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N. G. Schreiner

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THE BEHAVIOR OF FILLET WELDS WHEN SUBJECTED TO BENDING STRESSES

by

Norman George Schreiner

Lehigh University

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This Thesis is respectfully submitted to the Graduate Board of Lehigh University in partial fulfillment of the requirements for the degree of Master of Science.

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Date ______________ Head of the Department of Civil Engineering

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SYNOPSIS

In practically all positions in which fillet welds are placed they are subjected to combined bending and shearing stresses. In an effort to understand their action under these conditions, the investigation described in the following report was carried out in the Fritz Engineering Laboratory of Lehigh University, during the school year of 1934-1935. The fillet welds investigated covered lengths from 1-1/2 to 10 in. of 3/8 and 1/2-in. fillet size. Two types of lightly-coated and two types of heavily-coated electrodes were included in the twenty-seven specimens tested. The loads were applied in such a manner that in approximately half the specimens the welds were under pure bending moment; while the other specimens, the duplicates of the first group, were loaded so that the welds were subjected to bending moment and vertical shear. In addition tests on specimens cut entirely from the fillet welds were made, from which the physical properties and specific gravity of this deposited metal was determined. The ultimate bending moments observed are plotted against section modulus and are compared with the calculated resisting moments of the welds. It is shown that

the ratio of the modulus of rupture of the welds to their ultimate strength, as determined by the standard end-fillet qualification specimen, averages 1.87 for lightly-coated electrodes and 1.61 for heavily-coated electrodes. The results of the second series, in which the welds were subjected to average vertical shears up to eighty per cent of their ultimate shearing strength, show very little decrease in bending resistance in comparison with similar specimens in which no vertical shear was present.

The chief conclusions that are drawn on the basis of these results are:

1. That the factor of safety, the ratio of the observed ultimate strength to the designed strength, of welds subjected to combined bending and shearing stresses in these tests is at least seven.

2. That the vertical shearing stresses in the weld are of small importance in comparison to the bending stresses. As long as the weld is adequate to resist the bending, it is adequate for vertical shears of the magnitude allowed by present specifications, and will still give a factor of safety of seven.

3. That the use of heavily-coated electrodes increases the bending resistance of the weld in approximately the same proportion as the tensile resistance is increased.

4. For the 3/8 and 1/2-in. fillet welds tested, the bending resistance increases directly as the increase in fillet size.

I. INTRODUCTION

1. Purpose: It is very seldom, one might almost say impossible, that fillet welds are subjected to load conditions wherein the internal forces are purely bending stresses or shearing stresses. Under usual load conditions the internal forces are a combination of both the bending and shearing stresses.

This investigation arose from the difficulties in determining the stresses in the welds used in the seat angle investigation of 1934[1*], in accordance with the observed data and the knowledge of weld behavior then available. This thesis will discuss the testing and theoretical considerations entering into the behavior of fillet welds in bending and shear. A discussion of its application to the welds connecting the seat angles to the column will be presented under a separate title.

2. Acknowledgment: The specimens were fabricated and the tests were made in the Fritz Engineering Laboratory at Lehigh University. Acknowledgment is made to various members of the Structural Steel Welding Committee of the American Welding Society for their continued interest, to the Bethlehem Steel Company for the furnishing of the material, and to Inge Lyse, Research Associate Professor of Engineering Materials for his continued cooperation and valuable advice during the progress of the investigation.

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* These numbers apply to references given at the end of this thesis.

II. COMMON THEORETICAL CONSIDERATIONS:

Fillet welds under the influence of loadings producing bending moments are generally designed by the use of the ordinary theory of flexure. Let the rectangle in Fig. 1a represent some longitudinal cross-section of a fillet weld. We will then consider the neutral axis, NA, coincident with the gravity axis. The load "P" is applied at an eccentricity "e" from the weld. The section is now subjected to a bending stress due to the moment Pe and to vertical shearing stress due to the load P. The correct value to use for "e" is not well established; it may be the dimension from "P" to: (a) the center of gravity of the weld cross-section, (b) the center of the leg of the fillet, or (c) the root of the weld. Whichever it may be is of small importance, unless the difference between the values is large in comparison to the total lever arm.

Applying the flexure formula, the bending stress σ_t may be evaluated:

$$\sigma_t = \frac{Pe}{\frac{bd^2}{6}} = \frac{6Pe}{bd^2} \qquad (1)$$

and the average shearing stress σ_s may be evaluated:

$$\sigma_s = \frac{P}{bd} \qquad (2)$$

If "b" is assumed of unit dimension, the values for the internal resisting forces will be given in pounds per linear inch.

The common method of analysis, simple in application and included here for these reasons although admittedly an approximation, is to combine the two forces vectorily and call the resultant, σ, the maximum stress per linear inch, or:

$$\sigma = \frac{P}{d}\sqrt{\frac{36e^2}{d^2} + 1} = \frac{P}{d}\frac{\sqrt{36e^2+d^2}}{d} \qquad (3)$$

From the theory of combined stress, the maximum principal stress σ is given by:

$$\sigma = \frac{\sigma_t}{2} + \sqrt{\sigma_s^2 + \frac{\sigma_t^2}{4}} = \frac{P}{d}\left(\frac{3e}{d} + \frac{\sqrt{9e^2+d^2}}{d} \right) \qquad (4)$$

It will be noted that by either method the load P depends upon the allowable unit weld stress σ, the length of the weld and the eccentricity of the load. Present design practice uses a value of σ equal to the allowable stress given by the welding codes, and then assumes a factor of safety of at least four based upon the ultimate strength of the weld.

The above formula assumes that the bending stress in a fiber varies directly as its distance from the neutral axis, commonly known as a triangular distribution of stress, Fig. 1b line aob. This is true below the yield point of the material, but as the yield-point stress on the extreme fibres is reached, they stretch without any further application of load and the stress distribution diagram takes the form of cod. Not so the strain distribution which is planar throughout the full loading range because of the necessity of the parts fitting together.

The fibres nearer the neutral axis progressively reach the yield-point stress and the limiting shape of the distribution curve is ceofd. At this stage the expression for the resisting moment is:

$$MR_{yp} = \sigma_{yp}\frac{d^2}{4} \qquad (5)$$

which is fifty per cent greater than the resisting moment at the yield point before plastic yielding took place.

When plastic yielding ceases due to strain hardening of the material, the resisting power increases. The shape of the stress distribution curve is not exactly known but must be somewhat similar to that indicated in Fig. 1c while the strain distribution is still a straight line. Thus we still have essentially a rectangular distribution of stress and the ultimate resisting moment may be expressed by:

$$MR_{ult} = \sigma_{ult}\,\frac{d^2}{4} \qquad (6)$$

In mechanics of materials the modulus of rupture is a fictitious measure of the ultimate unit stress on the extreme fiber at the point of maximum moment. This value σ_m, as given by the flexure formula based on triangular distribution of stress is:

$$\sigma_m = \frac{6M_{max}}{d^2} \qquad (7)$$

hence is one and one-half times σ_{ult} given by equation (6) which is based on the rectangular stress distribution.

III. TEST PROGRAM

1. Object - With these fundamentals in mind the test program was laid out to ascertain:

(a) The factor of safety of welds in bending using present methods of design.

(b) The validity of the present design methods.

(c) The stress distribution in the welds.

(d) The physical properties of the weld metal and their effect on weld behavior.

2. Specimens - The specimens may be divided into three groups:

(a) Fillet welds under pure external bending moment, hence under zero vertical shear. These are designated as Series A (Fig.2) in which group sixteen specimens were tested. They were made up of two main plates and two splice plates ranging in depth from 1.5 to 10 in., the welds being placed along the full depth of the splice plates. The plates were designed so that the unit stresses would be below the yield point when weld failure occurred. Except for slight local yielding this requirement was maintained throughout the investigation.

(b) Fillet welds under transverse bending. These specimens are designated as Series B (Fig.2) and were nine in number. They were companion specimens to Series A, similar in material, size and fabrication.

This group also contained two specimens designated C 62 and C 124 as shown in Fig. 3. The wing plates in each specimen were so small in cross-sectional area that failure in the welds was impossible before the plates yielded to such an extent as to be worthless, as agencies for the transferal of the applied load.

(c) The physical tests were carried out on tensile bars entirely of fillet weld metal machined in accordance with Fig. 4. The physical constants determined for each specimen consisted of Johnson's apparent elastic limit (the point on the stress diagram at which the rate of deformation is fifty per cent greater than it is at the origin), yield strength (stress at which the material exhibits a 0.2 per cent elongation), ultimate strength, elongation in two inches, per cent reduction in area, modulus of elasticity and specific gravity.

(d) The welds were electric arc welds using both lightly-coated and heavily-coated electrodes. Two types of each electrode were used which are designated as follows:

Designation	Type	Trade Namd	Diameter Used
A	lightly-coated	Page B	5/32 and 3/16"
B	lightly-coated	Stable Arc	5/32
C	heavily-coated	Fleetweld	3/16
D	heavily-coated	Murex Cresta	3/16

All welding was done in the laboratory shop under direct supervision. The strength of the fillet welds of the lightly-coated electrodes was determined by means of the standard 3/8-in. end-fillet welded qualification specimen (Code for Fusion Welding and Gas Cutting in Building Construction - Code 1 Part A - 1934, American Welding Society, Appendix II). The average ultimate strength for Electrode A was 13,800 lb per lin in; for Electrode B was 15,350 lb per lin in. The D.C. arc characteristics were: voltage 15-18, amperes 160-200.

The strength of the welds made with the heavily-coated electrode was determined by means of a modified end-fillet welded specimen shown in Fig. 5. The average ultimate strength for both types of electrode was 18,900 lb per lin in. D.C. arc characteristics were: voltage 24-30, amperes 200-220.

In multilayer welding the previous layers were carefully cleaned of scale and slag by means of a chisel and stiff wire brush before adding the next layer. The slag due to the heavily-coated electrodes was allowed to thoroughly freeze and cool slightly before being removed, but in all cases the succeeding passes were laid while the preceding pass was still quite hot.

The welds were carefully gaged and without exception were within the designed limits of minus 0 plus 1/8-in. and quite uniform results were obtained.

3. Test Methods - The specimens of Series A and B were tested in the 300,000-lb. capacity Olsen or 800,000-lb. capacity Riehle screw-power testing machines in the Fritz Engineering Laboratory. The specimens of Series C were tested in a 50,000-lb. capacity Riehle and 20,000-lb. capacity Olsen screw-power testing machines. The screws of the 300,000 and 800,000-lb. machines were motor driven, moving the head of the machine at a speed of 0.05 in per min. The smaller machines were driven by hand-power, moving the head a smaller and somewhat indeterminate amount, although every effort was made to keep the speed constant.

The load was applied to specimens of Series A and B shown in Fig. 6 & 7, through a spherical bearing block and a loading beam to the specimen. Rollers were used so that there would be a minimum of lateral or longitudinal restraint due to the loading apparatus and especial care was taken so that the loads were accurately placed. The specimen was protected from crushing and the load distributed by blocks between the rollers and the specimen.

Observations on the specimens of Series A consisted of the determination of the position of the neutral axis by means of 10-in. Whittemore strain gage observations, an attempt at determining the stresses in the plates by the use of Huggenberger tensometers, determination of strains in the tension ends of the welds by the use of Huggenberger tensometers over a 1/2-in. gage length and determinations of the center deflections of the whole specimen by the wire-mirror-scale method. The observations on Series B specimens were confined to the measurement of center deflections because the method of loading did not allow sufficient clearance for the placing of instruments.

All specimens of Series A & B, C 62 & C 124, were coated before the test with a thin layer of hydrated lime and water which assisted materially in the determination of points of yield.

The determination of the strains for the stress-strain curve of the Series C specimens was made with the Huggenberger tensometers over a one-inch gage length and each value is the average of diametrically opposite tensometer readings.

The specific gravity of the electrode and of the tensile specimens cut from the weld was determined from their weight and volume. The electrodes were cleaned of all coating and polished to a smooth surface; the tensile specimens were thoroughly degreased by the use of various solvents. The weight was determined to the ten-thousandth of a gram on a Chainomatic balance and then rounded off. The volume was determined by the displacement of alcohol in a standardized burrette to a hundredth of a cubic centimeter. Alcohol was used instead of water because it wet the specimen more easily and there was less likelihood of including air bubbles in the volume determination. The specific gravities are thus accurate to the first decimal place or within plus or minus five per cent. The weights varied from 7.70 to 187.24 grams and the volumes from 0.99 to 24.66 cu cm.

In all tests sufficiently small increments of load were taken to assure a minimum of six observations below the proportional limit and as many points thereafter as the condition of the specimen or the range of the instruments would allow.

IV. TEST DATA

1. Series A - The test results of this series are presented in Table I, Columns 3 to 5.

Column 3 was determined from observation of the scaling of the whitewash on the surface of the weld. Without exception this occurred on the compression side first, near the end of the weld. The reason for this is not readily apparent since the loading blocks were at a sufficient distance from the weld to prevent local stress disturbance and it is generally considered that the compression yield point is at least equal to that in tension.

Column 4 was determined from observation of the points on the moment-weld strain curve designated τ or moment-center deflection curve designated Δ, at which the inclination of the tangent to the curve at that point was fifty per cent greater than the initial inclination.

Sometimes the specimen gave warning of impending failure by a drop of the beam of the testing machine at about 95 per cent of the ultimate load, but generally there was no definite yield of the weld metal without further addition of load. The ultimate applied moment in given in column 5.

Columns 6 and 7 give respectively the calculated modulus of rupture and the ultimate stress based on full rectangular distribution.

1 (b) - It was with A 33 that the investigation had its inception. The original specimen was made up as a standare 3/8-in. end-fillet welded qualification specimen and loaded to give pure bending across the welds as indicated in Fig. 2.

Measurements over a 10-in. gage length which included the main plates, welds and splice plates, were taken with a Whittemore gage. The average strain so measured was sixteen per cent in excess of that calculated by the flexure formula.

Measurements were taken of the tensile and compressive strains in the main plates by means of tensometers placed as close to the weld as was conveniently possible. These measurements established the fact that the neutral axis was coincident with the gravity axis in the parent metal very close to the weld, from which it is safe to conclude that the neutral axis of the weld is also its gravity axis. From these measurements an indication of the high skin-stress near the welds was noted. The measured strains on the main bar were approximately seven per cent in excess of those calculated, while those on the splice plates were twenty-one per cent less than the calculated.

The stress in the main bars soon reached the yield-point and great increases in vertical deflection occurred at a bending moment of only 24,600 in-lb. Increasing the load resulted in such greatly increased deflections that the test had to be abandoned at a bending moment of 30,600 in-lb. On the basis of the common theory this corresponds to a weld stress of 20,400 lb per lin in. At this point all welds showed slight cracks at the root, and some scaling of the whitewash on the surface.

The specimen designated A 33-2 was then made up using 3 by 1-1/4 in. main bars and 3 by 5/8-in. splice bars. Readings over the ten-inch gage length again gave average strains in excess of the calculated but again proved the location of the neutral axis as coincident with the gravity axis. Tensometers in the same location as in the above test showed similar results, the strains in the main plates being almost coincident with those calculated, while those on the splice plates were now 33 per cent less than those calculated.

In this specimen too the splice plates yielded at about seventy per cent of the ultimate load but they soon hardened sufficiently that the load could be increased to failure of the welds without excessive yielding of the plates.

A third specimen A 33-3 was then tested in which the splice plates were 3/4 in. thick and no distress was evident in any of the plates at the ultimate load. Accordingly the remaining specimens were designed with the maximum bending stresses in the main plates limited to 30,000 lb per sq in. The area of the splice plates was then made approximately twenty per cent greater than that of the main plates. With this design little difficulty was experienced due to yielding of the parent metal.

Tensometer readings on the plates and with the Whittemore gage were again taken on this specimen and it was felt that the following was established.

(a) The coincidence of the neutral axis of the weld and its gravity axis.

(b) The existence of skin stresses of unknown magnitude in the parent metal adjacent to the weld. This finding was corroborated in all succeeding tests but no means were taken to determine their magnitude.

Fig. 8 and 9 show groups of specimens of 3/8-in. and 1/2-in. fillet welds made with the lightly-coated electrode. In each photograph the specimens are designated top to bottom A 13, A 33 and A 63; A 14, A 34 and A 64 respectively. A typical performance of all specimens welded with a lightly-coated electrode may be described as follows. The loads were slowly applied and readings of the instruments taken until the deflections were beyond their range or failure seemed imminent. Cracking of the mill scale on the inside of the splice plates was observed at loads of less than fifty per cent of the ultimate, revealing a high skin stress in this part of the plates. Scaling of the whitewash was first noted on the surface of the weld under compressive stress at about 86 per cent (Table I, col. 11) of the ultimate load in the case of the specimens 1.5 and 3 in. deep. This occurred practically simultaneously over the full length of the welds. With only slightly greater deflection the welds fractured suddenly.

In the specimens 6 and 10 in. deep scaling on the compressive surface at the weld occurred at approximately 72 per cent of the ultimate load close to the end of the weld and as the loading continued the scaling proceeded towards the neutral axis. No great deflection was possible in these specimens either and they too failed suddenly. Where the fusion between the weld and parent metal was perfect, fracture occurred through the throat of the weld; where fusion was imperfect the fracture was along the line which was imperfectly fused.

The photographs of A 13, A 14, A 33 and A 34 illustrate very well the type of throat fracture on the right of the specimen, and the scaling of the whitewash on the left hand welds. Those of A 63 and A 64 illustrate the progressive scaling on the weld surface on the left and the failure due to lack of fusion in the weld on the right. These specimens were subsequently retested to a considerably higher value directly in line with the remaining specimens.

Fig. 10 shows the results obtained on a group of heavily-coated electrode welds. The specimens from top to bottom are A 13D, A 33C and A 64D. The scaling of the whitewash on the weld surface occurred at about sixty per cent of the ultimate load near the compressive end of the weld, and generally along the toe at the main plates. This scaling proceeded progressively toward the neutral axis. Considerable deflection was recorded before the ultimate load was reached (in Specimen A 13D a center deflection of 1-1/2 in. in an 18 in. span) and the fracture was very gradual, the weld metal exhibiting great tenacity. The fracture proceeded from the root of the weld at a flat angle to the main plate. The metal was finely-grained, almost free from inclusions and blowholes and the fractured surface was silky in texture.

The photograph shows the scaling along the toe of the weld on the left and the typical fractures on the right. All three specimens are still held together by small filaments of metal near the neutral axis.

Fig. 11, 12 and 13 are examples of the ductility of these welds. These are the tension ends of the welds on Specimens A 13D, A 33C and A 64D respectively. The machine tool marks were originally straight lines directly across the specimen. Fig. 11 shows much distortion of the weld and only slight cracks at the root of the weld. Fig. 12 and 13 show considerable distortion and exhibit the flat angle with the main plate at which fracture occurred.

