STRESS IN WELDED JOINTS

"An Investigation of Stress in

Welded Joints."

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"An Investigation of Stress in Welded Joints."

The object of this investigation was first, to evaluate the residual stresses in members which have been welded by various methods and second, to determine the effect which stress relieving has upon them.

Four types of weld were considered in each case, these being:

(1) Weld Metal deposited in one layer with bare electrodes.
(2) Weld Metal deposited in two layers with bare electrodes.
(3) Weld Metal deposited in one layer with covered electrodes.
(4) Weld Metal deposited in two layers with covered electrodes.

The specimens in all cases were mild steel plates 12 inches wide, 3/4 inches thick and 21 inches long with the weld metal deposited in "U" shaped grooves in the long sides of the plate.

The deformation caused by welding was first recorded after which the specimens were severed into strips in order to measure the elastic residual stresses throughout the various plates.

It was found that the stresses in the welds varied from about 10,000 to 40,000 lbs. per square inch and that, after stress relieving, the stresses in every case were reduced to less than 5,000 lbs. per square inch.

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INTRODUCTION.

The joining of ferrous and non-ferrous materials has always played an important role in the field of industry. The object of joining these materials is to make the various structures act as a whole under their applied loads.

Wood, stone, etc. eventually gave way to steel and consequently it was necessary to find new methods of joining members of this material. This new problem was solved by forging, brazing, soldering, pin connecting, bolting and rivetting. As was previously stated, any structure made of pieces must act as a whole under its applied loads, and consequently joint efficiencies determine the action of the structure. As steel became more widely used, more became known about its physical and chemical properties and consequently the allowable working stresses were increased. This made joint efficiencies even more important and as the loading cycle of a structure increases homogeneous joints become increasingly important. The introduction of welding to industry seems to offer a solution for these problems of homogeneous joints and high joint efficiency. The fundamental principle of welding is to bring the parts which are to be joined to a fusion temperature and form a perfect bond between them.

There are many methods of welding but the only one which will be considered in this paper will be electric welding with a metallic arc.

In the first stages of electric arc welding it was found that if a plain steel rod were used, the arc which was formed between the electrode and the work to be welded was difficult to "hold". That is to say, the arc would break and an unsatisfactory weld would be produced. This was due to the fact that the atmosphere through which the electrical current had to flow was a very poor conductor. This fault was remedied by dipping the electrode in certain chemicals which on being heated would give off gases which were more suitable conductors of electricity than the ordinary atmosphere. Electrodes of this type, despite the fact that they have a thin coating on them, are known as bare electrodes.

It was found, in practice, that welds produced by "bare" electrodes were unsuitable for certain types of work due to the contaminating effect of the atmosphere through which the molten metal had to pass. Coatings were then placed on the electrodes which would protect the metal from the atmosphere not only during transfer through the arc but also after deposition. Electrodes of this type are known as "covered" electrodes.

It is very often the case that a joint cannot be made completely at once due to the thickness of metal to be joined. Such joints as these are made by depositing a suitable number of layers to form the joint. Welding in this manner is known as multiple layer or multiple pass welding.

In using any of the above mentioned methods of welding, certain phenomena are likely to occur due to the intense heating of the materials to be joined. The two most important of these are first, internal stresses will be set up in the members which are joined by welding and second, the members will shorten and distort.

The object of this investigation is to determine something of the magnitude and distribution of the stresses induced into a member by the welding operation.

HISTORICAL SKETCH.

Investigations of residual stresses due to welding have been in progress since the earliest days of welding. For a great length of time, until shortly before 1923, discussion of this subject was discouraged because it was feared by manufacturers of welding equipment that "it would prevent the sale of welding apparatus". Despite this discouragement researches were carried on.

A very comprehensive study of this subject was made by James W. Owen in his book entitled "Fundamentals of Welding" first published in 1923. In this report Mr. Owen studied rigid, semi-rigid, non-rigid joints and the effects of welding sequence for single and multiple layer welding. The results indicate the distribution of residual stress in the various specimens but no attempt to investigate the magnitude of the elastic residual stresses was made.

Investigations along these lines were started at McGill University in 1928. The Dominion Bridge Company were manufacturing some large box girders of welded construction and it was observed that due to the welding process these girders shortened to the extent of 1/8 inch in 10 feet, and that, during welding the parts of the girder remote from the welds had not been raised in temperature sufficiently to create any marked degree of expansion. It was obvious then that high residual stresses must have existed and that these must have been balanced by stresses of opposite sign in the weld metal and a portion of the plate adjacent to the weld.

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 his investigation of stress distribution 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 taken before and after welding on a specimen prepared for his own research. The specimen was made up of two plates "A" and "B" joined together by two channels "C" and "D" back to back and welded to plates "A" and "B". (See Figure 1.)

Mr. Hardy expected to observe some change in the distribution of stress as the member was put under load. However, no noticeable redistribution of stress was observed nor did the initial stress in the joint affect the distribution of stress along the weld itself. A definite shortening of the member was the only effect recorded.

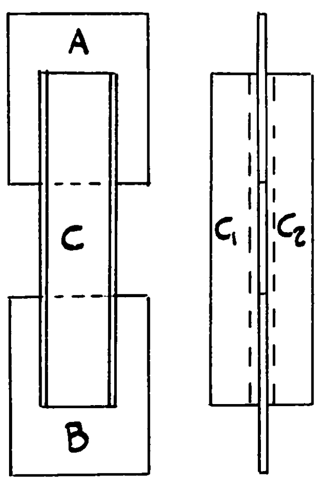

Fig. 1

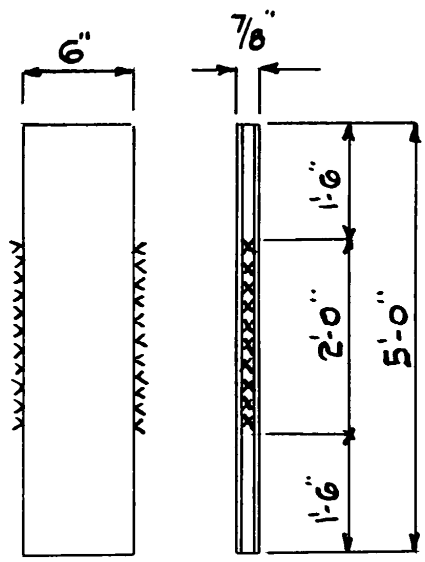

Fig. 2

The next investigation carried out at McGill University on this subject was made by J. F. McDougall, his thesis being entitled "The Initial Stress in Welded Joints".

The specimen studied in this case was a 7/8" thick plate 6" wide and 5'0" long with a "V" shaped groove along the long sides. The groove was filled with weld metal to within 18 inches of each end. (See Figure 2) The specimen was measured, welded and re-measured. A definite shortening was found to have taken place.

Mr. McDougall's theory was that if the central portion of the plate were initially in compression while the outer portions were in tension, upon subjecting the specimen to a tensile load the outer portions of the plate would reach their elastic limit before the central portion which was initially in compression. Thus the load would be redistributed with the central portion receiving more and more of the load as the outer portions reached the yield point. Thus if a stress-strain curve were drawn with average deformations plotted against loads, the graph produced would deviate from the straight line at an average stress well within that representing the elastic limit, considering the whole section as acting uniformly. This theory was corroborated by his tests.

The most recent investigations were those outlined by D. E. Evans in his thesis entitled "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" which was submitted to McGill University for the Degree of Master of Engineering in 1933.

In the first portion of the paper, which was devoted to the effect of residual stresses on a steel compression member, Mr. Evans used as a specimen a 4 inch column section weighing 13.8 lbs. per lineal foot, 3 feet 3 inches long which was welded along the fillets. (See Figure 3.)

Mr. Evans' contentions were that due to welding, compression stresses would be set up along the outer portions of the flanges and the central portion of the web while tension stresses would be set up in the neighbourhood of the welds; that upon subjecting the specimen to an axial compressive load the residual stresses would combine with the stresses caused by the applied load thus causing the portion of the column initially under compression to reach the yield point sooner than the portions initially in tension. Thus failure of the column might be expected to occur soon after any portion of the column had reached the yield point of the material. The results of this test showed that a compressive stress of considerable magnitude was set up due to welding (slightly less than 20,000 lbs. per square inch) which must have been balanced by a tensile stress in and about the deposited weld metal. Also, upon testing the column to failure it was observed that the initial stresses in the column do not materially affect its ultimate strength and that the weld itself adds to the cross-sectional area.

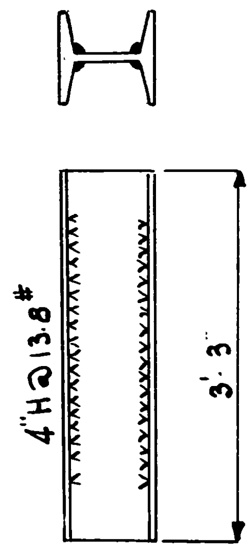

Fig. 3

In the second portion of his thesis entitled "An Analysis of the Distribution of Welding Stresses in Steel Plates", Mr. Evans studied four specimens of mild steel plate 7/8 inches thick, 1 foot 3 inches long and 2, 4, 6 and 8 inches in width. Each plate had a "V" shaped groove down the two long sides which was filled with weld metal. (See Figure 4.)

Mr. Evans contended that the molten weld metal and the portion of the plate adjacent to the weld which had been highly heated during welding was prevented from contracting during cooling by the central portion of the plate which remained relatively cool during the welding process and that this restraint of contraction would cause tensile stresses to be set up in and about the weld; also that these tensile stresses would be balanced by compressive stresses set up in the remainder of the specimen. This was found to be so and Mr. Evans also evaluated the elastic stress contained in the weld metal and in the plate.

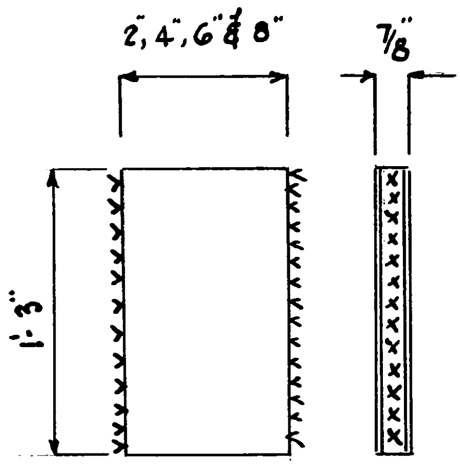

Fig. 4

RESOLUTION.

It is indicated by many investigations that residual stresses (stresses set up by reason of the heat of the welding process) do not affect the load carrying capacity of the members to any appreciable degree nor does the localized intense heating in the vicinity of the weld injure the parent metal. Welded joints are at present designed with a factor of safety which makes it possible for the designor to neglect the initial stress in the weld. However, for sound engineering design we must learn something definite regarding the magnitude of these residual stresses and their effect upon the member. Experience seems to show that their magnitude is of less importance than their effect upon the member. For instance members with continuous welds on them shorten about 1/8 inch in ten feet, circular members such as built up gears decrease in diameter while other members will warp out of line. In practise, certain methods of fabricating procedure will reduce the importance of these distortions and make fabrication much less costly. Sometimes when there is doubt as to the probable magnitude and direction of the expected distortion, a sample is fabricated and the distortion noted. Suitable precautions can then be prescribed for the purpose of offsetting or minimizing the distortion. Occasionally a weld will crack while cooling, due to the stress which has built up within it. It may be stated that, when considering the effects of temperature on any member, much has to be left to the judgment of the welder.

It is the purpose of this paper to investigate the magnitude and distribution of these residual stresses due to various types of electric arc welding, and to determine to what degree stress relieving affects them.

The types of welds which will be considered are:

(a) A weld deposited in one layer with bare electrodes.

(b) A weld deposited in two layers with bare electrodes.

(c) A weld deposited in one layer with covered electrodes.

(d) A weld deposited in two layers with covered electrodes.

(e) A weld deposited in one layer with bare electrodes and stress relieved after welding.

(f) A weld deposited in two layers with bare electrodes and stress relieved after welding.

(g) A weld deposited in one layer with covered electrodes and stress relieved after welding.
(h) A weld deposited in two layers with covered electrodes and stress relieved after welding.

THEORY.

Before attacking this problem from a practical point of view it should be considered purely theoretically in order to visualize these residual stresses and to see what to look for or expect upon examining the various specimens.

First it is necessary to see what happens, in terms of stress, when a temperature change occurs.

Consider a cube of steel at room temperature whose sides are of unit length, as in Figure 5. Let the temperature of the cube be raised one degree then, theoretically, the cube will become larger equally on all three sides as shown by the dotted lines.

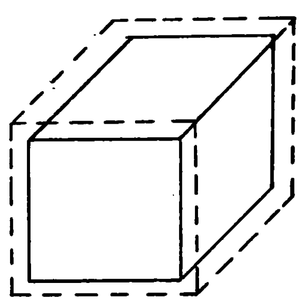

Fig. 5

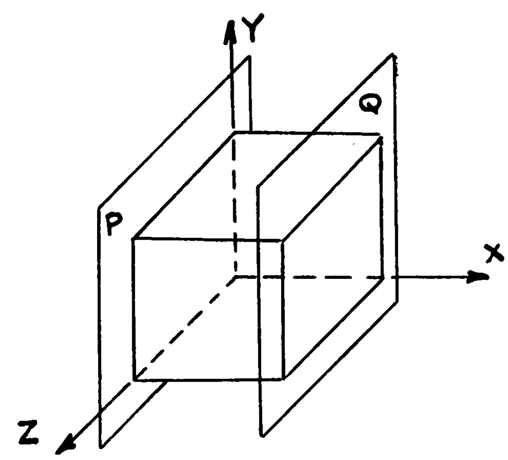

Fig. 6

Let this same cube be placed between two fixed supports, P and Q, (See Figure 6) and let the temperature be raised one degree.

Assuming the coefficient of linear expansion of steel to be 0.0000067 and Youngs Modulus to be 30×10^6 lbs. per square inch and considering a rise in temperature of one degree, the stress set up in the direction "X" would be approximately $0.0000067 \times 30 \times 10^6 = 200$ lbs. per square inch. Thus we see that a change of temperature of slightly less than 200 deg. F. would stress the cube beyond the elastic limit.

In the above illustration restraint in one direction only was considered, however, if the cube were restrained in more than one direction the stress would increase at an even greater rate than in the case considered. This is an ideal case and hardly more than serves to show that if expansion is free no stress is set up while if expansion is restrained high stresses are set up very rapidly.

The next consideration is the behaviour of stress-strain characteristics with the increase of temperature.

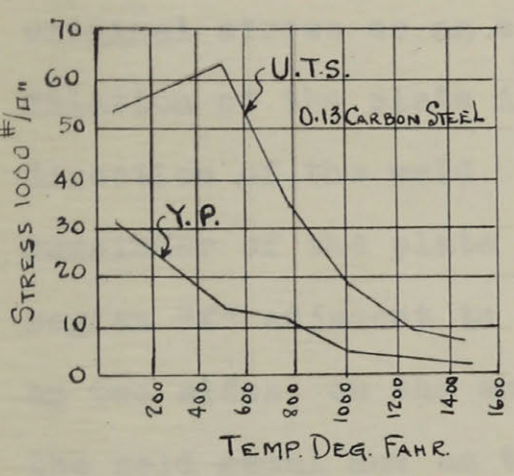

*Fig. 7

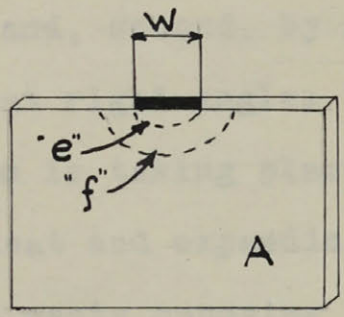

Fig. 8

As the temperature of a steel specimen is raised it becomes more ductile and as the ductility increases, the

*From Stability of Metals at Elevated Temperatures by C.L. Clark and A.E. White. A.S.S.T. Volume No.15

yield point and ultimate tensile strength decrease. The lowering of the yield point and ultimate strength is clearly shown in Figure 7.

Let "A" (Figure 8) be a rectangular steel plate upon the edge of which is placed a weld "W". When this weld is deposited the weld metal is heated to fusion temperature by means of the electric arc formed in welding. The plate itself is heated within some region "e" to about 2500 deg. F. while the remainder of the plate remains relatively cool. Thus expansion (longitudinally) is restrained. As the weld metal cools, high stress is set up in this region. This stress is greatly reduced first, by reason of the fact that the yield point is very low and a great part of the stress is transformed into a permanent distortion of the plate in a direction parallel to the weld,leaving the remainder of this original stress as an elastic stress and, second, by a dilation of the plate in a direction at right angles to the direction of the weld. As this action is taking place the remainder of the plate is acquiring heat and expanding. A region "f" adjacent to the weld metal meets opposing forces on two sides; on the one side by reason of the contraction of the weld metal and on the other side by reason of the stiffness of the relatively cool body of the plate. Thus a further permanent dilation will take place as the heat wave travels across the plate.

The rate of cooling is dependent on the temperature difference of the plate and the surrounding air. The weld, being at a much higher temperature than the body of the plate, will cool at a much faster rate than will the more remote portions of the plate and in this way will tend to reduce the initial dilation. The stress in the weld, while contracting, must remain at 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 plate cooling to room temperature would not affect the residual stresses because the plate as a whole would then be affected and consequently no restraint to contraction would be encountered.

From the above argument the following statements may be made:

(1) The original high stress set up in the weld is reduced due to the fact that the yield point is very low and also by a dilation of the plate in a direction at right angles to the weld.

(2) The stress set up in the plate adjacent to the weld is high due to the fact that this portion of the plate is restricted to expansion on two sides. This might result in the stress being higher than that in the weld.

(3) The stresses set up need not approximate the yield point at room temperature due to the fact that the stress equilibrium set up during welding has been stabilized by the plate reducing to practically uniform temperature at some point much higher than the temperature of the room.

Curve 1 in Figure 9 shows the expected or probable stress distribution in a wide plate with a weld deposited on the edge.

The above discussion is based on the assumption that all the deposited weld metal was placed on the plate at once. The next consideration is the effect on the ultimate stress in the weld and in the plate if the weld were deposited in two layers. (See Figure 10.) It may be reasoned as before that when the first layer is deposited the weld will be stressed in tension and that the portion of the plate adjacent to the weld will contain a higher tensile stress than does the weld. (See Curve 1, Figure 9.)

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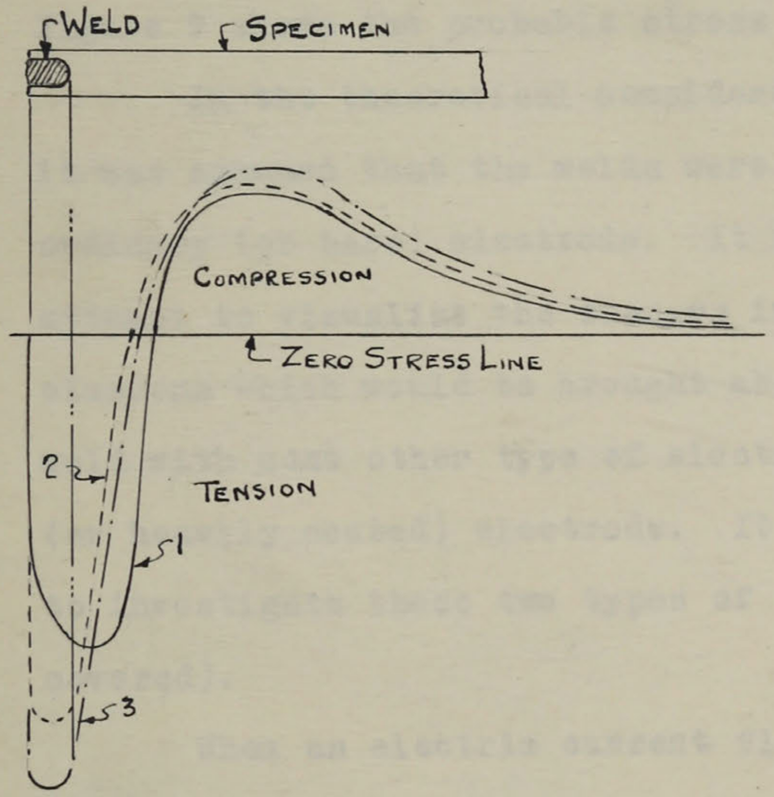

Fig. 9

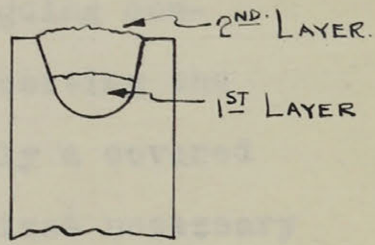

Fig. 10

When the second layer is deposited the heating action of the arc will have a stress relieving action on the highly stressed parent metal adjacent to the weld and will therefore reduce the residual stress in this region which had been set up in depositing the first layer, but in the second layer itself restraint to contraction is again encountered and thus tension will be set up in this layer. As the first pass or layer is now "adjacent" metal it encounters restraint on two sides and would be likely to have its stress increased. Thus the prcbable stress distribution in a plate which had been welded in this one of manner would be quite high tension in the weld (probably higher than if laid in one layer) and lower tension in the parent metal adjacent to the weld. Curve 2 in Figure 9 shows the probable stress distribution.

In the theoretical considerations outlined above, it was assumed that the welds were deposited with an ordinary (or bare) electrode. It is now necessary to attempt to visualize the changes in the foregoing conclusions which would be brought about by depositing the weld with some other type of electrode, namely a covered (or heavily coated) electrode. It will be first necessary to investigate these two types of electrodes (bare and covered).

When an electric current flows between the tip of an electrode and the work, the electrical energy is converted into heat which results in the melting of the electrode tip and of the work immediately adjacent to it. In the case of direct current welding, about one third of the total heat is developed at the negative pole and two thirds at the positive pole. Thus an electrode will melt at greatly different rates depending upon whether it is attached to the positive or negative pole. A bare electrode melts about 50 per cent. faster when attached to the positive pole than when attached to the negative pole.

