the foregoing investigation that residual stresses in structural compression members have little effect upon their loadcarrying capacity, it does not lessen the importance of the investigation of these stresses from an engineering point of view. The results derived from any one test with a compression member is usually insufficient to form definite conclusions. Many tests have to be made before the information can be accepted. It is found necessary in some types of work to anneal members after welding to reduce the high initial stresses. In other cases it is resorted to peening of the weld, or often the weld is made in two or more passes of the welding element. It is not infrequent to find also that, shortly after welding some types of fabrication, the weld unit fails without the application of external forces. Although practice has established means of coping with such difficulties, the true understanding of the service behaviour of this method of fabrication can be had only after the importance of this phenomenon has been well established.

It is the purpose now to investigate the magnitudes and distribution of residual stresses caused by electric arc welding on various sizes of steel plates.

THEORY

Before describing the experimental investigation, it will be helpful to make a tentative conjecture respecting the cause of the phenomenon of shrinkage in welding. But it is first necessary to understand what happens, in terms of stress, when a temperature change takes place.

Consider a cube of steel as in figure 13, placed between two fixed supports P and Q. Assuming that at room temperature the coefficient of linear expansion is 0.0000067 and Young's Modulus is 30×10^6, upon raising the temperature of the cube 1° F. the stress set up in the direction of the axis X would equal $(0.0000067 \times 30 \times 10^6)$, 201 lbs. per square inch. If the temperature were raised 200° F. the stress induced would be well above the elastic limit. In this case expansion is prevented in one direction only; greater than normal expansion would take place in the directions Y and Z. If expansion were prevented in two directions X and Y, leaving only the direction Z for unrestricted expansion, the stress set up in the directions X and Y, for the same degree rise in temperature, would be much greater than where the cube is restrained in one direction only. While the above case is an ideal situation, it serves to illustrate the tendency towards high stresses for comparatively small differences in temperature. A reduction in temperature would be analogous to the above, except that the stresses would be of opposite sign. It must be remembered, however, that a stress will be set up only if a resistance to expansion is encountered.

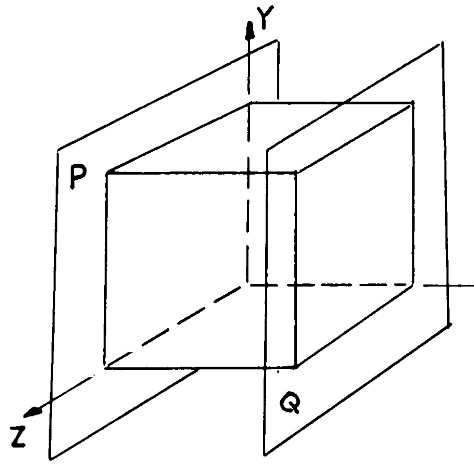


Fig. 13

The next consideration is the behaviour of the stress-strain characteristics as high temperatures are reached. While the deformation that steel is able to withstand without permanent displacement increases with the temperature, the force required to produce the displacement is lowered, and it follows that the yield point is also lowered as the temperature is raised. It has been shown that a .24% carbon steel with a modulus of 29 X 10^6 at room temperature has a modulus of only 18 X 10^6 at 1100°F.

With these factors in mind, let us trace the action on a steel plate when welded. Let a weld be commenced at a point "E" on the edge of a plate as shown in figure 14. As the arc is formed the temperature of the area about "E" is brought to the fusion point while the remainder of the plate remains relatively cool. The normal expansion of the region "E" that must take place is restricted by the stiffness of the remainder of the plate; and therefore must be rendered by a permanent dilation in a direction at right angles to the plate, i.e. in the direction of least resistance. It is to be remembered that the force required to produce this movement would be very small as the temperature of the region "E" is very high. As the heat is conducted radially through the plate, the weld metal begins to freeze, and at this stage the region "E" is contracting while the remainder of the plate is acquiring heat and expanding. A region "f", adjacent to the parent welded metal, in expanding meets opposing forces, on the one hand by the contraction of the weld, and on the other by the fact that the opposite edge of the plate is still relatively cool. Thus a further permanent dilation will take place as the heat wave proceeds across the plate. The rate of cooling being dependent upon the difference of temperature of the plate and the surrounding air, the weld, which is always at a higher temperature than any other portion of the plate, will cool at a faster rate than will the more re-

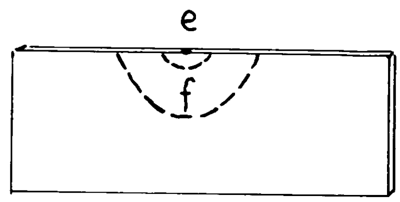


Fig. 14

mote sections which are at a lower temperature, and in this way will meet opposing forces which tend to reduce the initial permanent dilation. The stress, in the weld while contracting, must remain about the yield point until the stress equilibrium set up has been stabilized by the whole plate reducing to practically uniform temperature. Further contraction, due to the temperature dropping to room conditions, would not materially increase or decrease the stresses set up in the plate but will raise the yield point of the material.

From the above contention, we might deduce that the greatest part of the ultimate shrinkage is directly due to a permanent dilation of the plate in some direction other than parallel to the welds, and therefore all the contraction will not be elastic deformation; and the stress in the welds need not approximate the yield point at room temperature. It would appear that the shrinkage will depend on the amount of heat supplied relative to the extent of the plate, and also on the speed at which the welding is performed.

It is not our purpose, however, in this investigation to attempt to verify the above. The object here is to measure the magnitudes of the stresses set up in plates of various widths, but of the same lengths and thicknesses, for the same amounts of weld metal deposited. If a welded steel plate containing residual stresses were cut into strips parallel to the welds, the amounts by which these strips expanded or further contracted in length after cutting would be proportional to the locked up stress in the respective strips of the plate. The summation of the total forces, as represented by these deflections, will be zero.

SPECIMENS & PREPARATION

Four plates were selected of structural mild steel and cut from the same rolled stock. The plates were marked W, X, Y and Z according to their widths, the lengths and thicknesses being constant. The dimensions of the plates were as follows:

W - 1'-3" X 0'-2" X 7/8"

X - 1'-3" X 0'-4" X 7/8"

Y - 1'-3" X 0'-6" X 7/8"

Z - 1'-3" X 0'-8" X 7/8"

It was decided to confine the measurements to an overall length of one foot, leaving one and one half inches at each end beyond which no observations would be taken. Each plate was provided with a V- groove along the long edges where the weld metal was to be deposited. The dimensions of this groove together with the gauge lines and reference markings are shown in figure 15. The lanes along each plate where measurements were to be made are referred to by letters while the gauge lines are numbered. As both faces of every plate were to be measured, one face was marked 1, and the other face marked 2. The scratches on the plates were made precisely the same as in the case of the steel column in Part 1.

PROCEDURE

Each plate was first measured in the linear comparator, the same apparatus that was used to make the measurements with the welded column, (see page 8). Measurements were taken along each lane on both sides of every plate at the fine gauge lines. The method of making these measurements has already been fully described under Part 1 of this paper. In this case, however, two complete sets of readings were recorded for greater accuracy. The scratches were then protected by covering them with strips of galvanized sheet iron, and the plates were sent to the Dominion Bridge Company to be welded. The welding procedure was carried out in much the same manner as for the column H- section. The weld was made in one pass with bare wire electrodes so that it completely filled the V- notches over the entire length of the plates. Upon the return of the specimens to the laboratory, measurements as before were made in the comparator.

The ground surface of each scratch had become discoloured from the intense heat caused by the welding, which made it more difficult to read the scratches. After the shrinkage due to the welding had been determined, these surfaces were repolished and new scratches made. This time three complete sets of readings were taken at gauge lines 1, 3 and 5 for plates W, X and Y, and in the case of plate Z measurements were made of all gauge lines. The procedure from this point involved cutting the plates into strips and measuring the longitudinal deflections of each strip. The weld strips, including half an inch of each side of the plate, were cut off and measurements made on the remainder of the plate. Next, one inch strips on each side of the plate were removed and measurements on the remaining portion again recorded. This was continued until all the plates had been reduced to a series of one inch strips. The one inch strips were actually less than one inch by the thickness of the cutting tool,(3/32"). The cutting of the strips was done in a milling machine. This operation was carried out very slowly to prevent heating, the time required to sever one strip being approximately one hour.

The stress-strain characteristics of the plate material were determined from one of the central strips taken from plate Y. The test was made in tension in the Wicksteed machine using Martens extensometers over a length of eight inches. The sample used to determine the characteristics of the weld material was a $\frac{1}{4}$-inch round rod turned from one of the weld strips of plate W. The test in this case was made in a smaller 5- ton Riehle machine using extensometers over a length of four inches.

RESULTS & DISCUSSION

The results from the many observations and measurements can best be understood by graphical illustration.

In figure 16, the stress-strain characteristics of both the weld metal and the material of the plates are shown.

Figure 17 is the axometric projection of the shrinkage due to the welding process, derived from the mean of the measurements on both faces of each plate, with ordinates representing the shortening in inches per linear inch. It will be noticed that two diagonally opposite "humps" are present in plate X. It was previously stated that, during welding, when the specimen exihibited a tendency to go out of alignment, the operator would immediately shift to the opposite side of the plate and thus compensate for this distortion. It would be logical to assume that the wider the plate the less apparent would be this distortion. That the assumption is true is borne out by the fact that plates Y and Z, both wider than X, show no such behaviour. Plates Y and Z do exhibit varying shrinkage distribution. This is due to their free and unrestrained ends and would not be expected to take place in longer specimens.