The tensometer readings across the weld were plotted as applied bending moment against strain in the weld. Because of the great amount of data taken only a typical curve is presented in Fig. 14. The curve is of the same type as the stress-strain diagram for the weld metal. The point at which the inclination of the tangent becomes fifty per cent greater than the initial inclination is designated as the yield point. The moment corresponding to this point is given in column 4 of Table I and in column 5 of Table III. These values are identified by the τ which follows. The moments average about fifty per cent of the ultimate moment. The stress at this point determined by the measured strain and the stress-strain diagram of the weld metal corresponds very well with the Johnson limit of the weld metal. The average strain, calculated by the ordinary method discussed in section II, is also plotted and is always from 64 to 69 per cent greater than the measured strain. The ratios of calculated strain to measured strain is given in column 8 of Table I. The line determining the calculated strain intersects the plotted measured strain at points corresponding to the unit stresses given in column 9 of Table I. The applied bending moments corresponding to these points is given in column 10. It will be noted that these stresses of column 9 correspond closely to the yield strengths of the weld metal and the corresponding moments of column 10 to the moments at which scaling was first observed on the surface of the weld, column 3,

In Series B, tensometer readings of this nature were only taken on Specimens B 13 and B 33 where the average shearing stress on the weld was small. The same type of curve was obtained and the results corresponded closely to the external observations noted above.

2. <u>Series B</u> - The test results of this series are divided into Tables II and III. Table II presents the results from Specimens C 62 and C 124. It will be noted that the wing plates are separated from the center plate by a gap of approximately 3/64-in. (line 2, Table II and Fig.3). As the load was applied the gap closure was measured with a micrometer, the contact of which was determined by closure of an electrical circuit. The gap closure was found to be proportional to the applied load. It was determined that the weld rotated about the center of its length as long as the gap was open. Upon closure of the gap at one end, rotation took place about that end, and practically the full length of the weld came into use in resisting the applied bending moment, with subsequent great increase in strength.

Early in the tests the wing plates started to scale due to high compressive and shearing stresses in the region of the loading blocks. This yielding became general along before distress was evident in the welds. At the final load the welds were fractured a maximum of 3/8 in. at the ends subjected to tension while only scaling of the whitewash was observed to a depth of about one inch at the compression ends.

Lines 4 to 8 inclusive of Table II present the observed loads while lines 9 to 12 note the stresses in the members and the welds. Line 9 is calculated as the final load divided by the net shearing area of the wing plates; line 10 as the final load divided by the net bearing area under the loading blocks. Lines 11 and 12 use the values of lines 6 and 8 respectively and are calculated by the approximate Vector method. Fig. 15 exhibits very well the yielding due to the combined compression and shear of specimen C 124 at a total load of 240,000 lb.

These specimens indicated the high strengths of welds in combined bending and shear. It became evident that complete fracture of the weld with this design and method of loading was improbable; accordingly the tests were discontinued.

Table III presents the results of the tests on Series B specimens. The first three columns present statistical data. Columns 4, 5, and 6 give the observed bending moments at scaling of the whitewash, yield point from observation of the curves and at the ultimate load. The lever arm used is to the center of the parallel leg of the fillet weld. The use of the distance to the center of gravity of the weld would increase the ultimate bending moment a maximum of five per cent and an average of two per cent with the type of loading used. Column 7 gives the average shear per linear inch based on the total load divided by the total length of weld.

In column 8 the ratio of the resisting moment of column 6 to that of the specimen of similar depth in Series A (Table I column 5) is calculated.

3. Series C - The physical properties of the various welding electrodes and deposited weld metal are presented in Tables IV, V, and VI. The chemical composition of the welding electrodes, the deposited metal and the electrode coatings are given in Table VII.

Typical stress-strain diagrams of the original electrode and of the deposited metal appear in Fig. 16 and 17. The diagram Fig. 17 for the electrode is typical of that of an alloy steel, a definite straight line to a high unit stress followed by a gradual increase in strain in proportion to the stress up to the ultimate. The Johnson limit is high in proportion to the ultimate (75%) and the yield strength 92 per cent of the ultimate. The elongation in two inches is of medium degree, the reduction in area, modulus of elasticity and specific gravity normal in value. The fracture is of the full cup and cone type, showing a finely-grained structure.

The stress-strain diagram for the deposited weld metal Fig. 16 and 17, made with the lightly-coated electrode is a straight line to a limit of proportionality, followed by a gradual increase to the ultimate strength, when fracture occurs suddenly with very slight necking. The Johnson limit is approximately fifty per cent of the ultimate strength and the yield strength seventy-three per cent of the ultimate strength. The elongation and reduction in area is very small. The modulus of elasticity has been decreased in the case of the single pass weld to 84 per cent of the original while at the same time the specific gravity is only 96 per cent of the original electrode. When the weld is made in two passes the modulus of elasticity is only reduced to 90 per cent of the original metal while the specific gravity drops to 97.5 per cent of the original.

When the weld is deposited in a multiple number of passes, in this case five, so that a 1/2-in. tensile bar can be cut therefrom, the modulus of elasticity reaches 92 per cent of the original metal and the specific gravity 95.8 per cent.

The average ultimate strength of the tensile tests is 54,500 lb per sq in comparing with 52,000 lb per sq in on the throat area of the qualification specimens. The average elongation in two inches, approximately six per cent, is somewhat less than is generally shown on the free bend test specimens.

The stress-strain diagram Fig. 17, for weld metal deposited from the heavily-coated electrodes is similar in nature to that of mild steel. It consisted of a straight line, followed by a period at which the elongation increased without further addition of load, causing a distinct drop of the beam of the testing machine, followed by a steady climb to the ultimate after which considerable necking occurred before fracture. In no case was an upper yield point observed, possibly because of the slow application of the load. The Johnson limit is at 52 per cent of the ultimate and the yield strength at 65 per cent of the ultimate. The ductility as indicated by the reduction in area and the elongation in two inches increased markedly over that shown by the original electrode. The modulus of elasticity and specific gravity show the same values as in the original material. No variation in physical properties was observed beyond ordinary limits with respect to the number of passes by which the weld was deposited.

The average ultimate strength (64,000 lb per sq in) shown by these specimens compares with 70,800 lb per sq in obtained on the throat section of the qualification specimens. Reasons for this discrepancy are not definitely known. The percentage elongation in two inches compared rather favorably with the results obtained in the free bend test although the variability of repeated results may be criticised. This variability can be condoned when consideration is given to the many variables involved in depositing weld metal.

Fig. 18 shows the condition of the 3/16-in. tensile bars cut from a weld made with a lightly-coated electrode (Electrode A). Although the worst side was photographed, the porosity is quite marked. The highest stress naturally occurred at the most porous section and the fracture occurred at that point as indicated in the broken specimens. Specimens 1, 2 and 3 correspond to those of like number in Table IV while the cross-sections indicated 4, 5 and 6 are those deposited with a 5/32-in. diameter electrode and so labeled in Table IV. The porous patches are indicated on the cross-sections by letters and the extent of them is shown by their darker color. Inadvertently the solvent used in cleaning the specimens of grease preparatory to making specific gravity determinations formed a sort of a dye with the grease which was carried into the interior through the blowholes on the exterior, staining the exterior and parts of the interior and accounting for the darker color of the photographs of the fractured specimens. Specimen 6 which is generally out of focus was quite porous over the whole cross-section without giving any indication on the surface.

Fig. 19 exhibits similar action of the 5/16-in. diameter specimens. However the blowholes are not so apparent, and this is borne out by the higher specific gravity and modulus of elasticity.

Two 1/2-in. diameter specimens cut from the multipass weld were notable in the lack of blowholes appearing on the surface within the gage length. The specific gravity actually proved them to be more dense, but under load they revealed stress concentrations at blowholes very near the surface and the fracture shows a very coarse grain structure, inclusions and porosity.

An effort was made to determine the location at which the fillet structure was most porous and there are indications that this occurs most frequently on the vertical leg near the root of the weld and in the surface layer. However observations on test specimens most often indicated lack of fusion or porous structure along the horizontal leg near the root. The only fact definitely established is that lack of penetration and porosity is in the area about the root of the weld and porosity in the surface layer of weld metal.

In general the fracture of these specimens may be designated as of the flat cone type with a coarse crystalline texture as in Fig. 20a, No. 2 and 4 and Fig. 20b, No. 1 and 2, or of the sheared flat cone type with partly crystalline and partly silky texture as in the remainder of the illustrations. The fractured surface always exhibited the porous structure and some small inclusions even to the naked eye.

Fig. 21 illustrates the cross-sections of the fractures obtained on the specimens from welds of heavily-coated electrodes. The tensile bars themselves were quite satisfactory in appearance, clean looking, solid and finely grained. The fracture was generally full cup and cone, with a fine-grained structure and silky texture as illustrated in D 2, D 4 and D 5, and C 1, C 3 and C 4. Occasionally the failure was of the sheared cone type as in D 1, D 3 and C 2 exhibiting a silky texture and slight inclusions. Very probably these inclusions account for the type of fracture rather than the usual reason of eccentric loading conditions.

Specimens D 6 and D 7 show lens-shaped inclusions and blowholes due to a poor method of depositing the filler metal. This may be described as follows: with a welding current of 230 amperes and 30 volts using the D electrode, a 5/8-in. fillet was built up in five passes. The first pass was deposited at the root with the plates horizontal. The plates were then tilted at an angle of 45 degrees so that the filler metal was deposited in a horizontal trough. Since the pool of metal was considerable, the arc was directed steadily at the center of the trough and carried along the length of the welds for the next two passes. The fourth and fifth passes were then laid on either side of the center with a straight forward motion. The reason for the poor showing in the physicals is given in the method of depositing the second and third passes. The metal on the edges froze before full penetration was established, causing not only a plane of weakness but also blowholes and inclusions by preventing the escape of gases and the flotation of the slag. Except for this experiment the welding methods followed the general practice of depositing straight-through beads side by side and layer by layer until the desired cross section was obtained or by depositing a straight-through bead at the root followed by the succeeding beads, each layer of which was woven from side to side with a semi-circular motion, the convex side of which was in the direction of the advancing electrode. The importance of proper procedure in depositing the filler metal cannot be better emphasized than by the results of these tests. It is to be noted however that very slight effect was shown in the physical results due to this improper manipulation except in those related to ductility as indicated by the percentage of elongation and the reduction in area.

V. DISCUSSION OF RESULTS

1. <u>Series A and B</u>.

(a) Effect of Size of Weld. As each depth of specimen was duplicated with 3/8 and 1/2-in. welds the effect of increase in fillet size may be studied under identical conditions. Theoretically a 1/2-in. fillet is 33 per cent stronger than a 3/8-in. fillet and the average results show that this is true in the specimens of Series A under pure bending and in those few cases of Series B where comparison is possible. Where the weld is under transverse bending, the average shear load per inch should be equal to allow for a true comparion. From the results we may safely conclude that the bending resistance increases directly with the increase in fillet size.

(b) Effect of Electrode Coating. The ratio of the tensile qualification test values of the heavily-coated electrodes C and D to the lightly-coated electrode A is 1.37.

The ratio of the tensile qualification test values of Electrode A to Electrode B is 0.90. Since the majority of the specimens made with lightly-coated electrodes used Electrode A, the results from those specimens on which Electrode B was used will be reduced by ten per cent in order to place all results from the lightly-coated electrode welds on a comparable basis. In comparing the heavily-coated with the lightly-coated specimens a considerable diversity of ratios is apparent from which it seems that although the heavily-coated welds are stronger they do not give quite the increase in strength that the qualification specimens indicate. Again in the few specimens that can be compared in Series B the results at equal average shearing loads per inch must be used and these do show an increase in favor of the heavily-coated electrode, but slightly less than the tensile qualification test results indicate. While here the ratio of the qualification test results is taken as the criterion, the ratio of the calculated ultimate stress as given in column 7 of Table I may be used. This ratio is only 1.19 since the calculated ultimate strength as determined by bending is 25 per cent greater than that given by the qualification test results in the case of the lightly-coated electrode and only 7 per cent greater in the case of the heavily-coated electrode. Including these facts in the calculation it can be shown that the heavily-coated electrode increases the strength in bending in the same proportion as is shown by the tensile qualification test results.

(c) Fig. 22 shows the ultimate bending moments plotted against the section modulus of the specimens of Series A. Those specimens made with Electrode B have been reduced to allow for comparison. The points for 3/8-in. fillet welds fall on a straight line, while the specimens with the half inch fillet fall on another line 33 per cent above the 3/8-in. fillet specimens. The specimens made with the heavily-coated electrode of 3/8-in. fillet size fall midway between the above lines. It will be noted that the results for lightly-coated 3/8-in. welds lie considerably above the calculated curves even allowing for full rectangular distribution. The 1/2-in. curve is similarly too steep by about 25 per cent. On the other hand the curve of the heavily-coated electrode is very nearly coincident with the calculated assuming rectangular distribution. This is typical of the action of comparatively brittle and very ductile materials and the phenomena is explained in texts on the resistance of materials.[2]

In Fig. 23 the ultimate moment is again plotted against the section modulus. The figures beside each plotted point are the average shear per inch of weld at the ultimate load. The calculated curve is that for a 3/8-in. weld, assuming rectangular distribution. It will be noted that even though the average shear in the weld was as high as 82 per cent of the tensile qualification weld strength, the resultant bending strength did not fall below that of rectangular distribution, excluding shear, based on the tensile qualification strength. This is because of the large ratio between the modulus of rupture and the ultimate strength. In the case of the heavily-coated electrodes giving more ductile welds, the ratio is not so large and the points fall below the calculated rectangular distribution stress, especially where the average shearing load is high.

(d) Returning to Series A, and Fig. 14. Photoelastic investigation[3] of stress distribution in the weld show that the direction of one of the principal stresses is almost at right angles to the throat section. Hence the tensometers, since they were placed parallel to the hypotenuse, should measure the magnitude of this stress. The same investigation showed that the stress across the throat was almost constant for about half the distance from the edge to the root and then increased rapidly to a magnitude of about 2-1/2 to 3 times as much as that at the edge. The tensometers evidently measured approximately the strain across the throat section. The tensometers were placed about 80 per cent of the distance from the root of the weld and the average ratio between computed and measured strains was 1.63. If we now assume a parabolic distribution of stress along the throat section so that there is a balance between the average rectangular area and that bounded by the parabola which has its axis slightly beyond the boundary of the section, the maximum stress at the root will be about twice (1.96) the average calculated stress. This corresponds to a ratio of about 2.44 times the average stress as shown in the photoelastic investigation. The fact that the strain at the so-called yield point of the weld corresponds to the Johnson limit of the weld metal tends to show that the stress-strain curves of the weld-metal taken either from a tension specimen (Series C) or from the weld in place are similar. The strain in the weld increases until the yield strength is reached at which point there is a general correspondence between the yield strength, the scaling of the whitewash on the surface of the weld and the calculated strain. By this time the stress condition across the weld section must be almost uniform for the stress now increases very slowly compared to the strain increments.

While the data are not complete the following facts seem to be indicated:

(1) That the stress at the root of the weld is about three times that at the other end of the throat section and that this stress is also about twice the average stress on the weld.

(2) That the weld stress is proportional to the applied moment up to the Johnson limit of the weld metal.

(3) That scaling of the whitewash on the surface of the weld occurs when the yield strength of the weld metal is reached and at this point the stress distribution over the weld cross-section is practically uniform.

(4) That the ordinary design formulas will give the average stress condition in the weld for stresses up to the yield strength of the weld metal.

(e) It was pointed out that the specimens made with lightly-coated electrodes always fractured near the throat section while those welded with heavily-coated electrodes had the plane of failure at a very flat angle to the main plate. These same types of failure are common in the end fillet weld qualification tests where the welds are under tension. The photoelastic analysis shows, and it is somewhat generally conceded, that the stress along the splice plate leg of the weld is almost pure tension, that that across the throat section or very near to it is also in tension, while that along the main plate leg is at a maximum in shear. This shear plane is 1.41 times as great in area as that of the throat section. Since the ultimate shearing stress is generally eighty per cent of the tensile ultimate, it is easily seen that failure should occur along the throat plane. For the lightly-coated electrode this shearing ultimate stress would be about 42,000 lb per sq in. Furthermore should the ratio of the shearing ultimate to the tension ultimate decrease in the case of the heavily-coated electrodes, and should this ratio then be less than seventy per cent, failure would be due to shear and would be along the plane of the main plate or at a flat angle thereto.

The tensile tests give an average ultimate for Electrode D of 61,600 lb per sq in and including Electrode C the grand average is 63,830 lb per sq in. The shearing ultimate should therefore be about 49,300 to 51,200 lb per sq in. The qualification specimens showed an average ultimate on the throat section of the weld of 70,800 lb per sq in although the line of fracture was at a flat angle to the main plate. Since the ratio of the shearing ultimate as determined above th the ultimate as given by the qualification specimens is 0.69 to 0.71 it is possible that this explanation accounts for the failure of heavily-coated electrode welds. The ratio of 0.7 between the ultimate strengths in shear and in tension was reported by Professor H. Dustin[6]. Whether it accounts for it or not, the fact remains that welds with heavily-coated electrodes always exhibit this type of fracture as distinctive from those exhibited by a lightly-coated electrode weld.

(f) Let us now consider the method used in calculating stresses in the welds in Series B. If we consider formula (3) and consider only the stress set up by bending stress σ will then be proportional to $\frac{P}{d}$ and a factor $\frac{6e}{d} = K_1$. The value of K_1 will then vary linearly with the ratio of $\frac{e}{d}$. This is plotted on Fig. 24.

Considering the effect of shear the factor K_2 becomes $\frac{\sqrt{36e^2 + d^2}}{d}$ and the relation between this factor and $\frac{e}{d}$ is also plotted and labeled. Vector Method.

As stated previously this method is questionable. It will be noted that at low values of $\frac{e}{d}$ there is a considerable increase in the value of K_2 over K_1 and that the curve approaches the curve of pure bending asymtotically.

If the principal stress is determined by the general formula (4), K_3 is represented by:

$$K_3 = \frac{3e}{d} + \frac{\sqrt{9e^2 + d^2}}{d}$$

and the relation between K_3 and $\frac{e}{d}$ may be plotted. This departs still further from the curve of pure bending but again approaches it asymtotically. Above $\frac{e}{d} = 1.0$ the curves as determined by the Vector and Principal Stress Methods become almost coincident.

If, instead of considering the triangular distribution, we plot curves on the basis of rectangular distribution of stress, there results Fig. 25. K_4 for pure bending then = $\frac{4e}{d}$ while $K = \frac{2e}{d} + \frac{\sqrt{4e^2 + d^2}}{d}$ using the Principal Stress Method. On this figure too are plotted the $\frac{e}{d}$ ratios applicable to the specimens in this investigation and the ratio of the strength which they developed in shear and bending to that developed in pure bending. Comparison is then made with the ratio of the calculated strengths. It will be noted that the observed points fall very close to the curve determined by the Principal Stress Method.

The point for B 33D falls far to one side of this curve, which is probably due to the fact that the loading blocks on A 33C tilted, decreasing the lever arm and hence increasing the observed load at failure. Since the nominal lever arm was used in calculating the ultimate bending moment, this would give an abnormally high bending moment. This would account for the low ratio of B 33D to A 33C which is the basis for the plotting of the points on Fig. 25.

The point for B 63C is slightly high probably due to poor metal along the toe of the welds, which evidently lacked complete fusion with the base metal.

The loading blocks used with B 13C tilted a measurable amount thus shortening the lever arm. Calculations were based on the assumption that one of the lever arms was shortened 7/8 in. and the other 1/2 in. giving net lever arms of 0.43 and 0.81 in. respectively. Since failure occurred on the welds subjected to the 0.81-in. lever arm, the e/d ratio was calculated as 0.57. The ratio of the ultimate moments of B 13C to A 13D is then 92.8 per cent while the calculated ratio is 86.0 per cent. The calculated moment is very sensitive to variations in load distribution.