Bare electrodes are attached to the negative pole as otherwise the parent metal would not melt fast enough and poor penetration would be obtained. Covered electrodes require a large amount of energy to melt the coating and electrodes of this type are connected to the positive pole. The penetration obtained is as good as that obtained in the use of bare electrodes as there is a greater concentration of energy.

The voltage drop across the arc is influenced by the arc length and by the resistance of the incandescent vapour forming the arc. This latter factor varies from 16 to 24 volts with bare rods and from 22 to 38 volts with covered rods.

The following table shows the difference in arc energy for bare and covered electrodes. The arc length is the shortest possible..

Electrode	Arc Voltage	Current Amperes	Arc Energy K.W.
Bare	20.0	100	2.0
Covered	25.0	100	2.5

Thus it is seen that there is about 25 per cent. more energy developed at the arc when using a covered electrode than with the bare electrode, when using the same current. This results in faster deposition, better penetration and sounder welds than obtained with bare electrodes even allowing for the fusing of the covering.

The transfer of metal from the electrode to the work is considered to take place in the form of minute globules. These globules in passing across the arc unite quite freely with the oxygen and nitrogen in the atmosphere, which causes the weld metal to have a relatively low ductility, high yield point and high ultimate strength when compared with mild steel.

The placing of suitable coatings on electrodes eliminates this atmospheric contamination to a considerable degree. The following are the principal methods of protecting the transfer of metal by means of protective coverings:

(1) By forming a full protective slag covering over the deposit.

(2) By creating a shield of reducing gas around the arc.

(3) By a combination of (1) and (2)

TYPE I - The coating of this type is an all mineral flux which dissolves in the arc to form a film of fluid slag over the tip of the electrode. Each globule of metal carries a coating of slag which protects it from the air. The slag, being lighter than the liquid metal, rises to the surface after deposition to form a full protective coating over the deposited metal. This coating anneals the metal, tends to smooth its surface and keeps the metal in a plastic condition long enough to allow impurities to escape. Coverings of this type are designed to give friable slags in order to facilitate their removal.

The purity and ductility of the metal depends largely upon mechanical slag protection. The end of the rod must first be protected while molten, secondly the metallic globules must be slag coated during transfer and thirdly the deposited metal must have full slag protection. These coverings also produce an inert atmosphere about the active metal vapours and globules. In addition during operation, the coating extends slightly beyond the metal core of the electrode to form a small crucible which conserves the heat and further protects the metal during transfer.

TYPE 2 - The covering of this type creates a uniform flow of reducing gases which surround the arc and deposited metal and minimizes atmospheric contamination. Very little protection is obtained by means of slag.

TYPE 3 - The covering of this type provides gas and slag protection during the transfer of metal. When in operation a flame envelopes the arc and deposited metal, a slag fully covers the weld,and the coating forms an inverted crucible. The gaseous shield is formed by the combustion of organic material within the coating. The organic material breaks down at low temperature giving off carbon monoxide, hydrogen gas and other vapours which set up a reducing reaction in the crater. In addition to the shield and slag protection there is in some electrodes a metallic deoxidizer added to the covering which scavenges the deposit.

Physical Characteristics of Weld Metal:-

The bare electrode metal is low in carbon, manganese and silicon due to the burning out of these elements during transfer. The contaminating influence of the atmosphere is shown by the high oxygen and nitrogen content. Bare electrode weld metal has low ductility, low resistance to corrosion and low density. Weld metal deposited by covered electrodes contains a greater percentage of manganese, carbon and silicon while the oxygen and nitrogen content are quite low. The above mentioned points are clearly shown by an examination of the following tables which show the chemical and physical properties of bare and covered electrode weld metal deposits on 3/4 inch plate, 90 degree vee butt weld.

*	Original Rod	Deposited Metal Covered Electrode	Deposited Metal Bare Electrode
Carbon	.13 - .18	.07 - .17	.02 - .04
Manganese	.40 - .60	.30 - .50	.10 - .20
Silicon	.06 Max.	.10 - .15	.03 - .05
Sulphur	.04	.04 Max.	.04 Max.
Phosphorus	.04	.04 Max.	.04 Max.
Nitrogen	--	.014 - .02	.10 - .14
Oxygen	--	.025 - .04	.20 - .30

	Deposited Metal Covered Electrode	Deposited Metal Bare Electrode
Yield Point lbs. per sq.inch	57,300	43,500
Ultimate Strength lbs. per sq. inch	64,800	57,800
Elongation per cent.	31.0	10.0
Specific Gravity	7.80 - 7.83	7.40 - 7.60
Fracture	Fine, Silky	Coarse

The specific gravity of steel varies from 7.8 to 7.9 and, as is seen from the above table, weld metal deposited by means of covered rods has a specific gravity of 7.8 to 7.83 while that of the bare rod deposit is low being only 7.4 to 7.6.

*Data was obtained from actual tests made by the metallurgist of the Dominion Bridge Company.

Bearing these facts in mind the conclusions arrived at concerning the residual stresses in welds deposited with bare electrodes can now be modified to suit this new problem of welding with covered rods. It would be reasonable to assume that the distribution throughout the plate would be of the same character as in the case of bare electrode welding as there is no change of procedure in laying the deposit. That is to say, the curves would be of the same family as shown by Curves 1 and 2 in Figure 9 but the stresses themselves both in the plate and in the weld would be higher due first to the arc energy of the covered rod being 25 per cent. greater than that of the bare electrode; second, the heat is more concentrated when welding with covered electrodes; and third, since the covered rod deposit is very much more ductile than the bare rod metal, the stress would tend to be absorbed to a greater degree by the weld metal itself than it was in the case of the bare rod. Thus the probable distribution of stress would be as indicated by Curve 3 in Figure 9.

The final consideration is the effect of stress relieving these various types of welded plates. Stress relieving consists in placing the member in an oven and slowly raising the temperature to between 1150 and 1200 deg. F. This temperature is maintained for one hour per inch of thickness of metal in the specimen and then cooling the member slowly in the oven until it is at approximately room temperature.

Consider a specimen containing a residual elastic stress of say "f" lbs. per square inch. As the specimen is heated, the yield point drops until at 1200 deg. F. it is only about 5,000 lbs. per square inch. (See Figure 7) Thus when the temperature of the specimen is 1200 deg. F. the internal stress "f" will cause plastic deformation to take place until the stress "f" is reduced to 5,000 lbs. per square inch (the yield point at stress relieving temperature). This 5,000 lbs. per square inch will be left as an elastic stress in the member. In addition to this, the stress will be further reduced due to the fact that the crystals are comparatively free to move and will adjust themselves to a more comfortable position thereby reducing this elastic stress to some degree. Thus after stress relieving any member it would be reasonable to expect an elastic stress of something less than 5,000 lbs. per square inch.

Some engineers claim that the stress relieving cycle is not effective unless the material is heated in excess of 1550 deg. F. This would be truly annealing the member and causing grain refinement which is not the object of stress relieving. The maximum temperature of 1200 deg. F. required by the A.S.M.E. code was not arrived at haphazardly but was based on experiment. At temperatures of 1150 to 1200 deg. F. for the time required by the A.S.M.E. code, the material has sufficient strength to carry its own weight and should it be heated above this maximum temperature the member will distort due to its own weight and possibly collapse.

THE SPECIMEN.

Eight plates of structural mild steel were cut from the same stock and marked S, T, U, V, W, Y and Z in order to differentiate between the various types of welds which would be deposited. All the plates were 12 inches wide, 21 inches long and 3/4 inches thick.

APPARATUS

For measurement of the specimen before and after welding the Linear Comparator was used. This instrument, manufactured by the Waterville Iron Works, is set up in the constant temperature room of the Geodetic Laboratory where it is protected from rapid changes of temperature. The Comparator consists of a moveable block upon which two microscopes "A" and "B" are mounted. (See Figure 31). An adjustable platform carries 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-line scratches on both the standard bar and the specimen determine the points of measurement. It will be readily 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 microscopes, and on the character of the scratches. The smallest graduation on microscope "A" equals 0.001 of a revolution of the micrometer, one revolution being equal to 0.002213 inches. The smallest graduation on microscope "B" is also equal to 0.001 of a revolution while one full revolution is equal to 0.004538 inches.

For measurements before and after cutting the plate into strips, the Howard gauge and Berry gauge were used. The Howard gauge is a 10 inch micrometer screw gauge designed to read to 0.0001 inches on gauge lengths varying from 9.8 to 10.2 inches. It is necessary to drill holes in the specimen in which to rest the gauge points of the instrument. The instrument is accompanied by a steel bar in which there are drilled two holes at exactly 10 inches apart when the temperature of the bar is at a given value. The bar also contains a well in which is placed a thermometer so that variations in temperature may be readily noted.

The Berry gauge is essentially a strain gauge of the lever type and is mainly used for measuring the elongation of test specimens over 2" gauge lengths.

It consists of a dial indicator carried on a frame on one side of which there is a fixed gauge point. On the other side is a moveable gauge point which transfers its motion by means of a lever which bears against the plunger of the dial indicator. The movement of the plunger is transferred to the pointer on the dial by means of a rack and pinion arrangement. This gauge will read directly to 0.0001 inches.

PREPARATION.

It was decided to confine measurements to an overall length of 10 inches to suit the Howard gauge. This left $5\frac{1}{2}$ inches at each end in which lengths no measurements would be taken. The 10 inch gauge on the weld was divided into two spaces of 3 inches and one space, in the centre, of 4 inches for measurement with the linear comparator, while for measurememt with the Howard gauge this space was divided into five spaces at 2 inches each. The other 10 inch gauges were not subdivided.

Each plate was provided with a U shaped groove along the edges on which the weld metal was to be deposited. The dimensions of this groove, the gauge lines and reference markings are shown in Figures 11, 12 and 13. As both faces of the plate were to be measured one side was marked "A" and the other "B".

During the first stages of the investigation the plates were measured by means of the linear comparator and it was therefore necessary to place very fine scratches on the specimen. In order that the scratches could be made sufficiently fine and a bright reflecting plane be obtained, enabling them to be easily seen through the microscope, the surface of the plates at each point was spot ground by means of an emery wheel. The scratches were placed on these polished surfaces by means of a glass cutter having a hard steel disc as a cutting edge. The scratch to be used for measuring was crossed by two other scratches at right angles to its direction and at about 1/16 inches apart to ensure the use of the same portion of the line for all measurements.

For measurement by means of the Howard gauge and Berry gauge, holes were drilled with a number 55 drill then countersunk in the positions shown in Figure 11.

Before welding

PROCEDURE.

Measurements on each gauge line on both sides of every plate were taken by means of the linear comparator. In making these measurements three micrometer readings with microscope "B" (focused on the plate) were recorded for one setting of microscope "A" (focused on the standard bar). The reason for doing this was that microscope "A" was of a much higher power than microscope "B" and also the scratches on the standard bar were very much better than those placed on the specimen by hand. This procedure greatly simplified the work as it was not necessary to actually read the micrometer on "A" since it was fixed. The block supporting the two microscopes was moved until the fixed hair in the reticule became tangent to a zero scratch on the standard bar. Three readings were taken with the micrometer on "B" for the corresponding zero scratch on the specimen. In a similar manner readings were taken at all scratches on the specimen. then covered

The scratches were protected by galvanized iron plates which were bolted to both sides of the specimen. They were then sent to the Dominion Bridge Company to be welded.

The following table shows the manner in which each plate was welded.

Plate	Type of Rod	No. of Layers In Deposit.	Rod Diameter	Current Amps.	Voltage	Stress Relief
S	Bare	1	3/16	160	62	No
T	do.	2	3/16	160	62	No
Z	Covered	1	3/16	175	62	No
V	do.	2	3/16	175	62	No
W	Bare	1	3/16	160	62	Yes
X	do	2	3/16	160	62	Yes
Y	Covered	1	3/16	175	62	Yes
U	do	2	3/16	175	62	Yes

When welding with covered electrodes it was found that the sides of the groove were too thin to withstand the additional heat required to produce a proper weld. This necessitated the use of chill bars along the sides of the grooves. These chill bars were made up of a piece of heavy copper next to the plate and a piece of steel outside the copper. (See Figure 14.) It was found that these chill bars dissipated the heat sufficiently rapidly to prevent the sides of the groove from melting.

All welding was performed in such a manner as to minimize the distortion of the plate. Figures 15 and 16 show the manner in which this welding was carried out.

After the welding had been completed plates U, W, X and Y were stress relieved by placing them in an oven and slowly heating them to 1200 deg. F. The plates were kept at this temperature for one hour and then slowly cooled in the furnace.

Upon the return of the specimens to the laboratory measurements were taken as before by means of the linear comparator.

The specimens were then prepared for measurement by means of the Howard gauge and Berry gauge. In measuring with the Howard gauge five complete sets of readings were taken on both sides of the plate and temperature correction readings on the standard 10 inch bar were taken after every fourth reading on the plate. In measuring with the Berry gauge five sets of readings were recorded for all plates. However, no temperature correction could be made.

The procedure from this point involved the cutting of the plates into strips and measuring the longitudinal deflection of each strip. ? The weld strips, i.e. the outside half inch of the plate containing the weld, were cut off and these strips and the remainder of the plate were measured. Next, a strip 1 inch wide was cut off each side of the plate and as before both strips and the remainder of the plate were measured. This procedure was continued until the plate was reduced to a series of 1 inch strips. The 1 inch strips were actually less than 1 inch by the thickness of the saw (1/16 inch). The cutting of the strips was carried out in a milling machine with a saw blade 6 inches diameter by 1/16 inch thick. In order that the plate would not become overheated during cutting, the feed was reduced to 7/8 inch per minute, the spindle speed was 67 R.P.M. and a stream of oil was kept flowing over the cutting tool. The time required to sever one strip was approximately one half hour.

The stress-strain characteristics of the plate material were determined from the central strip of plate "X" which had been stress relieved and the central strip from plate "S" which had not been stress relieved. The tests were made in tension in the Wicksteed machine using Martin's extensometers over a gauge length of 8 inches.

To determine the characteristics of the weld metal, 1/4 inch diameter rods were turned down from one of the weld strips of each of the eight specimens. The test in this case was made in the 10,000 lb. Olsen testing machine using extensometers over a gauge length of 4 inches.

RESULTS & DISCUSSION.

Before studying the results of the investigation consideration will first be given to the accuracy of the various measurements.

The probable error for any one measurement of the deformations due to welding may be approximated as follows:

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

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

Let M_1 be the measurement before welding.

Then the error in $M_1 = \sqrt{\dfrac{\pm 0.02^2 + \dfrac{0.03^2}{\sqrt{3}}}{\sqrt{2}}} = \pm 0.0218$ revs. of "B"

After welding the scratches became discoloured. This made observations more difficult and $\pm$ 0.02 revs. of "B" should be allowed for this factor.

Let M_2 be the measurement after welding.

Then the error in $M_2 = \sqrt{\dfrac{\pm 0.02^2 \pm \dfrac{0.03^2}{\sqrt{3}} \pm 0.02^2}{\sqrt{2}}} = \pm 0.0248$ revs. (of "B".

Let X equal the deformation due to welding, i.e. $M_1 - M_2$

The error in X $= \sqrt{\pm 0.0248^2 \pm 0.0218^2}$

$= \pm 0.0326$ revs. of "B"

$= \pm 0.033 \times 0.004538$ in terms of inches.

$= \pm 0.00015$ inches.

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

The probable error due to setting the instrument vertical $=$ $\pm$ 0.5 ten thousandths inches.

The probable error due to reading the drum $= \pm 0.4$ ten thousandths inches.

Let M_3 be the measurement before cutting the plate.

Then the error in $M_3 = \sqrt{\pm 0.5^2 + 0.4^2} = \pm 0.64$ ten thousandths inches.

Let M_{t3} be the measurement of the temperature correction.

Then the error in $M_{t3} = \sqrt{\pm 0.5^2 + 0.4^2} = \pm 0.64$ ten thousandths inches.

If X_1 is the true distance before cutting (i.e. $M_3 + M_{t3}$)

The probable error in $X_1 = \pm\sqrt{0.64^2 + 0.64^2} = \pm 0.92$ ten thousandths inches.

Since the measurements taken after cutting were subject to the same errors as above the probable error in the true distance after cutting will be $\pm$ 0.92 ten thousandths inches as above.

Let X_1 equal the true distance before cutting and X_2 the true distance after cutting.

Let D equal the deformation due to cutting the plate (i.e. $X_1 - X_2$)

Then the error in $D = \pm\sqrt{0.92^2 + 0.92^2} = \pm 1.28$ ten thousandths inches.

In terms of stress, .00013 inches in 10 inches is equivalent to:

$$\frac{.00013 \times 29.2 \times 10^6}{10} = 380 \text{ lbs. per square inch.}$$

Figures 17 to 22 inclusive show the stress-strain characteristics for the parent metal and weld metal.

From a study of these curves it is apparent that stress relieving has no effect upon the physical characteristics of the metal.

The results for the weld specimens are hardly reliable as the test specimens which were turned down from the "weld strips" contained a great number of slag inclusions and gas pockets and these materially reduced the cross-sectional area of the specimens which were only 1/4 inch diameter. Figures 32 and 33 show the actual condition of the weld metal very clearly. This condition is due to depositing too much metal at once; also, since the sides of the groove were so thin sufficient heat could not be used to float the slag to the surface of the weld.

Since these results are so erratic it will be assumed, for calculating purposes, that the modulus of elasticity for metal deposited with a bare electrode is 28.0×10^6 lbs. per square inch and for metal deposited with a covered rod 29.0×10^6 lbs. per square inch.

The results will be treated in two groups; first, those specimens which have not been stress relieved and second, those which have been stress relieved.

In Figures 23 to 30 inclusive, the diagrams show the longitudinal deformation due to welding and longitudinal elastic deformation after cutting for each strip of the various plates. The deformations are plotted in ten thousandths of an inch and represent the total movement over a gauge length of 10 inches. In the diagram representing the longitudinal elastic recovery after cutting, since the thickness of the plate is constant, the width of each strip is proportional to its cross-sectional area. Thus the area under the curve represents the total longitudinal force in the plate before cutting it into strips. For equilibrium the total tension must equal the total compression in the plate. Therefore the area above the zero stress line must equal the area below the zero stress line. In plate "S" the difference is 0.67 per cent., in plate "T" 2.35 per cent., in plate "V" 0.69 per cent. and in plate "Z" 3.09 per cent. This is a very good check considering that errors are introduced by cutting the plates into strips, by the difference in moduli of the weld metal and parent metal, by residual stresses in other directions and by rolling stresses which were in the plate before welding.

The results of the observations are best understood by graphical illustration and these curves in Figures 23,24, 25 and 26 agree very well with those outlined in the theory for the various types of welds.

The following table shows the maximum average stresses with their locations in the various specimens.

Plate	Maximum Average Tension lbs./sq. in. Weld	Maximum Average Tension lbs./sq. in. adj. to Weld.	Maximum Average Compression lbs./ sq.inch & Location	Per centage of Weld Metal
S	11,800	17,150	7,640; 3" from edge of plate	3.03
T	18,050	17,920	7,480; 3" from edge of plate	3.03
V	36,600	12,180	10,300; 3" from edge of plate	3.03
Z	26,800	13,800	7,900; 3" from edge of plate	3.03

When the "weld strips" were severed from these plates it was noticed that all of them bowed in such a manner as to indicate that the residual tension at the root of the weld was higher than that at the surface or outside of the weld. However, the bowing of these strips on plates "T", "V" and "Z" was so small that it was impossible to measure them with any degree of accuracy.

In plate "S" strip 1-28 showed a deflection of .015 inches at the centre while strip 13-16 showed .019 inches. These offsets were measured by joining the ends of the strip by a straight line and measuring the offset at the centre.

If each strip is considered as a rectangular beam 0.5 inches deep and 21 inches long and it is assumed that the bowing at the centre is caused by a uniform bending moment along the strip, we may calculate the extreme fibre stresses as follows:

$$f = \frac{d \times E \times y \times 8}{l^2}$$

where f = the extreme fibre stress

d = the deflection at the centre

y = 1/2 the width of the strip

E = Youngs Modulus

l = length of strip

Whence f for strip 1-28 equals 1,900 lbs. per square inch and for strip 13-16 2,420 lbs. per square inch.

Combining these values with the direct stress in these strips it is seen that the stress at the face of the weld in strip 1-28 is 7550 - 1900 = 5650 lbs. per square inch and at the root of the weld 7550 + 1900 = 9450 lbs. per square inch. Similarly in strip 13-16 the stress at the face of the weld is 11800 - 2420 = 9360 lbs. per square inch and at the root of the weld 11800+ 2420 = 14,220 lbs. per square inch.

This bowing effect was observed by Mr. Evans in his recent investigation. His explanation of the condition read as follows:

> "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 centre of the metal cools last and therefore is the last portion to readjust itself."

That the weld metal cools from the surface inwards is not the case. Actually it cools from the root of the weld outward towards the surface. When the weld metal is deposited in the groove it is all at the same temperature but as soon as it touches the bottom of the groove, the lower portion gives up a great deal of heat to the relatively cool plate and solidifies before the upper or surface layers. In so doing it meets restraint to contraction. While this is occurring, the surface or upper layers are still at practically fusion temperature and consequently the stress set up due to cooling will cause a greater amount of plastic deformation to take place than occurred at the bottom of the weld and therefore a smaller elastic stress will be left at the surface than at the root of the weld.

From the above reasoning we may state that there is higher tension at the root of the weld than at the surface. Hence when the weld strip is removed from the plate it will curve in such a manner that the surface of the weld will be convex.

The next consideration is the effect of stress relieving these same types of weld. The following is a tabulation of the maximum average elastic stresses as read from the curves in Figures 27, 28, 29 and 30.

Plate	Maximum Average Stress lbs./sq. inch in Weld	Maximum Average Stress lbs./sq. inch in Plate	Location	Percentage of Weld Metal
W	4,430 Compression	1,170 Compression	3" from edge of plate	3.03
X	3,340 Compression	2,630 Compression	4" from edge of plate	3.03
Y	2,900 Tension	2,950 Compression	2" from edge of plate	3.03
U	4,460 Tension	1,750 Compression	2" from edge of plate	3.03

A study of the results obtained from the stress relieved specimens shows that there is a lack of consistency in the elastic stresses left after stress relieving.