Let us now consider figure 18 which shows the total shrinkage, due to the welding process, in the twelve inches under observation. There again the varying distribution across the plates is most probably due to end effects. In longer plates the shortenings would be more uniform. It is apparent from these diagrams that the average shortening is less in the wider plates -- a condition to be expected.

The following is an indication of the probable error in taking the shrinkage measurements:

The probable error in setting microscope "A" $= \pm$ 0.02 revs.of"B".

The probable error of reading microscope "B" $= \pm$ 0.03 revs.of"B".

As an improvement on the previous methods was made with regard to the intensity and direction of light cast on the scratches, no error was introduced here. However, after welding, the scratches were slightly discoloured, which made observations more difficult; $\pm$.02 should be allowed for this factor.

Let M_1 equal the measurement before welding and M_2 the same measurement after welding.

$$\text{Error in } M_1 = \sqrt{\frac{\pm .02^2 + \frac{.03}{\sqrt{3}}}{\sqrt{2}}} = \pm .0218$$

$$\text{Error in } M_2 = \sqrt{\frac{\pm .02^2 \pm \frac{.03}{\sqrt{3}}}{\sqrt{2}} \pm .02^2} = \pm .0248$$

If X equals $M_2 - M_1$

$$\text{Error in } X = \sqrt{\pm .0248^2 \pm .021^2}$$

$$= \pm .0326$$

$$= \pm .033 \text{ X } .004464 \text{ in terms of inches}$$

$$= \pm .00014 \text{ inches.}$$

The probable error for any one measurement of the deformations when the plates were cut into strips:

Let M_3 equal the measurement before cutting and M_4 the same measurement after cutting.

$$\text{Error in } M_3 \text{ or } M_4 = \frac{\sqrt{\pm .02^2 \pm \frac{.03}{\sqrt{3}}}}{\sqrt{3}}$$

$$= \pm .017$$

If X equals $M_4 - M_3$

$$\text{Error in } X = \sqrt{\pm .017^2 \times 2}$$

$$= \pm .0248$$

$$= \pm .0248 \times .004464 \text{ inches.}$$

$$= \pm .00011 \text{ inches.}$$

In terms of stress, .00011 inches error in 12 inches is equivalent to:

$$\frac{.00011 \times 29.1 \times 10^6}{12} = 265 \text{ lbs. per square inch.}$$

Over a length of 3"—— 1050 lbs. per square inch.

When cutting the plates into strips, measurements were taken on both the strips and on the remainder of the plate after each pair of strips was severed. This discussion will be limited to the ultimate recoveries or further shortenings in the strips themselves. All measurements, however, are recorded in the observations.

In figure 19, a diagram is shown for each plate, representing the longitudinal elastic deformation of each strip after cutting. These deformation are plotted in terms of revolutions of micrometer "B", and are totals over 12 inches. To another scale the ordinates represent stress in lbs. per square inch. As the thickness is constant, the width of each strip is proportional to its cross-sectional area. The shaded portions of the diagrams, being products of the unit stress and width of each strip, will represent the total longitudinal forces in each plate before cutting them into strips. For equilibrium the total force in tension must equal the total force in compression. It follows, therefore, that the areas below and above the zero stress line should be equal. With plate Y the difference is only 2½%, with plate Z, 8%, the area in tension being larger. This is a remarkable agreement when it is considered that errors are introduced by loss of some of the metal in cutting, by residual stress in other directions, and by a noticeable bowing of some of the strips as they were separated from the remainder of the plate. The difference in the moduli of the weld and parent ~~weld~~ metal would also affect the comparison slightly. All these errors, except the latter, would tend to be compensating.

It will be observed that no record was made of the deformations of the weld strips for plates W and X, but, from the results obtained with plates Y and Z, the deformations can be safely estimated by balancing the total forces. This was done and is shown in the dotted areas in figure 19.

The following is a tabulation of the maximum average stresses in each plate, read from the diagrams in figure 19.

Plate	Average maximum tension lbs./sq. inch	Location	Average maximum compression lbs./sq.inch	Location	Percent of weld metal
W	7,700	welds	7,800	center of plate	20.6
X	18,300 14,100	do	9,000	center, 2" from weld	10.3
Y	11,100 9,700	do	4,800 6,100	2" from weld	6.8

Plate	Average maximum tension lbs./sq. inch.	Location	Average maximum compression lbs./ sq. inch.	Location	Percent of weld metal
Z	17,200 13,700	welds "	6,700 5,300	2" from weld	5.2

Referring back to figure 19, the dotted lines show the lack of recovery of the plates from their original length or condition before welding, in other words, the permanent deformation caused by the welding process. There is no definite proof that some of the lack of recovery does not represent residual stresses that might have been in the plates even before welding; but it is certain such stresses would be greatly reduced, if not eliminated, by the annealing effect of the welding.

A more extensive analysis was made with plate Z than with the three narrower plates. Measurements of the deformations were taken at each gauge line, and the distribution of stress throughout the plate was calculated. Figure 20 is an axometric diagram, showing this distribution of stress. Let us examine a cross-section of this diagram at gauge line No.3. The stress distribution is not much influenced by the end effects and might be considered to represent the average distribution in a similar very long specimen. In figure 21, an attempt has been made to illustrate the stress distribution in plate Z by joining all points of equal stress intensity. These contour or iso-stress lines have been produced beyond the measured section of the plate to show the likely distribution at the ends.

One of the most interesting observations was the bowing of the weld strips upon separation from the main plate. At first it was supposed that the greatest tensional stress would be at the extreme edges of the plates, i.e. at the outside faces of the welds. If this had been the case, the weld strip, including one half inch of the plate, would have bowed in such a manner that the cut face of the strip would have been convex, if indeed any bowing were noticed at all. Actually the bowing was in the opposite direction, i.e. the cut face of the strip was concave. As the modulus of the weld metal was lower than the modulus of the material of the plate, this fact would tend to lessen the observed direction of bowing. Our conclusion is, then, that the maximum tension stress was not at the extreme edge of the plate, but rather at some distance in from the front of the weld, probably at the junction of the weld and the parent weld metal.

The offset at the center of each strip was measured from a straight line joining two points on gauge lines 1 and 5 respectively. These figures are shown in Table XV, together with the width and thickness of each strip. While these measurements do not provide any exact means of estimating just how much difference in stress there might have been between the two faces of the bowed strips, an indication of this difference can be shown by making certain assumptions.

If we consider each strip as a rectangular beam, and that the bowing at the center is due to a uniform bending moment along the strip, then this bending moment can be calculated, and therefore the stresses present on both faces of the strip, when the strip is straight, can be determined. These calculations are shown on page 63 for plate 3, together with the resulting distribution of stress across the mid section of this plate. The calculated released bending stresses are superimposed on the measured longitudinal stress of each strip. The resulting maximum tension in strip A does not check with the figured maximum tension stress in the adjacent weld strip. Perhaps the maximum stress is somewhere between these two figures! A very good check is noticed with strip G and its adjacent weld strip. A more exact analysis might be obtained if the offset or deflection could be measured over a smaller distance at the center of the strip, but it must be remembered that the section of the weld is not uniform and that these offsets are very small and any means of determining them would produce approximate results only. From the analysis made, no stress is shown at the outside face of weld G at the mid section of the plate, but there is shown a maximum stress of 19,000 lbs. per square inch at 0.5 inches in from the back of the weld. This must be viewed with suspicion as we cannot be sure that all the stress in the strip has been released upon separation from the plate; and the analysis of the bending is only approximate. At the ends of the plate, due to their unrestrained condition, the front of the weld is probably stressed very highly, or at least higher than at the center.

To account for the stress being highest at about 0.5 inches in from the edge of the plate, the following reasoning is offered. When the deposited weld metal begins to cool, temperature reduction proceeds from the surface inwards; the center of the metal cools last and therefore is the last portion to readjust itself. The center in the 7/8 inch plate is roughly $\frac{1}{2}$ an inch in from the front face of the weld. We would then expect to find the point of maximum stress at this point. This was borne out in our test.

CONCLUSIONS.

By comparing the initial shrinkages in the plates, it is apparent that the average shortening is less in the wider plates. This result would be expected in plates of uniform thickness with the same amount of weld similarily deposited. But on consulting the results obtained with the welded column in Part 1, it is shown that the column with four weld fillets, making a total amount of weld metal equal to 9.3% of the cross-section initially contracted 0.00133 inches per linear inch; while plate X with 10.3% of the cross-section weld metal, deposited in two fillets, contracted only 0.000422 inches per linear inch, about one third as much as in the case of the column. Thus, while there seems to be some relation between the amount of shrinkage and the amount of weld metal deposited, the total shrinkage must depend to a very large extent upon the shape of the member, and perhaps on the number of welds made.

From the results of this investigation it does not appear that the magnitude of the residual stresses bear any direct relation to the size of the member. These initial stresses must depend on the amount of heat supplied relative to the cross-section of the member. In welding, the operator applies a greater amount of heat in the case of heavier specimens. This is accomplished by increasing the voltage, by using heavier electrodes, or by progressing the weld more slowly. An increase in heat causes greater penetration, and will set up tension in the parent metal for some distance in from the weld, and thereby relieve what might otherwise produce excessively high stresses in the weld itself. From this it appears that the maximum tensile stress in the welds will not necessarily be a function of the size of the member welded, but rather the amount of penetration procured. It was also indicated that the greatest tensile stress, which in this series of tests amounted to about 20,000 lbs. per square inch, takes place at, or very close to, the junction of the weld and parent metal.