In Specimens B 13, B 14 and B 33 the effect of the shearing stress should be negligible since the e/d ratio is above two. The ultimate bending moments should be almost equal to those of their companion specimens in Series A. That they do not thus agree is probably due to variations in the deposited welds. It is generally considered that variations of plus or minus ten per cent of the average in the results of weld tests are quite reasonable. The majority of the results in this investigation fall well within this range and are generally consistent.

Here again the results tend to indicate that full rectangular distribution of stress is reached in the welds at failure and that the ultimate strength may be based on this method of calculation.

The curves show the very small effect that a low average shearing stress has upon the strength of the weld. The bending strength will not be decreased more than ten per cent as long as the lever arm of the load is at least twice the length of the weld. For shorter lever arms in relation to weld length it would be better to consider the effect of shear. There is also indicated the small difference in the results whether based on the **Vector Method** or **Principal Stress Method**; but the **Principal Stress Method** gives more conservative and probably more accurate values.

(g) Turning again to Table I, the ratio of the average modulus of rupture to the ultimate strength of the qualification specimens is 1.87 for both 3/8 and 1/2-in. lightly-coated electrode fillet welds. The heavily-coated electrode welds show a ratio of only 1.61. From these figures the factor of safety can be calculated using weld stresses of 3,000, 4,000 and 3,750 lb per lin in. for 3/8, 1/2 "bare wire" and 3/8-in. heavily-coated electrode welds respectively. The factors of safety, column 11, range from 6.5 to 10.3 including all specimens.

Discarding A 34-1, A 63-1 and A 64 with factors between 6 and 7 because they were definitely low due to poor fusion in the weld, the lowest factor is 7.5.

Consider Table III, column 11. Here calculations based on the Principal Stress Method give factors of safety from 6.7 to 9.1. Using the Vector Method the factors of safety would be slightly less.

(h) It has been suggested that some variation in results is reasonable and as far as possible the causes of these variations have been discussed. The strains in the weld measured by the tensometers showed particularly well any lack of fusion or porosity in the weld long before failure. These observations were omitted in working up the average bending moment-weld strain curves.

A possible cause of variation is found in the secondary stresses to which the weld was subjected, the consideration of which has been entirely omitted in the discussion. One of these secondary stresses is that caused by the longitudinal buckling of the compression side of the splice plate due to the eccentric compression load to which it was subjected. This phenomenon was quite noticeable in certain specimens, notably A 64D, A 63-2, A 103 and A 104. The result was a prying action at the root of the weld and may account for the scaling of the weld at the compression end before scaling occurred at the tension end. In addition there are the secondary stresses due to the necessity for the stress to follow a broken path and the influence of localized stresses due to the loading blocks, especially in Series

B. These probably have small effect on the total strength of the weld.

2. Specimens C 62 and C 124 - The total angle of rotation of the welds on these two specimens was 0.0125 and 0.0075 radians respectively. At this point the calculated maximum weld stress was approximately equal to the ultimate strength shown by the tensile tests (54,500 lb per sq in), and small cracks were noted in the tension ends of the welds.

The plates were displaced due to the gouging action of the loading blocks 5/16 and 3/16 in. respectively at the final load. It is inconceivable that this great distortion of the wing plates could occur without detrimentally affecting the weld strength.

The ratio of the thickness of the wing plates to the total throat section of the welds was respectively 0.93 and 1.32. In both these tests yielding occurred in the plates before any distress was evidenced by the welds themselves.

3. Comments on Series C Specimens -

(a) The considerable porosity manifested in the lightly-coated electrode welds is not unusual and is well presented in METALLURGICAL DATA ON FUSION WELD JOINTS by A.J. Moses - Journal, American Welding Society, Vol.14, No.4, April 1935. As the number of passes increases the porosity is reduced, probably because the subsequent pass removes the porous top layer and replaces it with denser metal. With the decrease in porosity, the modulus of elasticity increases, there is a slight improvement in ductility and a slightly higher Johnson limit. The most interesting phenomena is the relation of the modulus of elasticity to the specific gravity of the specimen. This is as follows: The ratio of the moduli of elasticity of the deposited weld metal and the electrode varies directly as the fourth power of the ratio of their specific gravities. No explanation is offered for this relation.

The specimens of each group and as a whole give remarkably uniform results considering the inhomogeneity of the metal. The decrease in the physical properties of the deposited weld metal compared to those of the original electrode amounted to 33 per cent in ultimate strength, 66 per cent in elongation in 2 in. and 78 per cent in reduction in area.

(b) With the welds from heavily-coated electrodes the results are different. The specific gravity and modulus of elasticity remained constant; the ultimate strength only showed a decrease of 25 per cent in the extreme case of Electrode D, compared with the original electrode properties. Electrode C only showing a loss of 18.4 per cent of the original electrode strength. The percentage elongation was double that of the original electrode while the reduction in area was about constant at approximately 58 per cent.

Both electrodes showed weld throat stresses in the qualification tests of high order, 71,000 lb per sq in. Electrode C approached this with an average of 67,200 lb per sq in in the tensile tests, but Electrode D persistently showed ultimates which averaged 61,600 lb per sq in. This is the reverse of the performance of the lightly-coated electrode welds and no explanation is offered. The tests were sufficiently conclusive and of uniform results to prove the facts as stated above.

(c) Observations of current and voltage across the arc were taken during welding and an effort made to maintain them at a constant value. An exact rate of weld deposit was rather difficult to obtain because of the short lengths of many of the welds but with the lightly-coated electrode of 3/16 in. diameter 16 volts and 180 amperes, 3/8 in. fillet welds were deposited at the rate of approximately 4.5 ft per hour assuming continuous welding and allowing for renewal of electrodes. The rate with the 3/16 in. diameter heavily-coated electrodes at 28 volts and 220 amperes was approximately 22.5 ft per hour made by one electrode 18 in long with the Vee in a horizontal position.

Some difficulty was encountered in the handling of Electrode C which at first caused much spatter and undercutting. This was overcome by holding a much shorter arc (1/16 to 1/8 in. length), the electrode coating being almost immersed in the molten pool. The current could be maintained at 210 amperes while the decrease in arc voltage from 32 to 27 gave much better control, no undercutting and little spatter.

The slag of Electrode C was much thinner and denser than that from Electrode D and was slightly more difficult to remove although upon thorough cooling it chipped off easily.

The coating of Electrode C broke off upon bending of the electrode, the resultant bare spot caused trouble in handling, spatter and extinguishment of the arc. The coating gives off heavy, white fumes which are rather choking, hence plenty of ventilation was required.

Electrode D performed best also when the arc was kept quite short and the end of the coating was almost dragging in the molten pool. The slag produced was very voluminous, porous and glassy. It was so brittle that it could easily be chipped off immediately the pass was finished. A good weld could be identified by the smooth even appearance of the puffed up slag, covering all the deposited metal.

An asbestos cord spiralled around the electrode, was embedded in the coating securely tying it to the electrode, hence allowing it to be bent without splitting off and causing bare spots. The fumes given off are slight and mild and require no special ventilation.

It is not the purpose of this thesis to suggest one electrode in preference to the other. Both give an excellent quality of deposited metal, both are equally easy to handle and cause slight spatter loss or loss of time in slag removal. Their chief differences in behavior are shown in the bending of the electrode and the fumes given off from the burning coating.

VI. SUMMARY AND CONCLUSIONS

Based upon the observed behavior of the specimens and subject to the limitations imposed by them, the following summary and conclusions are presented.

1. The bending tests showed that the present design methods are very conservative and give a factor of safety of at least 7 when based on the ultimate strength of the weld.

2. The ordinary design formulas will give the stress condition in the weld for stresses up to the yield strength of the material. The principal stress method for computing combined stress is found to be more conservative and probably more exact.

3. The stress condition in the weld may be summarized as follows:

(a) The weld stress is proportional to the applied load up to the Johnson limit of the weld material.

(b) The stress at the root of the weld is about twice the average stress and about three times that at the free boundary of the weld.

(c) The stress is practically uniformly distributed over the weld cross-section at the loading which causes scaling of the whitewash on the surface of the weld.

4. Despite the low ductility of welds made with the lightly-coated electrode, the ductility is sufficient to allow for the development of the full rectangular distribution of stress along the length of the weld.

5. Using this rectangular distribution of stress, the full resisting moment based upon the ultimate strength of the qualification tests is developed even though the average shearing stress is as great as eighty per cent of this ultimate strength.

6. The full theoretical increase in strength is observed in the comparison of 1/2-in. fillets and 3/8-in. fillets in both the lightly-coated and heavily-coated electrodes.

7. The use of heavily-coated electrodes gives some increase in strength, approximately in the ratio of their tensile ultimate strengths, rather than in the ratio of the qualification tests.

8. Welds of lightly-coated electrodes are rather porous despite their good external appearance and maintenance of the prescribed ultimate strength. This porosity decreases the specific gravity and the modulus of elasticity in a rather unusual ratio.

9. Multilayer welds with lightly-coated electrodes tended to become more compact, with resultant increase in specific gravity, modulus of elasticity and ductility.

10. Heavily-coated electrodes gave physical properties equal to or exceeding in all the items tested the usual grades of structural steel.

11. The tests indicated the necessity of determining the shearing modulus and shearing strengths of weld metal from both the lightly-coated and heavily-coated electrodes.

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TABLE I - TEST RESULTS - SERIES A

Specimen Number	Length of Weld in.	Bending Moment Per Weld At: Scaling of White-wash in-lb	Bending Moment Per Weld At: Yield Point by Observation of Curves in-lb	Bending Moment Per Weld At: Ultimate in-lb	Modulus of Rupture lb/lin in	Ultimate Stress lb/lin in	Ratio Calculated to Measured Stress	Intersection of Calculated and Observed Strains: Stress lb/sq in	Intersection of Calculated and Observed Strains: Bending Moment in-lb	Ratio Scaling / Ultimate	Factor of Safety
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
A 13	1.52	8,424	4,425$^{\tau}$	9,435	24,900	16,600	1.62	36,000	6,870	89.5	8.3
A 14	1.51	10,800	5,850$^{\tau}$	12,250	32,400	21,600	1.65	36,850	9,000	88.2	8.1
A 33-2	3.03	27,160	22,800*	35,400	23,200	15,500	--	--	--	76.9	7.7
A 33-3	3.02	33,360	29,800*	38,500	25,400	16,900	--	--	---	86.0	8.5
A 34-1	3.00	36,400	22,000*	38,820	25,800	17,300	1.78	35,900	32,000	93.5	6.5
A 34-2/	2.94	44,000	25,600$^{\tau}$	54,800	38,000	25,400	1.61	37,400	40,600	80.4	9.5
A 63-1	6.00	92,100	69,000$^{\tau}$	117,500	19,700	13,200	1.64	35,800	97,500	78.4	6.6
A 63-2/	5.91	126,900	81,500$^{\tau}$	181,150	31,000	20,700	1.63	36,900	121,850	70.0	10.3
A 64	6.00	117,250	68,500$^{\tau}$	158,150	26,400	17,600	1.65	35,700	121,000	73.7	6.6
A 103	10.00	325,000	237,000Δ	463,000	27,700	18,500	--	--	--	70.2	9.2
A 104	10.00	390,600	346,500Δ	586,355	35,200	23,500	--	--	--	66.7	8.8
A 13D	1.50	5,370	3,660$^{\tau}$	10,530	28,060	18,800	1.63	39,000	5,030	51.0	7.5
A 33C	3.00	27,520	26,800$^{\tau}$	50,730	33,700	22,600	1.69	40,800	34,200	54.1	9.0
A 63C	5.82	---	93,000$^{\tau}$	168,350	29,700	19,800	1.62	42,000	133,250	79.4	7.9
A 64D	6.00	156,150	94,000$^{\tau}$	261,400	43,500	29,000	1.61	41,000	149,750	59.5	8.7

/ Electrode B used. Other specimens of Electrode A except as noted.

τ From weld strain data by tensometers

* By strain gage over 10-in. gage length specimen including welds

Δ By center deflection readings

TABLE II

TEST RESULTS - SPECIMENS C 62 AND C 124

WELDS OF ELECTRODE A

				C 62	C 124
		(1)	Specimen No.	C 62	C 124
		(2)	Average Gap in.	0.039	0.045
		(3)	Fillet Size in.	0.336	0.330
Total Load (pounds) at		(4)	Scaling of Wing Plates	53,700	130,000
		(5)	General Yielding of Wing Plates	118,000	---
		(6)	Cracks in Weld	140,000	250,000
		(7)	Gap Closure Complete at One End	152,000	271,000
		(8)	Final Load	180,000	271,000
Calculated Stresses	Wing Plates At Final Load lb per sq in	(9)	Shearing	23,100	12,900
		(10)	Bearing	48,000	42,800
	Maximum Weld Stresses lb per in	(11)	Cracks	12,100 51,000*	11,650 50,000*
		(12)	Final Load	15,600 65,700*	12,650 54,200*

*Stresses in pounds per square inch over net throat section

TABLE III - TEST RESULTS OF SERIES - ELECTRODE B WELDS EXCEPT AS NOTED

Specimen Number	Length of Weld "d" in.	Lever Arm To Center Of Weld "e" in.	Bending Moment Per Weld At: Scaling of Whitewash in-lb	Yield Point by Observation of Curves in-lb	Ultimate in-lb	Average Shear At Ultimate Load lb/lin in	Ratio MR with Shear / MR	Ratio e/d	Ratio Scaling / Ultimate	Design Load lb.	Factor of Safety
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
B 13	1.48	3.56	8,010	4,850τ	9,010	1,710	86.0	2.410	88.9	306	8.3
B 14	1.48	3.50	10,720	---	12,720	2,460	93.7	2.360	84.3	416	8.7
B 33	2.90	6.60	31,680	20,200τ	38,400	2,010	93.5	2.280	82.5	640	9.1
B 34	2.89	1.50	28,590	29,060Δ	44,900	10,370	82.0	0.519	63.7	3,380	8.9
B 63	5.92	1.56	95,550	90,850Δ	118,000	12,600	65.1	0.264	81.0	8,530	8.8
B 103	9.96	3.81	324,000	269,000Δ	379,000	9,980	73.9	0.385	85.0	11,140	8.9
B 13C	1.42	1.31	9,500	7,200Δ	16,900	9,120	84.0*	0.922	56.5	940	7.6*
B 33D	2.88	1.88	27,000	19,300Δ	32,400	5,980	64.5	0.650	83.1	2,600	6.7
B 63C	5.92	1.81	123,000	105,000Δ	151,000	14,150	89.6	0.309	81.5	9,690	8.6

* See discussion

τ From weld strain data by tensometers

Δ By center deflection readings

TABLE IV - PHYSICAL PROPERTIES OF WELD METAL - ELECTRODE A

	Specimen Number	Johnson Limit lb/sq in	Yield Strength lb/sq in	Ultimate Strength lb/sq in	Equivalent Elongation in 2 in. per cent	Reduction In Area per cent	Modulus of Elasticity lb/sq in	Specific Gravity
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Electrode 3/16" dia	1	64,000	76,800	81,150	17.3	63.0	29,500,000	7.74
	2	64,000	77,500	80,340	16.0	60.3	29,500,000	7.72
	3	63,800	75,600	79,350	--	62.8	29,000,000	7.77
	4	64,000	79,400	81,150	17.3	61.0	29,400,000	--
	Average	64,000	77,300	80,500	16.9	61.8	29,350,000	7.74
3/16" dia Deposited Metal	1	25,500	36,500	49,500	4.6	13.8	24,400,000	7.49
	2	25,500	37,000	51,560	6.7	15.3	24,500,000	7.50
	3	26,200	41,600	59,300	8.7	10.3	24,900,000	7.41
	Average	25,700	38,400	53,450	6.7	13.1	24,600,000	7.47
3/16" dia Deposited Metal*	4	30,500	43,600	52,000	7.3	17.4	25,200,000	7.32
	5	30,500	43,600	59,300	5.3	15.7	24,600,000	7.38
	6	27,800	42,500	57,100	1.3	10.9	24,500,000	7.37
	Average	29,600	43,[illegible]00	56,100	4.6	14.7	24,800,000	7.36
5/16" dia Deposited Metal	1	26,000	38,200	55,370	5.2	8.3	29,200,000	7.55
	2	27,500	39,200	55,600	---	---	26,200,000	7.47
	3	26,500	39,200	57,800	6.8	11.2	25,400,000	7.53
	4	26,000	37,200	50,500	4.2	15.7	24,700,000	7.52
	Average	26,500	38,400	54,800	5.4	11.7	26,400,000	7.52
1/2" dia Deposited Metal	1	30,800	43,000	54,290	5.7	13.2	27,500,000	7.59
	2	29,500	38,600	51,760	7.7	14.9	26,500,000	7.59
	Average	30,200	40,800	53,000	6.7	14.0	27,000,000	7.59

* Weld deposited using electrode 5/32" diameter and suitable current and voltage

TABLE V - PHYSICAL PROPERTIES OF WELD METAL - ELECTRODE C

	Specimen Number	Johnson Limit lb/sq in	Yield Strength lb/ sq in	Ultimate Strength lb/sq in	Equivalent Elongation in 2in. per cent	Reduction In Area per cent	Modulus of Elasticity lb/sq in	Specific Gravity
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Electrode 3/16" dia	1	60,000	73,200	79,890	16.0	55.6	29,200,000	7.75
	2	62,000	75,100	83,440	16.0	55.9	29,400,000	7.80*
	3	63,000	77,200	83,500	14.6	58.4	29,200,000	7.71*
	Average	61,700	75,200	82,300	15.5	56.6	29,300,000	7.75
3/16" dia Deposited Metal	1	36,500	44,300	70,300	22.8	65.7	29,200,000	7.73
	2	32,400	44,300	69,400	22.0	44.4	29,500,000	7.75
	Average	34,500	44,300	69,900	22.4	55.1	29,350,000	7.74
5/16" dia Deposited Metal	1	32,100	40,400	64,500	26.3	65.0	29,200,000	7.79
	2	33,800	39,500	64,300	35.5	66.8	28,700,000	7.78
	Average	33,000	40,000	64,400	30.9	65.9	29,000,000	7.78

* Taken from same electrodes as the tension specimens

Specimen No.1 taken from electrode picked at random

TABLE VI - PHYSICAL PROPERTIES OF WELD METAL - ELECTRODE D

	Specimen Number	Johnson Limit lb/sq in	Yield Strength lb/sq in	Ultimate Strength lb/sq in	Equivalent Elongation in 2 in. per cent	Reduction In Area per cent	Modulus of Elasticity lb/sq in	Specific Gravity
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Electrode 3/16" dia	1	60,000	73,500	82,500	17.3	57.5	28,800,000	7.81
	2	55,000	74,000	82,000	18.6	59.8	28,700,000	7.78
	3	58,500	75,000	82,640	17.3	57.9	29,700,000	7.86
	Average	57,800	74,200	82,380	17.7	58.4	29,100,000	7.82
3/16" dia Deposited Metal	1	26,300	35,700	58,900	26.8	52.0	30,000,000	7.81
	2	41,500	50,600	64,100	24.7	56.4	29,500,000	7.75
	3	28,800	37,800	62,100	23.5	32.1 ≠	29,800,000	7.75
	Average	32,200	41,400	61,700	25.0	54.2	29,800,000	7.77
5/16" dia Deposited Metal	1	36,100	43,900	61,800	33.0	56.8	28,800,000	7.77
	2	34,400	41,000	60,800	28.3	64.8	28,900,000	7.78
	3*	29,000	38,500	59,200	15.2	43.6	28,700,000	7.75
	4°	28,700	39,600	61,300	21.6	35.2	28,900,000	7.79
	5	41,000	42,500	63,470	32.8	53.9	28,500,000	7.76
	6	34,500	42,500	62,520	32.0	57.1	28,500,000	7.75
	Average	36,500	42,500	62,150	31.5	58.2	28,700,000	7.77