One point, however, is shown very clearly. All the residual elastic stresses are less than 5,000 lbs. per square inch. This fact would indicate that the theory outlined regarding stress relieving action is reasonably correct.

It will be noticed that in the diagrams showing elastic stress in Figures 27, 28, 29 and 30, the tension areas do not anywhere nearly check with the compression areas under the curves.

This lack of agreement between the tension and compression areas is probably due to the fact that the rolling stresses, of unknown magnitude, originally in the plate were relieved along with the welding stresses, and the curves shown in Figures 27, 28, 29 and 30 are the residuals of an unknown and possibly very irregular stress condition and not the residuals of stress induced by welding procedure alone.

The question might be raised as to why these rolling stresses did not affect the results of plates S, T, V and Z. There is no doubt that these stresses have some effect but the reason that they do not materially affect the elastic stresses in the first group of specimens is that they were not relieved. It is a known fact that these rolling stresses are localized in a thin layer of metal on the surface of the plate which came into contact with the rolls during fabrication and to relieve these stresses it is necessary to remove this "skin" by machining. These stresses are necessarily in equilibrium and since this skin was not removed during this part of the experiment, their equilibrium was not upset to any appreciable degree and consequently did not affect the results of the specimens which had not been stress relieved.

In the first group of specimens it was noticed that the weld strips, after severing, curved in such a manner as to indicate higher tension at the root of the weld than that which existed at the surface of the weld. The weld strips after being severed from the stress relieved specimens showed no such tendency to curve. To all practical purposes they remained straight. This is not surprising because the stresses have been reduced to a very small quantity and the bowing tendency must also have been reduced to the same degree.

It is not logical to assume that the intensity of stress is constant throughout the length of a weld and it was with this in mind that the gauges on the "weld strips" (strips 1-28 and 13-16) were subdivided. It will be noticed that many of these readings are missing from the tables of results showing the deformation due to welding. This is due to the fact that the weld strips became so hot when being welded that the scratches were "burnt off" the plate. Thus no readings could be obtained on certain specimens. It will also be observed in the tables, showing the elastic recovery due to cutting the plates into strips, that no readings are recorded for the subdivisions on the weld strips. Readings were taken on these two inch gauges by means of the Berry gauge both before and after cutting the plate into strips but the recoveries shown by these readings did not agree with the overall recovery measured by means of the Howard gauge. In fact the sum of these recoveries varied from .001 to .0025 inches from the overall recovery and it was owing to this fact that they were not recorded. The inaccuracy in these readings was due to the gearing of the instrument being badly worn and also to the difficulty in handling the instrument.

It is definitely shown in the results of the deformation due to welding that the central gauge of the weld strip suffered greater deformation per lineal inch than did the two outer gauges. This would lead us to believe that the central portion of the weld was more highly stressed than the end portions. This large deformation of the central gauge is not a true measure for the reason that in depositing the weld metal, five inches of metal was first laid down at each end of the groove; as these deposits cooled they contracted and, due to the fact that the edges of the groove were very thin, the force which they exerted in contracting elongated the sides of the groove and consequently the gauge points moved from their original position before any weld metal was deposited between them. Therefore we have no "true" measures of these gauges to correspond to the "before welded" condition. By referring to Figures 11 and 15 and applying the above reasoning it will be seen that the central gauge would be the one which was mostly affected.

It must not, however, be assumed that this theory disproves the original idea that "the intensity of stress throughout the length of the weld is not constant". It has been shown above that as each deposit cools it is comparatively free to contract due to the fact that the sides of the groove are thin. However, when the last deposit is made, the groove has been completely filled with metal and it now offers almost perfect restraint to the contraction of this last deposit and consequently the last deposit will have a higher stress in it than any other deposit in the weld.

CONCLUSION

In the investigation of the specimens which were not stress relieved the magnitudes of the residual stresses were measured. These stresses should hold fairly true for members having approximately the same quantity of deposited weld metal and similar dimensions but would vary according to the resistance of the member to buckling. For example, should the member be very "flimsy", the weld in cooling would relieve its stress by twisting the member out of shape. In the case of a rigid member this buckling would not occur and consequently the stress would not be relieved. Their greatest value lies in the comparison of one type of deposit with the other.

From a study of these values it is apparent that the residual stresses in the welds are considerably increased by depositing the weld metal in two layers instead of one. In the case of bare electrode welding the stress in the weld deposited in two layers was 53 per cent. greater than the stress in the weld deposited in one layer. Similarly in the case of covered electrode welding, the residual stress in the weld deposited in two layers was 37 per cent. greater than that in the weld deposited in one layer.

By comparing the results of the bare and covered electrode specimens it will be seen that, in the case of single layer welding, the residual stress in the covered electrode weld is 140 per cent. greater than that in the bare electrode weld; while in the case of double layer welding, the stress in the covered electrode weld is 103 per cent. greater than that in the bare electrode deposit.

The above facts show that the residual stresses in welds deposited with covered electrodes are much greater than the residual stresses in those deposited with bare electrodes. This is borne out in practice as more careful preparation and procedure is required to eliminate the cracking of welds deposited with such electrodes. Two very common methods of avoiding such failures are:

(1) To heat the member to about 300 deg. F. and maintain this temperature throughout the welding process.

(2) To reduce the welding speed.

By pre-heating the member to say 300 deg. F., restraint to contraction of the weld is lessened to such an extent that the residual stresses in the welds are of insufficient magnitude to cause failure. In the case of reducing the welding speed, the action which takes place is much the same. The arc proceeds sufficiently slowly to allow the heat to be conducted into the plate ahead of the arc and in so doing it is pre-heating the member locally.

From the results of this investigation it may be seen that the magnitude of the residual stresses is dependent upon the heat used in depositing the weld metal and upon the ductility of the weld metal. However, while the quantity of heat used has a very important influence upon these stresses, it was pointed out in the preceeding paragraph that the speed at which the welding is performed has a marked effect on these stresses. Up to the present no consideration has been given to the effect of welding speed upon residual stresses and it is suggested that further tests be carried out to determine something of its effects.

It was seen from the results obtained from the stress relieved specimens that the rolling stresses combined with the welding stresses during the relieving process and consequently the test was not entirely satisfactory. However, one very obvious fact is that the elastic stresses left in the specimens after stress relieving them was less than 5,000 lbs. per square inch. Consequently we may feel confident that any specimen or member which has been stress after welding, by heating it to 1200 deg. F. and then slowly cooling, will contain a residual elastic stress not in excess of 5,000 lbs. per square inch.

Owing to the fact that the rolling stresses interfered with the welding stresses it is suggested that further investigation be carried out along these lines to determine, more exactly, the effect which stress relieving has upon the welding stresses themselves. This, it seems, could be accomplished by using specimens which have had the rolling stresses relieved before any weld metal was deposited.

BIBLIOGRAPHY

1. "Fundamentals of Welding" by James N. Owens.

2. "Further Investigation of the Distribution of Stress in Welded Joints", Thesis by Robert M. Hardy, M.Sc. McGill University Library.

3. "The Initial Stress in a Welded Joint", Thesis by J. F. McDougall, M.Sc. McGill University Library.

4. "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", Thesis by D. E. Evans, M. Eng. McGill University Library.

5. "Welded Joints" by Everett Chapman, American Welding Society Journal, February 1934.

6. "Arc-Welded Steel Frame Structures" by Gilbert D. Fish

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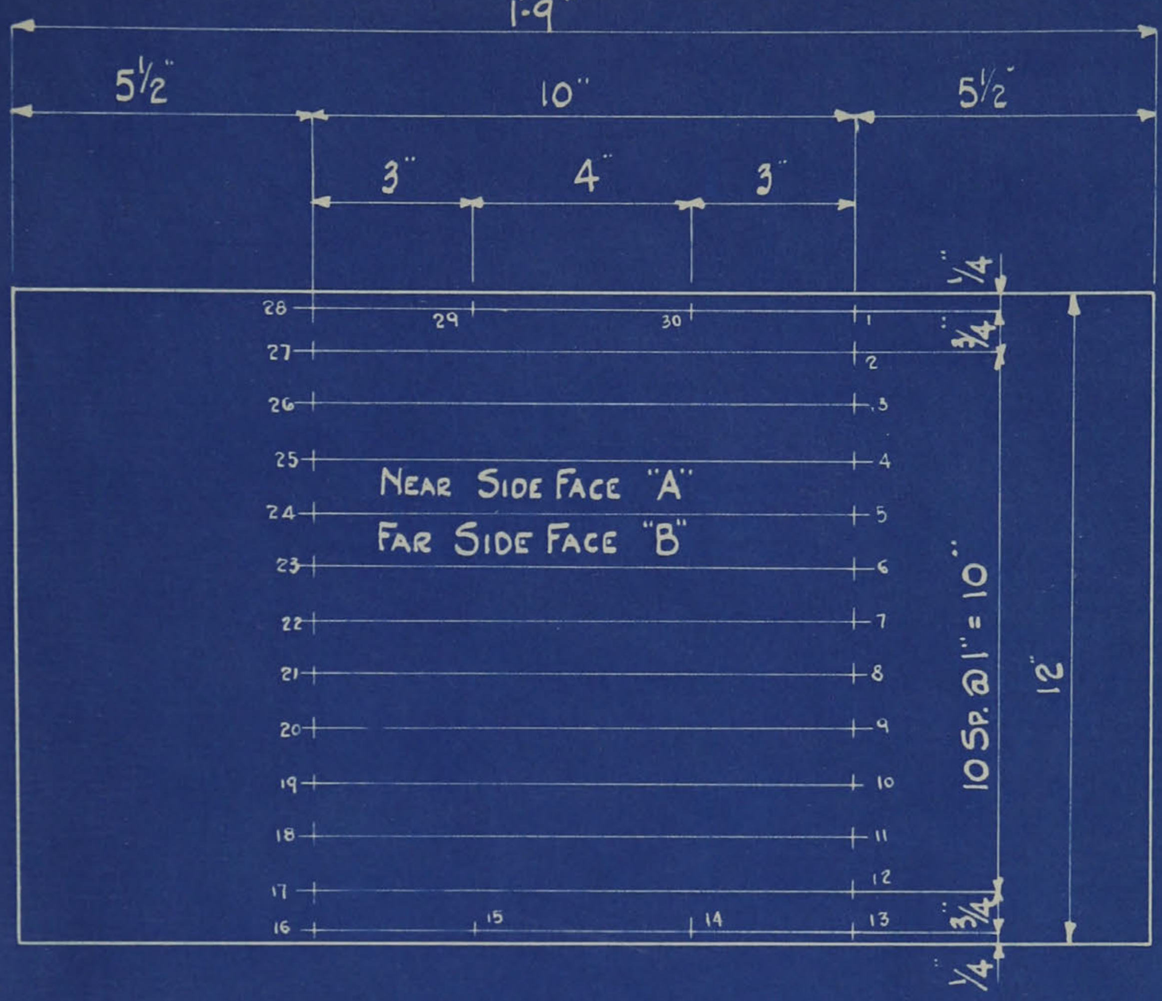
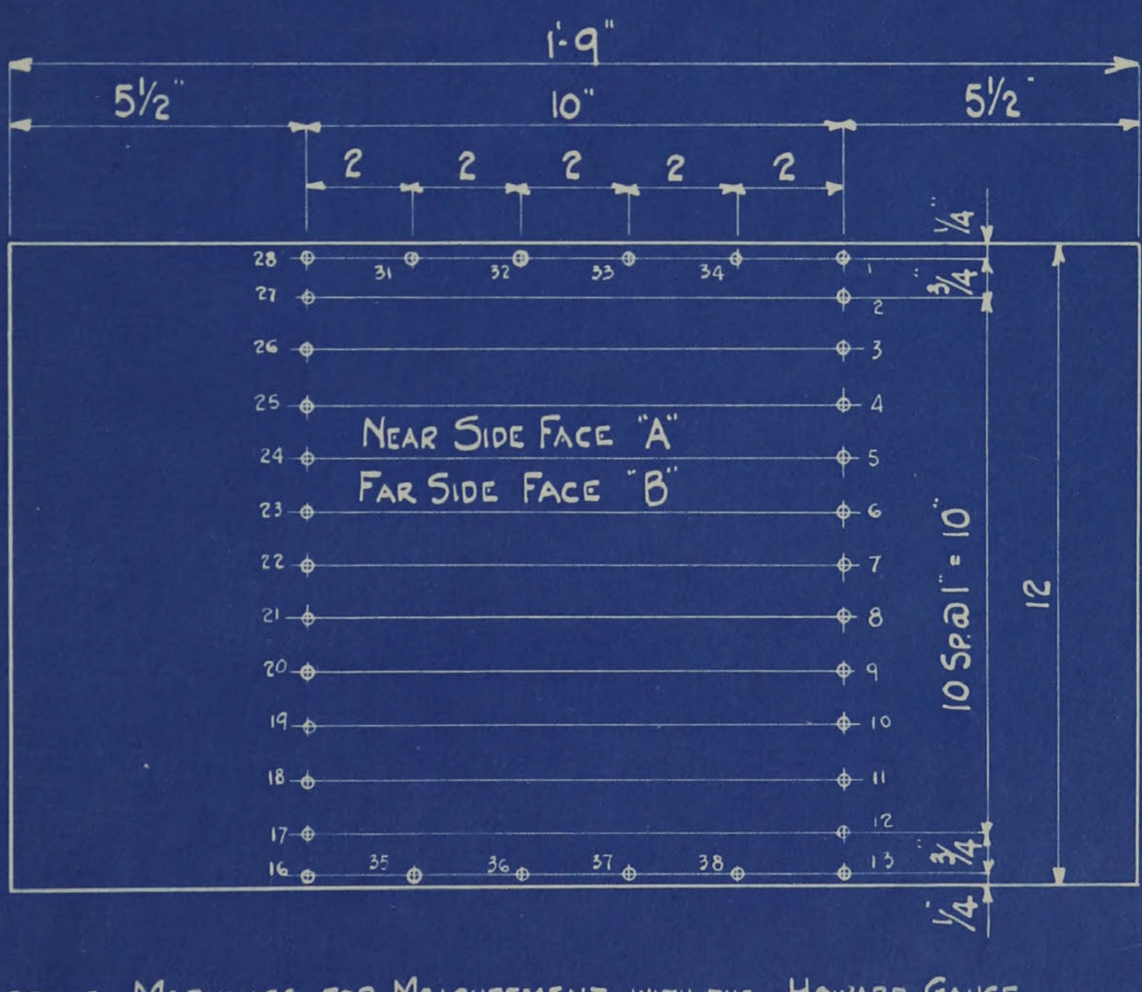
The work was done in consultation with R. E. Jamieson, William Scott Professor of Civil Engineering, McGill University.