While the maximum stress in compression, observed from the analysis of the plates, was considerably less than the maximum compression stress estimated in the case of the welded column, it must be taken into consideration that the specimens were much different in shape; that the column contained four welds while the plates but two weld fillets; and that the initial shrinkage was greater in the case of the column. These facts tend to substantiate our deduction that a compression stress close to 20,000 lbs. per square inch, was set up in the column due to the welding. However, it was stated that within the usual factor of safety limits such high stresses could not be expected to affect greatly the load carrying capacity of short compression members.

Since the completion of this investigation changes have been made in the type of electrode commonly used in electric arc welding. Covered wire electrodes are now much used in place of the bare wire weld rods. The covered wire electrodes have the property of producing a more ductile weld and of finer texture. In using the new rod a greater amount of heat must be applied to the specimen than in the case of the bare wire type. Further tests are required to determine the effects that the use of the covered rod will produce. Equally important are the results from depositing the weld in two or more passes of the welding element. Perhaps this latter procedure would produce lower initial stresses, or cause the point of maximum tension to be at some point other than at the junction of the weld and parent metal.

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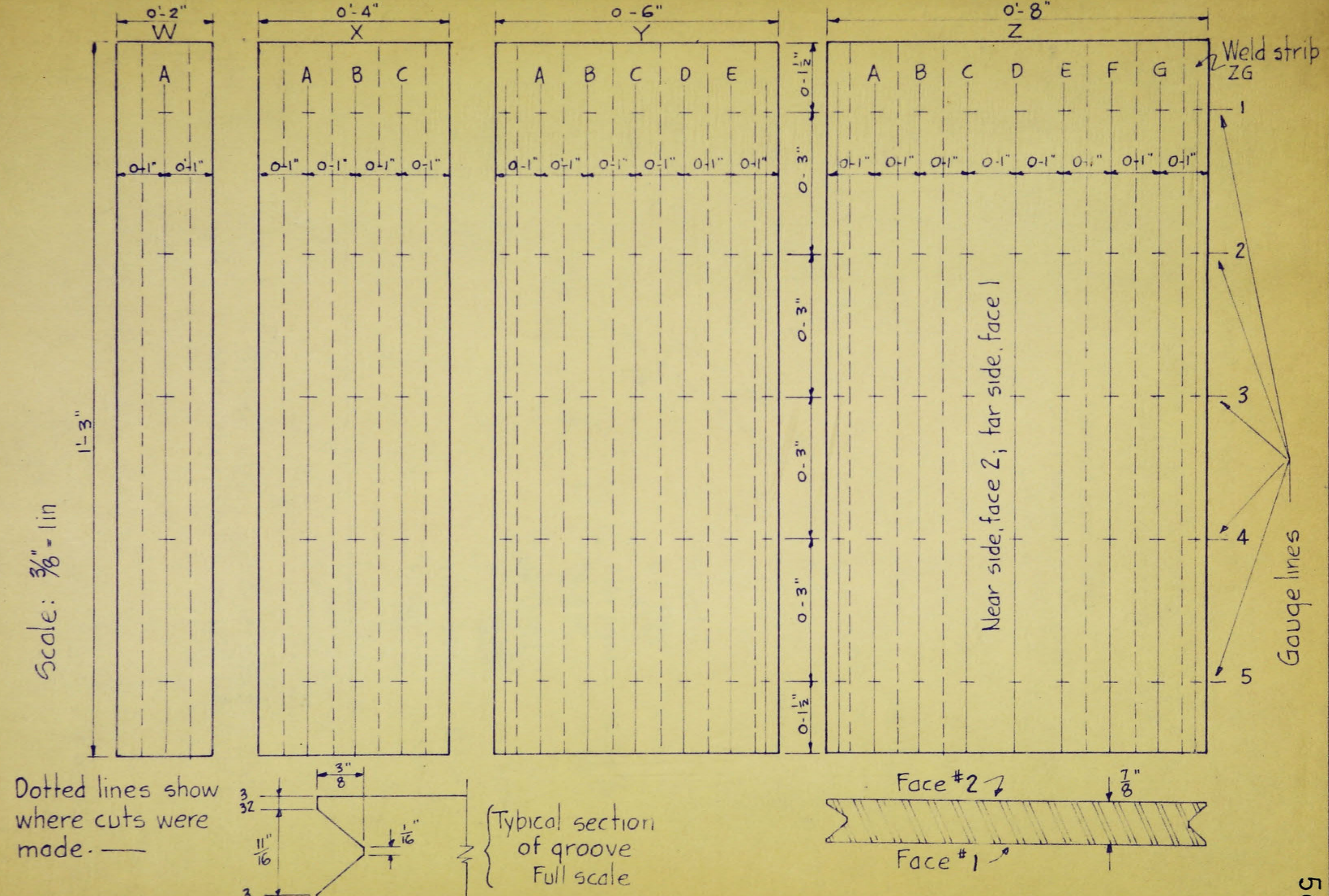
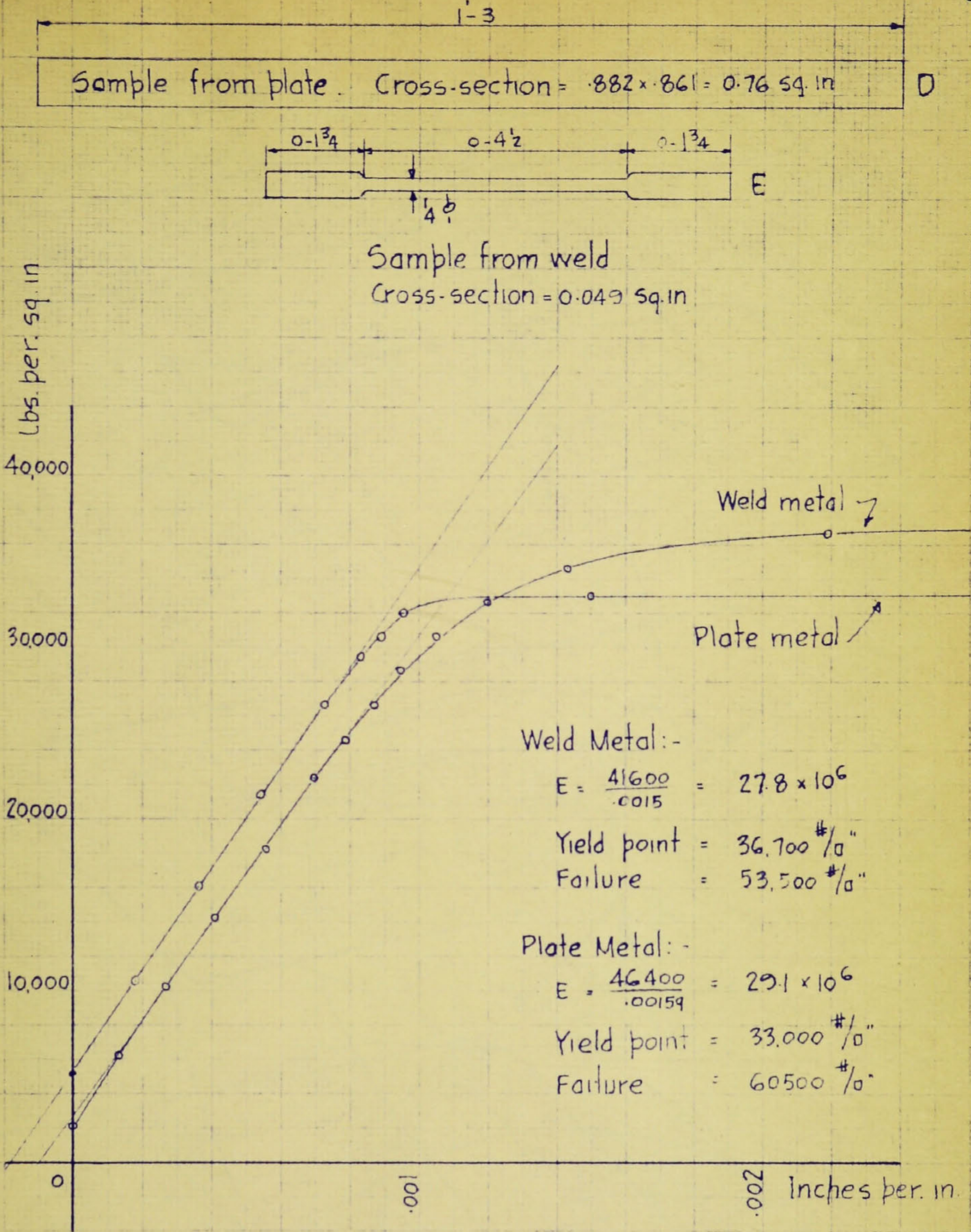
The work was done in consultation with Professor R. E. Jamieson, William Scott Professor of Civil Engineering, McGill University.