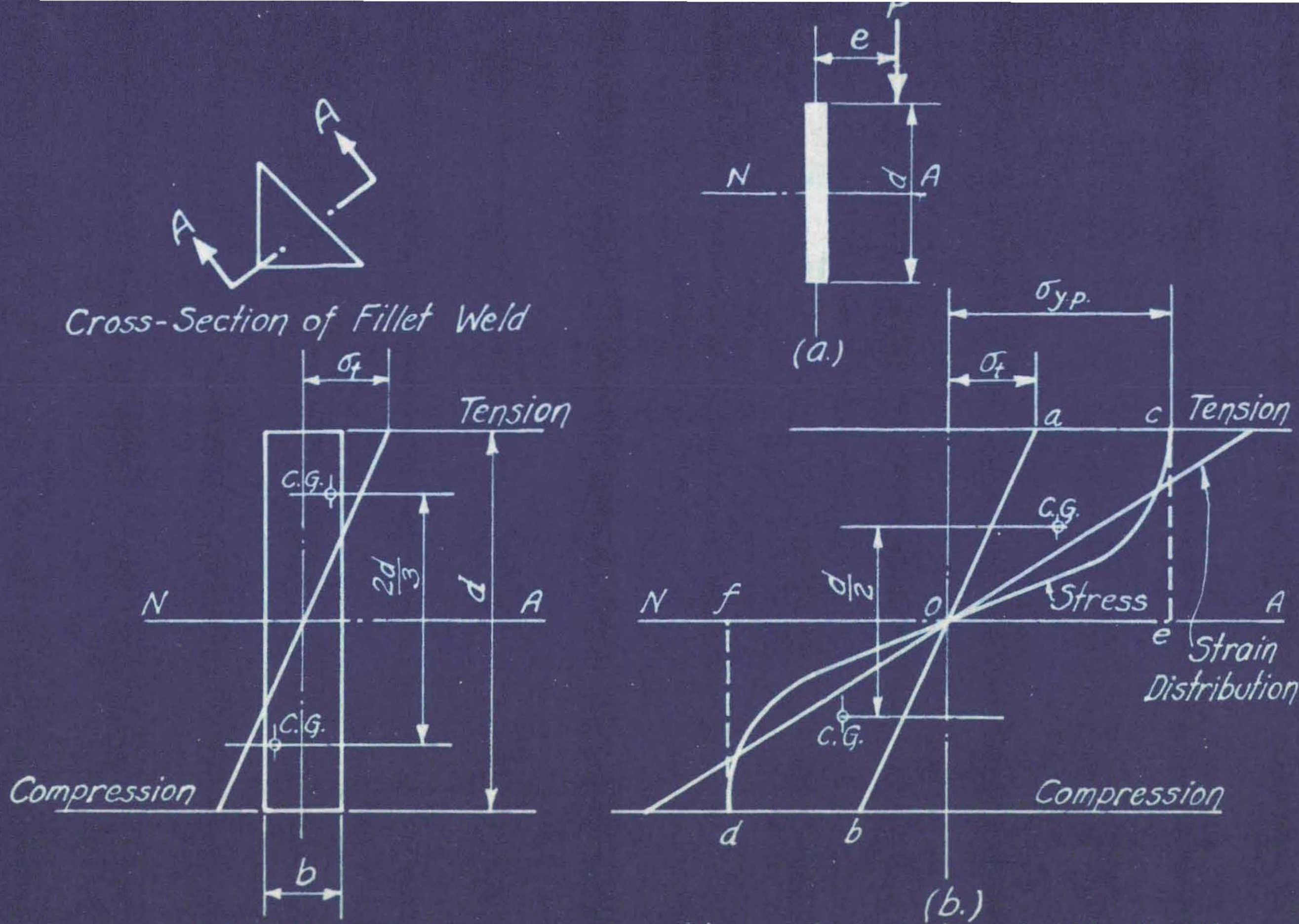
≠ Slight blowholes reduced ductility, omitted in average
* Large blowholes on axis, omitted in average
° Blowholes throughout fractured section, omitted in average

TABLE VII - CHEMICAL ANALYSIS OF ELECTRODES AND DEPOSITED METAL

Element	Electrode A		Electrode C		Electrode D	
	Electrode	Deposited Metal	Electrode	Deposited Metal	Electrode	Deposited Metal
	per cent	per cent	per cent	per cent	per cent	per cent
C	0.16	0.15	0.13	0.11	0.14	0.08
Mn	0.42	0.25	0.50	0.62	0.51	0.31
P	0.017	0.014	0.012	0.015	0.015	0.020
S	0.022	0.030	0.023	0.023	0.029	0.030
Si	0.01	trace	0.01	0.28	---	0.10
Mo	none	none	mone	none	---	0.02
Ni	--	--	--	none	---	0.05
Cr	--	--	--	none	---	none
Cu	--	--	--	0.12	---	0.05

CHEMICAL ANALYSIS OF ELECTRODE COATINGS

Compound	Electrode C	Electrode D
SiO_2	28.94%	37.96%
Fe_2O_3	4.63	28.52
Al_2O_3	0.54	5.30
Mn O	10.22	20.01
Ca O	1.35	4.74
TiO_2	13.98	0.05
Mg O	6.64	
MoO_3	0.48	
Ignition Loss	29.46	3.42
	96.24	100.00



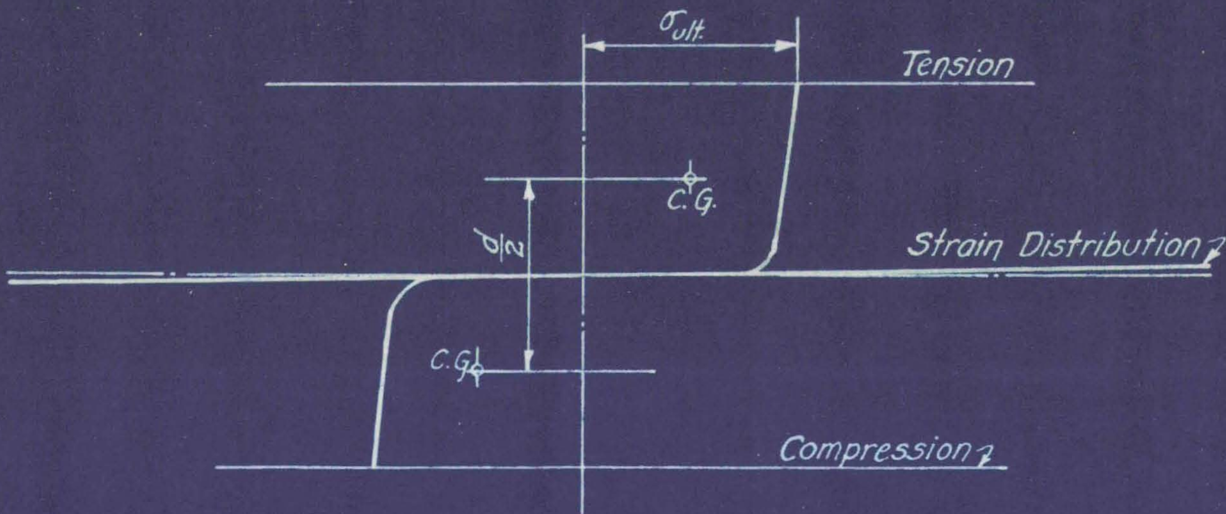
SECTION A-A

Stress Distribution in Elastic Stage

$$MR = \sigma \frac{bd}{2\times 2}\cdot\frac{2d}{3} = \sigma\frac{bd^2}{6}$$

Stress Distribution in Plastic Stage

$$\text{Limiting } MR = \sigma_{y.p.}\frac{bd}{2}\cdot\frac{d}{2} = \sigma_{y.p.}\frac{bd^2}{4}$$



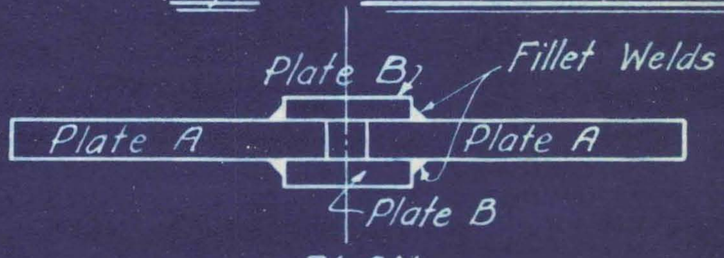
(c.)

Stress Distribution at Ultimate Strength

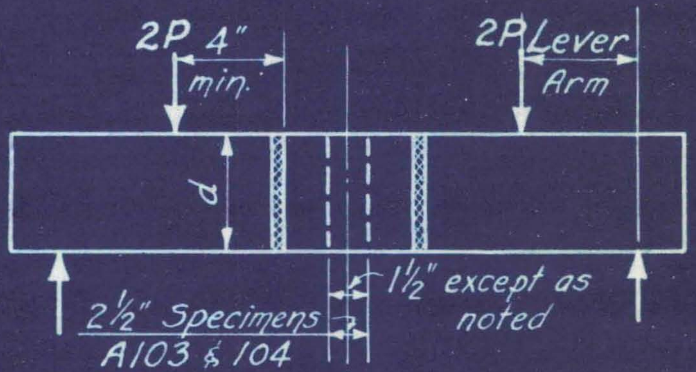
$$\text{Approx. } MR = \sigma_{ult.}\frac{bd}{2}\cdot\frac{d}{2} = \sigma_{ult.}\frac{bd^2}{4}$$

FIG. 1. - BEHAVIOR OF WELDS IN BENDING

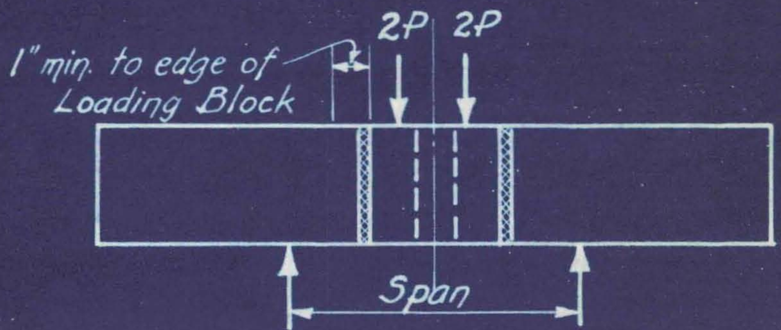
FIG. 2 ~ TEST PROGRAM - SERIES A & B



PLAN



ELEVATION
Showing Loading of Series A Specimens



ELEVATION
Showing Loading of Series B Specimens

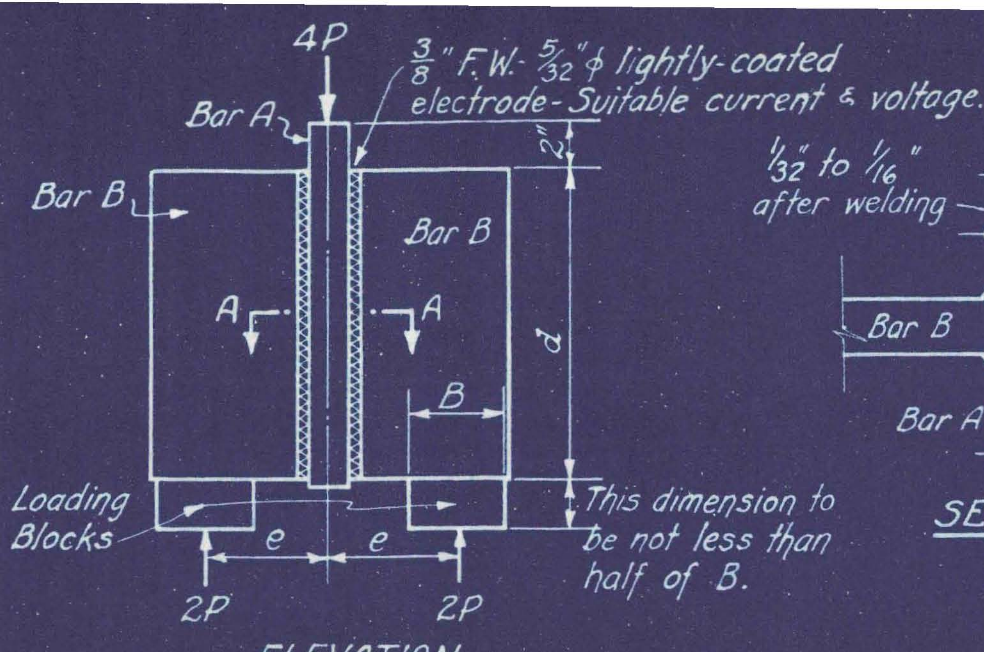
NOTE:- Bearing surfaces to be machined plane & parallel.
Welding to be on machined edges.

SPECIMEN SCHEDULE ~ SERIES A

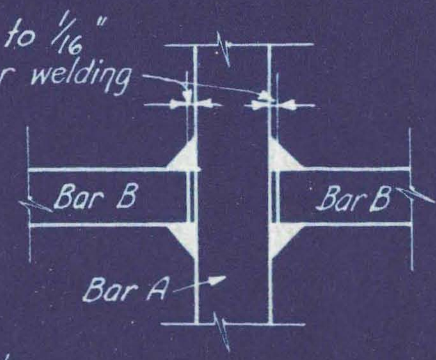
Spec. No.	Weld Data Size	Weld Data Type	Depth d	Two (2) of each Plates A	Two (2) of each Plates B	Lever Arm
A13	3/8"	Bare	1½"	1¼ x 1½ x 10"	¾ x 1½ x 4½"	3"
A33	3/8	"	3	1¼ x 3 x 11"	¾ x 3 x 4½"	4"
A63	3/8	"	6	1½ x 6 x 13"	7/8 x 6 x 5½"	5"
A103	3/8	"	10	1½ x 10 x 18"	7/8 x 10 x 7"	10"
A14	½	"	1½	1¾ x 1½ x 10"	1 x 1½ x 4½"	3"
A34	½	"	3	1¾ x 3 x 11"	1 x 3 x 4½"	4"
A64	½	"	6	2 x 6 x 13"	1¼ x 6 x 5½"	5"
A104	½	"	10	2 x 10 x 18"	1¼ x 10 x 7"	11"
A13D	3/8	Coat'd	1½	1¼ x 1½ x 10"	¾ x 1½ x 4½"	3"
A33C	3/8	"	3	1½ x 3 x 11"	¾ x 3 x 4½"	4"
A63C	3/8	"	6	1½ x 6 x 13"	7/8 x 6 x 5½"	5"
A64D	½	"	6	2 x 6 x 13"	1¼ x 6 x 5½"	5"

SPECIMEN SCHEDULE ~ SERIES B

Spec. No.	Weld Data Size	Weld Data Type	Depth d	Two (2) each of Plates A	Two (2) each of Plates B	Span
B13	3/8"	Bare	1½"	1¼ x 1½ x 10"	¾ x 1½ x 4½"	12"
B33	3/8	"	3	1¼ x 3 x 11"	¾ x 3 x 4½"	18"
B63	3/8	"	6	2 x 6 x 13"	1¼ x 6 x 5½"	9"
B103	3/8	"	10	2 x 10 x 18"	1¼ x 10 x 7	15"
B14	½	"	1½	1¾ x 1½ x 10"	1 x 1½ x 4½"	12"
B34	½	"	3	1¾ x 3 x 11"	1 x 3 x 4½"	8"
B13C	3/8	Coat'd	1½	1¾ x 1½ x 10"	1 x 1½ x 4½"	7½"
B33D	3/8	"	3	1¼ x 3 x 11"	¾ x 3 x 4½"	8½"
B63C	3/8	"	6	2 x 6 x 13"	1¼ x 6 x 5½"	9½"



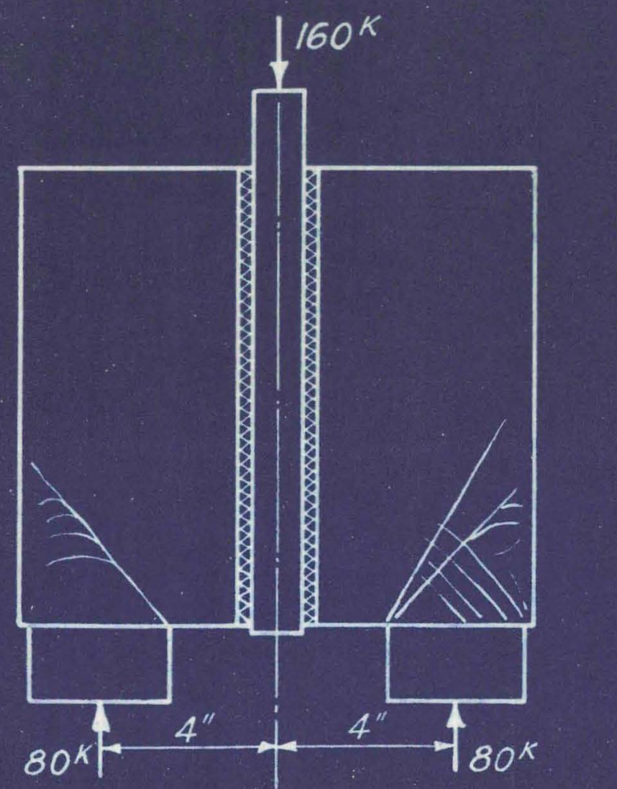
ELEVATION



SECTION A-A

TABLE OF SPECIMENS

Specimen No.	Length of Weld - d in.	Lever Arm - e in.	Bearing B - in.	Bar A Main Plate	Bar B Wing Plates
C62	6.25	2	3	1 PL - 6"x 7/8"x 8 1/4"	2 PLs - 3 1/2"x 5/8"x 6 1/4"
C124	12	4	3 5/8	1 PL - 8"x 1 1/4"x 14"	2 PLs - 6"x 7/8"x 12"



APPEARANCE OF SCALING OF WHITEWASH - C124 - LOAD 160 Kips
Scale 1:50

FIG. 3 - SPECIMENS C62 & C124

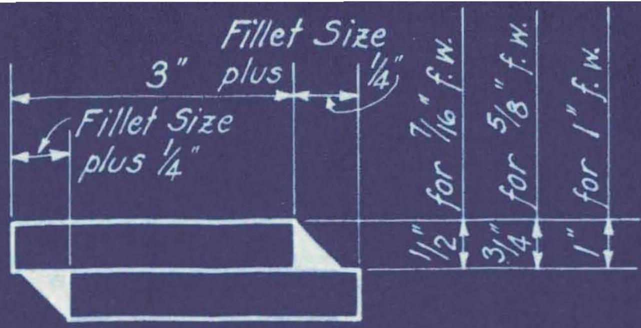
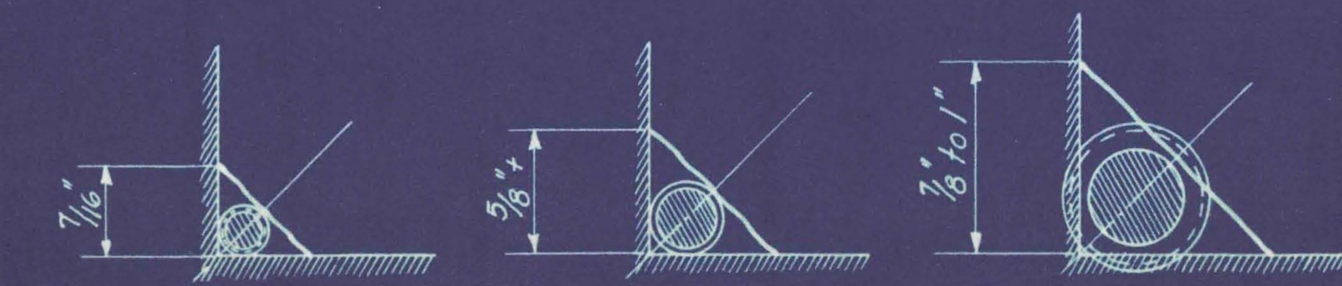