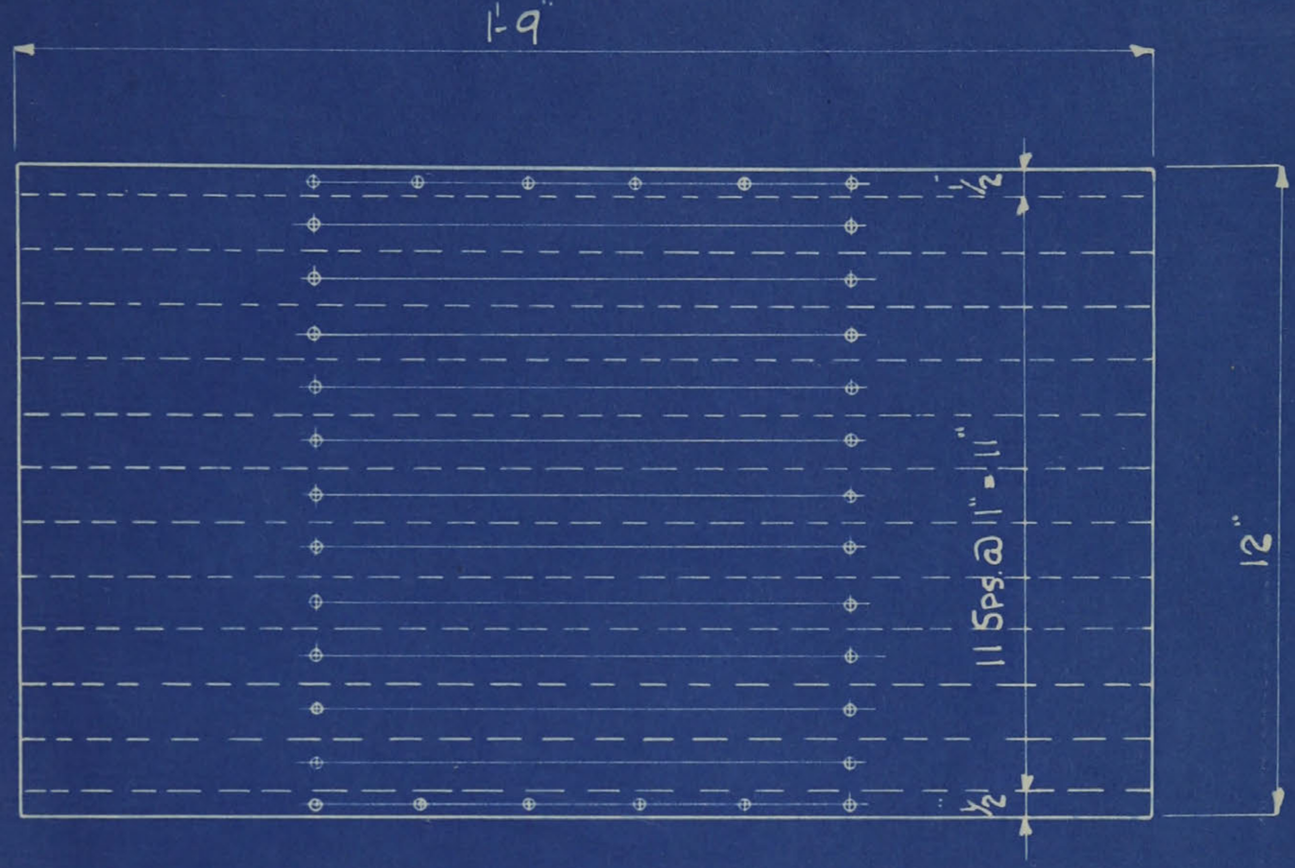


Reference Markings for Measurement with the Lineal Comparator

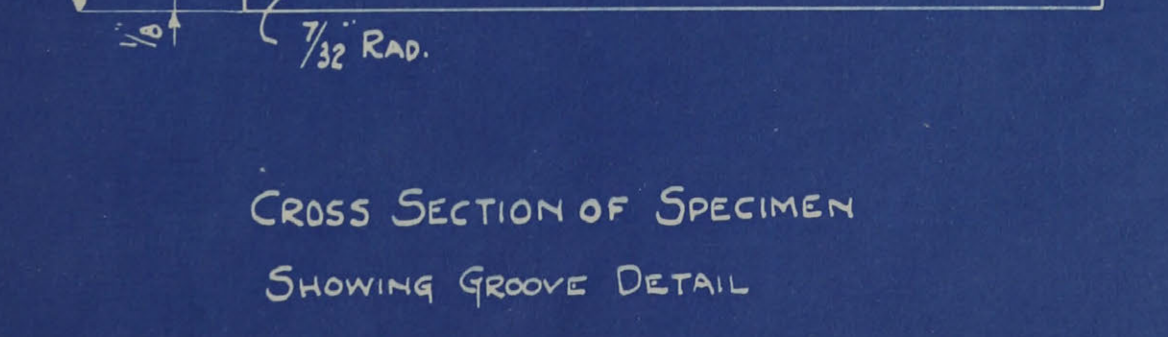


Reference Markings for Measurement with the Howard Gauge

Figure – 11

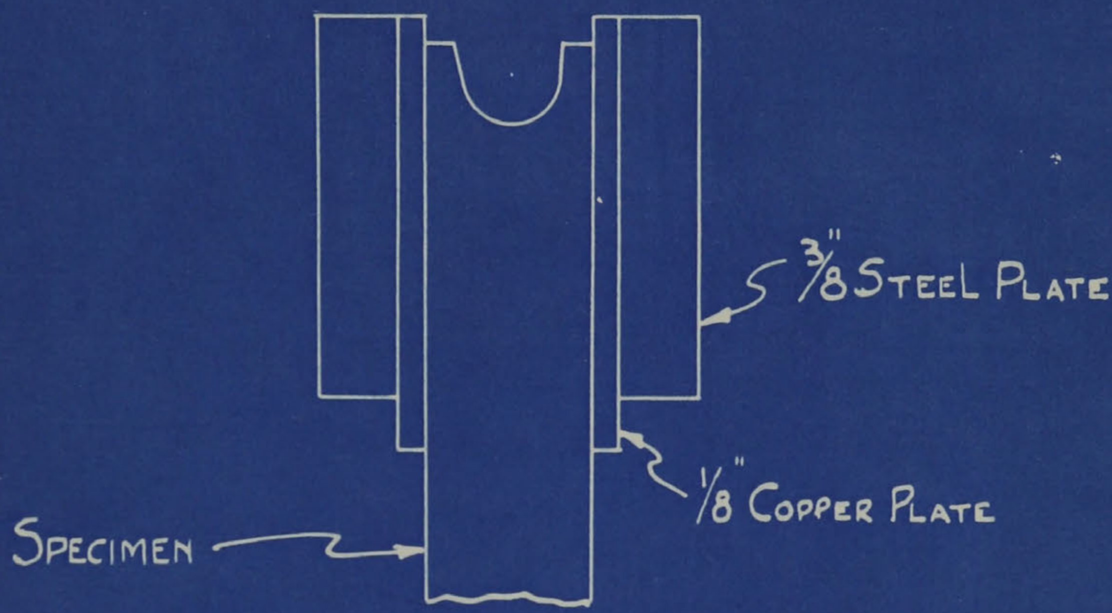


Lines Along Which Cuts Were Made to
Sever Plates Into Strips
Figure - 12

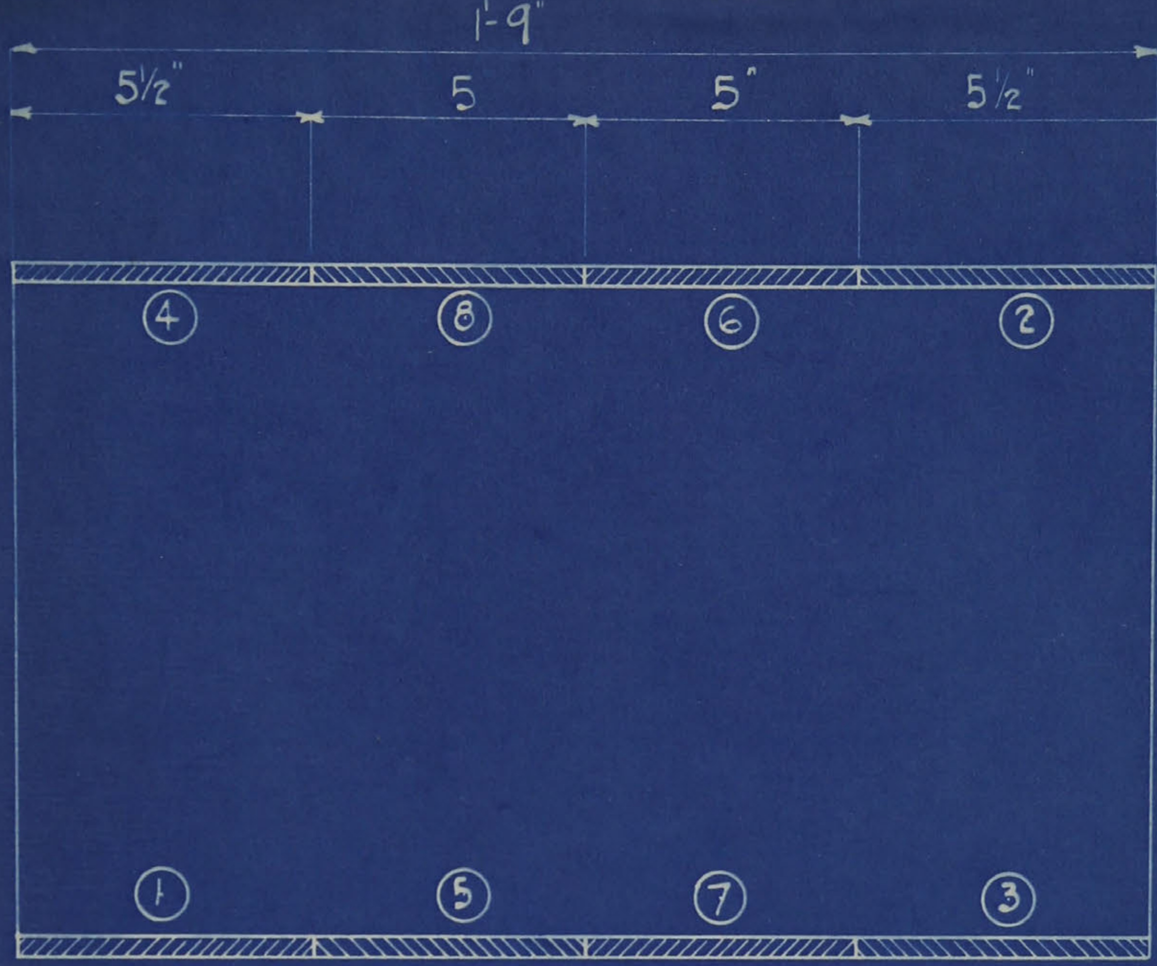


Cross Section of Specimen
Showing Groove Detail

Figure - 13



Chill Bar Arrangement Used
in Welding Specimens with Covered Electrodes
Figure – 14



WELDING SEQUENCE FOR SINGLE LAYER WELDS.

FIGURE - 15

WELDING SEQUENCE FOR DOUBLE LAYER WELDS.

FIGURE - 16

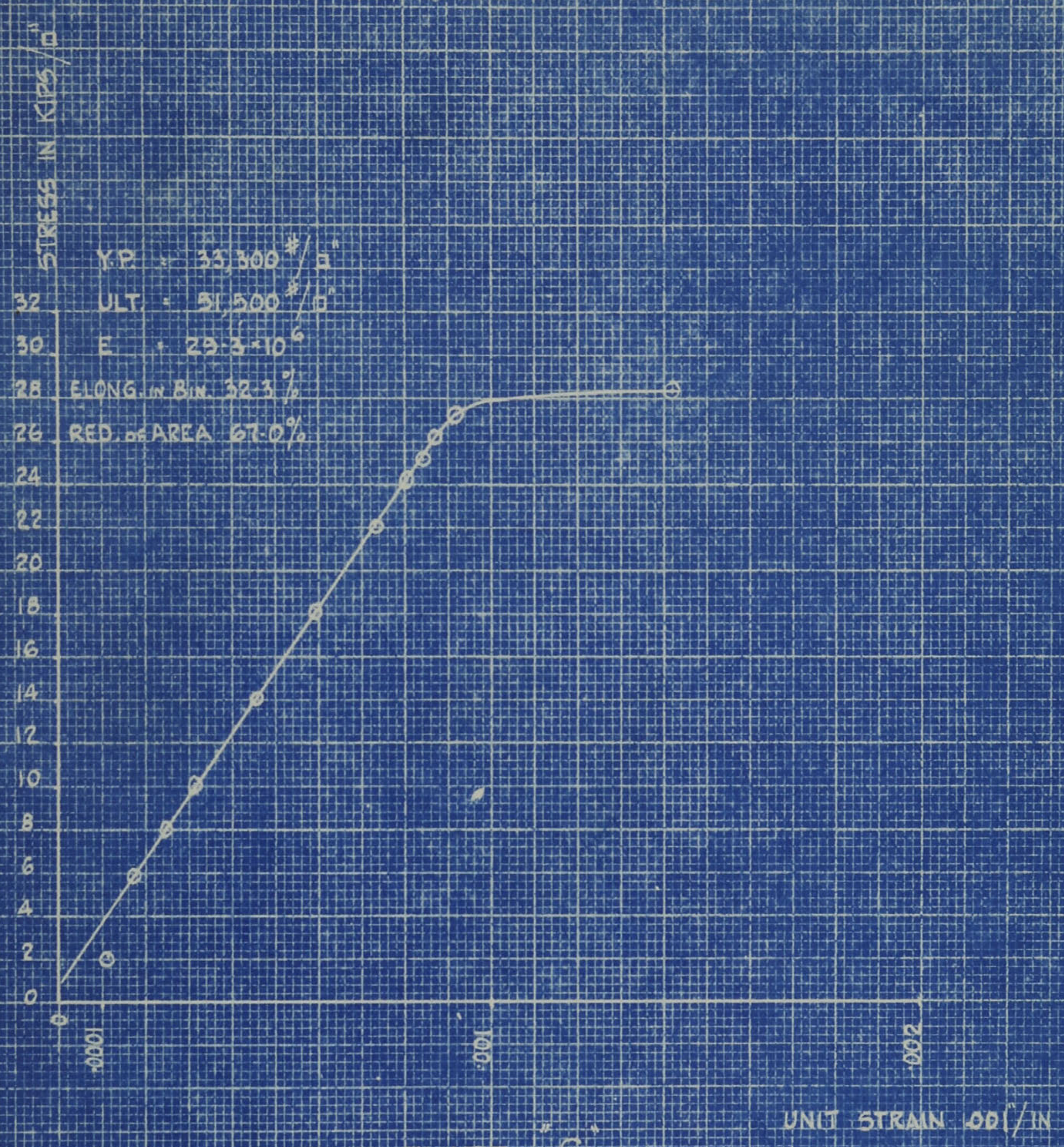


PLATE "S"

STRESS - STRAIN CHARACTERISTICS OF PLATE MATERIAL

FIG. Nº 17

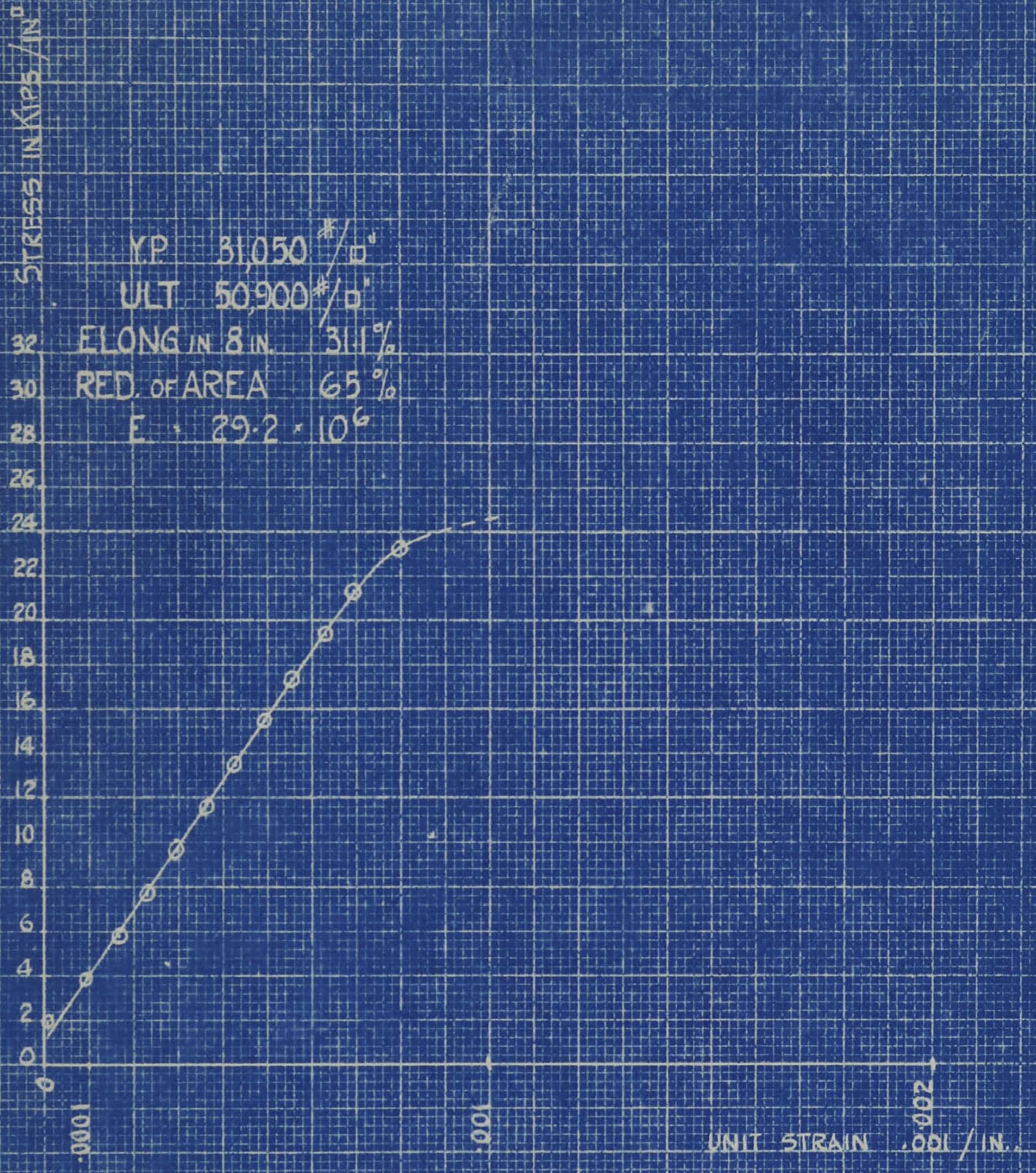


PLATE "X"

