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Residual Stresses in Thick Welded Plates

WELDING PARAMETERS, THICK PLATES, AND COLUMN STRENGTH

by

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ABSTRACT

This paper presents a study on the influence of different welding parameters on the magnitude and distribution of residual stresses in flame-cut plates 24" x 2" made of A36 steel. The residual stress diagrams obtained after complete sectioning and after slicing are related to the original conditions of manufacture and fabrication.

The welded flame-cut plates studied have been used as parent plates of a built-up section 24H428, and the strength of this heavy section is analyzed. The differences observed in column strength of this simulated section 24H428, built up with flanges of 24" x 2" flame-cut center-welded plates and a web of a 20" x 1.½" flame-cut edge-welded plate, is correlated to the different heat inputs caused by the different fabrication processes. Conclusions are drawn with respect to the effect of the different welding parameters on the strength of the column.

The variation of the mechanical properties through the thickness and at different locations across the 24" x 2" plates was determined by means of tension tests on the

small size specimens. The results are discussed with respect to the specimen location, and compared with the patterns of residual stress obtained previously.

1. INTRODUCTION

Thermal stresses due to different sources of heat have been investigated both analytically and experimentally during the past few decades. The derivation of the temperature distribution in plates during welding and cutting held the attention of several investigators.[1,2] After having first assumed erroneously an elastic behavior of the formation of residual stresses during the process of welding or during the process of welding or during cooling after rolling, it was later recognized[3] that the residual stresses resulting after welding were due to plastic deformations. Physical and analytical explanation of the formation of residual stresses due to different thermal effects have been developed more recently.[4,5,6] Much attention was paid to the existence of, and to the possible effect of, residual stresses on the strength of structural members. Important analytical and experimental contributions to the solution of this problem and in particular of the effect on column strength[5,7,8] was made at Lehigh University through various research projects over the past two decades, under the technical guidance of the Column Research Council.

The scope of the study described in this report was to investigate the effect of different welding parameters on the magnitude and distribution of residual stresses. The experiments were carried out on six flame-cut plates 24" x 2" and one flame-cut plate 20" x 1 ½" made of A36 steel. The welding parameters chosen were based on the AWS recommendations.[9] The parameters were adopted such that they would be of practical interest while staying within the limits of variation inherent to any fabrication process, and the requirements specified by the AWS. In addition, one plate was kept "as-manufactured" for the purpose of comparison. Another plate was annealed to investigate if the heat-treating process would lead to a significant reduction of the magnitude of the residual stresses. A stress-relieving process by thermal treatment may be of interest in special cases.

The second aspect was to investigate the influence of the welding conditions on the strength of a simulated welded section 24H428 built up from the investigated plates. It had already been shown[10,11] that the residual stress distribution obtained for a welded section is more or less the same as it would be for the individual component plates with the same welds. The strength of structural compression members can be predicted knowing the magnitude and distribution of residual stress in individual welded plates.

Nowadays heavy welded columns* of different shapes are being used to an increasing extent in steel structures, but for technical and economical reasons, an extensive series of column tests cannot be performed on such heavy sections as was done in the past with lighter sections. Little information has been available on residual stress and the strength of heavy columns, in spite of the intensive utilization of these heavy shapes in construction. Thus, the column strength data obtained in the study should be of considerable interest.

Little information has been available on the mechanical properties of the heat-affected parent material and the weld material. The third part of the report describes the investigation on the through-thickness variation of mechanical properties and the variation across the width of several flame-cut center-welded plates.

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*A "heavy" column may be defined as one where the component plates are 2" or more in thickness.

2. DESCRIPTION OF RESIDUAL STRESS SPECIMENS

The tests were conducted as a part of an extensive investigation concerned with the study of the magnitude and distribution of residual stresses in thick welded plates, and with the purpose of relating this phase of the investigation towards the strength of the compression members.

The manufacture and fabrication of thick flame-cut and universal-mill plates made of A36 steel was observed. Information collected during the manufacture and fabrication of these test specimens, starting from the rolling of the component plates and up to the final fabrication processes, was recorded.[12]

The phase described in this report is concerned mainly with 24" x 2" and 20" x 1½" A36 flame-cut plates. The six specimens of 24" x 2" flame-cut plates, see Fig. 1, were prepared to the required size by simultaneously flame-cutting both longitudinal edges of a 26" x 2" universal-mill plate. The 20" x 1½" flame-cut plate was obtained by flame-cutting the edges of a 22" x 1½" universal-mill plate. The machine used was a standard burning machine equipped with two torches to burn both edges at the same time. Air burning tips (#3, style 263) were used with propane fuel at 316 psi and oxygen at 55 psi. The flame-cutting speed was set on the burning machine at 10 ipm. Temperature measurements were taken by drawing lines on the plate surface with Tempelstick temperature crayons.[(13)] Results obtained for the temperature distribution across the width can be found in Ref. 12.