PLATE SCHEDULE

Weld Size	No. of Pl. Req.	Size of Plates
7/16"	6	1/2 x 3 x 9"
5/8"+	6	3/4 x 3 x 9"
1"-	2	1 x 3 x 9"

WELD DEPOSITION PLATES

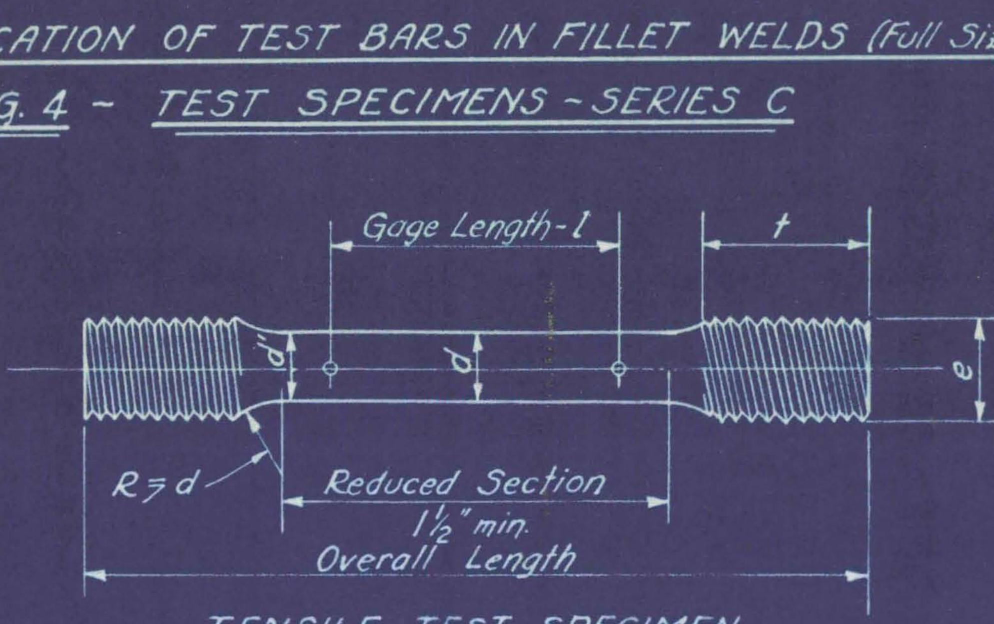
NOTE:- Welding electrodes, both "bare" and heavily-coated to be 3/16" dia. Discard approx. 1" from each end of fillet. Welding to start at one end and finish at opposite end. Craters to be filled.



	Bare Electrode- Single Pass Heavily-Coated ~ Three Pass	Two-Pass Six-Pass	Six-Pass
Diameter of Tensile Bar	3/16"	5/16"	1/2" (0.505")

LOCATION OF TEST BARS IN FILLET WELDS (Full Size)

FIG. 4 – TEST SPECIMENS - SERIES C



TENSILE TEST SPECIMEN

DIMENSIONS

Nominal Size	Dia. at Center-d	Dia. at Fillet d'	Gage Length-l	Reduced Section	Dia. at End-e	Threaded Length-t	Threads per inch	Overall Length
3/16"	0.188±0.001	d + 0.001	3/4"	1 1/2"	1/4"	1/2"	20	2 3/4"
5/16"	0.313±0.002	d + 0.002	1 1/4"	1 1/2"	3/8"	3/4"	16	3 1/2"
1/2"	0.500±0.005	d + 0.004	2"	2 1/4"	3/4"	1"	10	5 1/2"

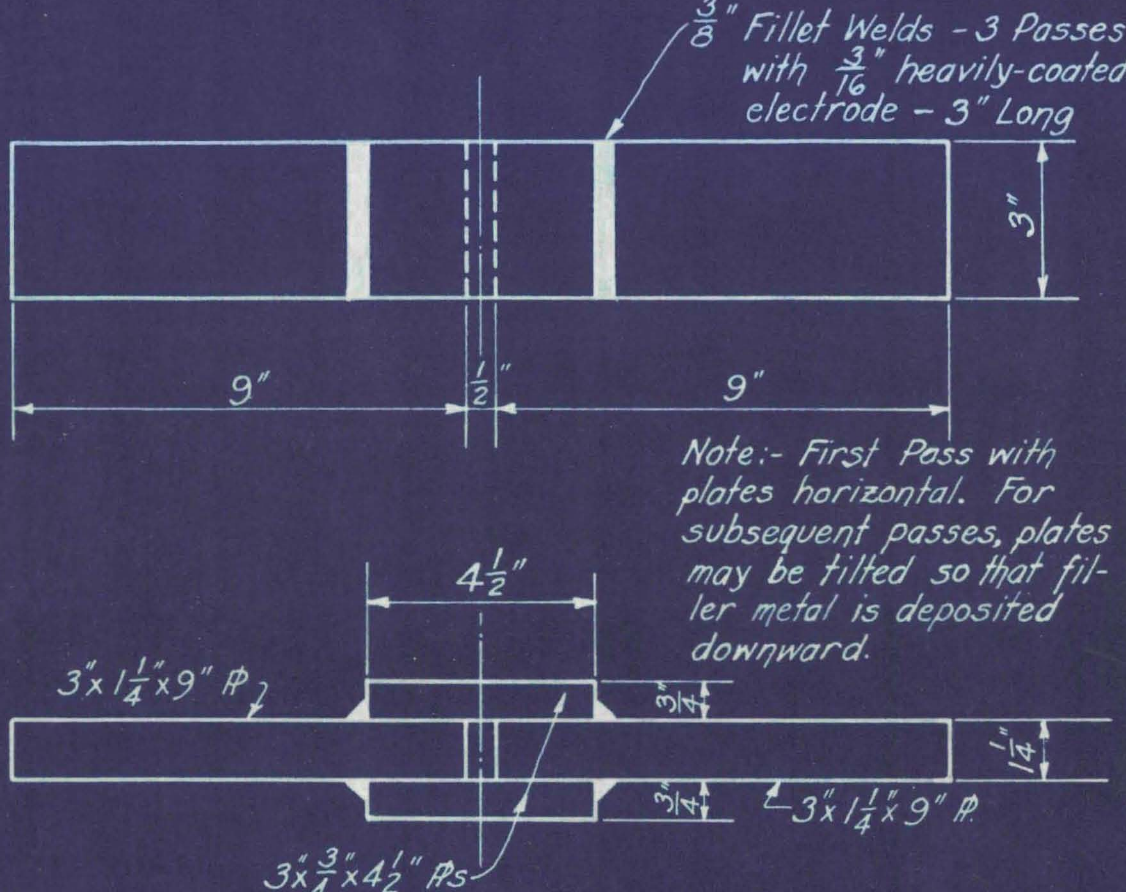


FIG. 5 - MODIFIED QUALIFICATION SPECIMEN FOR HEAVILY-COATED ELECTRODE WELDS.