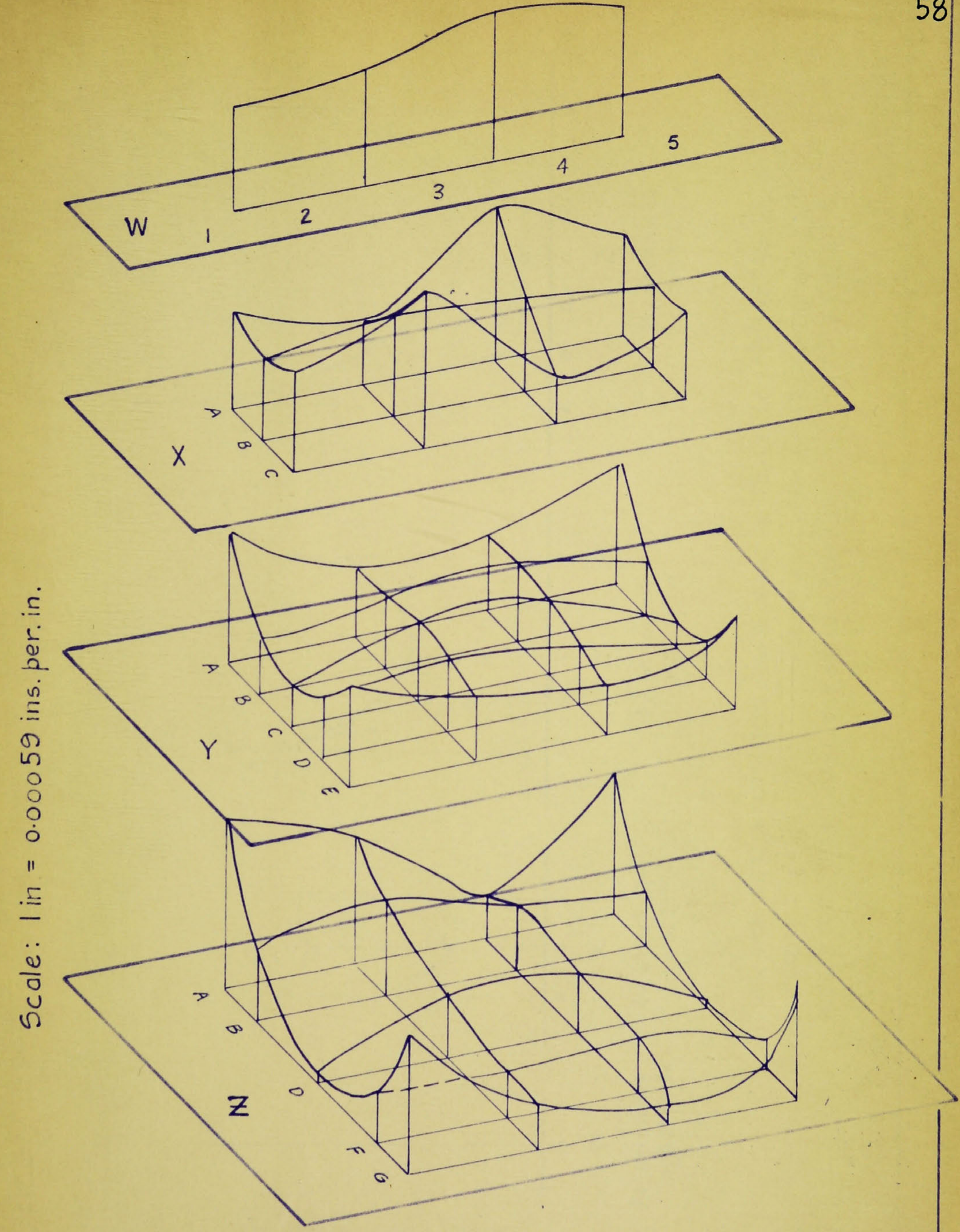
DETAILS OF THE STEEL PLATES

FIGURE -15-



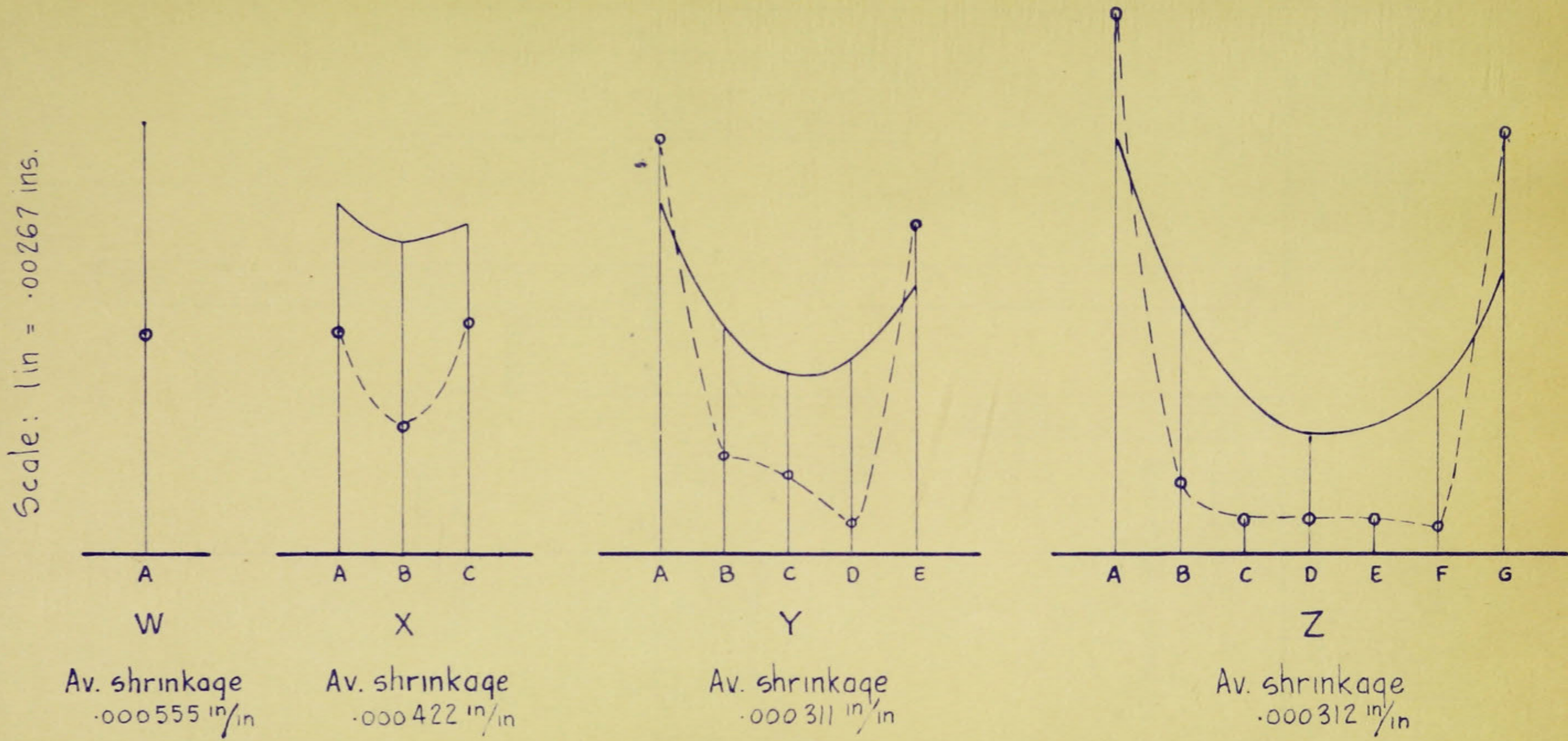
Stress-strain Characteristics of the Material of the plates and the Weld Metal.

FIGURE -16-



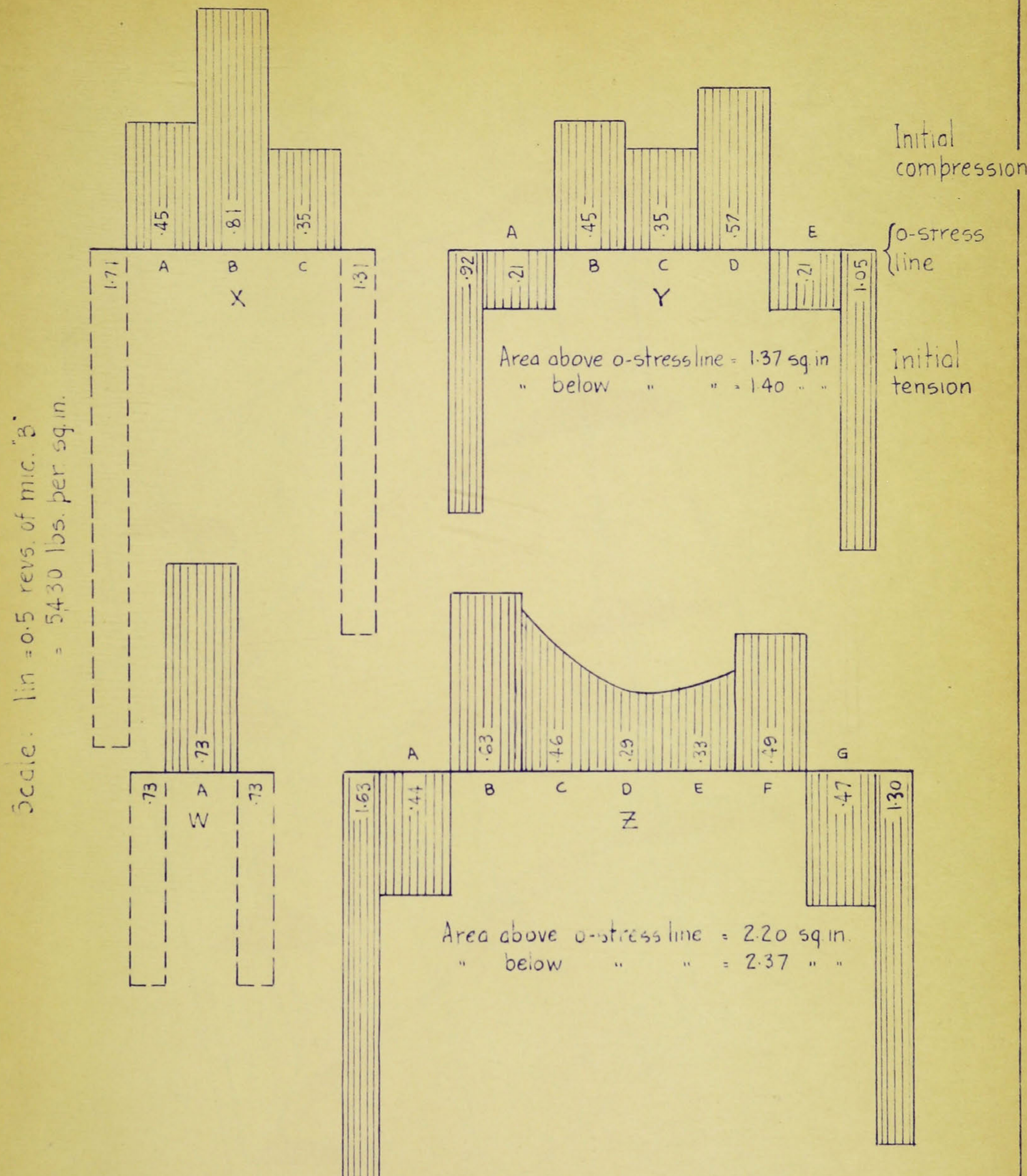
AXOMETRIC DIAGRAMS SHOWING THE SHRINKAGES IN THE FOUR PLATES DUE TO THE WELDING PROCESS