STRESS-STRAIN CHARACTERISTICS
OF PLATE MATERIAL
AFTER STRESS RELIEVING

FIG. Nº 18

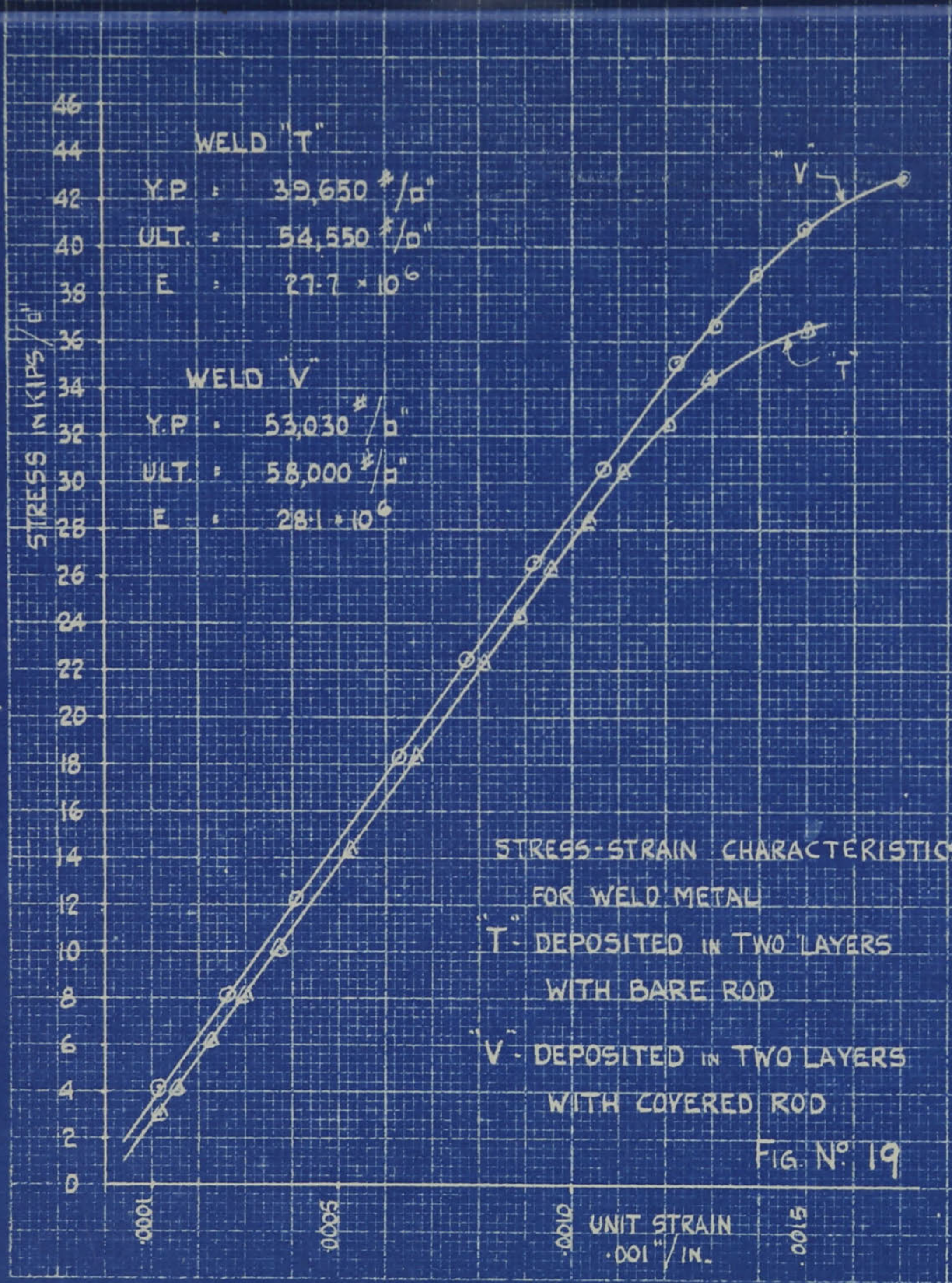


FIG. No 19

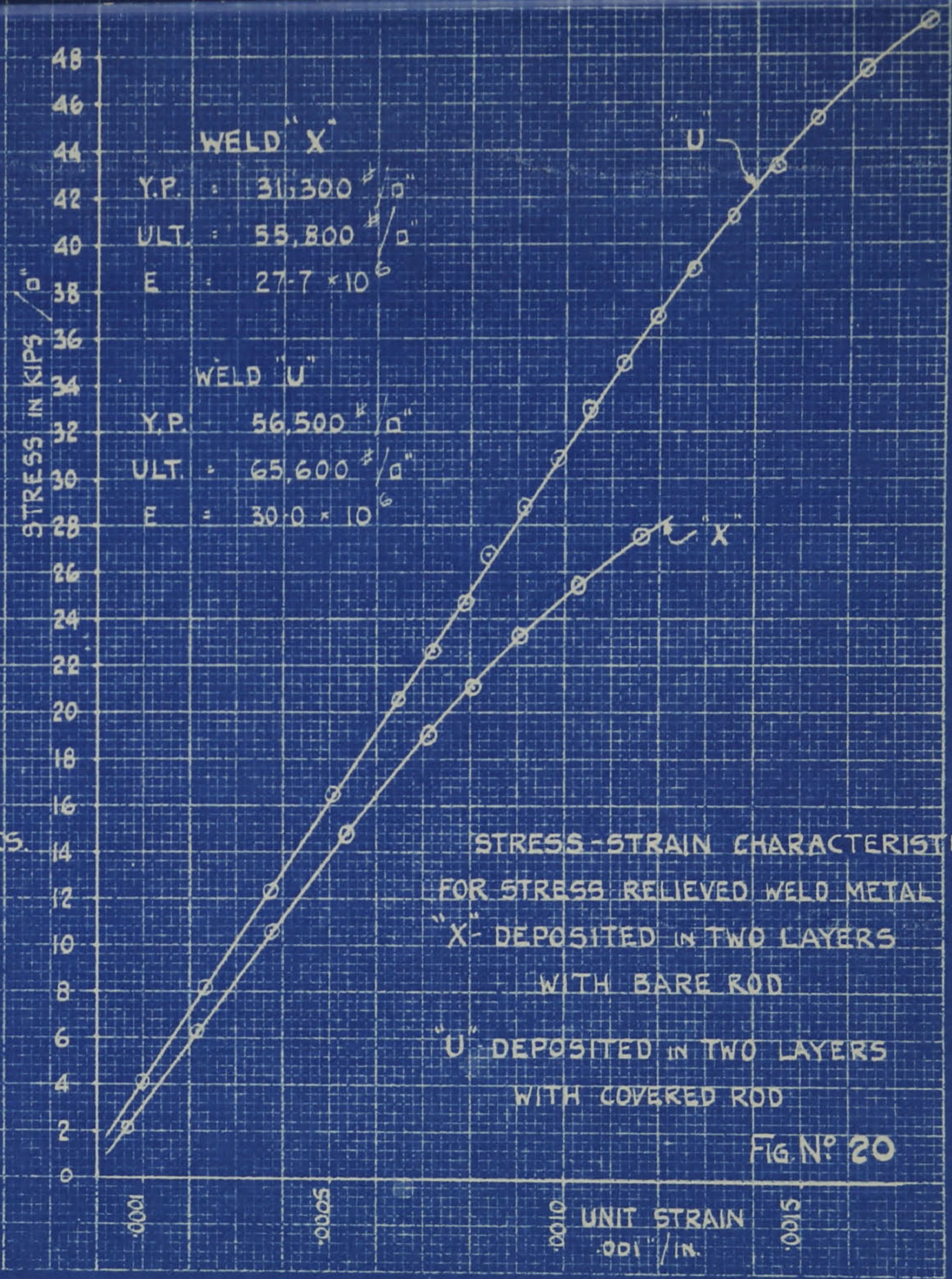


FIG. No 20

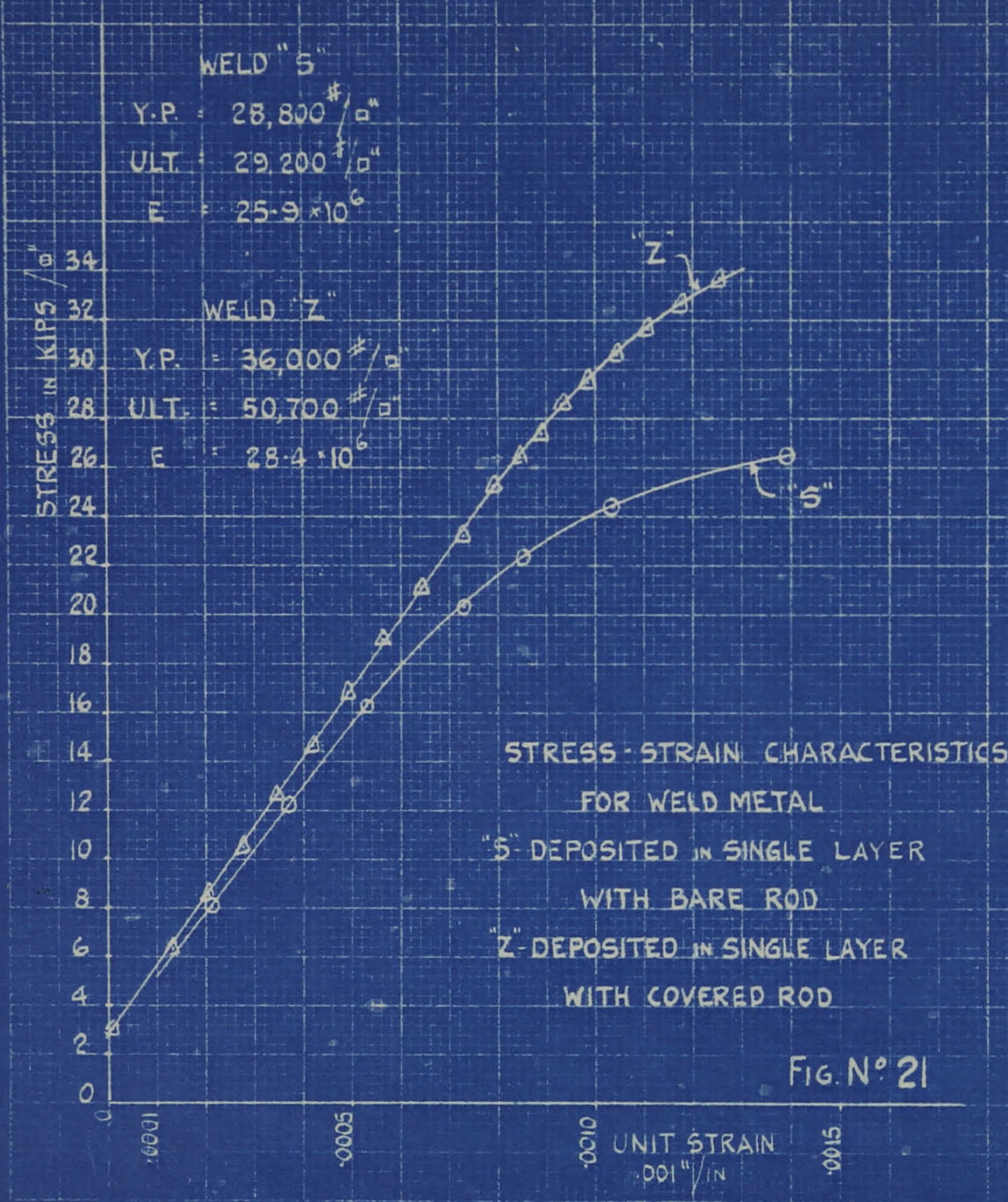


Fig. No. 21

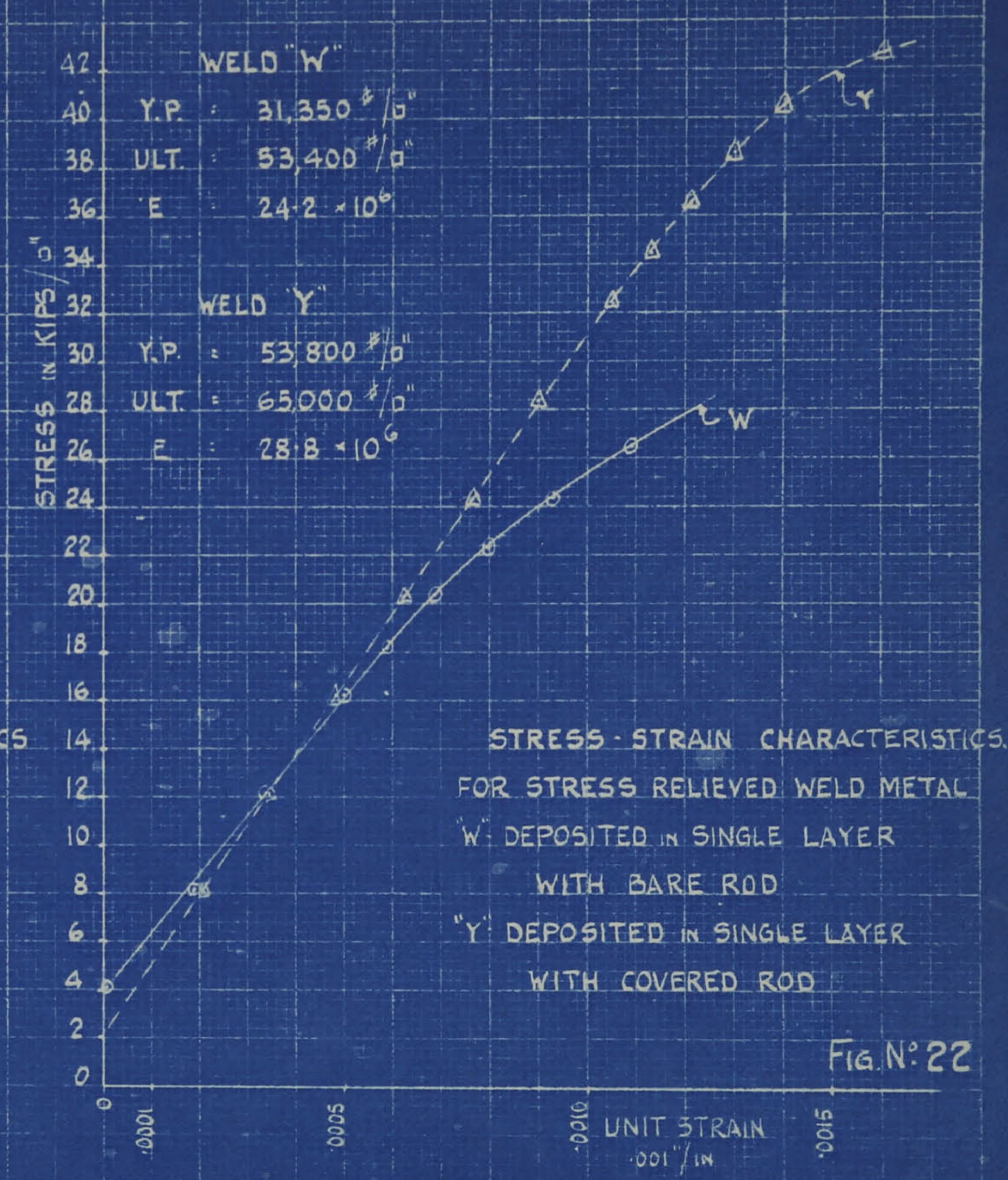


Fig. No. 22

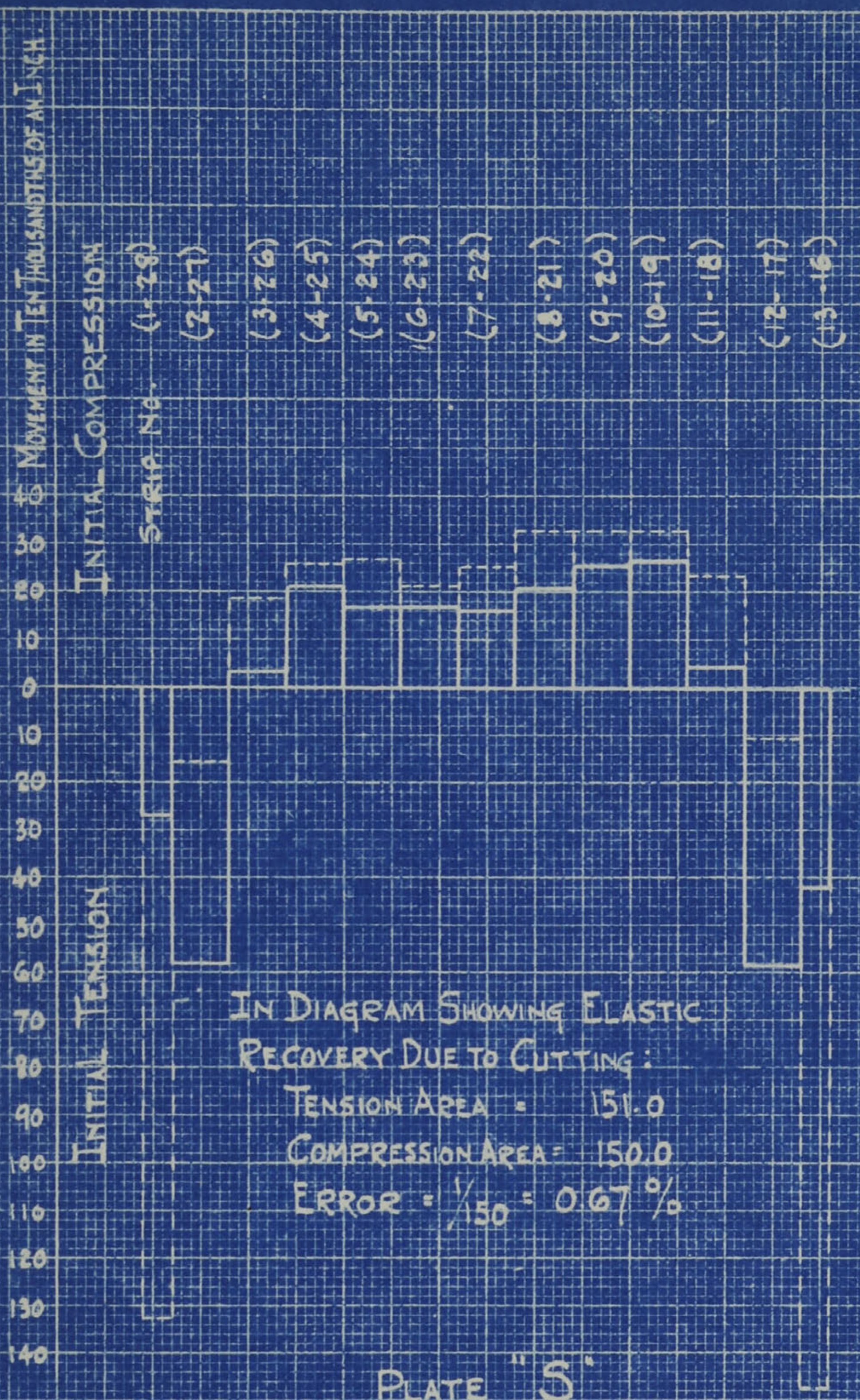


Plate "S"

Weld Deposited in One Layer with Bare Electrodes.
Dotted Lines Show Longitudinal Deformation Due to Welding.
Full Lines Show Longitudinal Elastic Deformation Resulting from Cutting the Plates Into Strips.

Figure — 23

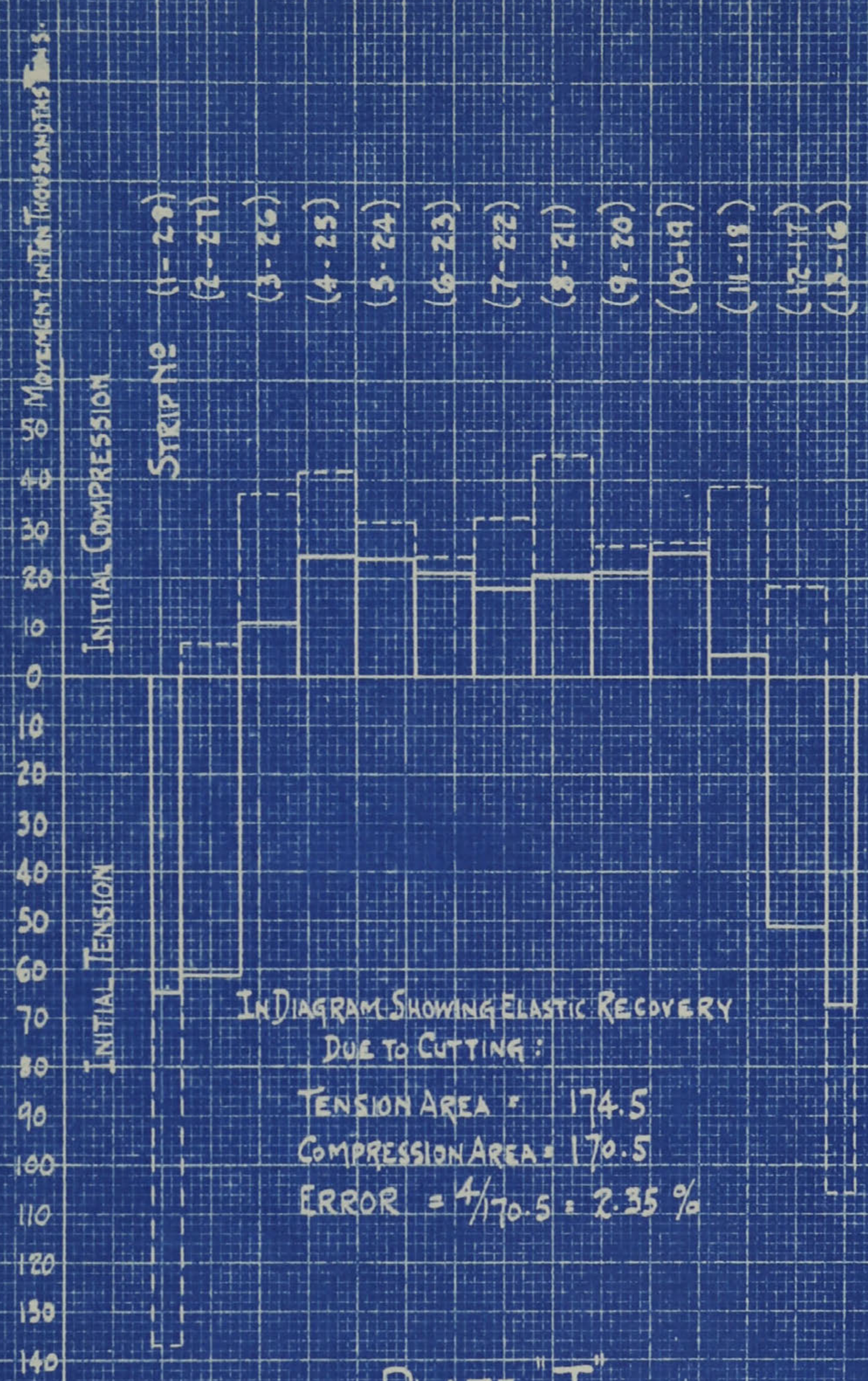


PLATE "T"

WELD DEPOSITED IN TWO LAYERS WITH BARE ELECTRODES.
DOTTED LINES SHOW LONGITUDINAL DEFORMATION DUE TO WELDING.
FULL LINES SHOW LONGITUDINAL ELASTIC DEFORMATION RESULTING FROM CUTTING THE PLATE INTO STRIPS.

FIGURE - 24

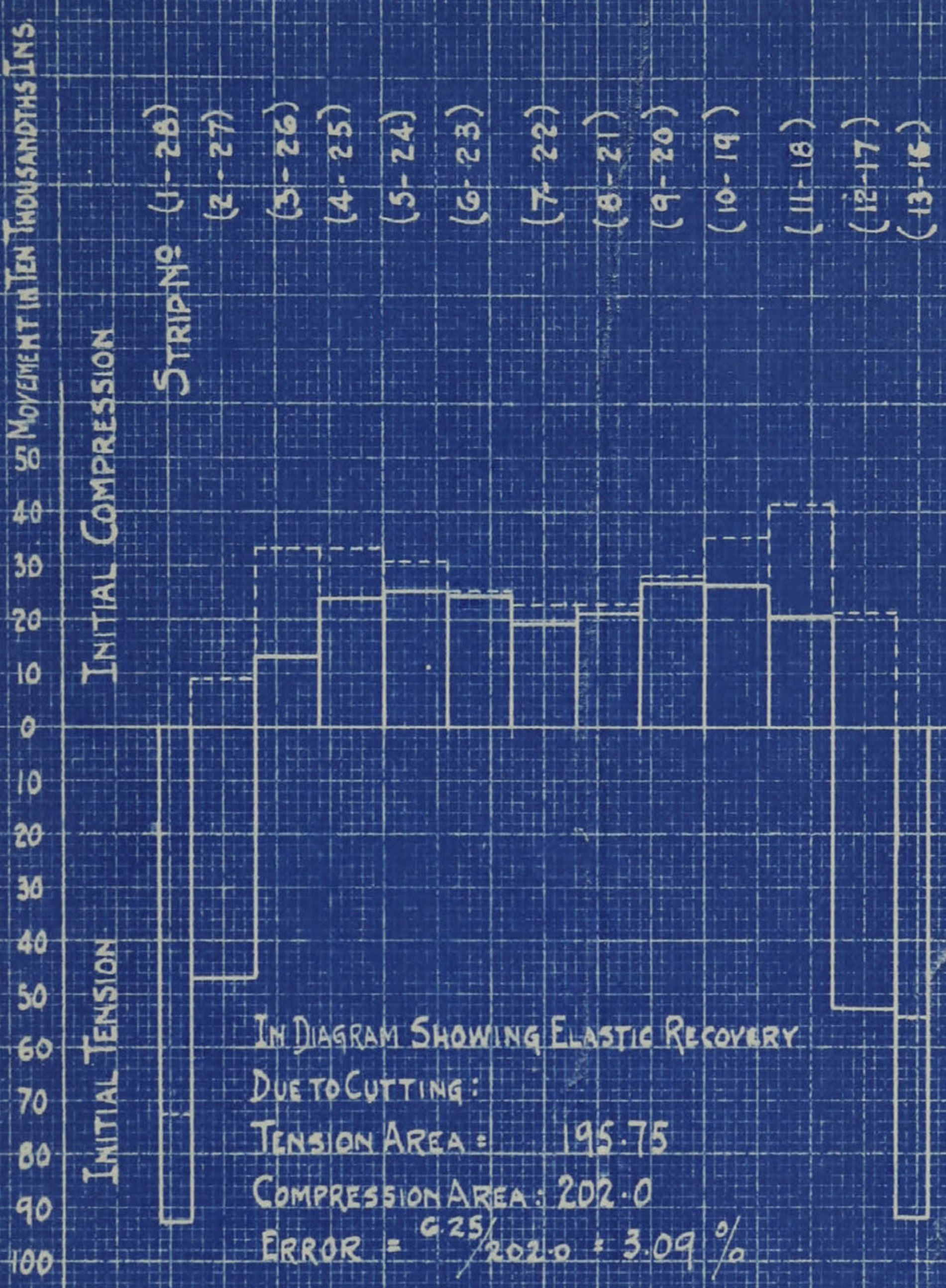


PLATE "Z"

WELD DEPOSITED IN ONE LAYER WITH COVERED ELECTRODES
DOTTED LINES SHOW LONGITUDINAL DEFORMATION DUE
TO WELDING.
FULL LINES SHOW LONGITUDINAL ELASTIC DEFORMATION
RESULTING FROM CUTTING THE PLATES INTO STRIPS.

FIGURE - 25

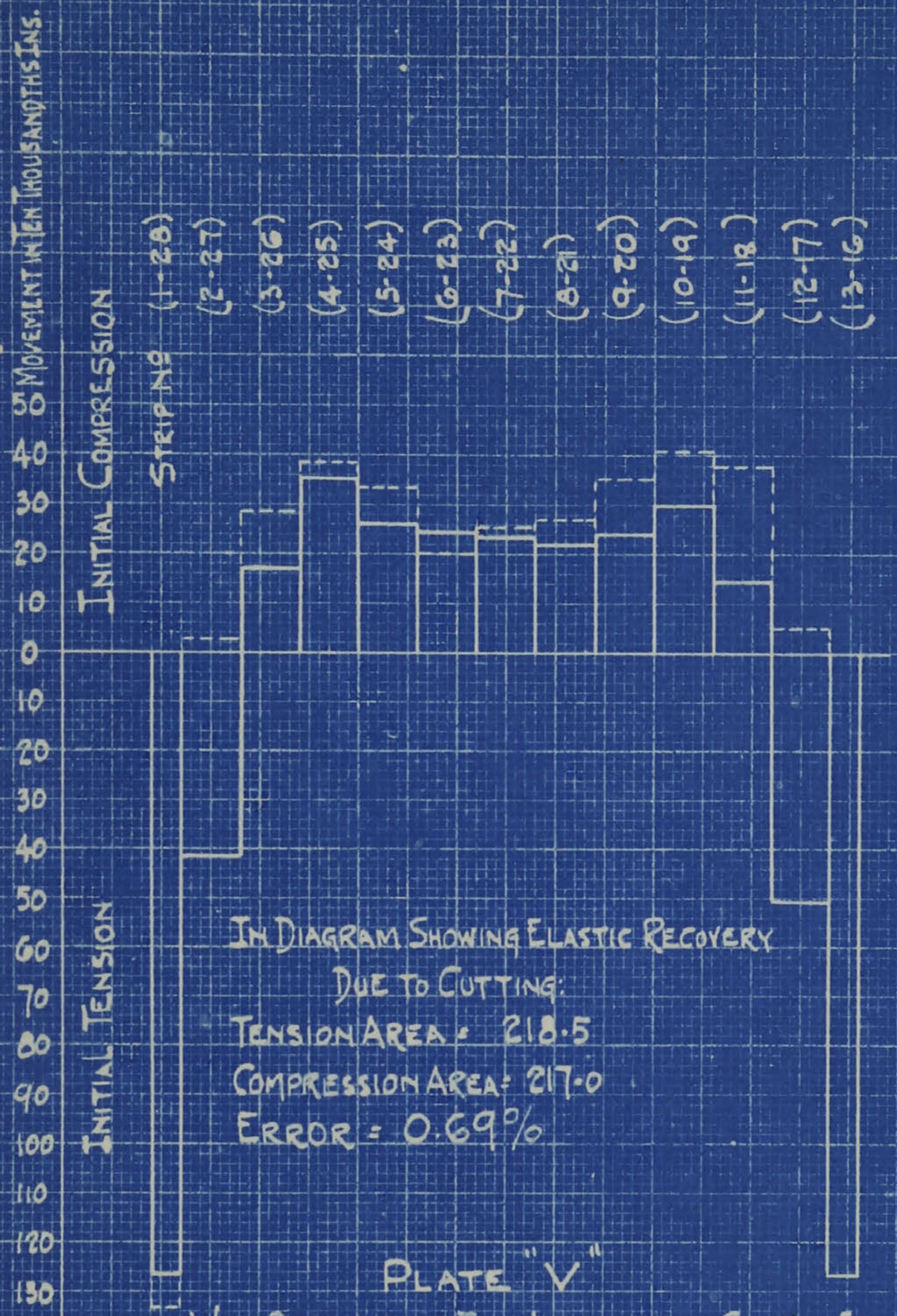


PLATE "V"

WELD DEPOSITED IN TWO LAYERS WITH COVERED ELECTRODES.
DOTTED LINES SHOW LONGITUDINAL DEFORMATION DUE
TO WELDING.
FULL LINES SHOW LONGITUDINAL ELASTIC DEFORMATION
RESULTING FROM CUTTING THE PLATE INTO STRIPS.