2 Req'd for each type of electrode.

Fig. 6 - Specimen A 34 Set-Up In Pure Bending in 300,000-Lb. Machine

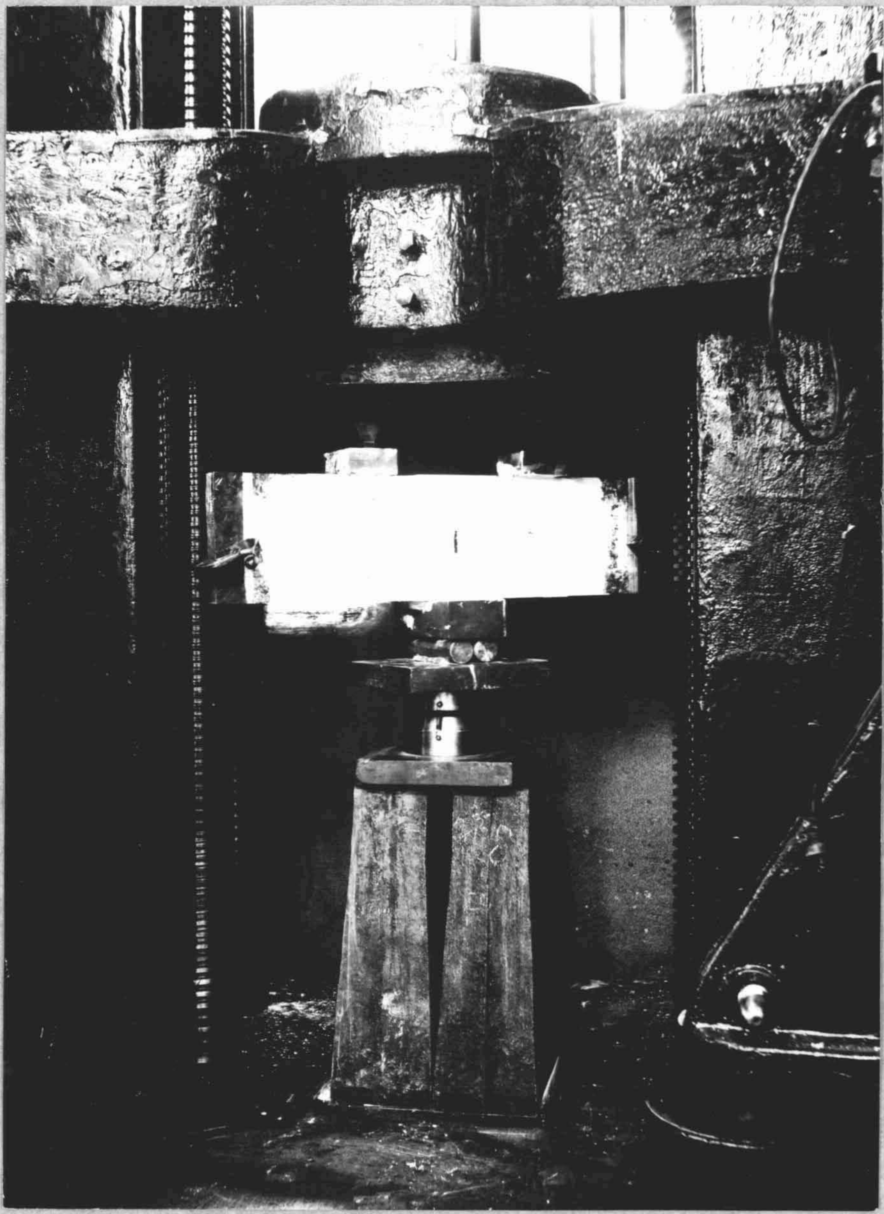


Fig. 7 - Specimen B 103 Set-Up In Transverse
Bending In 800,000-Lb. Machine

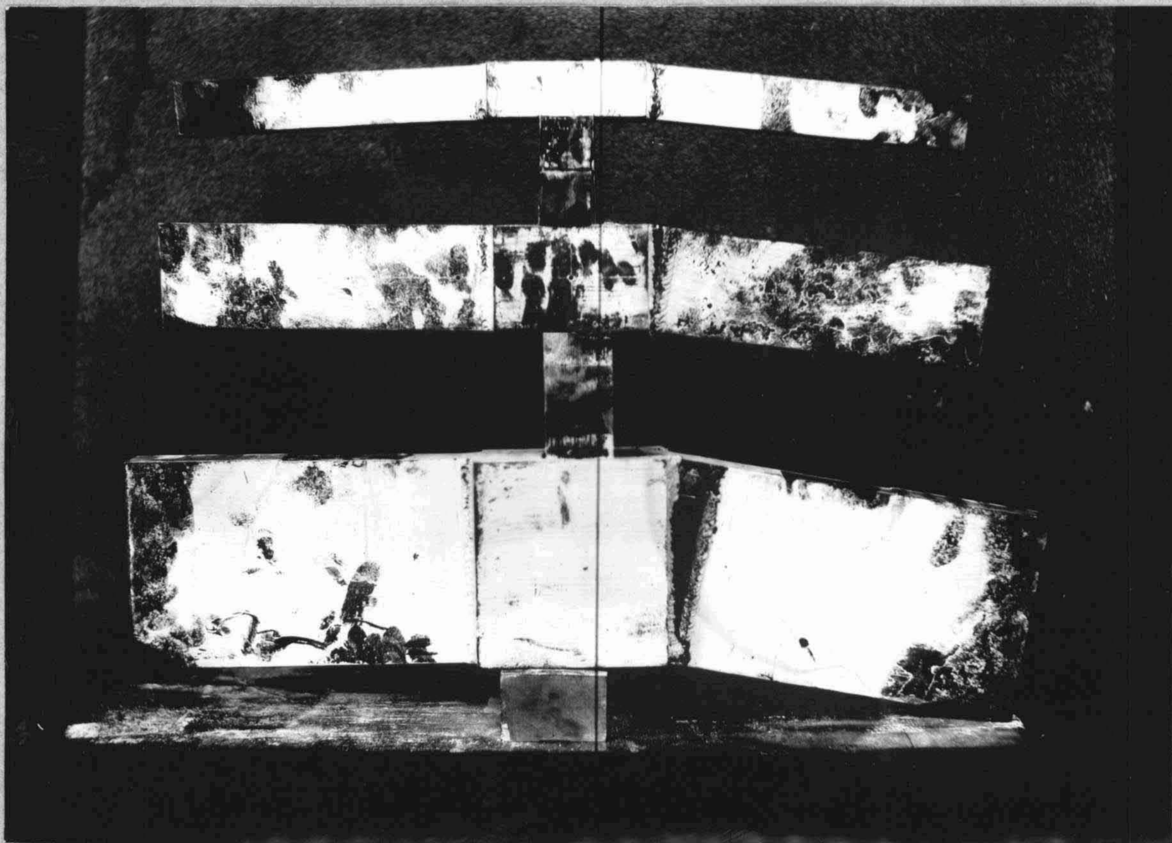


Fig. 8 - Set Of Series A Specimens

Lightly-Coated Electrode - 3/8" Fillet Welds

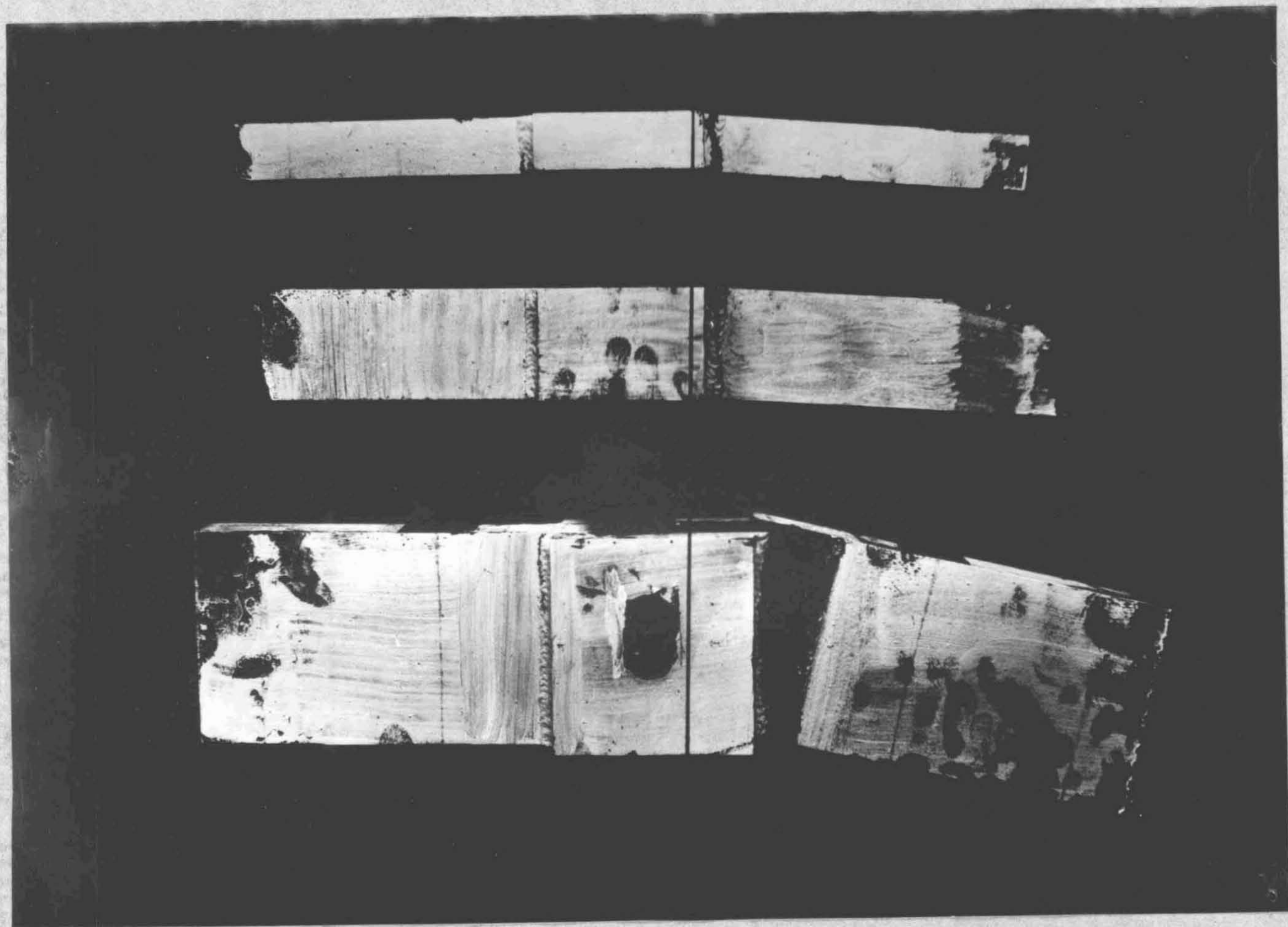


Fig. 9 - Set Of Series A Specimens

Lightly-Coated Electrode - 1/2" Fillet Welds

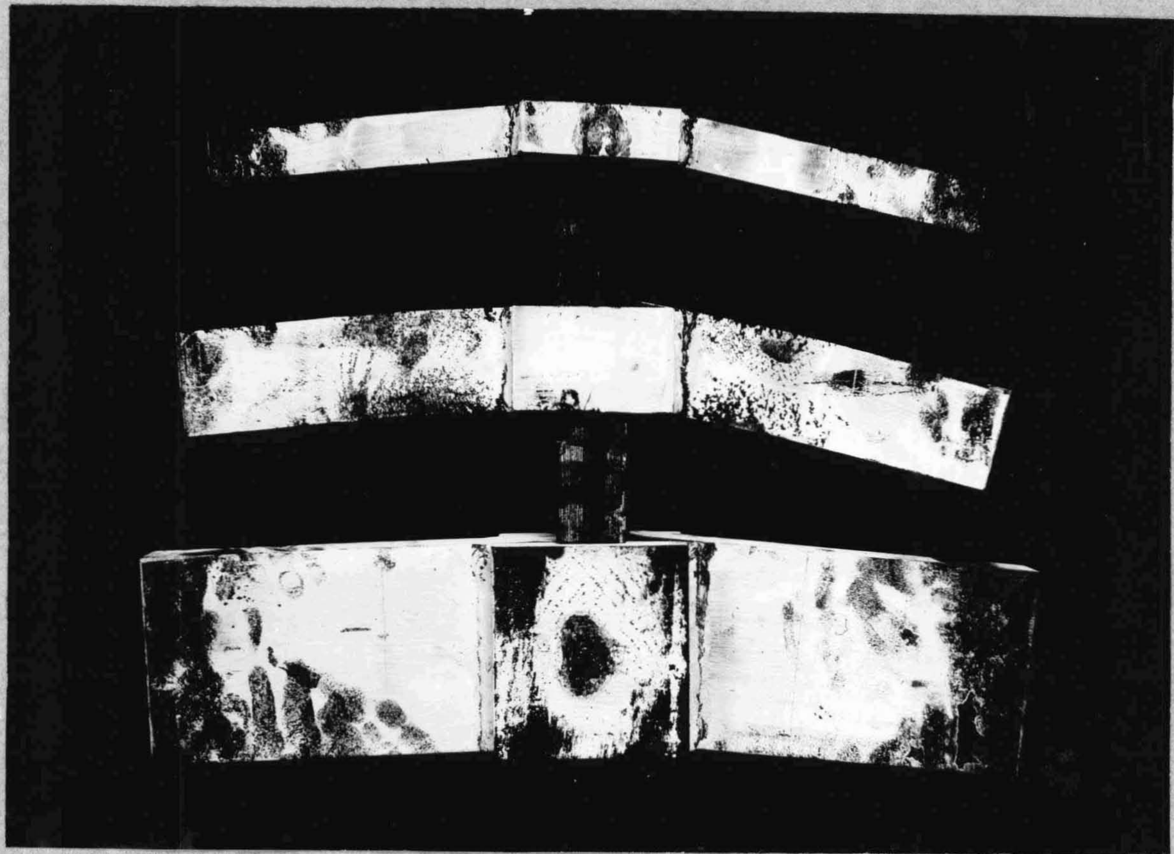


Fig. 10 - Set Of Series A Specimens
Heavily-Coated Electrode Welds

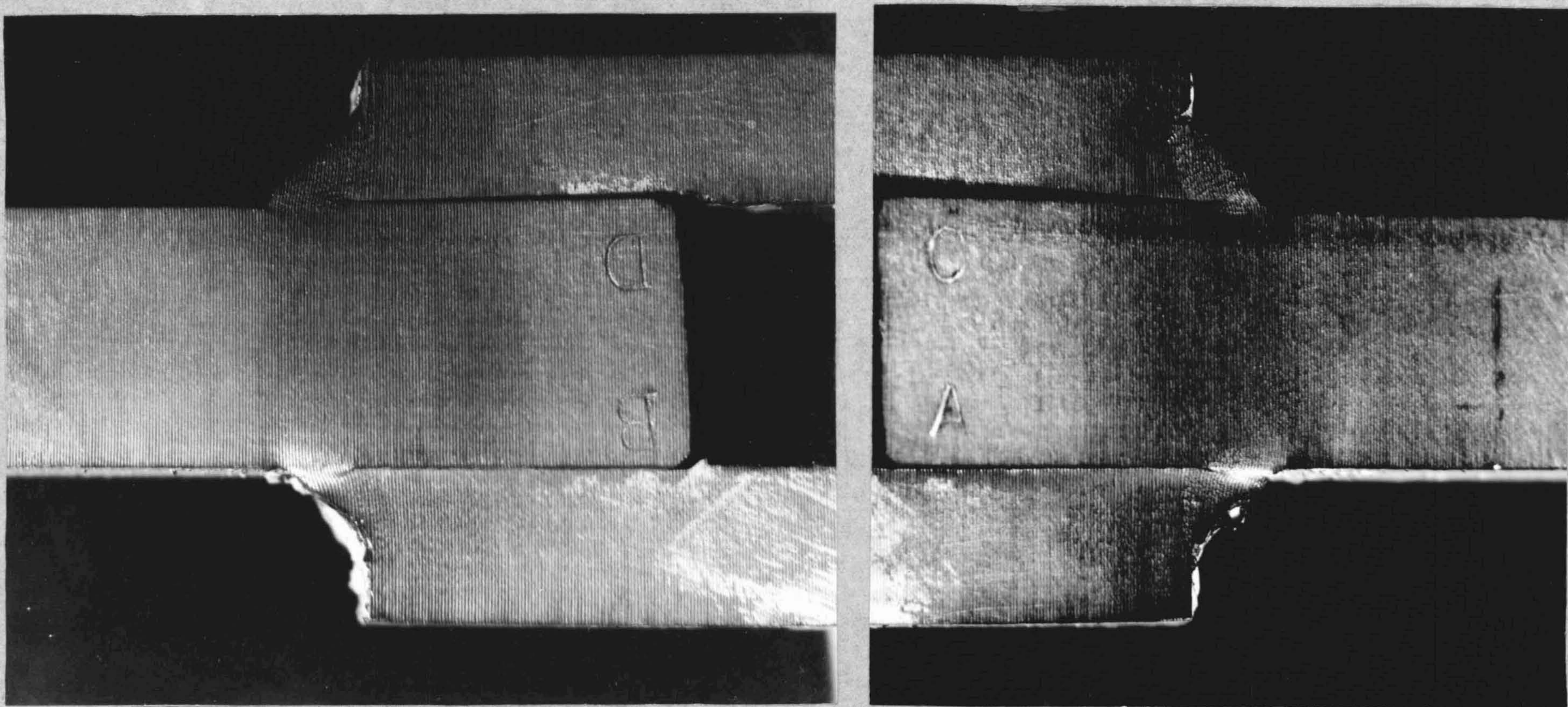


Fig. 11 - Showing Ductility Of Heavily-Coated Electrode Welds - Tool Lines Originally Straight - Specimen A 13D

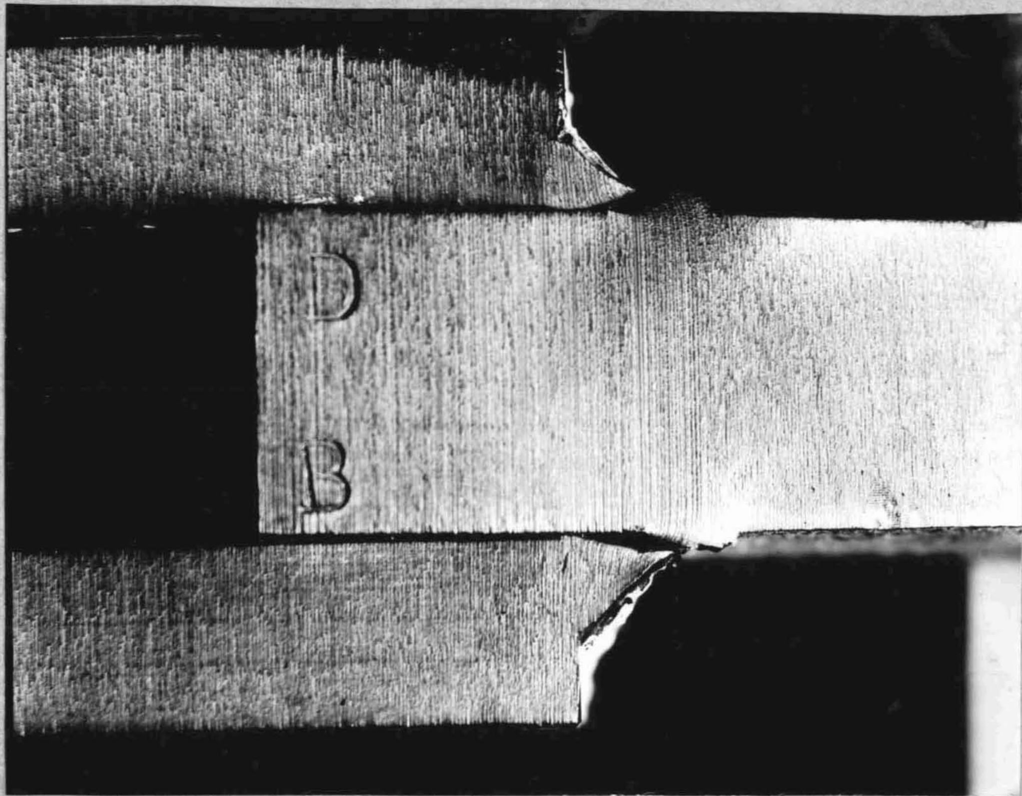


Fig. 12 - Specimen A 33C
Coated Electrode Welds

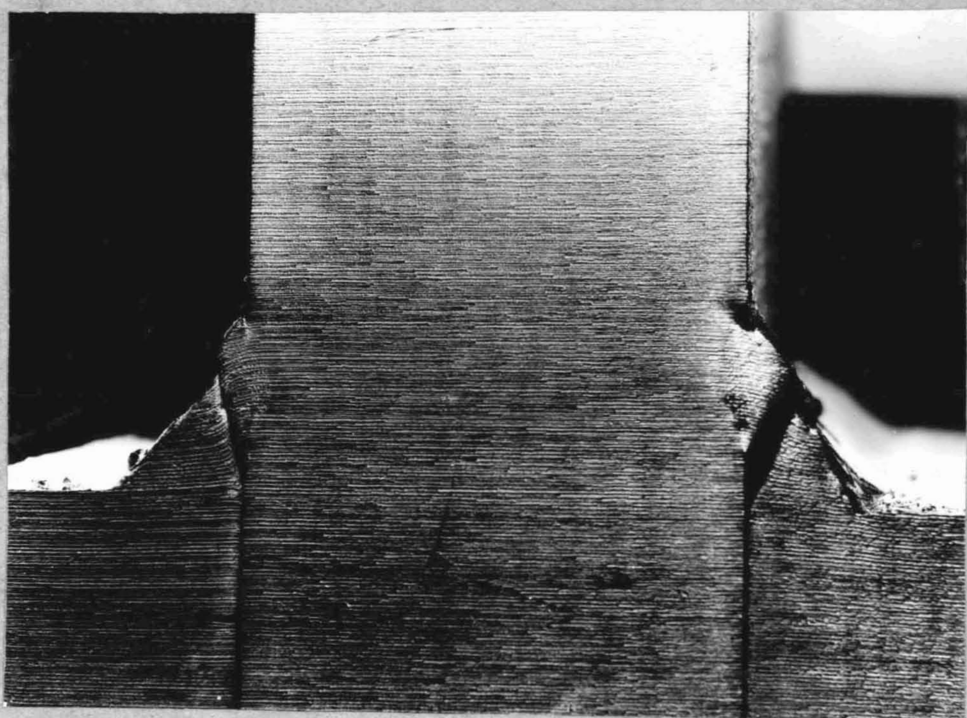


Fig. 13 - Specimen A 64D
Coated Electrode Welds

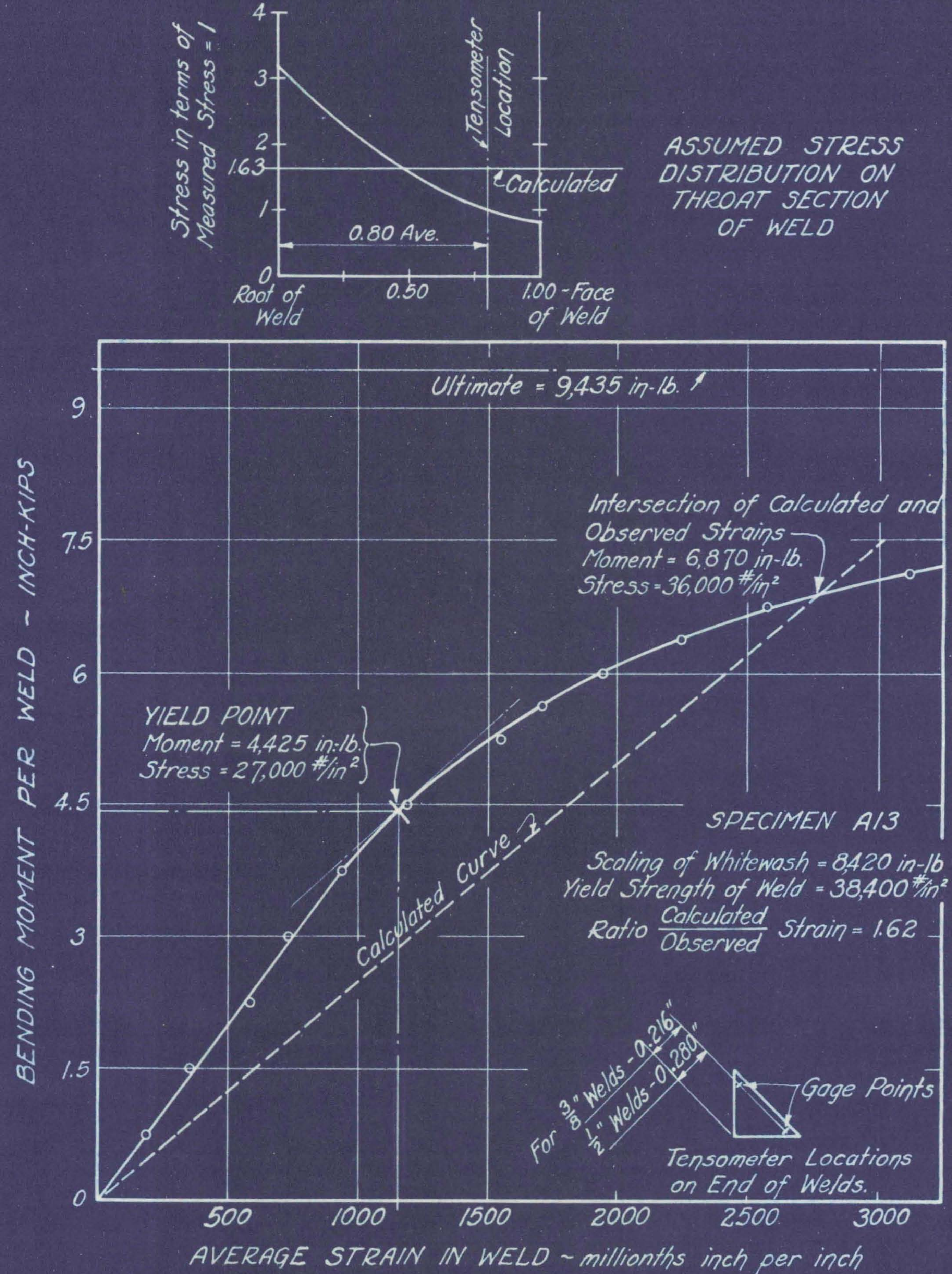


FIG. 14 - TYPICAL CURVE - BENDING MOMENT - WELD STRAIN.

Fig. 15 - Specimen C 124 at Total Load
of 240,000 lb.

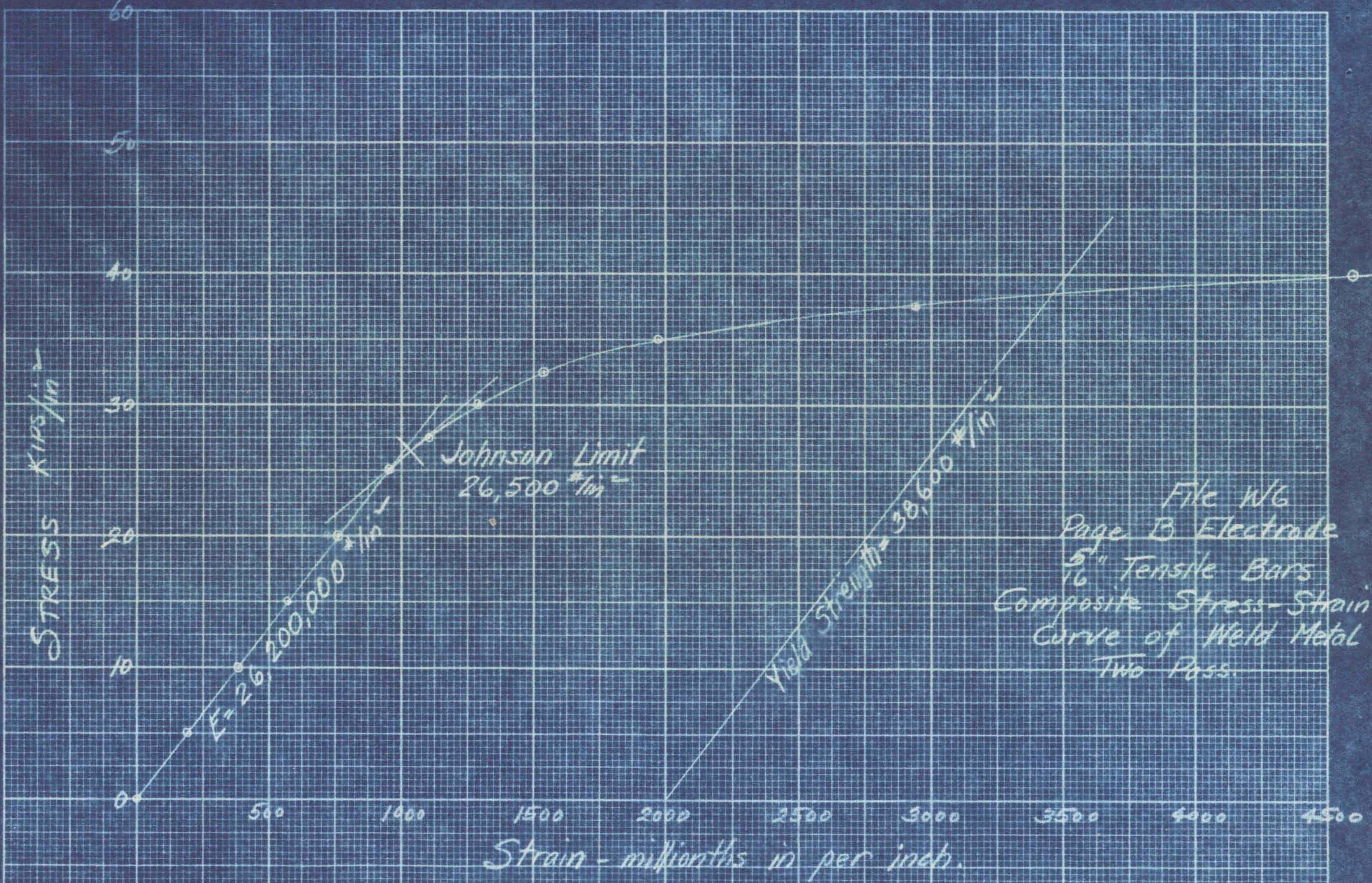
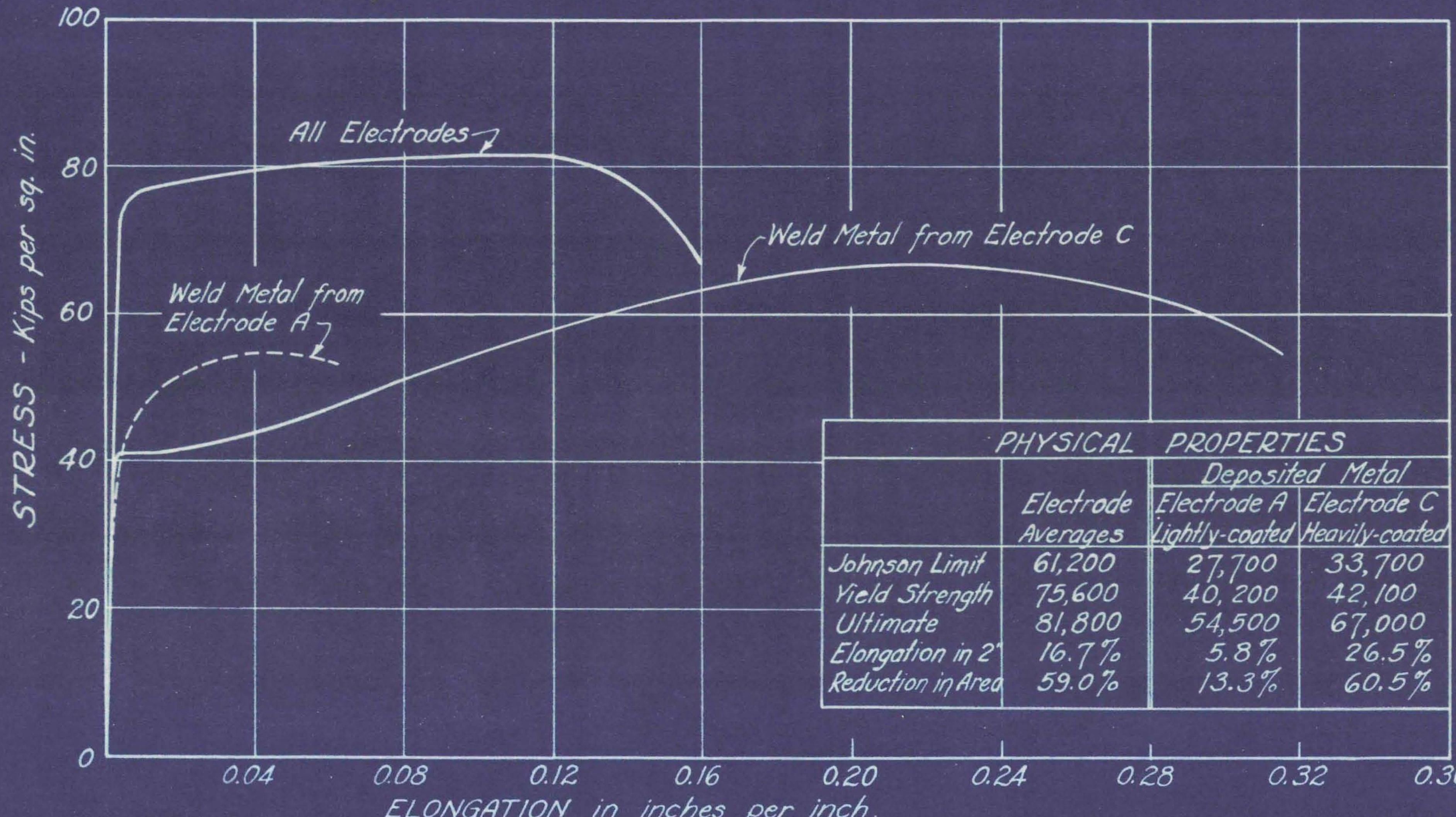