FIGURE -17-



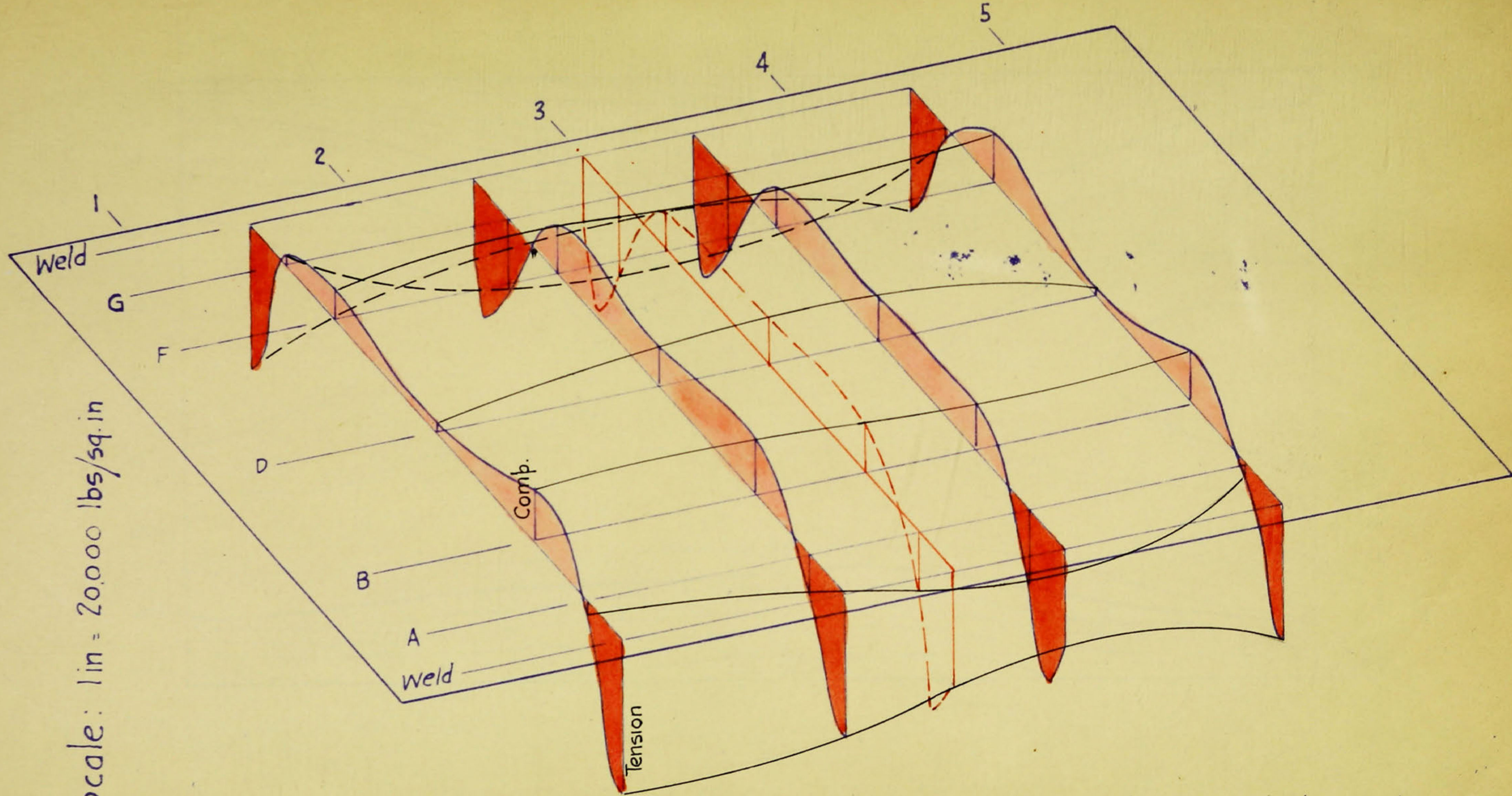
FULL LINE REPRESENTS TOTAL SHRINKAGE IN 12 INS. DUE TO THE WELDING
DOTTED " " " LACK OF RECOVERY AFTER PLATE WAS CUT
INTO STRIPS (EXCLUDING THE WELD STRIPS)

FIGURE -18-



Diagrams showing the total longitudinal elastic deformations resulting from cutting the plates into strips —

FIGURE - 19 -



Scale: 1 in = 20,000 lbs/sq.in

Axometric diagram showing the magnitudes and distribution of residual stresses in plate Z

FIGURE -20-

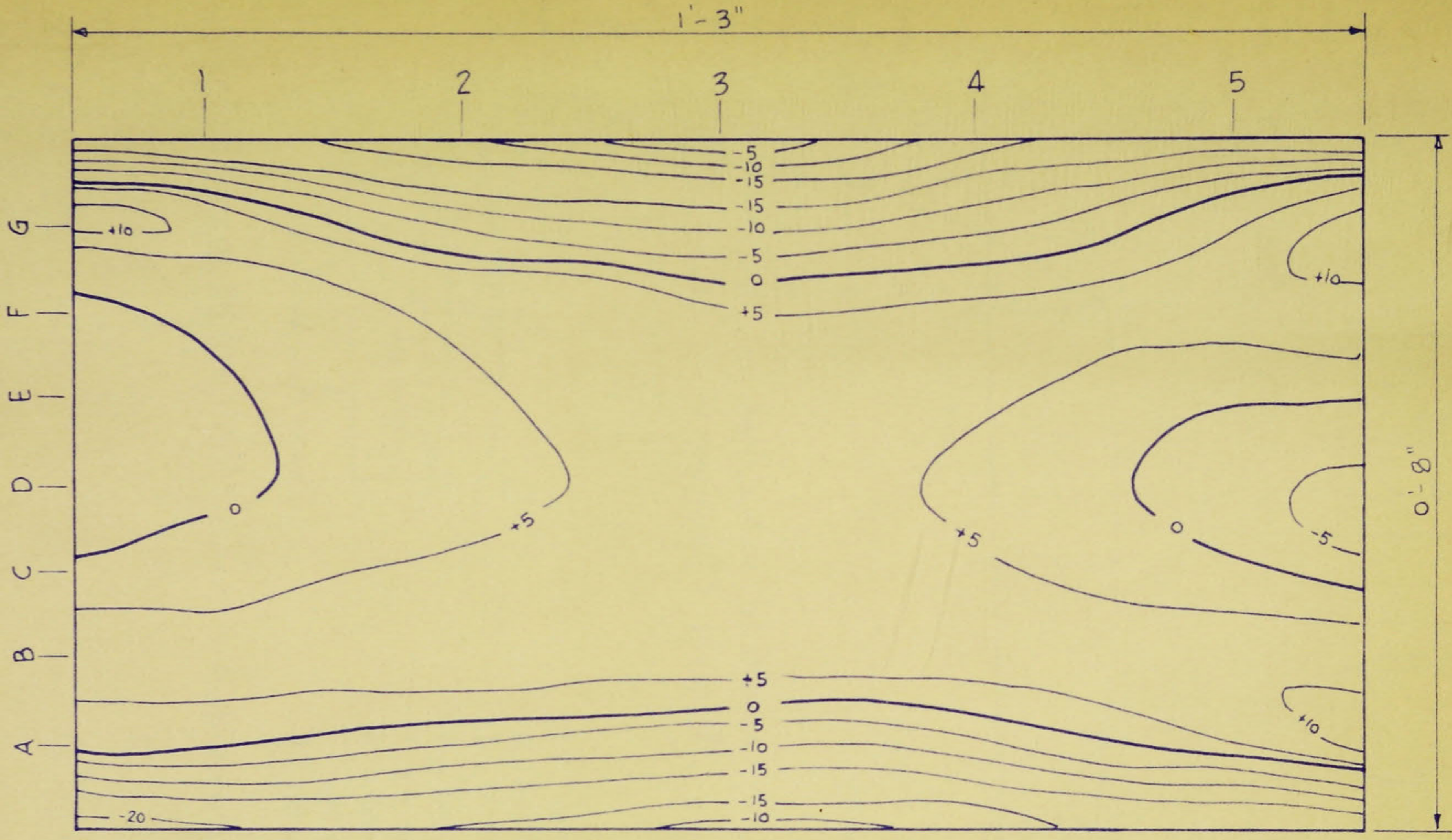
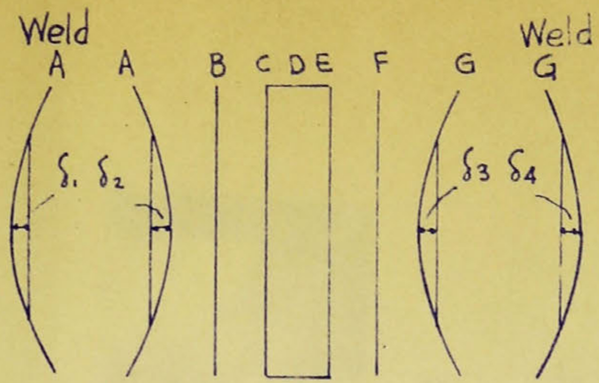