FIGURE - 26

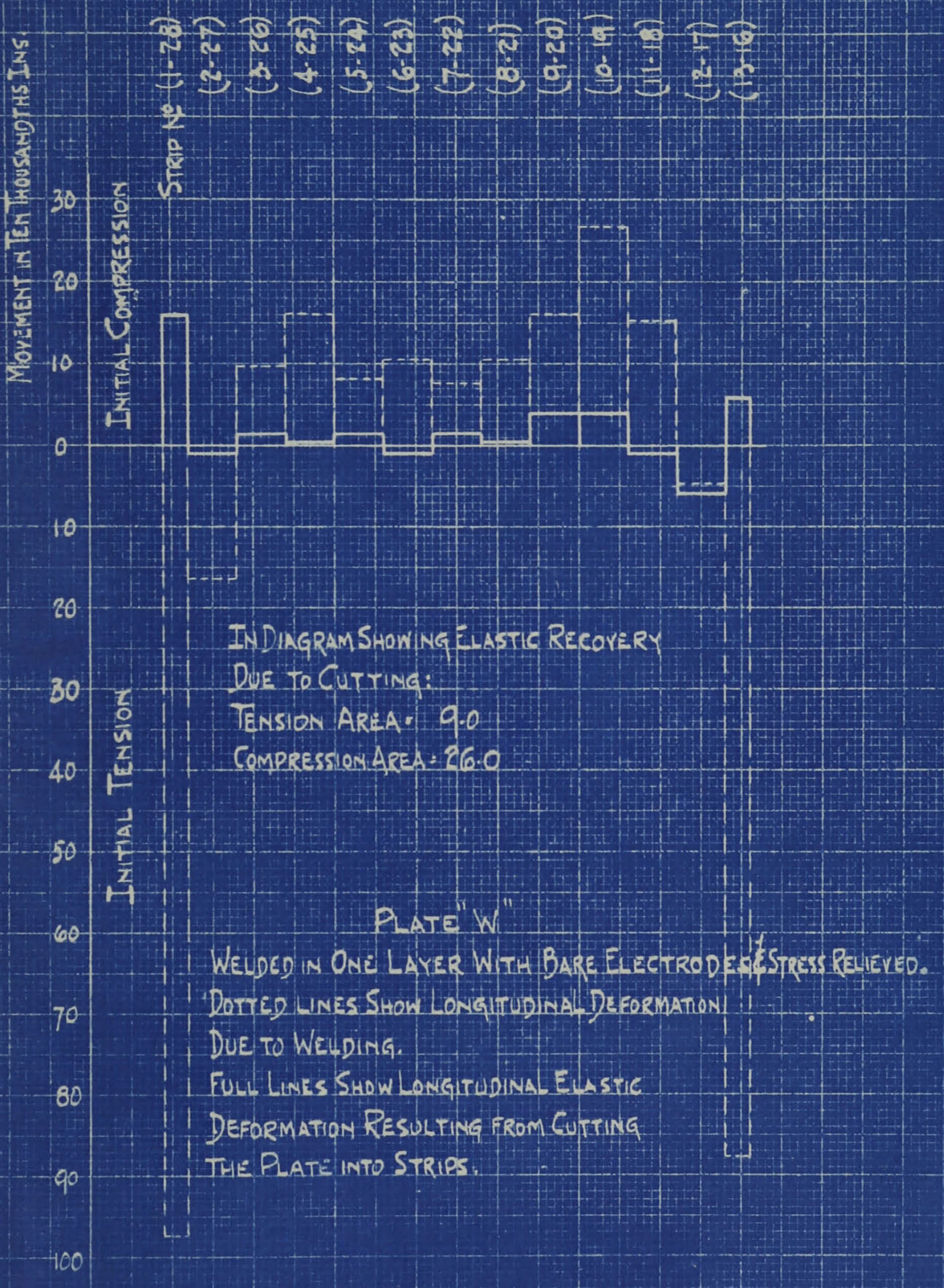

Movement in Ten Thousandths Ins.
Strip No (1-28) (2-27) (3-26) (4-25) (5-24) (6-23) (7-22) (8-21) (9-20) (10-19) (11-18) (12-17) (13-16)
Initial Compression
Initial Tension
30
20
10
0
10
20
30
40
50
60
70
80
90
100
In Diagram Showing Elastic Recovery
Due to Cutting:
Tension Area: 9.0
Compression Area: 26.0
Plate "W"
Welded in One Layer With Bare Electrodes & Stress Relieved.
Dotted lines Show Longitudinal Deformation
Due to Welding.
Full Lines Show Longitudinal Elastic
Deformation Resulting from Cutting
The Plate into Strips.

FIGURE — 27

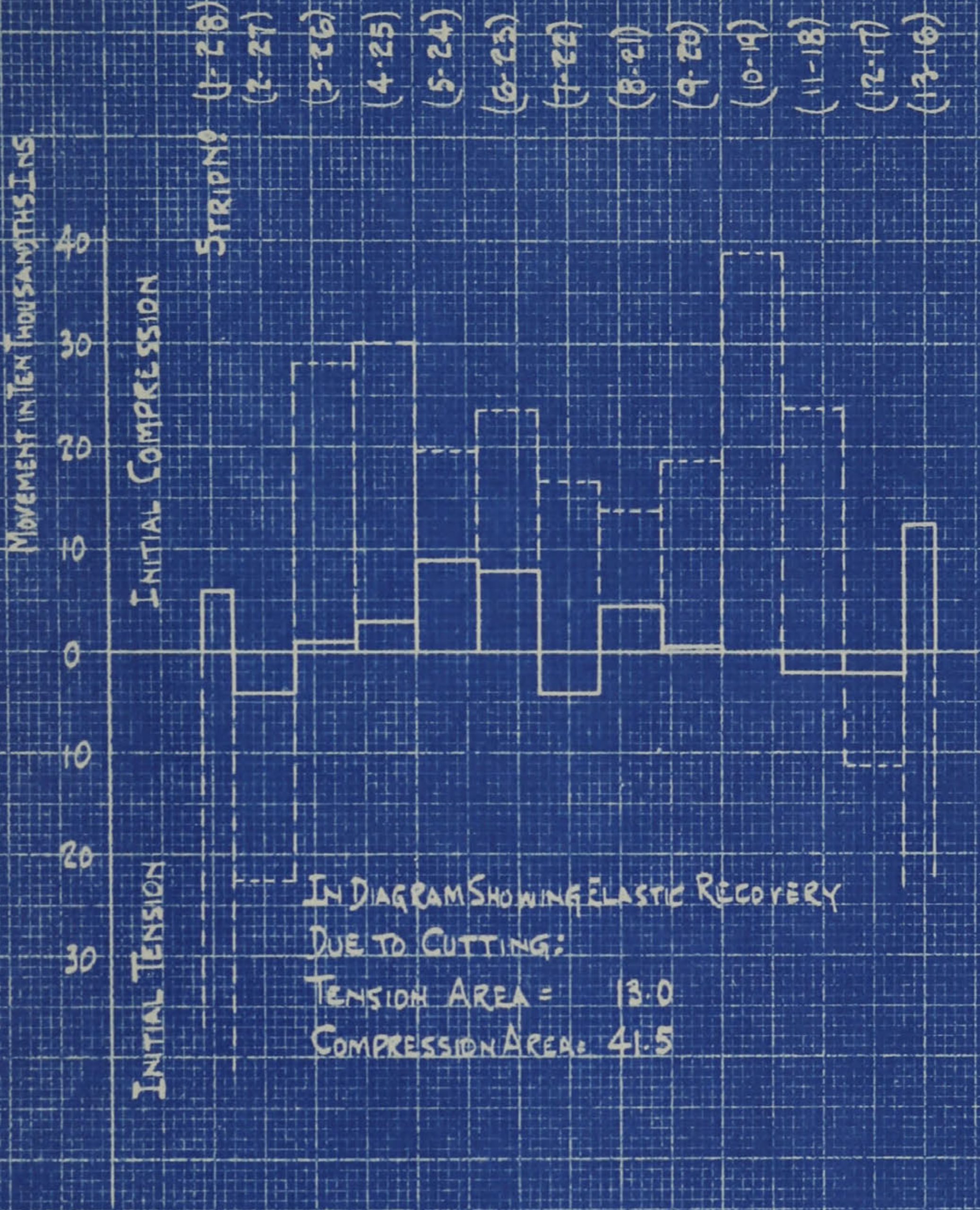


PLATE "X"

WELDED IN TWO LAYERS WITH BARE ELECTRODES & STRESS RELIEVED.
DOTTED LINES SHOW LONGITUDINAL DEFORMATION DUE TO WELDING.
FULL LINES SHOW LONGITUDINAL ELASTIC DEFORMATION
RESULTING FROM CUTTING THE PLATES INTO STRIPS.

FIGURE — 28

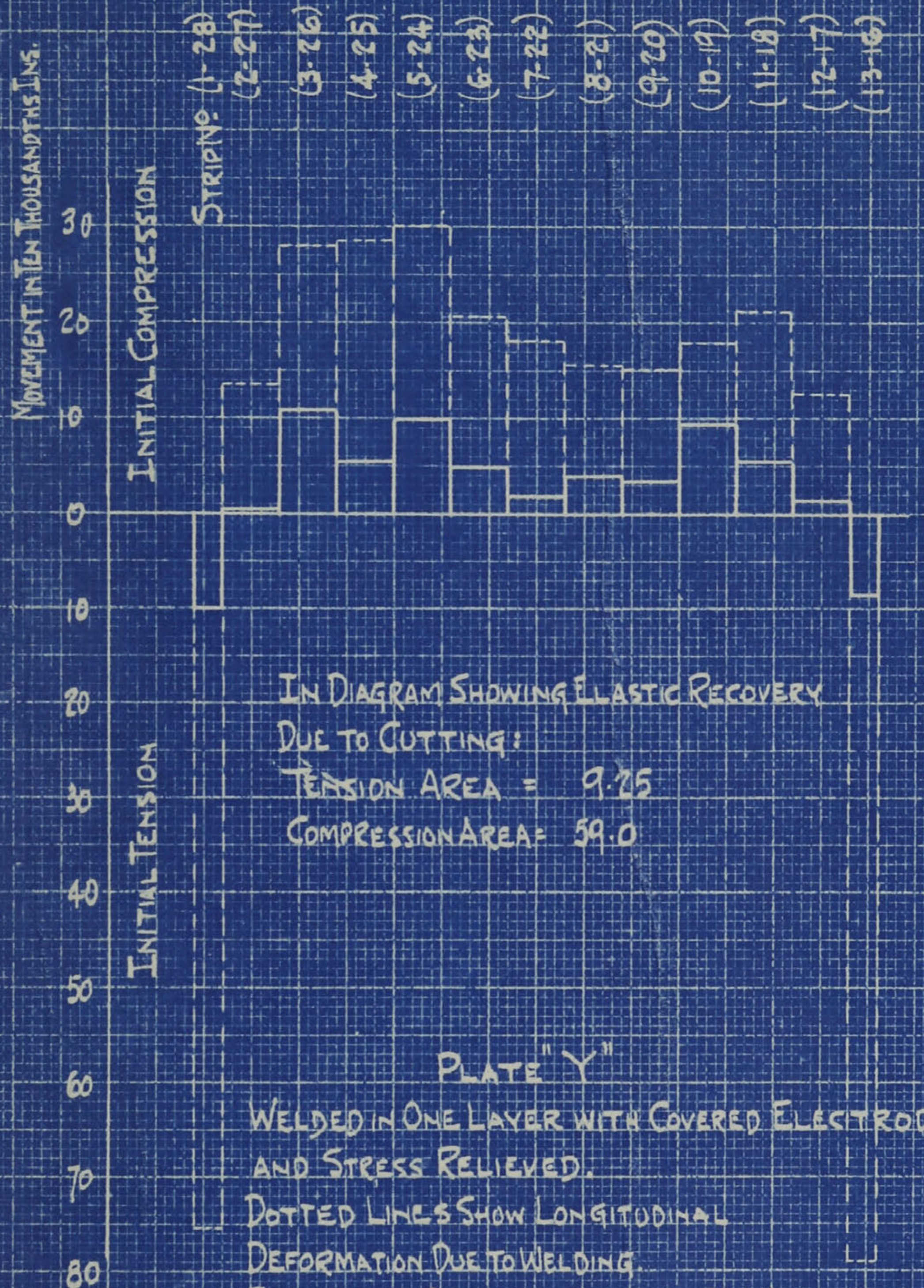


Plate "Y"

Welded in One Layer with Covered Electrodes and Stress Relieved.

Dotted Lines Show Longitudinal Deformation Due to Welding.

Full Lines Show Longitudinal Elastic Deformation Due to Cutting the Plates Into Strips.

Figure — 29

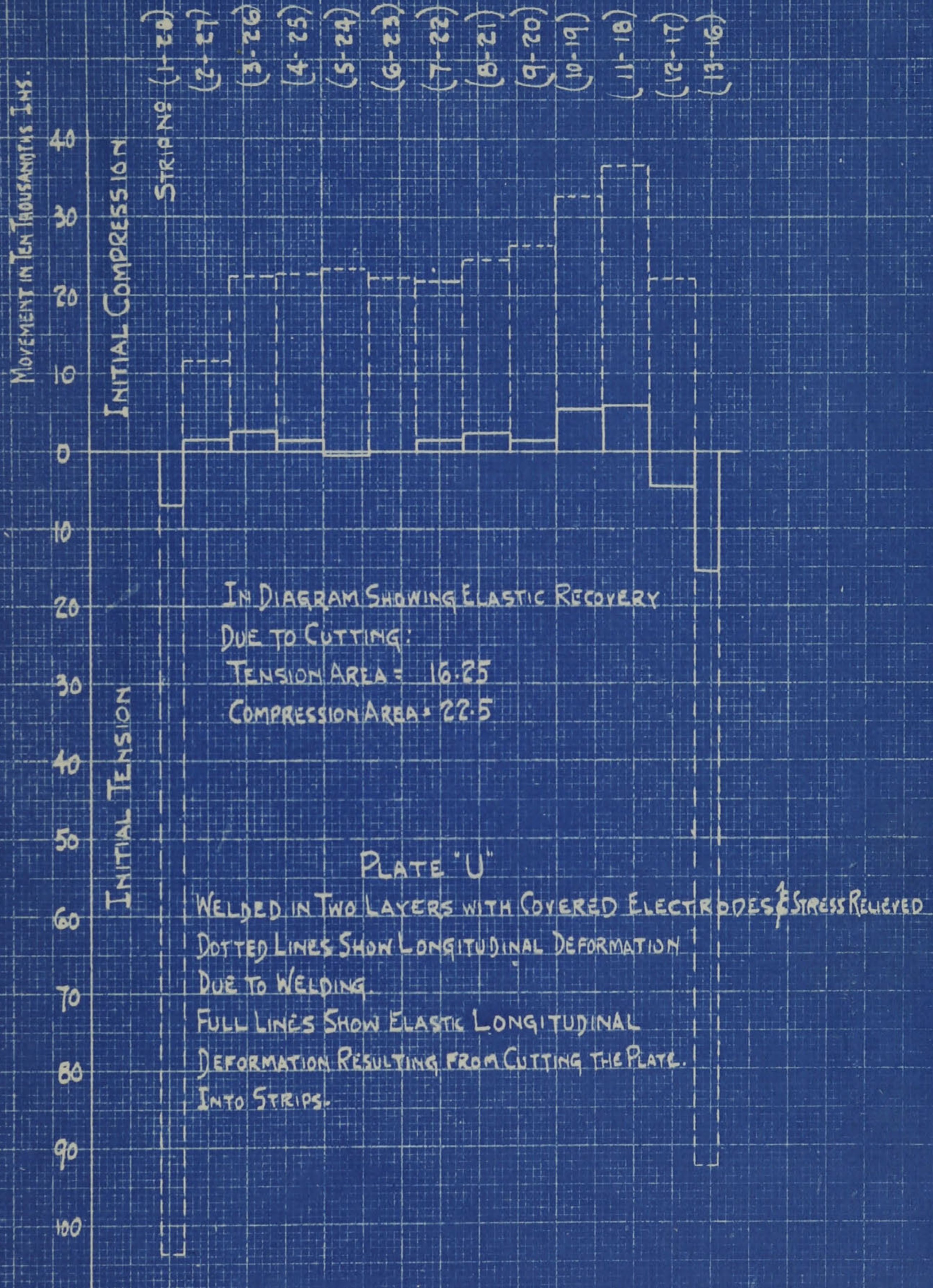
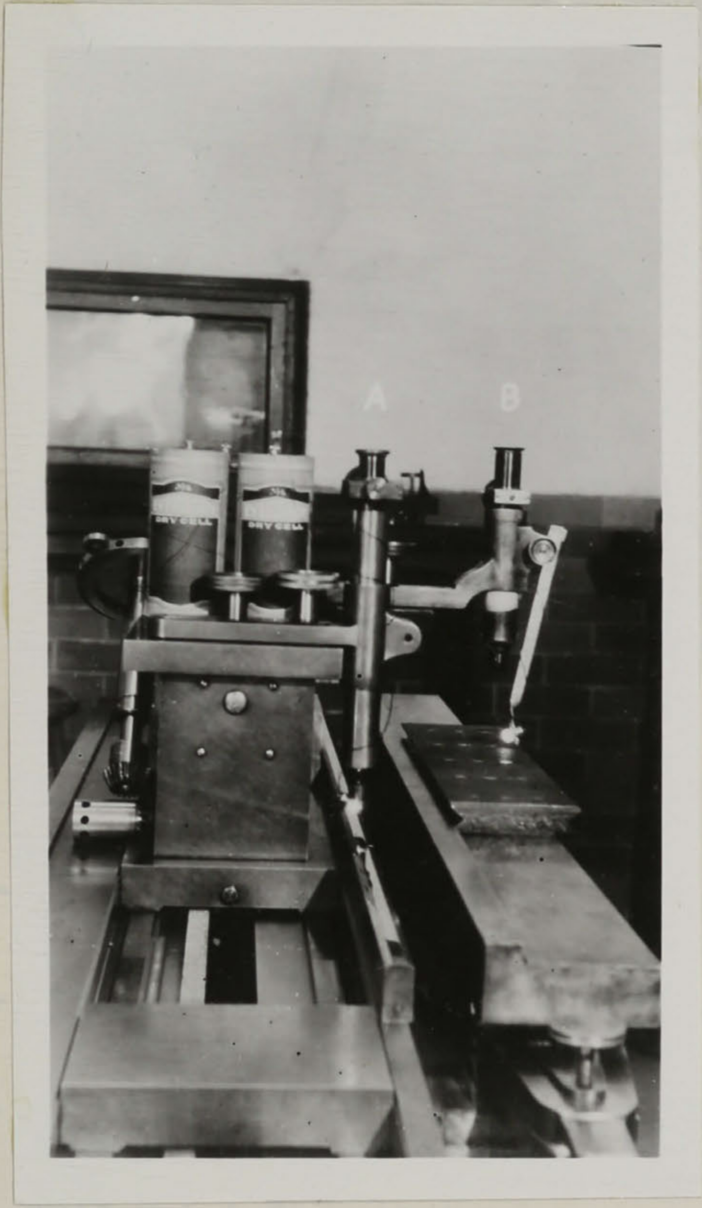
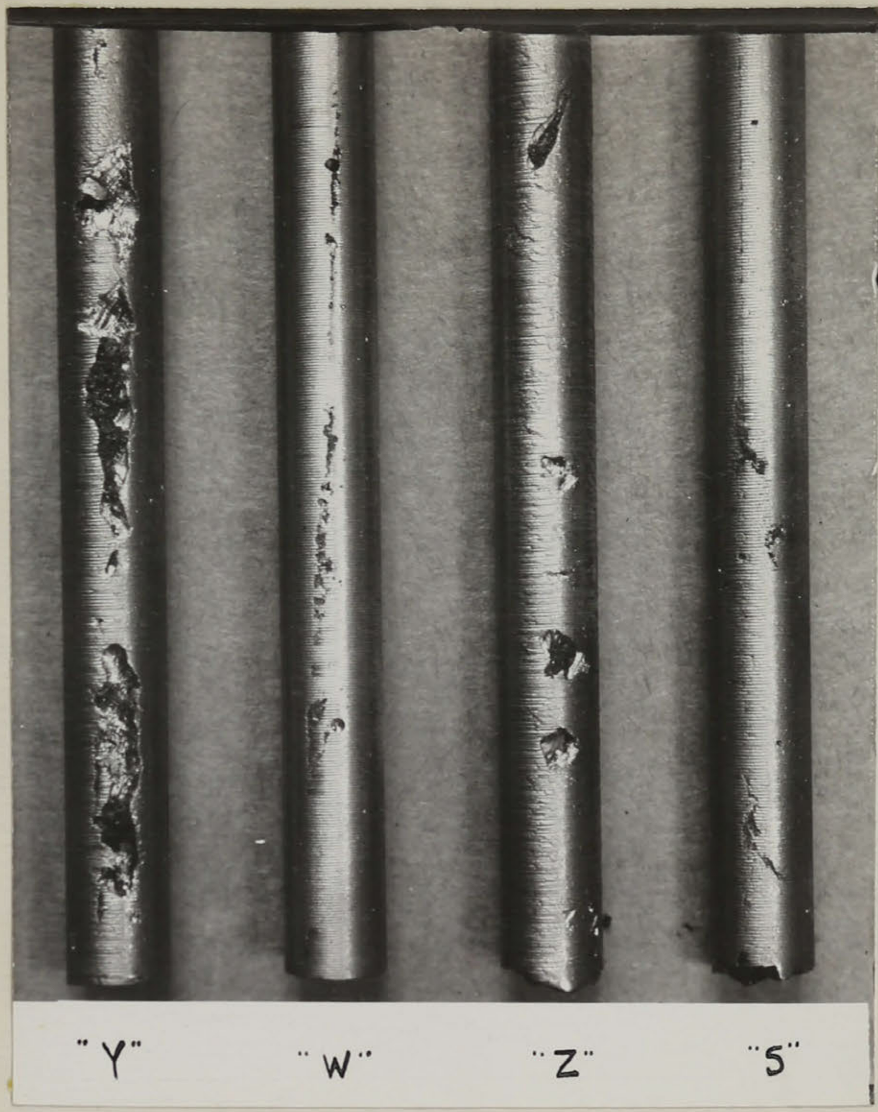

Movement in Ten Thousandths Ins.
Initial Compression
Initial Tension
Strip No (1-28) (2-27) (3-26) (4-25) (5-24) (6-23) (7-22) (8-21) (9-20) (10-19) (11-18) (12-17) (13-16)
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
In Diagram Showing Elastic Recovery
Due to Cutting:
Tension Area = 16.25
Compression Area = 22.5
Plate "U"
Welded in Two Layers with Covered Electrodes & Stress Relieved
Dotted Lines Show Longitudinal Deformation
Due to Welding.
Full Lines Show Elastic Longitudinal
Deformation Resulting from Cutting the Plate.
Into Strips.

Figure- 30



The Linear Comparator

Figure 31.