STRESS Kips/in²
60
50
40
30
20
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Johnson Limit
26,500 #/in²
E = 26,200,000 #/in²
Yield Strength = 38,600 #/in²
File W6
Page B Electrode
5/16" Tensile Bars
Composite Stress-Strain
Curve of Weld Metal
Two Pass.
Strain - millionths in per inch.

FIG. 16



PHYSICAL PROPERTIES			
		Deposited Metal	
	Electrode Averages	Electrode A Lightly-coated	Electrode C Heavily-coated
Johnson Limit	61,200	27,700	33,700
Yield Strength	75,600	40,200	42,100
Ultimate	81,800	54,500	67,000
Elongation in 2"	16.7%	5.8%	26.5%
Reduction in Area	59.0%	13.3%	60.5%

FIG. 17 - TYPICAL STRESS-STRAIN DIAGRAMS FOR ELECTRODES AND DEPOSITED WELD METAL

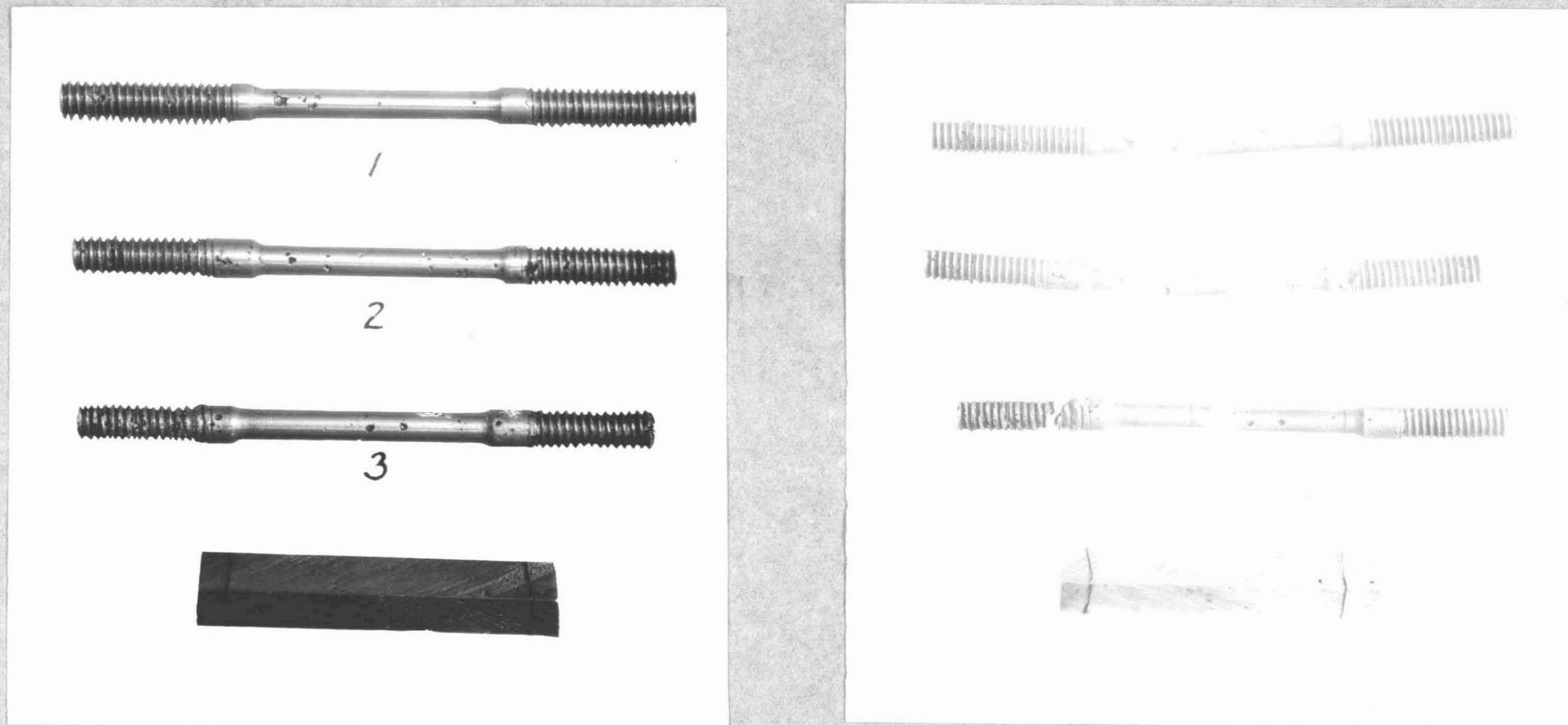


Fig. 18 - 3/16" Diameter Tensile Specimens
Lightly-Coated Electrode Welds

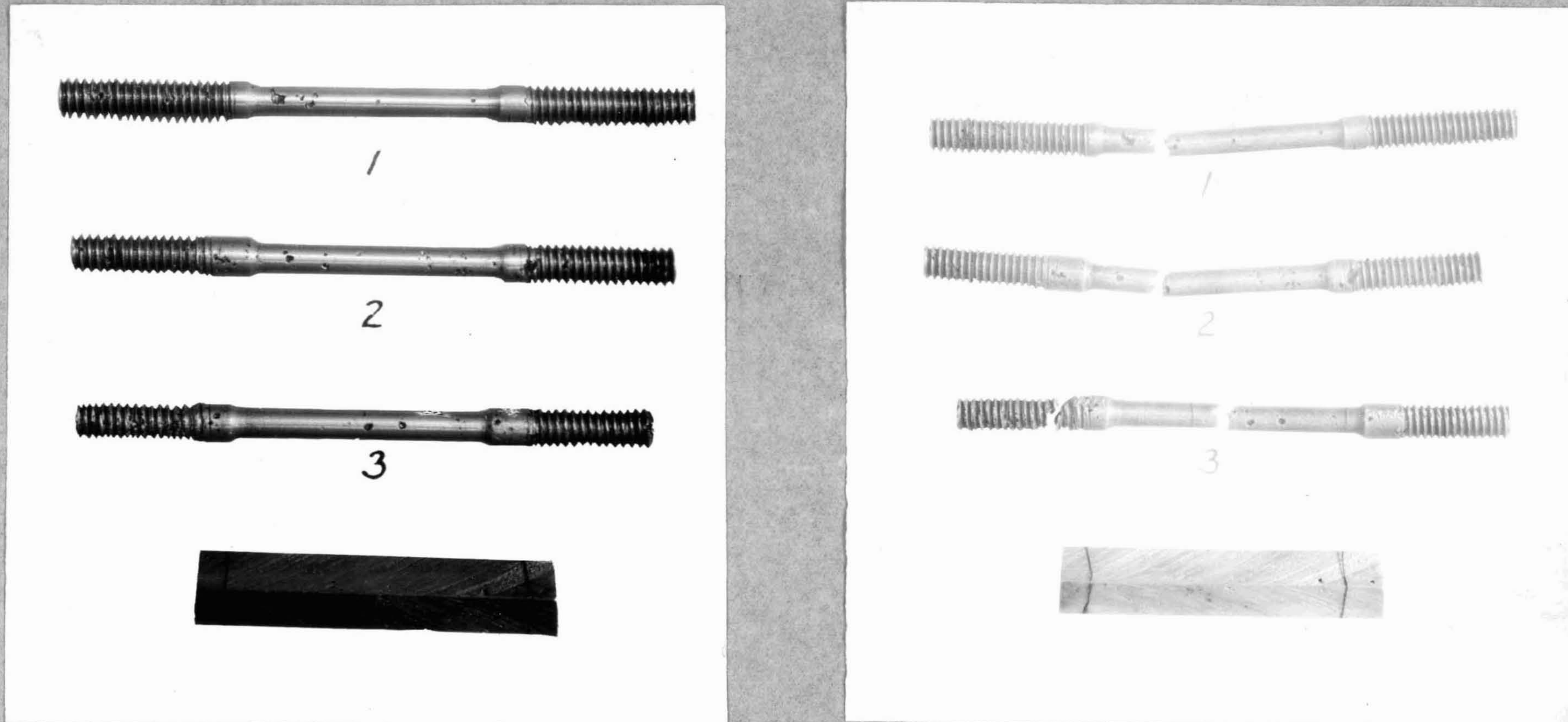


Fig. 18 - 3/16" Diameter Tensile Specimens
Lightly-Coated Electrode Welds

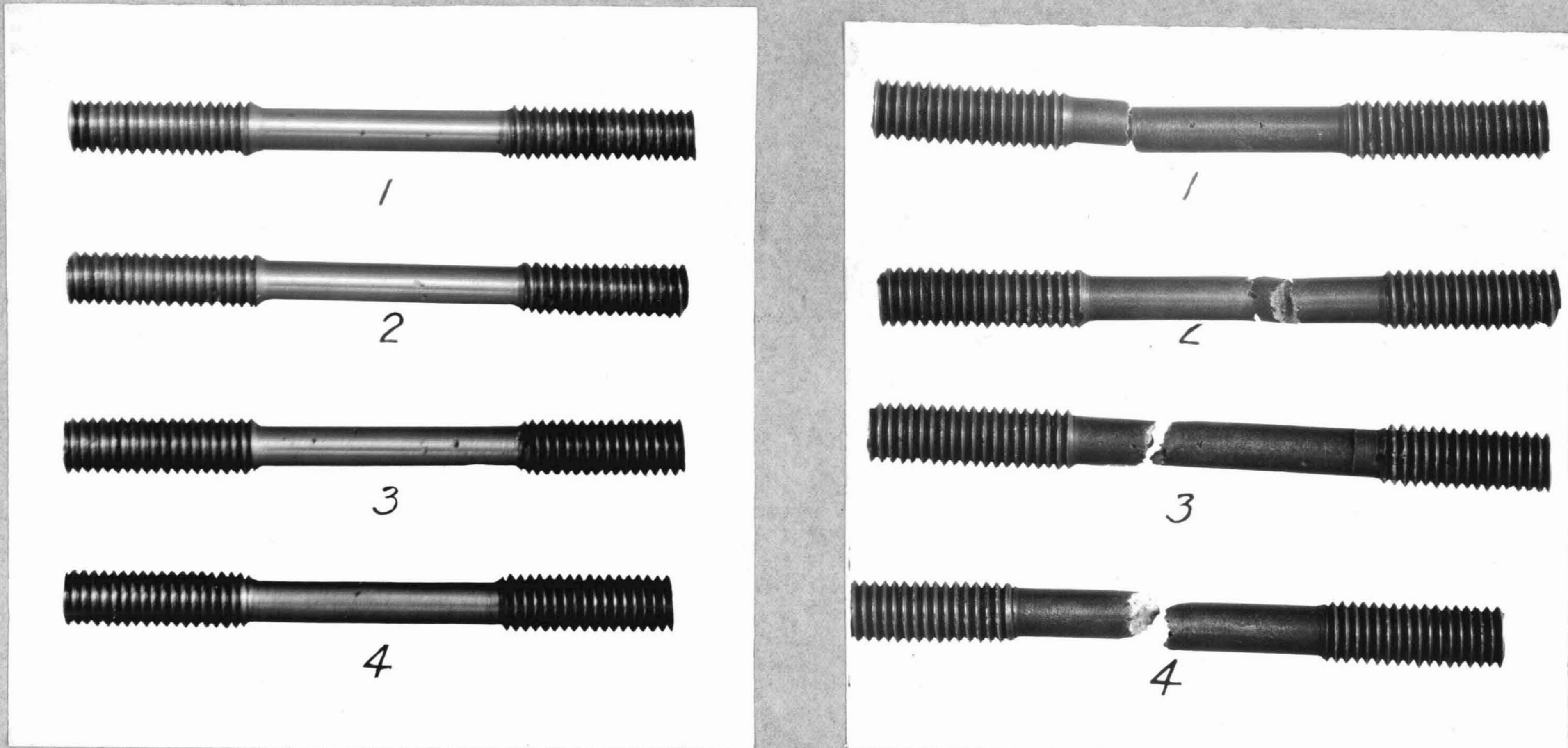


Fig. 19 - 5/16" Diameter Tensile Specimens
Lightly-Coated Electrode Welds

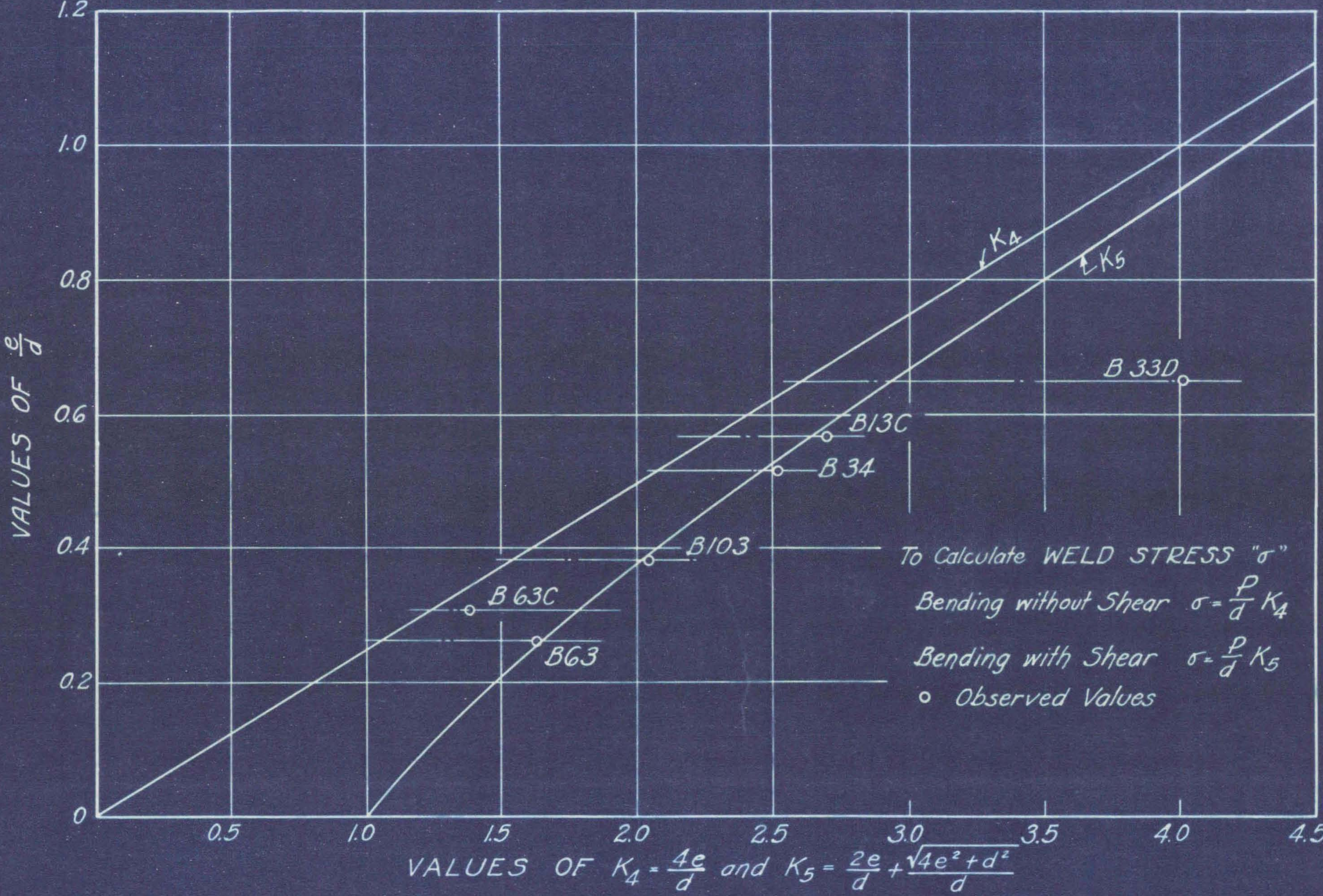


FIG. 25 - STRESS VARIATION WITH $\frac{e}{d}$ RATIO ASSUMING FULL RECTANGULAR DISTRIBUTION OF STRESS.