Diagram showing the magnitudes and distribution of residual stresses in plate Z, by means of lines joining points of equal stress intensity. Stresses are in kips per square inch and are component stresses parallel to the welds.

FIGURE - 21 -

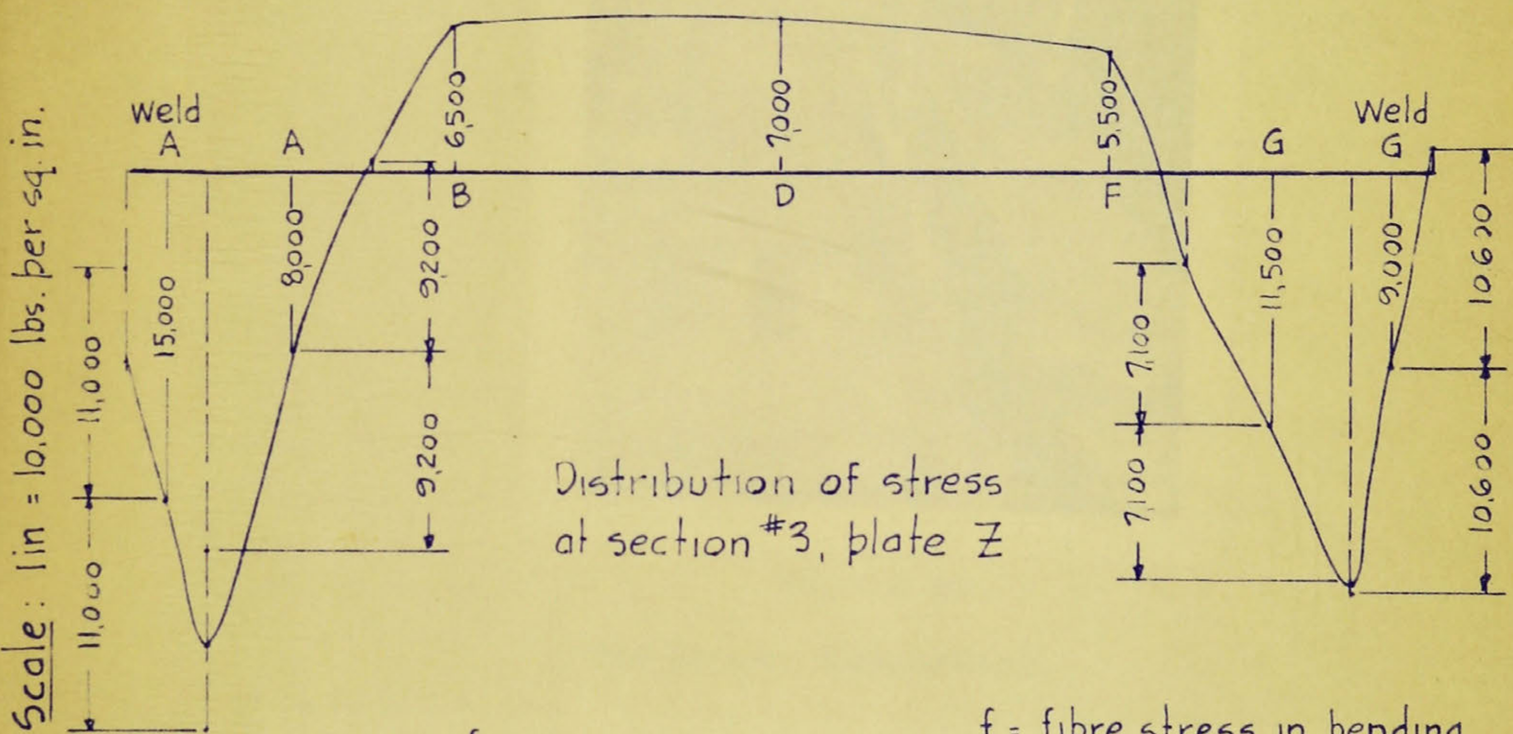


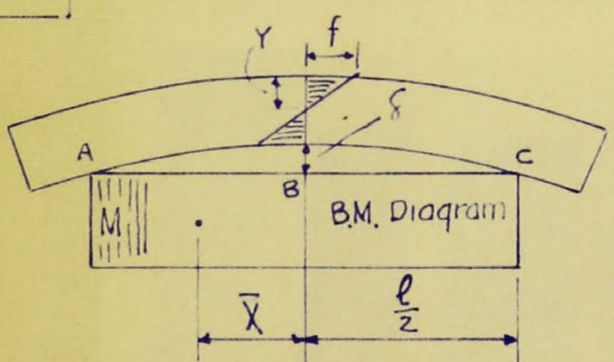
$\delta_1 = 0.027''$ $\quad Y_1 = 0.26''$

$\delta_2 = 0.013''$ $\quad Y_2 = 0.44''$

$\delta_3 = 0.010''$ $\quad Y_3 = 0.44''$

$\delta_4 = 0.028''$ $\quad Y_4 = 0.24''$





f = fibre stress in bending
M . Bending moment.
I . Moment of inertia
E . Youngs' modulus
Y = $\frac{1}{2}$ width of strip.
δ . deflection or bending at center of the strip.
l = length of strip (12")

$$\delta = \frac{(\text{Area of BM diag. btn. A\&B}) \times \bar{X}}{EI}$$

$$= M \times \frac{l}{2} \times \frac{l}{4} \times \frac{1}{EI}$$

$$f = \frac{MY}{I}$$

$$f = \frac{\delta \times E \times Y \times 8}{l^2} \quad \text{-----} \quad (1)$$

E for weld strips, 28.5×10^6
E .. strips A & G, 29.1×10^6

Substituting the unknowns in (1):

$f_1 = \pm 11,000$ lbs/sq.in

$f_2 = \pm 9,200$ do

$f_3 = \pm 7.100$ do

$f_4 = \pm 10600$ do

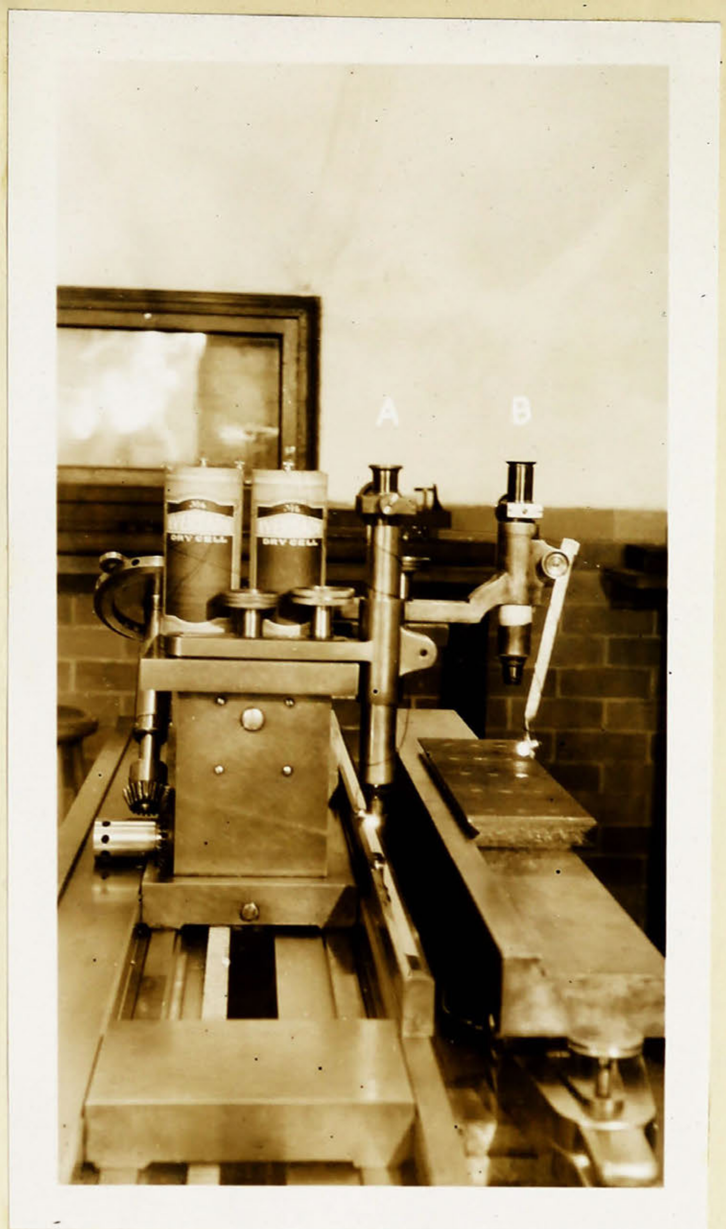


Figure 22.