Five 24" x 2" test specimens were set apart from the same parent plate as shown in Fig. 1, and the sixth specimen was taken from another flame-cut plate. Identical manufacturing conditions were used for all plates in order to reduce the number of parameters. For this reason all plates were sampled from the same heat and subjected to the same rolling conditions and the same rolling procedures in order to minimize the effect of different lots upon the mechanical properties. This objective was essentially fulfilled, and only small differences can be found for the mechanical and chemical properties of the two plate sizes. This is illustrated in the mill test report shown in Table 1. A previous study has shown that the variation of the magnitude and distribution of residual stresses within members manufactured from one lot is relatively small, but somewhat larger variation may exist between residual stress distributions from different lots.[7]

The residual stress specimens were located at the center of each plate specimen to eliminate end effects, as shown in Fig. 1. Except at both ends, the variation of residual stress along a member free of any straightening effects is small.[7] For technical reasons the plate specimens were cut from the parent plate by transverse flame-cutting. In the flame-cutting, the distance from the gage length was made sufficiently great, to avoid any effects on the measurements due to heat input.

Some of the plate specimens were center-welded, and when the electrode reached the center part of the plate specimen the thermal state may be expected to be quasi-stationary; consequently, no significant variation of longitudinal residual stresses due to the welding was expected in this part. This assumption has been satisfactorily fulfilled in tests by different investigators.[1,4,7]

The plate specimens designated CW-1, CW-2, CW-3, CW-4, CW-5 (CW for center-welded, and AM for as-manufactured) were prepared to contain the welds by making two V-shaped grooves as shown in detail A of Fig. 1. The welds were deposited by a semi-automatic welding machine Lincoln ML-2½. The type of electrode conformed to the AWS class E 7018. Table 2 shows the mechanical properties of the as-welded electrode as required by the AWS specifications AW 5.1-64T. The shielding was accomplished by enveloping the arc created between the plate and the electrode of 5/32" diameter wire with a granular 780 flux type. The details concerning the welding parameters are discussed further in Section 3.

3. EFFECT OF WELDING PARAMETERS ON THE MAGNITUDE AND DISTRIBUTION OF RESIDUAL STRESS

3.1 Welding Parameters

Five plate specimens of size 24" x 2", welded with different welding parameters as described in Table 3 were used in this investigation. One plate 24" x 2" was left unwelded to give the initial residual stresses. A flame-cut plate 20" x 1.½" also was included in the study. The results of the residual stress measurements are needed for the investigation of the column behavior of a simulated built-up section.

The different welding parameters involved are the following:

- number of passes and speed of welding,
- temperature of pre-heating,
- effect of a local and uniform pre-heating,
- effect of a post-heating.

The actual welding parameters were prepared in cooperation with the fabricator. In order to study the separate effect of each welding parameter on the magnitude and distribution of the residual stress, it was endeavored to keep the material properties similar for all plate specimens. The same manufacturing and fabrication conditions were used; in particular, the welds in each plate specimen were deposited according to the same welding sequence.

All specimens were selected to conform to the requirements of the AWS specifications.[9] Specimen CW-1 corresponds to the fabricator's normal choice of fabrication conditions. CW-2 was used to show the difference which may appear due to a different number of passes, whereas CW-3 was proposed to study the effect of a higher pre-heating temperature on the magnitude of residual stress. The influence of a local pre-heating at a temperature of 400°F, in the vicinity of the grooves, is given by the specimen CW-4. The specimen CW-5 was stress relieved by heat treating at 1200°F, maintained for 2 hours, followed by slow cooling in the furnace down to a temperature of 600°F. Finally the specimen reached room temperature by air cooling.

The criteria which guided the choice were to stay as close as possible to practical welding conditions; in particular, the temperature of pre-heating was selected in terms of economics. The specimen CW-5 was included in this investigation to study whether the stress-relieving by heat-treatment reduces the magnitude of the residual stress, and to investigate if an appreciable change occurs in the yield strength of the weld and the parent material.