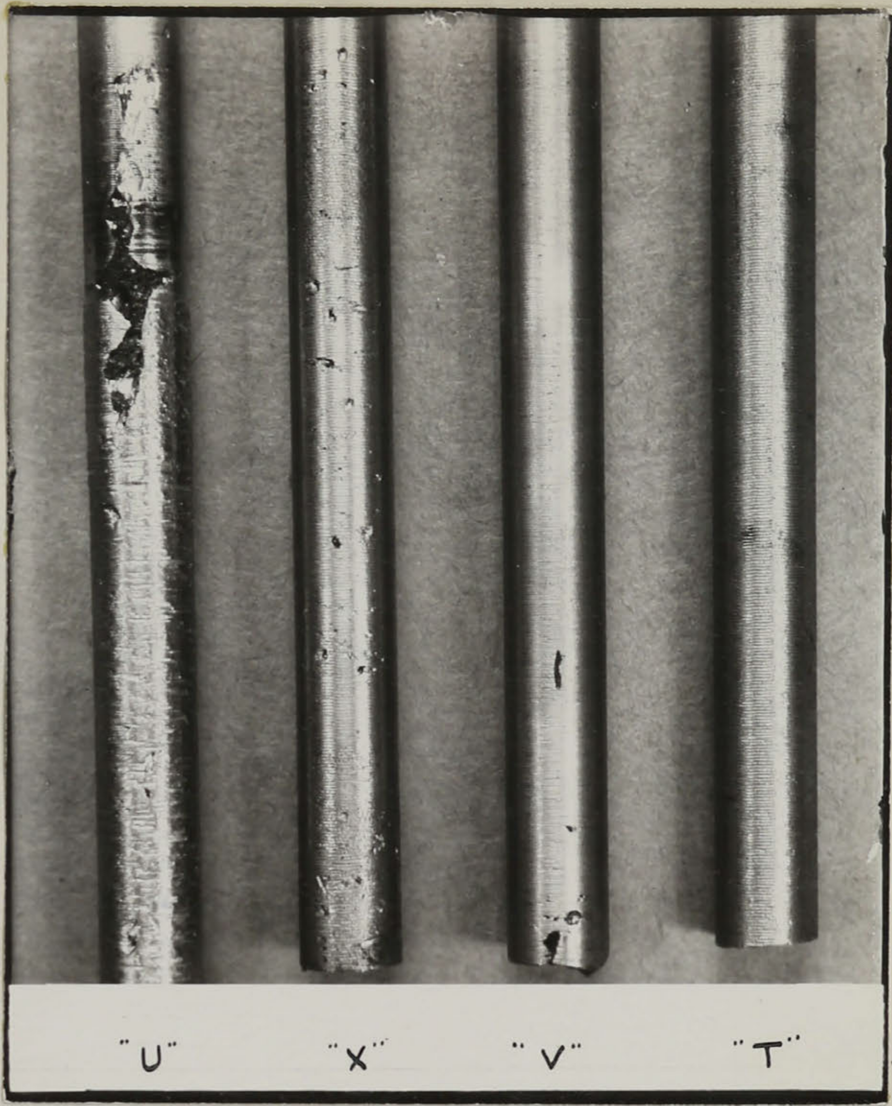
"Y" - Weld Metal deposited in one layer with covered electrodes and stress relieved after Welding.

W - Weld Metal deposited in one layer with bare electrodes and stress relieved after Welding.

Z - Weld Metal deposited in one layer with covered electrodes.

"S" - Weld Metal deposited in one layer with bare electrodes.

Figure 32.



U - Weld Metal deposited in two layers with covered electrodes and stress relieved after Welding.

X - Weld Metal deposited in two layers with bare electrodes and stress relieved after Welding.

V - Weld Metal deposited in two layers with covered electrodes.

T - Weld Metal deposited in two layers with bare electrodes.

Figure 33.

TABLE I

PLATE "S"

Space	SIDE "A" Distance Before Welding Inches	SIDE "A" Distance After Welding Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Welding Inches	SIDE "B" Distance After Welding Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	2.99781	2.99980	+ 19.9	3.00956	--	--	--
30-29	3.99821	4.00894	+107.3	3.98423	--	--	--
29-28	3.00050	3.00113	+ 6.3	3.00137	--	--	--
1-28	9.99663	10.00987	+132.4	10.00516	--	--	+132.4
2-27	9.99861	10.00139	+ 27.8	10.00456	10.00493	+ 3.7	+ 15.8
3-26	10.00488	10.00357	- 13.1	9.99682	9.99450	- 23.2	- 18.2
4-25	9.99992	9.99812	- 18.0	10.00454	10.00121	- 33.3	- 25.7
5-24	10.00244	10.00048	- 19.6	10.00477	10.00148	- 32.9	- 26.3
6-23	9.99926	9.99763	- 16.3	9.99795	9.99537	- 25.8	- 21.1
7-22	10.00328	10.00157	- 17.1	9.99808	9.99468	- 34.0	- 25.6
8-21	10.00603	10.00380	- 22.3	10.01738	10.01314	- 42.4	- 32.4
9-20	9.99743	9.99477	- 26.6	10.01357	10.00978	- 37.9	- 32.3
10-19	10.00008	9.99754	- 25.4	10.00573	10.00180	- 39.3	- 32.4
11-18	10.00072	9.99830	- 24.2	10.00592	10.00366	- 22.6	- 23.4
12-17	10.00538	10.00647	+ 10.9	10.00267	10.00361	+ 9.4	+ 10.2
13-14	2.98520	--	--	2.99949	--	--	--
14-15	4.00398	--	--	4.01040	--	--	--
15-16	3.01212	--	--	2.99849	--	--	--
13-16	10.00149	--	--	10.00839	--	--	--

TABLE II.

PLATE "T"

Space	SIDE "A" Distance Before Welding Inches	SIDE "A" Distance After Welding Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Welding Inches	SIDE "B" Distance After Welding Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	2.99852	--	--	3.00512	3.00467	- 4.5	--
30-29	3.99963	--	--	4.00979	4.02720	+174.1	--
29-28	3.00306	--	--	2.99694	2.99360	- 33.4	--
1-28	10.00121	--	--	10.01180	10.02549	+136.9	+136.9
2-27	10.00648	10.00533	- 11.5	10.00384	10.00368	- 1.6	- 6.6
3-26	10.00251	9.99876	- 37.5	10.00118	9.99751	- 36.7	- 37.1
4-25	10.00627	10.00284	- 34.3	10.00239	9.99748	- 49.1	- 41.7
5-24	10.00801	10.00697	- 10.4	10.00553	10.00029	- 52.4	- 31.4
6-23	10.00489	10.00375	- 11.4	9.99361	9.98989	- 37.2	- 24.3
7-22	9.99761	9.99430	- 33.1	10.00929	10.00616	- 31.3	- 32.2
8-21	9.99286	9.98908	- 37.8	10.01849	10.01329	- 52.0	- 44.9
9-20	9.99205	9.99018	- 18.7	10.01971	10.01633	- 33.8	- 26.3
10-19	9.97946	9.97660	- 28.6	10.01799	10.01542	- 25.7	- 27.2
11-18	9.98214	9.97930	- 28.4	10.00185	9.99700	- 48.5	- 38.5
12-17	9.96839	9.96653	- 18.6	10.00602	10.00422	- 18.0	- 18.3
13-14	3.01060	3.00735	- 32.5	3.00575	--	--	--
14-15	3.98258	3.99859	+160.1	3.99534	--	--	--
15-16	2.99764	2.99555	- 20.9	2.99791	--	--	--
13-16	9.99086	10.00143	+105.7	9.99894	--	--	+105.7

TABLE III

PLATE "Z"

Space	SIDE "A" Distance Before Welding Inches	SIDE "A" Distance After Welding Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Welding Inches	SIDE "B" Distance After Welding Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	2.99017	2.99111	+ 9.4	3.02145	3.02252	+ 10.7	+ 10.0
30-29	3.95420	3.96215	+ 79.5	3.95592	3.96390	+ 79.8	+ 79.7
29-28	3.01107	3.00844	- 26.3	3.00543	3.00485	- 5.8	- 16.0
1-28	9.95548	9.96170	+ 62.2	9.98286	9.99130	+ 84.4	+ 73.3
2-27	9.96428	9.96321	- 10.7	9.98058	9.97996	- 6.2	- 8.5
3-26	9.96378	9.96051	- 32.7	9.98918	9.98581	- 33.7	- 33.2
4-25	9.96383	9.96010	- 37.3	9.99490	9.99197	- 29.3	- 33.3
5-24	9.96353	9.96011	- 34.2	10.00080	9.99803	- 27.7	- 31.0
6-23	9.96730	9.96461	- 26.9	9.99250	9.99011	- 23.9	- 25.4
7-22	9.96630	9.96371	- 25.9	9.99927	9.99738	- 18.9	- 22.4
8-21	9.96568	9.96361	- 20.7	10.00225	9.99981	- 24.4	- 22.6
9-20	9.97173	9.96861	- 31.2	10.00561	10.00313	- 24.8	- 28.0
10-19	9.97693	9.97341	- 35.2	9.99617	9.99261	- 35.6	- 35.4
11-18	9.97818	9.97451	- 36.7	10.00262	9.99810	- 46.2	- 41.5
12-17	9.98220	9.98030	- 19.0	10.00665	10.00421	- 24.4	- 21.7
13-14	2.99841	2.99546	- 29.5	2.98459	2.98191	- 26.8	- 28.2
14-15	3.98268	3.98842	+ 57.4	4.02180	4.02865	+ 68.5	+ 63.0
15-16	2.98946	2.99156	+ 21.0	3.00190	3.00368	+ 17.8	+ 19.4
13-16	9.97057	9.97548	+ 49.1	10.00833	10.01424	+ 59.1	+ 54.1

TABLE IV.

PLATE "V"

	SIDE "A"			SIDE "B"			
Space	Distance Before Welding Inches	Distance After Welding Inches	Deformation In Ten Thousandths Inches	Distance Before Welding Inches	Distance After Welding Inches	Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	3.00330	3.00155	- 17.5	3.01614	3.01560	- 5.4	- 11.5
30-29	3.98799	3.99628	+ 82.9	4.02470	4.03307	+83.7	+ 83.3
29-28	3.00612	3.01260	+ 64.8	2.95068	2.95655	+58.7	+ 61.8
1-28	9.99740	10.01044	+130.4	9.99156	10.00523	+136.7	+133.6
2-27	9.97238	9.97195	- 4.3	10.00298	10.00287	- 1.1	- 2.7
3-26	9.98806	9.98600	- 20.6	10.00089	9.99725	-36.4	- 28.5
4-25	9.98857	9.98553	- 30.4	9.99822	9.99356	-46.6	- 38.5
5-24	9.98786	9.98495	- 29.1	9.99668	9.99290	-37.8	- 33.5
6-23	9.98933	9.98688	- 24.5	9.99768	9.99612	-15.6	- 20.0
7-22	9.98478	9.98310	- 16.8	9.99840	9.99498	-34.2	- 25.5
8-21	9.98246	9.98095	- 15.1	9.99440	9.99050	-39.0	- 27.0
9-20	9.98206	9.97880	- 32.6	10.00063	9.99680	-38.3	- 35.5
10-19	9.97730	9.97400	- 33.0	9.99967	9.99480	-48.7	- 40.9
11-18	9.97898	9.97575	- 32.3	9.99821	9.99389	-43.2	- 37.8
12-17	9.97488	9.97535	+ 4.7	10.00121	9.99975	-14.6	- 5.0
13-14	3.00068	3.00712	+ 64.4	3.00225	3.00800	+57.5	+ 61.0
14-15	3.97905	3.98740	+ 63.5	3.99769	4.00458	+68.8	+ 66.2
15-16	2.99590	2.99435	- 15.5	3.00154	3.00100	- 5.4	- 10.5
13-16	9.97565	9.98890	+132.5	10.00148	10.01352	+120.4	+126.5

TABLE V.

PLATE "W"

Space	SIDE "A" Distance Before Welding Inches	Distance After Welding Inches	Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Welding Inches	Distance After Welding Inches	Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	2.98758	3.00955	+ 219.7	3.00399	3.00617	+ 21.8	+120.7
30-29	4.03075	4.01710	-136.5	4.01479	4.02100	+ 62.1	- 37.2
29-28	2.98803	2.99025	+ 22.3	2.98528	2.98685	+ 15.8	+ 19.1
1-28	10.00638	10.01690	+ 95.2	10.00407	10.01404	+ 99.7	+ 97.5
2-27	10.00271	10.00429	+ 15.8	9.99286	9.99454	+ 16.8	+ 16.3
3-26	10.00566	10.00479	- 8.7	9.99471	9.99360	- 11.1	- 9.9
4-25	10.00720	10.00587	- 13.3	9.99450	9.99261	- 18.9	- 16.1
5-24	10.00275	10.00193	- 8.2	9.99830	9.99750	- 8.0	- 8.1
6-23	10.00430	10.00333	- 9.7	9.99187	9.99072	- 11.5	- 10.6
7-22	9.99582	9.99535	- 4.7	9.99589	9.99480	- 10.9	- 7.8
8-21	9.99455	9.99440	- 1.5	9.98930	9.98736	- 19.4	- 10.5
9-20	9.99280	9.99160	- 12.0	9.99165	9.98965	- 20.0	- 16.0
10-19	9.98353	9.98069	- 28.4	9.98743	9.98490	- 25.3	- 26.9
11-18	9.98113	9.98069	- 4.4	9.98853	9.98593	- 26.0	- 15.2
12-17	9.98066	9.98203	+ 13.7	9.98256	9.98215	- 4.1	+ 4.8
13-14	2.98749	2.98735	- 1.4	3.01391	3.01373	- 1.8	- 1.6
14-15	4.00250	4.00825	+ 57.5	3.97440	3.97920	+ 48.0	+ 52.7
15-16	2.98990	2.99395	+ 40.5	2.99785	3.00113	+ 32.8	+ 37.7
13-16	9.97988	9.98955	+ 96.7	9.98616	9.99407	+ 79.1	+ 87.9

TABLE VI.

PLATE "X"

	SIDE "A"			SIDE "B"				
Space	Distance Before Welding Inches	Distance After Welding Inches	Deformation In Ten Thousandths Inches	Distance Before Welding Inches	Distance After Welding Inches	Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	3.01715	--	--	2.97790	--	--	--
30-29	4.00132	--	--	4.02165	--	--	--
29-28	2.97840	--	--	3.00663	--	--	--
1-28	9.99685	--	--	10.00618	--	--	--
2-27	10.00038	10.00207	+ 16.9	10.01089	10.01365	+ 27.6	+ 22.3
3-26	10.00645	10.00376	- 26.9	10.01352	10.01061	- 29.1	- 28.0
4-25	10.00631	10.00253	- 37.8	10.01347	10.01125	- 22.2	- 30.0
5-24	10.00663	10.00303	- 36.0	10.01157	10.01129	- 2.8	- 19.4
6-23	10.02005	10.01715	- 29.0	10.01356	10.01179	- 17.7	- 23.4
7-22	10.00984	10.00712	- 27.2	10.03575	10.03516	- 5.9	- 16.6
8-21	10.01211	10.00952	- 25.9	10.01388	10.01374	- 1.4	- 13.7
9-20	10.02260	10.01960	- 30.0	10.01605	10.01533	- 7.2	- 18.6
10-19	10.01683	10.01343	- 34.0	10.01111	10.00675	- 43.6	- 38.8
11-18	10.01583	10.01211	- 37.2	10.03518	10.03416	- 10.2	- 23.7
12-17	10.02419	10.02429	+ 1.0	10.02589	10.02801	+ 21.2	+ 11.1
13-14	2.99664	--	--	3.00278	--	--	--
14-15	4.01996	--	--	4.00344	--	--	--
15-16	3.01098	--	--	3.02265	--	--	--
13-16	10.02759	--	--	10.02888	--	--	--

TABLE VII.

PLATE "Y"

Space	SIDE "A" Distance Before Welding Inches	SIDE "A" Distance After Welding Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Welding Inches	SIDE "B" Distance After Welding Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	3.02988	2.97055	-593.3	2.98798	2.99093	+ 19.5	-286.9
30-29	3.95070	4.01759	+668.9	3.98989	3.99574	+ 58.5	+363.7
29-28	3.02721	3.02585	- 13.6	3.03003	3.03077	+ 7.4	- 3.1
1-28	10.00780	10.01395	+ 61.5	10.00796	10.01685	+ 88.9	+ 75.2
2-27	10.00910	10.00715	- 19.5	9.99792	9.99867	- 7.5	- 13.5
3-26	10.00923	10.00551	- 37.2	10.00251	10.00062	- 18.9	- 28.0
4-25	10.01663	10.01309	- 35.4	10.00220	10.00007	- 21.3	- 28.3
5-24	10.01273	10.00801	- 47.2	10.01146	10.01019	- 12.7	- 30.0
6-23	10.01633	10.01359	- 27.4	10.01923	10.01790	- 13.3	- 20.4
7-22	10.01592	10.01349	- 24.3	10.02173	10.02056	- 11.7	- 18.0
8-21	10.02068	10.01808	- 26.0	10.00910	10.00860	- 5.0	- 15.5
9-20	10.01711	10.01431	- 28.0	10.01119	10.01100	- 1.9	- 15.0
10-19	10.01319	10.01050	- 26.9	10.02087	10.01998	- 8.9	- 17.9
11-18	10.01619	10.01327	- 29.2	10.02473	10.02343	- 13.0	- 21.1
12-17	10.01208	10.00914	- 11.4	10.02331	10.02196	- 13.5	- 12.5
13-14	2.99070	2.98975	- 9.5	2.98833	2.98827	- 0.6	- 5.1
14-15	3.97480	3.98119	+ 63.9	3.98040	3.98712	+ 67.2	+ 65.5
15-16	3.04663	3.04875	+ 21.2	3.05000	3.05150	+ 15.0	+ 18.1
13-16	10.01219	10.01975	+ 75.6	10.01873	10.02697	+ 82.4	+ 79.0

TABLE VIII

PLATE "U"

Space	SIDE "A" Distance Before Welding Inches	SIDE "A" Distance After Welding Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Welding Inches	SIDE "B" Distance After Welding Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-30	3.04038	3.04465	+ 42.7	3.02600	3.02820	+ 22.0	+ 32.4
30-29	4.00263	4.01007	+ 74.4	3.94490	3.95130	+ 64.0	+ 69.2
29-28	2.94180	2.94070	- 11.0	2.98760	2.98930	+ 17.0	+ 3.0
1-28	9.98490	9.99540	+105.0	9.95848	9.96873	+102.5	+103.8
2-27	9.97973	9.97873	- 10.0	9.96288	9.96425	- 13.7	- 11.9
3-26	9.98386	9.98055	- 33.1	9.95513	9.95395	- 11.8	- 22.5
4-25	9.99124	9.98818	- 30.6	9.95953	9.95805	- 14.8	- 22.7
5-24	9.98196	9.97887	-30.9	9.97103	9.96945	- 15.8	- 23.4
6-23	9.99840	9.99463	- 37.7	9.95873	9.95805	- 6.8	- 22.3
7-22	9.99594	9.99228	- 36.6	9.96008	9.95935	- 7.3	- 22.0
8-21	9.99586	9.99230	- 35.6	9.96588	9.96455	- 13.3	- 24.5
9-20	9.99886	9.99477	- 40.9	9.96023	9.95805	- 11.8	- 26.4
10-19	10.00552	10.00039	- 51.3	9.95283	9.95040	- 24.3	- 32.8
11-18	10.00465	9.99972	- 49.3	9.96328	9.95985	- 24.3	- 36.8
12-17	10.01000	10.00715	- 28.5	9.96313	9.96155	- 15.8	- 22.2
13-14	2.98490	2.98262	- 22.8	3.03007	3.03897	+ 89.0	+ 33.1
14-15	4.02623	4.03455	+ 83.2	3.98371	3.98230	- 14.1	+ 34.5
15-16	3.00165	3.00506	+ 34.1	2.95300	2.95470	+ 17.0	+ 25.5
13-16	10.01277	10.02220	+ 93.3	9.96680	9.97599	+ 91.9	+ 92.6

TABLE IX.

PLATE "S"

Space	SIDE "A" Distance Before Cutting Inches	SIDE "A" Distance After Cutting Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	SIDE "B" Distance After Cutting Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	9.9899	9.9880	- 19	10.0052	10.0017	- 35	- 27
2-27	10.0023	9.9967	- 56	10.0069	10.0009	- 60	- 58
3-26	9.9944	9.9958	+ 14	10.0095	10.0087	- 8	+ $3\frac{1}{2}$
4-25	9.9917	9.9953	+ 36	10.0020	10.0026	+ 6	+ 21
5-24	9.9928	9.9956	+ 28	10.0078	10.0083	+ 5	+ $16\frac{1}{2}$
6-23	9.9967	9.9987	+ 20	10.0010	10.0023	+ 13	+ $16\frac{1}{2}$
7-22	9.9981	9.9998	+ 17	9.9867	9.9882	+ 15	+ 16
8-21	10.0042	10.0066	+ 24	10.0263	10.0282	+ 17	+ $20\frac{1}{2}$
9-20	9.9885	9.9902	+ 17	10.0016	10.0050	+ 34	+ $25\frac{1}{2}$
10-19	9.9957	9.9974	+ 17	9.9888	9.9924	+ 36	+ $26\frac{1}{2}$
11-18	9.9994	9.9989	- 5	9.9973	9.9986	+ 13	+ 4
12-17	10.0040	9.9979	- 61	9.9974	9.9918	- 56	- $58\frac{1}{2}$
13-16	9.9898	9.9858	- 40	10.0107	10.0063	- 44	- 42

TABLE X

PLATE "T"

Space	SIDE "A" Distance Before Cutting Inches	SIDE "A" Distance After Cutting Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	SIDE "B" Distance After Cutting Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	10.0503	10.0439	- 64	10.0273	10.0208	- 65	- 64½
2-27	10.0091	10.0028	- 63	10.0012	9.9953	- 59	- 61
3-26	10.0379	10.0382	+ 3	10.0034	10.0053	+ 19	+ 11
4-25	10.0047	10.0072	+ 25	10.0025	10.0049	+ 24	+ 24½
5-24	10.0121	10.0153	+ 32	10.0059	10.0073	+ 16	+ 24
6-23	9.9977	10.0004	+ 27	9.9979	9.9996	+ 15	+ 21
7-22	9.9921	9.9945	+ 24	10.0158	10.0170	+ 12	+ 18
8-21	9.9933	9.9960	+ 27	10.0118	10.0132	+ 14	+ 20½
9-20	9.9735	9.9756	+ 21	10.0258	10.0280	+ 22	+ 21½
10-19	9.9626	9.9645	+ 19	10.0140	10.0172	+ 32	+ 25½
11-18	9.9773	9.9773	+ 0	10.0080	10.0089	+ 9	+ 4½
12-17	9.9630	9.9567	- 63	10.0041	9.9981	- 40	- 51½
13-16	10.0159	10.0091	- 68	10.0193	10.0126	- 67	- 67½

TABLE XI.