The Linear Comparator.

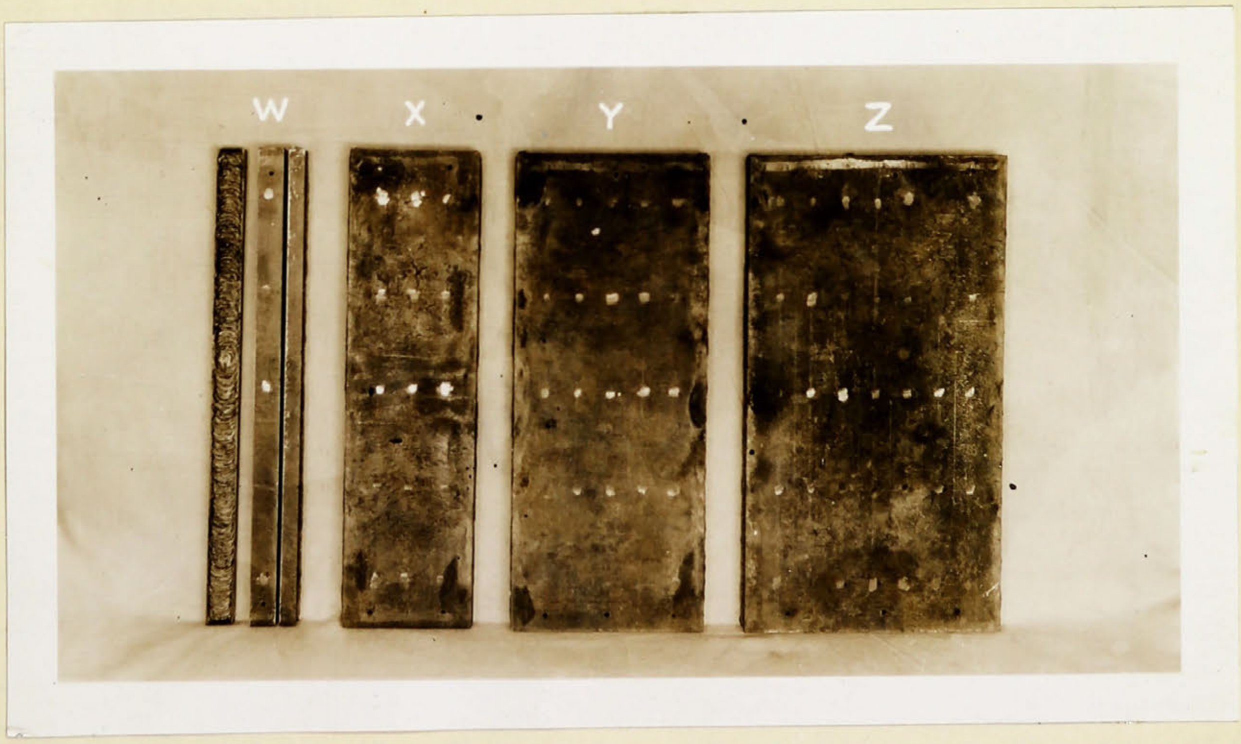


Figure 23.

The four plates, with the weld strips severed from Plate W.

OBSERVATIONS

TABLE XII

Tabulation of shrinkages in the various plates due to the process of welding. (Shrinkages are in terms of revolutions of micrometer "B". To reduce to inches multiply by 0.004464).

PLATE W

Gauge Line	W_1A	W_2A	Mean W A
1			
	.34	.29	.32
2			
	.37	.32	.34
3			
	.50	.41	.46
4			
	.43	.35	.39
5			
		Total	1.51

PLATE X

	X_1A	X_2A	X A	Gauge Line	X_1B	X_2B	Mean X B	Gauge Line	X_1C	X_2C	Mean X C
1				1				1			
	.27	.31	.29		.17	.28	.23		.27	.32	.29
2				2				2			
	.11	.22	.17		.29	.34	.32		.41	.53	.47
3				3				3			
	.51	.41	.46		.31	.25	.28		.17	.08	.13
4				4				4			
	.23	.37	.30		.18	.29	.24		.19	.32	.26
5				5				5			
		Total	1.22			Total	1.07			Total	1.15

PLATE Y

Gauge Line	Y_1A	Y_2A	Mean Y A	Gauge Line	Y_1B	Y_2B	Mean Y B	Gauge Line	Y_1C	Y_2C	Mean Y C
1				1				1			
	.50	.29	.39		.25	.07	.16		.18	.05	.11
2				2				2			
	.29	.13	.21		.27	.14	.21		.29	.19	.24
3				3				3			
	.30	.17	.24		.30	.19	.25		.25	.20	.22
4				4				4			
	.47	.29	.38		.24	.07	.16		.19	.05	.07
5				5				5			
		Total	1.22			Total	.78			Total	.64

Explanatory Note:

In the headings to all tabulations, reading on one side of the plate are denoted by the figure 1, and readings on the opposite side, by the figure 2. The first letter denotes the plate (W,X,Y or Z), and the second letter indicated the particular strip, e.g., W_1A - Plate W, face 1, strip A; W_2A - Plate W, face 2, strip A; - W A - mean of the readings on both faces, plate W strip A.

TABLE XII (continued)

PLATE Y

Gauge Line	Y_1D	Y_2D	Mean Y D	Gauge Line	Y_1E	Y_2E	Mean Y E
1				1			
	.23	.12	.17		.34	.26	.30
2				2			
	.27	.15	.21		.24	.16	.20
3				3			
	.20	.15	.17		.16	.13	.14
4				4			
	.22	.01	.11		.43	.15	.29
5				5			
		Total	.66			Total	.93

PLATE Z

Gauge Line	Z_1A	Z_2A	Mean Z A	Gauge Line	Z_1B	Z_2B	Mean Z B	Gauge Line	Z_1D	Z_2D	Mean Z D
1				1				1			
	.55	.47	.51		.25	.18	.21		.03	.04	.03
2				2				2			
	.40	.36	.38		.33	.25	.29		.29	.11	.20
3				3				3			
	.17	.06	.11		.24	.15	.19		.24	.10	.17
4				4				4			
	.57	.30	.44		.30	.02	.16		.08	-.06	.01
5				5				5			
		Total	1.44			Total	.85			Total	.41

Gauge Line	Z_1F	Z_2F	Mean Z F	Gauge Line	Z_1G	Z_2G	Mean Z G
1				1			
	.11	.18	.14		.41	..43	.42
2				2			
	.21	.10	.16		.21	.06	.14
3				3			
	.20	.14	.17		.11	-.01	.05
4				4			
	.21	-.03	.09		.47	.26	.36
5				5			
		Total	.56			Total	.97

TABLE XIII

Longitudinal elastic deformations resulting from cutting the plates into strips. (Measurements are in terms of revolutions of micrometer "B". To reduce to inches multiply by 0.004464). (Plus sign denotes expansion, minus sign - contraction).

PLATE W. (weld strips severed)

Gauge Line	W_1A	W_2A	Mean W A
1			
	+.37	+.34	+.36
3			
	+.38	+.37	+.37
5			
	+.75	+.71	+.73
1			

PLATE X. (weld strips severed)

Gauge Line	X_1A	X_2A	Mean X A	X_1B	X_2B	Mean X B	X_1C	X_2C	Mean X C
1									
	+.24	+.26	+.25	+.25	+.35	+.30	+.35	+.34	+.34
3									
	+.37	+.37	+.37	+.28	+.23	+.25	+.27	+.26	+.27
5									
	+.61	+.63	+.62	+.53	+.57	+.55	+.62	+.60	+.61
1									

PLATE X. (strips A & C, adjacent to weld strips, severed)

Gauge Line	X_1A	X_2A	Mean X A	X_1B	X_2B	Mean X B	X_1C	X_2C	Mean X C
1									
	-.08	-.08	-.08	+.17	+.07	+.12	-.17	-.05	-.11
3									
	-.14	-.04	-.09	+.14	+.15	+.14	-.13	-.18	-.15
5									
	-.22	-.12	-.17	+.31	+.22	+.26	-.30	-.23	-.26
1									

Summation of the elastic deformation in Plate X.