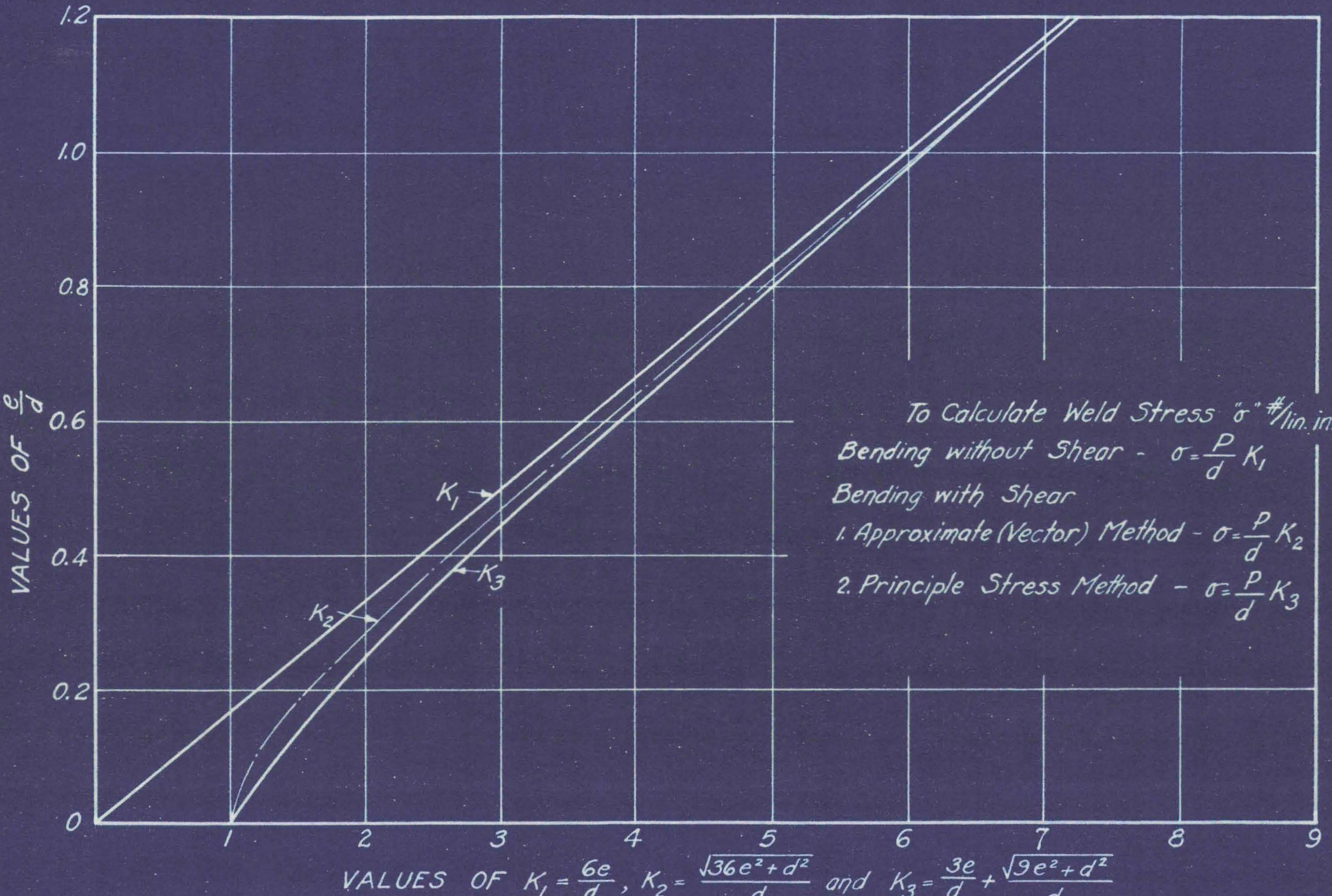


FIG. 24 - STRESS VARIATION WITH $\frac{e}{d}$ RATIO BY COMMON THEORY

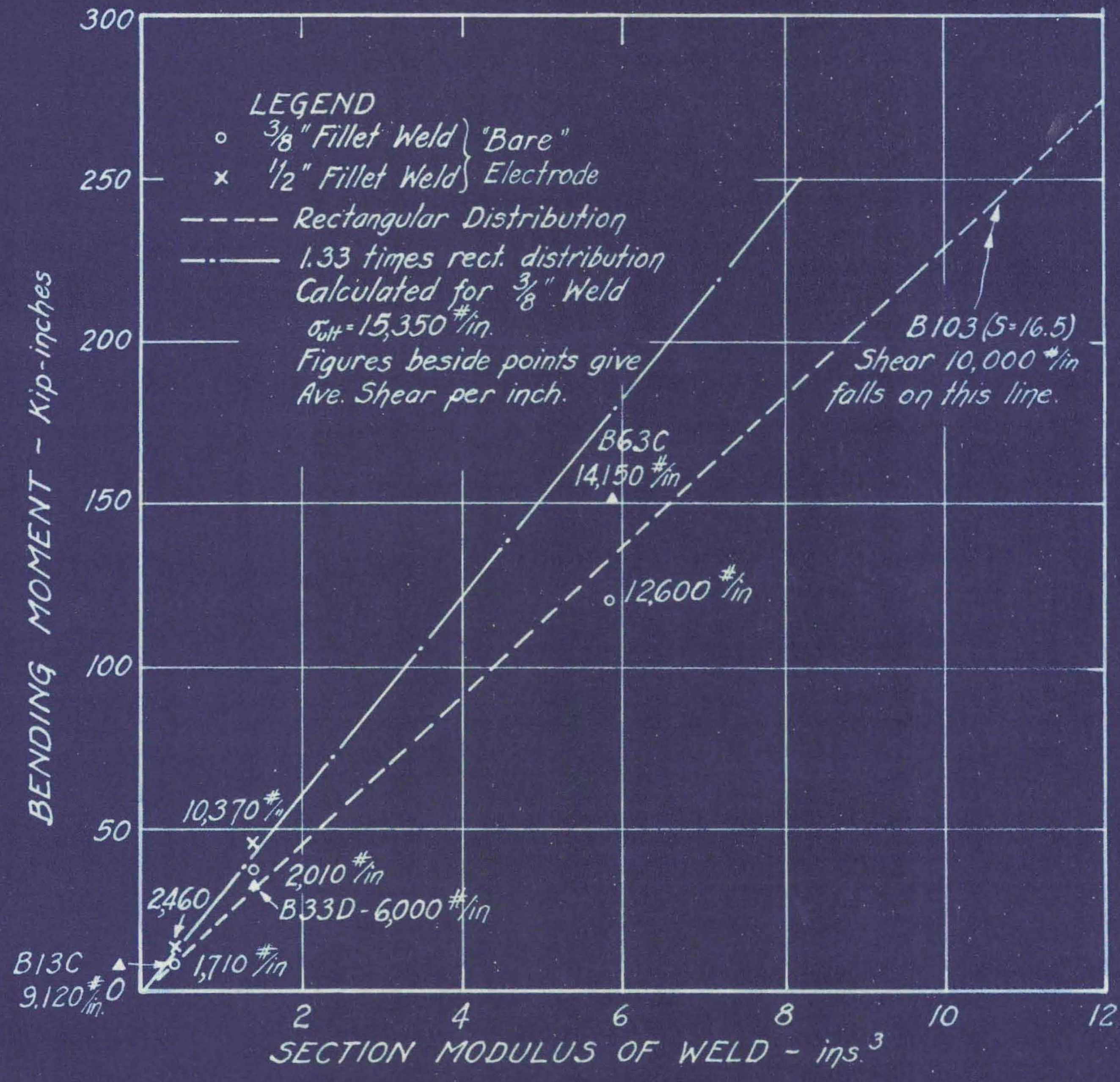


FIG. 23 - BENDING MOMENT - SECTION MODULUS CURVES - SERIES B.

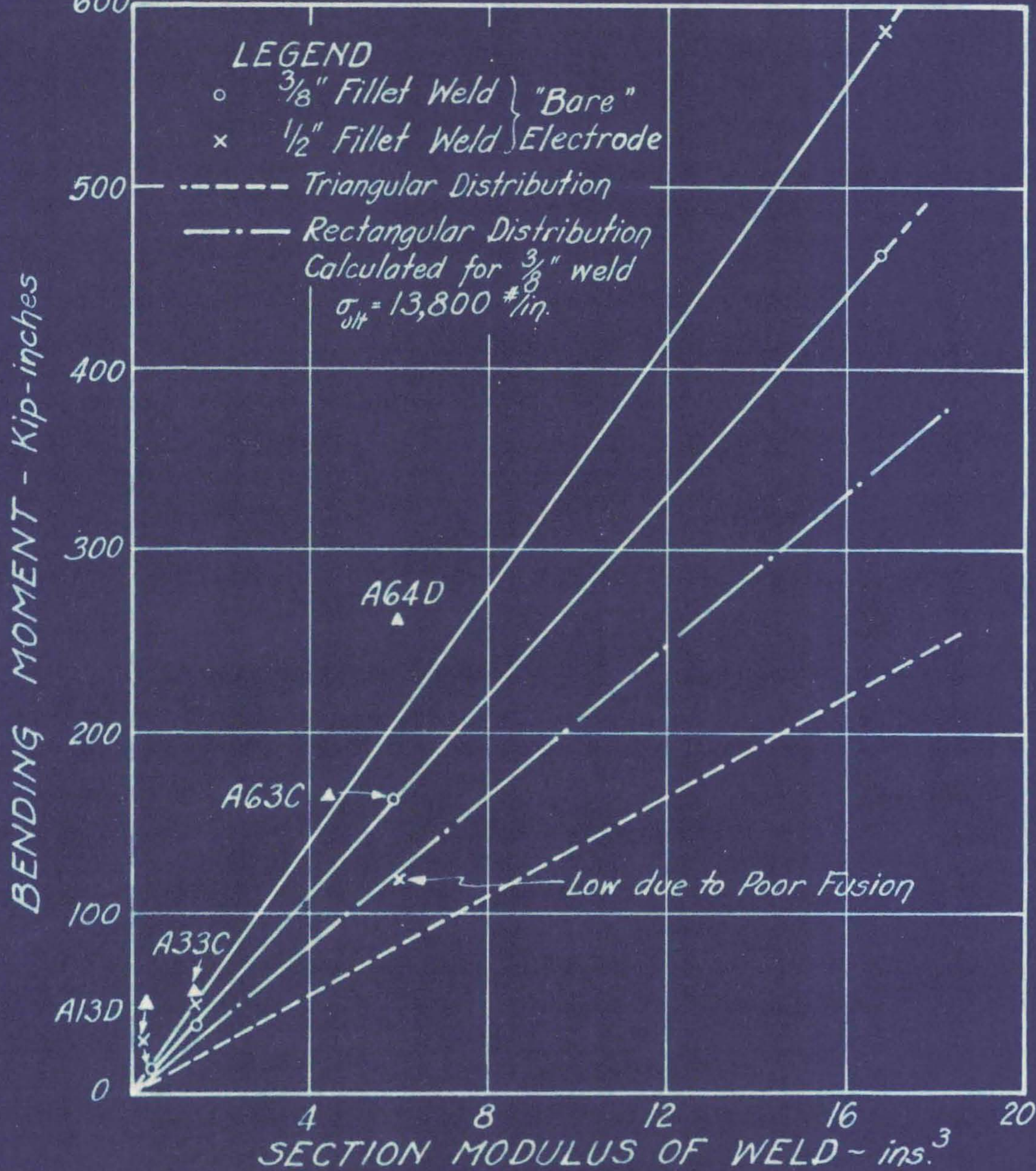


FIG. 22 - BENDING MOMENT - SECTION MODULUS CURVES - SERIES A

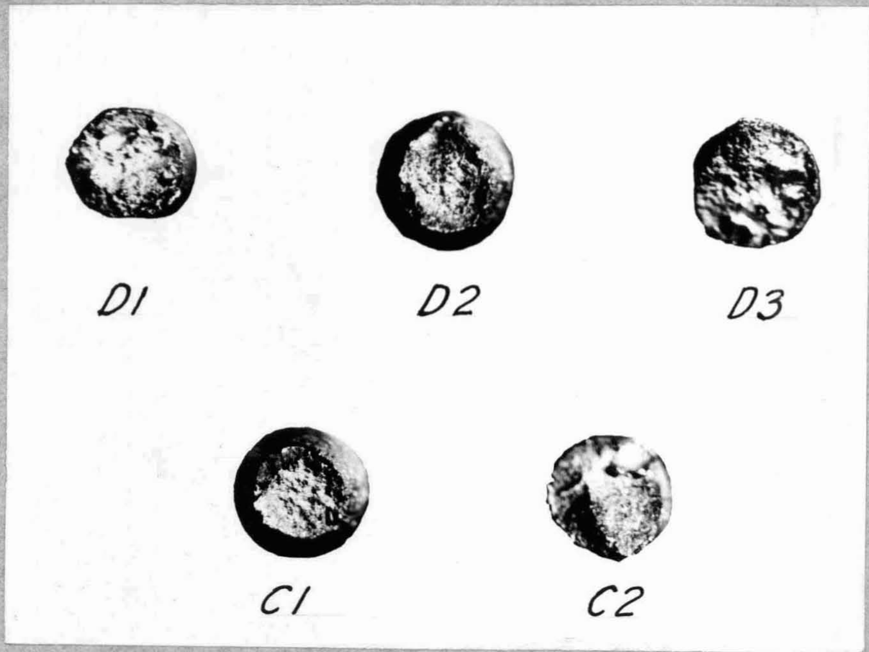


Fig. 21a - Cross-Sections x 5 - 3/16" Diameter
Tensile Specimens - Heavily-Coated Electrode

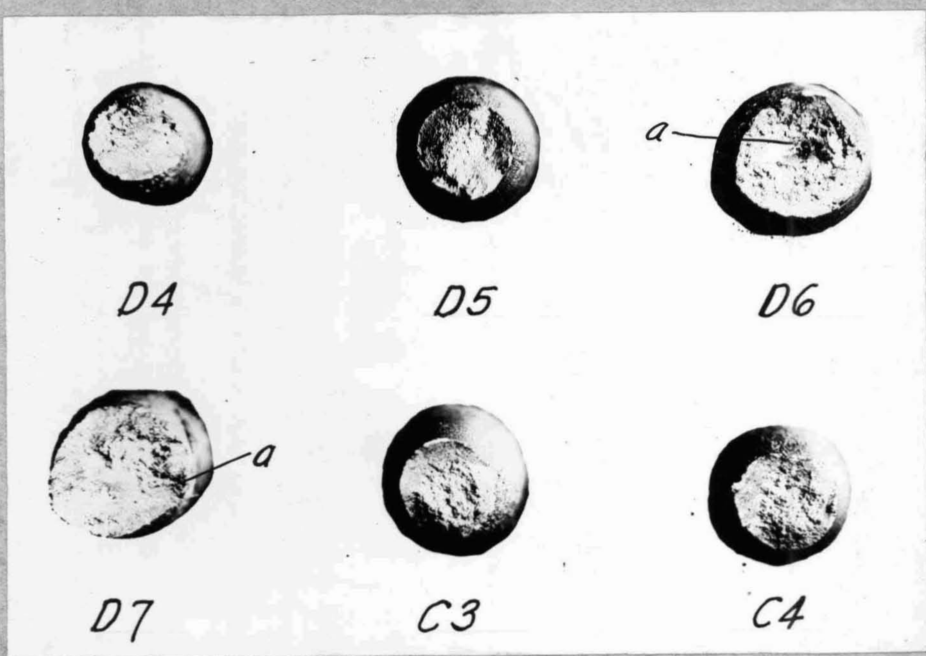


Fig. 21b - Cross-Sections x 2-1/2 - 5/16" Diameter
Tensile Specimens - Heavily-Coated Electrodes

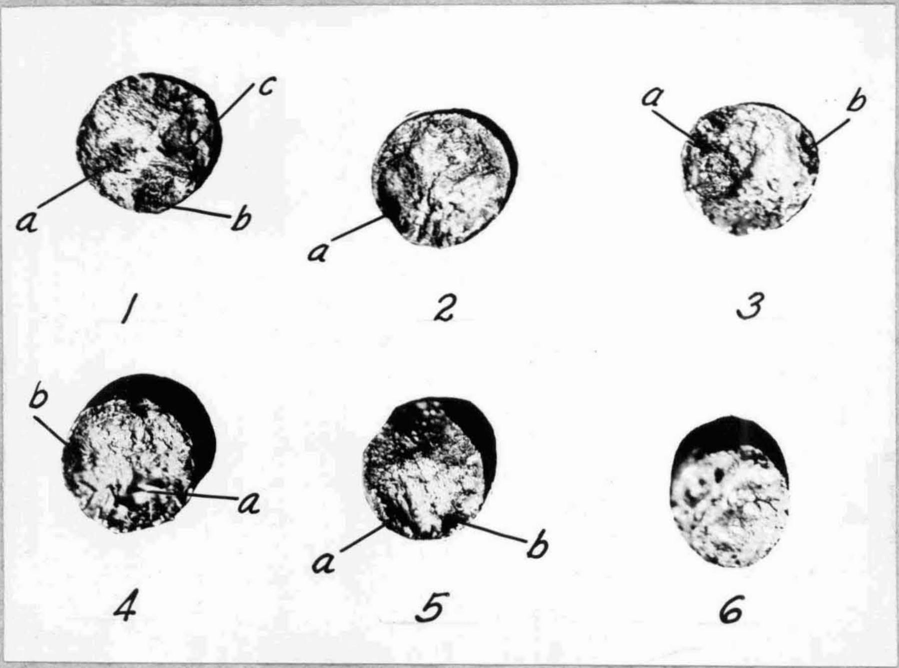


Fig. 20a - Cross-Section x 5 - 3/16" Diameter
Tensile Specimens -- Lightly-Coated Electrode

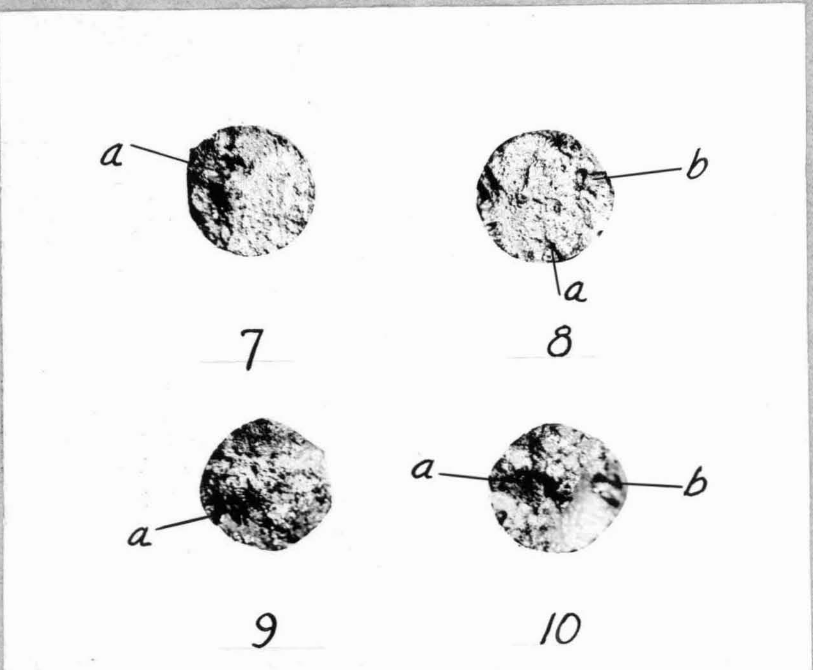


Fig. 20b - Cross-Section x 2-1/2 -- 5/16" Diameter
Tensile Specimens -- Lightly-Coated Electrodes