PLATE "Z"

Space	SIDE "A" Distance Before Cutting Inches	SIDE "A" Distance After Cutting Inches	SIDE "A" Deformation in Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	SIDE "B" Distance After Cutting Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	9.9505	9.9413	- 92	9.9942	9.9849	- 93	- 92½
2-27	9.9629	9.9580	- 49	9.9801	9.9756	- 45	- 47
3-26	9.9686	9.9697	+ 11	9.9713	9.9729	+ 16	+ 13½
4-25	9.9646	9.9670	+ 25	9.9840	9.9862	+ 23	+ 24
5-24	9.9530	9.9563	+ 33	9.9996	10.0014	+ 18	+ 25½
6-23	9.9601	9.9634	+ 33	9.9878	9.9893	+ 16	+ 24½
7-22	9.9692	9.9722	+ 30	9.9952	9.9961	+ 9	+ 19½
8-21	9.9665	9.9687	+ 22	9.9955	9.9975	+ 20	+ 21
9-20	9.9710	9.9720	+ 10	9.9993	10.0037	+ 44	+ 27
10-19	9.9832	9.9836	+ 4	10.0063	10.0112	+ 49	+ 26½
11-18	9.9764	9.9778	+ 14	9.9987	10.0014	+ 27	+ 20½
12-17	9.9799	9.9749	- 50	10.0128	10.0073	- 55	- 52½
13-16	9.9827	9.9740	- 87	10.0087	9.9990	- 97	- 92

TABLE XII

PLATE "V"

Space	SIDE "A" Distance Before Cutting Inches	SIDE "A" Distance After Cutting Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	SIDE "B" Distance After Cutting Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	10.0065	9.9940	- 125	10.0036	9.9908	- 128	- 126½
2-27	9.9801	9.9750	- 51	10.0042	10.0010	- 32	- 41½
3-26	9.9731	9.9728	- 3	9.9892	9.9929	+ 37	+ 17
4-25	9.9754	9.9768	+ 14	9.9871	9.9928	+ 57	+ 35½
5-24	9.9821	9.9855	+ 34	9.9820	9.9838	+ 18	+ 26
6-23	9.9792	9.9824	+ 32	9.9907	9.9924	+ 17	+ 24½
7-22	9.9775	9.9809	+ 34	9.9875	9.9888	+ 13	+ 23½
8-21	9.9732	9.9764	+ 32	9.9818	9.9830	+ 12	+ 22
9-20	9.9655	9.9682	+ 27	9.9876	9.9897	+ 21	+ 24
10-19	9.9625	9.9657	+ 32	9.9882	9.9910	+ 28	+ 30
11-18	9.9847	9.9868	+ 21	9.9885	9.9893	+ 8	+ 14½
12-17	9.9749	9.9693	- 56	9.9991	9.9946	- 45	- 50½
13-16	9.9882	9.9756	- 126	10.0159	10.0032	- 127	-126½

TABLE XIII

PLATE "W"

Space	SIDE "A" Distance Before Cutting Inches	SIDE "A" Distance After Cutting Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	SIDE "B" Distance After Cutting Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	10.0214	10.0230	+ 16	10.0120	10.0136	+ 16	+ 16
2-27	10.0038	10.0037	- 1	9.9958	9.9957	- 1	- 1
3-26	10.0050	10.0049	- 1	9.9921	9.9925	+ 4	+ 1½
4-25	10.0035	10.0034	- 1	9.9666	9.9668	+ 2	+ ½
5-24	10.0037	10.0041	+ 4	9.9935	9.9934	- 1	+ 1½
6-23	9.9969	9.9973	+ 4	9.9966	9.9960	- 6	- 1
7-22	9.9890	9.9895	+ 5	10.0134	10.0132	- 2	+ 1½
8-21	9.9838	9.9939	+ 1	9.9813	9.9813	+ 0	+ ½
9-20	9.9914	9.9919	+ 5	9.9677	9.9680	+ 3	+ 4
10-19	9.9875	9.9879	+ 4	9.9848	9.9852	+ 4	+ 4
11-18	9.9807	9.9804	- 3	9.9819	9.9819	+ 1	- 1
12-17	9.9844	9.9838	- 6	9.9841	9.9835	- 6	- 6
13-16	10.0018	10.0034	+ 10	9.9940	9.9948	+ 8	+ 9

TABLE XIV

PLATE "X"

Space	SIDE "A" Distance Before Cutting Inches	Distance After Cutting Inches	Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	Distance After Cutting Inches	Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	9.9752	9.9757	+ 5	10.0045	10.0052	+ 7	+ 6
2-27	9.9975	9.9967	- 8	10.0108	10.0108	+ 0	- 4
3-26	10.0104	10.0106	+ 2	10.0138	10.0138	+ 0	+ 1
4-25	9.9916	9.9923	+ 7	10.0127	10.0131	- 1	+ 3
5-24	9.9958	9.9969	+ 11	10.0131	10.0138	+ 7	+ 9
6-23	10.0130	10.0136	+ 6	10.0083	10.0093	+ 10	+ 8
7-22	10.0032	10.0031	- 1	10.0337	10.0346	- 9	- 5
8-21	10.0066	10.0071	+ 5	10.0095	10.0099	+ 4	+ 4½
9-20	10.0083	10.0087	+ 4	10.0197	10.0194	- 3	+ ½
10-19	10.0095	10.0097	+ 2	9.9914	9.9912	- 2	+ 0
11-18	10.0105	10.0106	+ 1	10.0240	10.0235	- 5	- 2
12-17	10.0314	10.0314	+ 0	10.0017	10.0013	- 4	- 2
13-16	10.0204	10.0218	+ 14	10.0162	10.0173	+ 11	+ 12½

TABLE XV.

PLATE "Y"

Space	SIDE "A" Distance Before Cutting Inches	SIDE "A" Distance After Cutting Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	SIDE "B" Distance After Cutting Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	10.0101	10.0092	- 9	10.0133	10.0122	- 11	- 10
2-27	10.0948	9.9955	+ 7	9.9984	9.9978	- 6	+ ½
3-26	9.9791	9.9809	+ 18	10.0014	10.0018	+ 4	+ 11
4-25	9.9954	9.9961	+ 7	10.0016	10.0020	+ 4	+ 5½
5-24	10.0071	10.0077	+ 6	10.0098	10.0112	+ 14	+ 10
6-23	10.0101	10.0106	+ 5	10.0156	10.0161	+ 5	+ 5
7-22	10.0079	10.0078	- 1	10.0178	10.0183	+ 5	+ 2
8-21	10.0165	10.0169	+ 4	10.0093	10.0097	+ 4	+ 4
9-20	10.0101	10.0101	+ 0	10.0101	10.0108	+ 7	+ 3½
10-19	10.0214	10.0230	+ 16	10.0214	10.0217	+ 3	+ 9½
11-18	10.0106	10.0111	+ 5	10.0230	10.0236	+ 6	+ 5½
12-17	10.0070	10.0071	+ 1	10.0157	10.0159	+ 2	+ 1½
13-16	10.0279	10.0268	- 11	10.0343	10.0337	- 6	- 8½

TABLE XVI

PLATE "U"

Space	SIDE "A" Distance Before Cutting Inches	SIDE "A" Distance After Cutting Inches	SIDE "A" Deformation In Ten Thousandths Inches	SIDE "B" Distance Before Cutting Inches	SIDE "B" Distance After Cutting Inches	SIDE "B" Deformation In Ten Thousandths Inches	Mean Deformation In Ten Thousandths Inches
1-28	9.9925	9.9916	- 9	9.9707	9.9702	- 5	- 7
2-27	9.9781	9.9784	+ 3	9.9683	9.9681	- 2	+ ½
3-26	9.9754	9.9761	+ 7	9.9512	9.9510	- 2	+ 2½
4-25	9.9911	9.9915	+ 4	9.9554	9.9553	- 1	+ 1½
5-24	9.9742	9.9741	- 1	9.9627	9.9627	+ 0	+ ½
6-23	10.0056	10.0059	+ 3	9.9429	9.9426	- 3	+ 0
7-22	10.0018	10.0023	+ 5	9.9537	9.9535	- 2	+ 1½
8-21	9.9870	9.9873	+ 3	9.9593	9.9595	+ 2	+ 2½
9-20	9.9961	9.9961	+ 0	9.9589	9.9592	+ 3	+ 1½
10-19	9.9963	9.9970	+ 7	9.9487	9.9491	+ 4	+ 5½
11-18	9.9956	9.9966	+ 10	9.9578	9.9580	+ 2	+ 6
12-17	9.9932	9.9928	- 4	9.9591	9.9586	- 5	- 4½
13-16	10.0207	10.0194	- 13	9.9793	9.9775	- 18	- 15½

TABLE XVII.

PLATE "S"

STRESS-STRAIN CHARACTERISTICS OF PLATE MATERIAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
0.5	7.0	19.00	--	--	--	--	--	--
1.0	7.11	18.53	.11	.47	.29	0.29	.000036	2,020
2.0	7.32	17.63	.21	.90	.55½	0.84½	.000106	4,040
3.0	7.78	17.00	.46	.63	.54½	1.39	.000174	6,065
4.0	8.34	16.43	.56	.57	.56½	1.95½	.000244	8,090
5.0	8.89	15.90	.55	.53	.54	2.49½	.000312	10,100
6.0	9.41	15.30	.52	.60	.56	3.05½	.000382	12,120
7.0	9.92	14.70	.51	.60	.55½	3.61	.000451	14,150
8.0	10.44	14.10	.52	.60	.56	4.17	.000521	16,180
9.0	10.96	13.50	.52	.60	.56	4.73	.000590	18,200
10.0	11.48	12.90	.52	.60	.56	5.29	.000660	20,200
10.5	11.71	12.59	.23	.31	.27	5.56	.000695	21,200
11.0	11.97	12.27	.26	.31	.28½	5.85	.000730	22,250
11.5	12.21	11.96	.24	.31	.27½	6.12½	.000765	23,250
12.0	12.48	11.62	.27	.34	.30½	6.43	.000803	24,250
12.5	12.73	11.31	.25	.31	.28	6.71	.000840	25,300
13.0	13.02	11.00	.29	.31	.30	7.01	.000877	26,300
13.5	13.31	10.70	.29	.30	.29½	7.30½	.000915	27,300
14.0	14.71	10.00	1.40	.70	1.05	8.35½	.001420	28,300
16.5	Yield Point							33,300
25.5	Fracture							51,500

TABLE XVIII

PLATE "X"

STRESS-STRAIN CHARACTERISTICS OF PLATE MATERIAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
0.5	18.00	7.00	--	--	--	--	--	--
1.0	17.72	7.25	.28	.25	.26½	0.26½	.000033	1,940
2.0	17.19	7.77	.53	.52	.52½	0.79	.000099	3,882
3.0	16.67	8.29	.52	.52	.52	1.31	.000164	5,825
4.0	16.14	8.82	.53	.53	.53	1.84	.000230	7,775
5.0	15.61	9.33	.53	.51	.52	2.36	.000295	9,700
6.0	15.08	9.87	.53	.54	.53½	2.89½	.000362	11,650
7.0	14.52	10.38	.56	.51	.53½	3.43	.000428	13,590
8.0	14.00	10.90	.52	.52	.52	3.95	.000494	15,510
9.0	13.47	11.40	.53	.50	.51½	4.46½	.000558	17,480
10.0	12.90	11.92	.57	.52	.54½	5.01	.000626	19,400
11.0	12.31	12.42	.59	.50	.54½	5.55½	.000695	21,380
12.0	11.42	13.15	.89	.73	.81	6.36½	.000796	23,300
16.0	Yield Point							31,050
26.2	Failure							50,900

TABLE XIX

PLATE "S"

STRESS-STRAIN CHARACTERISTICS OF WELD METAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
0.1	20.00	8.00	--	--	--	--	--	--
0.4	19.41	9.08	.59	1.08	.83½	.83½	.000210	8,150
0.6	18.78	9.69	.63	.61	.62	1.45½	.000364	12,210
0.8	18.10	10.34	.68	.65	.66½	2.12	.000530	16,300
1.0	17.30	11.12	.80	.78	.79	2.91	.000727	20,380
1.1	16.80	11.61	.50	.49	.49½	3.40½	.000852	22,400
1.2	16.12	12.32	.78	.71	.74½	4.15	.001038	24,400
1.3	14.74	13.78	1.38	1.46	1.42	5.57	.001392	26,450
1.415	Yield Point							28,800
1.435	Fracture							29,200

TABLE XX.

PLATE "T"

STRESS-STRAIN CHARACTERISTICS OF WELD METAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
.05	20.00	8.00	--	--	--	--	--	--
.10	19.76	7.91	.24	.09	.16½	.16½	.000080	2,026
.15	19.68	7.98	.08	.07	.07½	.24	.000120	3,040
.20	19.60	8.05	.08	.07	.07½	.31½	.000157	4,050
.30	19.46	8.19	.14	.14	.14	.45½	.000227	6,080
.40	19.29	8.31	.17	.12	.14½	.60	.000300	8,100
.50	19.12	8.43	.17	.12	.14½	.74½	.000372	10,125
.60	19.00	8.60	.12	.17	.15	.89½	.000447	12,160
.70	18.85	8.76	.15	.16	.15½	1.05	.000523	14,200
.80	18.72	8.90	.13	.14	.13½	1.18½	.000592	16,200
.90	18.59	9.07	.13	.17	.15	1.33½	.000667	18,250
1.00	18.43	9.20	.16	.13	.14½	1.48	.000740	20,260
1.10	18.29	9.33	.14	.13	.13½	1.61½	.000807	22,300
1.20	18.12	9.48	.17	.15	.16	1.77½	.000887	24,350
1.30	17.98	9.61	.14	.13	.13½	1.91	.000955	26,350
1.40	17.84	9.78	.14	.17	.15½	2.06½	.001033	28,400
1.50	17.73	9.97	.11	.19	.15	2.21½	.001107	30,400
1.60	17.68	10.21	.15	.24	.19½	2.41	.001205	32,420
1.70	17.67	10.59	.01	.38	.18½	2.59½	.001297	34,450
1.80	17.38	11.13	.29	.54	.41½	3.01	.001500	36,470
1.958	Yield Point							39,650
2.698	Fracture							54,550

TABLE XXI

PLATE "Z"

STRESS-STRAIN CHARACTERISTICS OF WELD METAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
.10	21.00	8.50	--	--	--	--	--	2,108
.15	21.04	8.77	.04	.27	.15½	.15½	.000039	3,162
.20	20.98	8.98	.06	.21	.13	.28½	.000071	4,220
.30	20.79	9.31	.19	.33	.26	.54½	.000136	6,330
.40	20.51	9.58	.28	.27	.27½	.82	.000205	8,440
.50	20.21	9.87	.30	.29	.29½	1.11½	.000279	10,530
.60	19.92	10.12	.29	.25	.27½	1.38½	.000346	12,650
.70	19.60	10.39	.32	.27	.29½	1.68	.000420	14,770
.80	19.30	10.66	.30	.27	.28½	1.96½	.000491	16,880
.90	18.98	10.93	.32	.27	.29½	2.26	.000565	18,980
1.00	18.66	11.20	.32	.29	.30½	2.56½	.000641	21,080
1.10	18.31	11.50	.35	.30	.32½	2.89	.000723	23,200
1.20	17.99	11.78	.32	.28	.30	3.19	.000797	25,300
1.25	17.80	11.97	.19	.19	.19	3.38	.000845	26,400
1.30	17.61	12.13	.19	.16	.17½	3.55½	.000888	27,400
1.35	17.42	12.31	.19	.18	.18½	3.74	.000935	28,500
1.40	17.21	12.50	.21	.19	.20	3.94	.000985	29,530
1.45	16.99	12.75	.22	.25	.23½	4.17½	.001045	30,600
1.50	16.72	13.00	.27	.25	.26	4.43½	.001108	31,650
1.55	16.47	13.30	.25	.30	.27½	4.71	.001179	32,680
1.60	16.15	13.61	.32	.31	--	5.02½	.001258	33,750
1.707	Yield Point							36,000
2.403	Fracture							50,700

TABLE XXII.

PLATE "V"

STRESS-STRAIN CHARACTERISTICS OF WELD METAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
.05	16.00	7.00	--	--	--	--	--	--
.2	15.79	7.70	.21	.70	.45½	.45½	.000114	4,080
.4	15.20	8.31	.59	.61	.60	1.05½	.000264	8,160
.6	14.60	8.88	.60	.57	.58½	1.64	.000410	12,240
.8	13.98	9.40	.62	.52	.57	2.21	.000553	16,320
.9	13.66	9.69	.32	.29	.30½	2.51½	.000630	18,380
1.0	13.36	9.97	.30	.26	.28	2.79½	.000699	20,400
1.1	13.03	10.26	.33	.29	.31	3.10½	.000776	22,450
1.2	12.74	10.53	.29	.27	.28	3.38½	.000847	24,500
1.3	12.43	10.81	.31	.28	.29½	3.68	.000920	26,530
1.4	12.13	11.10	.30	.29	.29½	3.97½	.000994	28,600
1.5	11.80	11.40	.33	.30	.31½	4.29	.001071	30,600
1.6	11.49	11.70	.31	.30	.30½	4.59½	.001149	32,650
1.7	11.19	12.00	.30	.30	.30	4.89½	.001223	34,700
1.8	10.85	12.35	.34	.35	.34½	5.24	.001310	36,750
1.9	10.50	12.70	.35	.35	.35	5.59	.001390	38,800
2.0	10.13	13.10	.37	.40	.38½	5.97½	.001493	40,800
2.1	9.73	13.56	.40	.46	.43	6.40½	.001602	42,850
2.2	9.20	14.20	.53	.64	.58½	6.99	.001747	44,900
2.3	8.35	15.20	.85	1.00	.92½	7.91½	.001980	46,950
2.6	Yield Point							53,050
2.840	Fracture							58,000

TABLE XXIII

PLATE "W"

STRESS-STRAIN CHARACTERISTICS OF WELD METAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
.1	18.00	7.00	--	--	--	--	--	--
.2	17.98	7.47	.02	.47	.22½	.22½	.000056	4,075
.4	17.57	8.13	.42	.66	.54	.76½	.00019	8,150
.6	16.99	8.76	.58	.63	.60½	1.37	.00034	12,210
.8	16.33	9.41	.66	.65	.65½	2.02½	.00050	16,300
.9	16.00	9.78	.33	.36	.34½	2.37	.00059	18,220
1.0	15.62	10.19	.38	.41	.39½	2.76½	.00069	20,380
1.1	15.21	10.64	.41	.45	.43	3.19½	.00080	22,400
1.2	14.73	11.20	.48	.56	.52	3.71½	.00093	24,400
1.3	14.11	11.90	.62	.70	.66	4.37½	.00109	26,450
1.54	Yield Point							31,350
2.62	Fracture							53,400

TABLE XXIV.

PLATE "X"

STRESS-STRAIN CHARACTERISTICS OF WELD METAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
.05	17.00	6.00	--	--	--	--	--	--
.1	17.06	6.46	.06	.46	.26	.26	.000065	2,114
.3	16.70	7.43	.36	.97	.61½	.87½	.000219	6,345
.5	16.08	8.08	.62	.65	.63½	1.51	.000378	10,570
.7	15.42	8.72	.66	.64	.65	2.16	.000540	14,800
.9	14.73	9.42	.69	.70	.69½	2.85½	.000714	19,000
1.0	14.37	9.80	.36	.38	.37	3.22½	.000806	21,140
1.1	13.97	10.22	.40	.42	.41	3.63½	.000909	23,250
1.2	13.50	10.71	.47	.49	.48	4.11½	.001030	25,400
1.3	13.00	11.29	.50	.58	.54	4.65½	.001162	27,480
1.48	Yield Point							31,300
2.64	Fracture							55,800

TABLE XXV

PLATE "Y"

STRESS-STRAIN CHARACTERISTICS OF WELD METAL

Load Kips	Ext. Front	Ext. Back	Diff. Front	Diff. Back	Mean Diff.	Mean Movement	Unit Strain	Unit Stress
.1	19.00	7.50	--	--	--	--	--	--
.4	18.72	8.83	.28	1.33	.80½	.80½	.000201	8,110
.6	18.18	9.42	.54	.59	.56½	1.37	.000342	12,180
.8	17.62	9.97	.56	.55	.55½	1.92½	.000481	16,220
1.0	17.04	10.51	.58	.54	.56	2.48½	.000622	20,270
1.2	16.46	11.08	.58	.57	.57½	3.06	.000765	24,370
1.4	15.89	11.62	.57	.54	.55½	3.61½	.000904	28,400
1.6	15.29	12.22	.60	.60	.60	4.21½	.001051	32,420
1.7	14.99	12.54	.30	.32	.31	4.52½	.001131	34,470
1.8	14.68	12.88	.31	.34	.32½	4.85	.001212	36,520
1.9	14.32	13.25	.36	.37	.36½	5.21½	.001304	38,560
2.0	13.98	13.67	.34	.42	.38	5.59½	.001398	40,520
2.1	13.56	14.12	.42	.45	.43½	6.03	.001506	42,600
2.2	13.00	14.74	.56	.62	.59	6.62	.001654	44,600
2.3	12.20	15.61	.80	.87	.83½	7.45½	.001865	46,650
2.65	Yield Point							53,800
3.212	Fracture							65,000