The temperature of pre-heating and welding at the surface of the plate were taken with a thermo-couple as shown in Fig. 2. Slight modifications appear between the predetermined welding conditions as expressed in Table 1 and the actual technical working conditions. It has been noticed that the V-shaped grooves were at a higher temperature than any other part of the plate during the pre-heating. Figure 3 illustrates the typical set-up for pre-heating. Using this equipment, it was not possible to realize a narrow heated region. The edges of the plate specimen were at a temperature of about 150°F and the gradient of temperature between the edges and the center part of the plate was fairly small due to the thermal conductivity properties of the steel. In case of the plate specimen CW-2 the speed of welding was set up somewhat higher than proposed in order to satisfy the technical restrictions of the automatic welding machine.

3.2 Nature of Residual Stresses

The welded specimens were not free of residual stresses prior to welding. The study is intended to show also the variation of the strength under different welding conditions, and thus consideration must be given to residual stresses existing in the parent plates before welding. Residual stresses are introduced into the material during the different stages of manufacture and fabrication conditions. Prior to welding, the pattern of residual stresses is the result of a complex state of superposition of different distributions and magnitudes of residual stress.(11)

First the plates were rolled to the required size of 26" x 2", and the resulting residual stresses were due to the cooling after the hot rolling. No measurements were made on this plate 26" x 2", but to give an idea of the magnitude and distribution of residual stresses after this first operation, results of measurement made on a 24" x 2" plate of A36 steel, which belongs to the same material order, is shown in Fig. 4.(14) The edges show compressive residual stresses of about -20 ksi, which are balanced in the center part of the plate by tensile residual stresses, whose maximum is about +10 ksi.

Next, the flame-cutting operation reduces the sizes of the universal-mill plate to a 24" x 2" flame-cut plate, the resulting pattern of residual stresses is indicated in Fig. 5. It can be seen that the previous distribution of residual stresses has been completely changed by the flame cutting procedure. The edges are now in tension due to the heat input, (as a general rule the part of the plate cooling most slowly will be left in residual tension), whereas the center part of the plate is now in compression.

Only these two types of residual stresses existed in the plate prior to welding. Special care was brought to the fabrication operations in order to avoid any other stresses due to cold-bending or any processes of cold-straightening. The distribution and magnitude of residual stresses as reported in Fig. 5 can be assumed to be similar for all flame-cut specimens concerned in this study. The assumption made earlier, that the distribution of rolling stresses and flame-cutting stresses is uniform for all residual stress specimens prior to welding, seems to be reasonable because of the care in observing the same manufacture and fabrication procedures for all specimens.[15]

3.3 Results of Residual Stress Measurement

The longitudinal residual stresses were determined by the sectioning method described elsewhere.[16] Only longitudinal stresses have been measured, because of their prevailing effect on the load carrying capacity of steel columns. First, the residual stress specimen was cut into elements of different thickness depending upon the stress gradient expected. From this procedure, referred to as the complete sectioning, the magnitude and distribution of residual stresses on the large surface of the plates was determined. Figures 5 through 11 present the results of the measurements for each plate specimen, as well as the sectioning detail.

The isostress diagrams as presented in Figs. 12 through 16 have been obtained from the superposition of the residual stresses after sectioning, and the residual stress variation across each element as determined by slicing the element into small strips.[11] In the part of the plate affected by a local heat input such as produced by a flame-cutting or a welding operation, the variation of longitudinal residual stresses across the thickness of the plate was found to be very important. In the plates investigated, the stresses released by the slicing procedure have been observed to vary between +6 ksi at the edges and -5 ksi at the center part of the thickness of the plate for an element located at the flame-cut edges and between +9 ksi at the non-welded edge and -7 ksi at the mid-thickness of the plate for a strip containing the weld. In the part of the plate not drastically influenced by the external heat input, the variation is between -2 ksi and 2 ksi at the mid section.

Results are shown in Fig. 11 for the residual stress measurements on the 24" x 2" universal-mill plate, referred to as UM-2, which was center-welded with approximately the same welding parameters as the specimen CW-1.[12] These results have been incorporated into this study to see the effect of the welding upon the magnitude and the distribution of residual stresses of two plates of the same dimension but with a different manufacturing procedure, that is, universal-mill or flame-cut plates. As pointed out previously, the patterns of residual stresses in a universal-mill plate, Fig. 4, and in a flame-cut plate Fig. 5, differ considerably.

Table 4 summarizes the magnitude of residual stresses for the different plate specimens investigated.

The data summarized in this table give information about the level of residual stresses at the edges and at the weld location of the plates, where largest magnitudes of residual stresses are to be expected.