Gauge Line	X A	X B	X C
1			
	+.17	+.12	+.23
3			
	+.28	+.14	+.12
5			
Total	+.45	+.26	+.35

TABLE XIII (continued)

PLATE Y. (weld strips severed)

Gauge Line	Weld Y_1A	Weld Y_2A	Mean Weld Y A	Y_1A	Y_2A	Mean Y A	Y_1C	Y_2C	Mean Y C	Y_1E	Y_2E	Mean Y E
1												
	-.58	-.55	-.56	+.10	+.27	+.18	+.07	+.12	+.09	+.24	+.22	+.23
3												
	-.46	-.25	-.36	+.17	+.12	+.15	+.02	+.09	+.06	+.16	+.22	+.19
5												
	-1.04	-.80	-.92	+.27	+.39	+.33	+.09	+.21	+.15	+.40	+.44	+.42
1												

Gauge Line	Weld Y_1E	Weld Y_2E	Mean Weld Y E
1			
	-.62	-.45	-.53
3			
	-.48	-.55	-.52
5			
	-1.10	-1.00	-1.05
1			

(strips A & E, adjacent to weld strips, severed)

Gauge Line	Y_1A	Y_2A	Mean Y A	Y_1B	Y_2B	Mean Y B	Y_1C	Y_2C	Mean Y C	Y_1D	Y_2D	Mean Y D
1												
	-.19	-.28	-.24	+.06	+.20	+.13	+.12	+.14	+.13	+.09	+.20	+.15
3												
	-.29	-.31	-.30	+.05	+.07	+.06	+.06	+.17	+.12	+.11	+.20	+.15
5												
	-.48	-.59	-.54	+.11	+.27	+.19	+.18	+.31	+.25	+.20	+.40	+.30
1												

Gauge Line	Y_1E	Y_2E	Mean Y E
1			
	-.26	-.29	-.28
3			
	-.32	-.39	-.35
5			
	-.58	-.68	-.63
1			

(strips B & D, adjacent to A & E, severed)

Gauge Line	Y_1B	Y_2B	Mean Y B	Y_1C	Y_2C	Mean Y C	Y_1D	Y_2D	Mean Y D
1									
	+.05	+.04	+.04	-.11	+.08	-.02	+.08	-.04	+.02
3									
	+.03	+.01	+.02	-.02	-.05	-.03	+.06	0	+.03
5									
	+.08	+.05	+.06	-.13	+.03	-.05	+.14	-.04	+.05
1									

TABLE XIII (continued)

Summation of the elastic deformations in Plate Y.

Gauge Line	Weld A	Strip A	Strip B	Strip C	Strip D	Strip E	Weld E
1							
	-.56	-.06		+.20		-.05	-.53
3							
	-.36	-.15		+.15		-.16	-.52
5							
Total	-.92	-.21	+.45	+.35	+.57	-.21	-1.05

PLATE Z. (weld strips severed)

Gauge Line	Weld Z_1A	Weld Z_2A	Mean Weld Z A	Z_1A	Z_2A	Mean Z A	Z_1B	Z_2B	Mean Z B	Z_1D	Z_2D	Mean Z D
1												
	-.49	-.47	-.48	+.18	+.18	+.18	+.11	+.08	+.09	-.01	+.01	0.
2												
	-.42	-.43	-.43	+.13	+.11	+.12	+.05	+.12	+.08	+.03	+.07	+.05
3												
	-.36	-.26	-.31	+.07	+.06	+.07	+.06	+.07	+.07	+.06	+.04	+.05
4												
	-.42	-.42	-.42	+.10	+.21	+.15	+.02	+.05	+.04	-.07	+.04	-.01
5												
	-1.69	-1.57	-1.63	+.48	+.57	+.52	+.24	+.33	+.28	0	+.17	+.09
1												

Gauge Line	Z_1F	Z_2F	Mean Z F	Z_1G	Z_2G	Mean Z G	Weld Z_1G	Weld Z_2G	Mean Weld Z G
1									
	+.01	+.04	+.02	+.21	+.19	+.20	-.47	-.43	-.45
2									
	+.05	+.07	+.06	+.02	-.01	+.01	-.21	-.27	-.24
3									
	+.04	+.04	+.04	-.03	+.02	-.01	-.28	-.19	-.24
4									
	+.03	+.07	+.05	+.19	+.21	+.20	-.39	-.37	-.38
5									
	+.12	+.22	+.17	+.39	+.41	+.40	-1.35	-1.25	-1.30
1									

(strips A & G, adjacent to weld strips, severed)

Gauge Line	Z_1A	Z_2A	Mean Z A	Z_1B	Z_2B	Mean Z B	Z_1D	Z_2D	Mean Z D
1									
	-.13	-.30	-.21				+.03	+.03	+.03
2				+.12	+.22	+.17			
	-.17	-.34	-.25				+.03	+.08	+.05
3									
	-.18	-.42	-.30				+.05	+.09	+.07
4				+.11	+.28	+.19			
	-.03	-.36	-.20				0	+.06	+.03
5									
	-.51	-1.42	-.96	+.23	+.49	+.36	+.11	+.27	+.19
1									

TABLE XIII (continued)

PLATE Z. (strips A & G, adjacent to weld strips, severed)

Gauge Line	Z_1F	Z_2F	Mean Z F	Z_1G	Z_2G	Mean Z G
1						
				-.23	-.13	-.18
2	+.09	+.17	+.13			
				-.22	-.23	-.23
3						
				-.23	-.24	-.23
4	+.15	+.26	+.20			
				-.18	-.27	-.23
5						
	+.24	+.43	+.33	-.86	-.88	-.87
1						

(strips B & F, adjacent to strips A & G, severed)

Gauge Line	Z_1B	Z_2B	Mean Z B	Z_1C	Z_2C	Mean Z C	Z_1D	Z_2D	Mean Z D
1									
							-.06	+.03	-.01
2	+.14	-.19	-.02	-.01	+.13	+.06			
							-.01	+.04	+.01
3									
							-.03	+.06	+.01
4	+.39	-.39	0	-.03	+.10	+.03			
							-.01	+.01	0
5									
	+.54	-.57	-.02	-.04	+.23	+.09	-.11	+.15	+.02
1									

Gauge Line	Z_1E	Z_2E	Mean Z E	Z_1F	Z_2F	Mean Z F
1						
2	-.06	+.05	0	-.05	+.06	0
3						
4	-.05	+.08	+.01	-.15	+.11	-.02
5						
	-.10	+.13	+.01	-.20	+.16	-.02
1						

TABLE XIII (continued)

Summation of the elastic deformations in Plate Z.

Gauge Line	Weld ZA	Strip ZA	Strip ZB	Strip ZC	Strip ZD	Strip ZE	Strip ZF	Strip ZG	Weld G
1									
	-.48	-.03	+.16		+.02		+.09	+.02	-.45
2									
	-.43	-.13	+.17		+.12		+.13	-.22	-.24
3									
	-.31	-.23	+.14		+.14		+.12	-.24	-.23
4									
	-.42	-.03	+.16		+.01		+.15	-.03	-.38
5									
Total	-1.63	-.44	+.63	+.46	+.29	+.33	+.49	-.47	-1.30

TABLE XIV

Stress-strain observations for Coupon "D". (material of the plates)

Load kips	Ext. Front	Ext. Back	Front Diff.	Back Diff.	Mean Diff.	Unit Strain	Unit Stress
0.3	23.0	7.0					
4	21.88	8.42	0	0	0	0	5340
8	20.30	9.72	1.58	1.30	1.44	.00180	10500
12	19.21	11.55	2.67	3.13	2.90	.00362	16000
16	18.14	13.35	3.74	4.93	4.33	.00542	21400
20	17.10	15.28	4.78	6.86	5.82	.00727	26700
22	16.38	16.21	5.50	7.79	6.65	.00831	29400
23	15.92	16.72	5.96	8.30	7.13	.00891	30700
24	15.40	17.21	6.48	8.79	7.63	.00955	32000
25	11.50	19.50	10.38	11.08	10.73	.01341	33000
46	Fracture						60500

Stress-strain observations for Coupon "E". (material of the weld)

0.1	17.0	25.0	0	0	0	0	2040
0.3	17.43	24.42	.43	.58	.51	.0013	6120
0.5	17.98	23.81	.98	1.19	1.08	.0027	10200
0.7	18.48	23.19	1.48	1.81	1.64	.0041	14300
0.9	19.00	22.51	2.00	2.49	2.25	.0056	18350
1.1	19.52	21.89	2.52	3.11	2.81	.0070	22400
1.2	19.81	21.53	2.81	3.47	3.14	.0079	24500
1.3	20.12	21.18	3.12	3.82	3.47	.0087	26500
1.4	20.43	20.80	3.43	4.20	3.82	.0095	28600
1.5	20.79	20.35	3.79	4.65	4.22	.0105	30600
1.6	21.25	19.65	4.25	5.35	4.80	.0120	32600
1.7	22.04	18.60	5.04	6.30	5.67	.0142	34700
1.8	24.90	15.40	7.90	9.60	8.75	.0219	36700
2.63	Fracture						53500

TABLE XV

Average net width of each strip and the measurement of the amount of bowing observed.

Strip	Average width inches	Bowing of strip at the center inches
W-weld	0.501	+0.015
W A	0.804	--
W-weld	0.507	+0.011
X A weld	0.482	+0.024
X C "	0.483	+0.017
X A	0.867	--
X B	0.859	--
X C	0.890	--
Y A-weld	0.526	+0.019
Y E- "	0.505	+0.027
Y A	0.901	-0.018
Y B	0.885	--
Y C	0.829	--
Y D	0.878	--
Y E	0.921	-0.009
Z A-weld	0.517	+0.027
Z G- "	0.486	+0.028
Z A	0.887	-0.013
Z B	0.886	--
Z F	0.883	--
Z G	0.887	-0.010

NOTE: 1. Average thickness of the plates -0.862 inches.

2. The bowing is a measure of the offset at the center of the strip from a straight line joining two points on gauge lines 1 and 5 respectively. Plus sign indicates that the bowing on the cut face nearest the center of the plate is concave, a minus sign indicates that the bowing is convex.