3.4 Discussion of the Results

Different patterns of residual stress have already existed in the plate specimens prior to welding, and these are known or may be estimated. First, there are the residual stresses which remain after cooling from the rolling, on which are superimposed the residual stresses due to the flame-cutting. Since all plates were rolled and flame-cut to the specified sizes, the pattern and magnitude of residual stresses given in Fig. 5 can be assumed for all plate specimens before welding.

During the welding operation, there are two heat inputs, which lead to a modification in the magnitude and distribution of residual stresses; that is, the heat input due to the pre-heating or post-heating, and finally, the heat input created by the welding procedure itself.

The symmetry obtained in the distribution of residual stresses in the flame-cut plate, Fig. 5, is explained by the fact that the flame-cut edges have been burnt simultaneously. Furthermore, the results obtained on the two surfaces of the flame-cut plate are almost identical. Thus, as a first approximation, the analytical problem of temperature distribution in a flame-cut plate can be considered as a two-dimensional problems, in which the heat input per unit thickness is constant. The slightly non-symmetrical pattern of residual stresses after welding, see Figs. 6 through 9, is due to the sequence of weld passes adopted. In addition to the weld region, where a major modification in magnitude and distribution of residual stresses occurs, changes take place also at the edges of the plate under the combined influence of the pre-heating and of the heat conduction in the plate during welding. Because of the welds being deposited on one side of the plate, significant differences are noticed in the magnitude and distribution of residual stresses on both surfaces of the plate.

When comparing Fig. 11 with Figs. 6, 7, 8, and 9, it can be pointed out that whatever the pre-heating and welding condition, and whatever the pattern of residual stresses prior to welding, the tensile stress in the weld material reaches the yield strength of the weld material.

This is clearly shown by comparing the yield strength requirement of the as-welded electrode material E7018 indicated in Table 2, with the maximum tensile stresses given in lines 5 and 6 of Table 4.

Due to the high gradient of cooling temperature in the vicinity of a local heat input, such as flame-cutting or welding, the mechanical properties of the parent material there may change. The tensile residual stresses in the parent material, resulting from such a heat source, indicate a higher yield strength than that of the non-heat-affected parent material. This fact appears more clearly in Figs. 12 through 16 than in Table 4 which did not include the residual stress variation through the thickness of the plate which is obtained by the slicing procedure as explained above.

The residual stresses at the welded surface undergo a major modification compared with the initial pattern existing prior to welding. The variation of residual stresses through the thickness after welding is found to be nearly 10 ksi, which is substantially greater than that found in thinner plates.[17]

The isostress diagrams show the influence of the welding effect. It can be noticed in the case of the specimen CW-2, Fig. 14, that there is a greater penetration of the weld, perhaps due to the lower speed of welding.

The specimen CW-3, pre-heated at 400°F, does not show a significant modification of the magnitude and distribution of residual stresses, compared to the specimen CW-1; (Figs. 15 and 13 respectively). The raising of the pre-heating temperature from 200°F to 400°F does not provide a real benefit as far as the magnitude and distribution of residual stresses is concerned.

The residual stresses in the annealed specimen CW-5, Fig. 10, are practically negligible; they are of the same order of magnitude as the possible errors of measurement.

The differences obtained in the residual stresses diagrams for specimens CW-1, CW-2, CW-4 are small, see Figs. 6, 7, 8, and 9 respectively. The influence of the welding condition will be discussed further in Section 4, by considering their effect on the strength of a column.

4. EFFECT OF WELDING PARAMETERS ON THE STRENGTH OF A SIMULATED BUILT-UP SECTION 24H428

4.1 Introduction

Since the recognition of the importance of the effect of residual stresses on compression members, a great deal of research has been spent on the strength of such members, both experimentally and analytically. Based upon the concepts of the tangent modulus load and the maximum strength, a significant contribution for predicting the load-carrying capacity of rolled sections was done in the past.[7,18,19] More recently, the same approaches have been used successfully for predicting the strength of welded built-up columns.[20,21] However, the problem is more complex, and more involved than the determination of the strength of rolled sections, because of the great number of parameters involved:

- manufacture of the components of the section (universal-mill, or flame-cut plates),
- geometry of the component plates,
- geometry of the section,(H, box, etc.),
- welding conditions,
- type of steel.

In the past, a rather good agreement has been found experimentally between predictions by the tangent modulus concept and tests results.[21] As discussed below, the simplifications often introduced in the theoretical analysis do not warrant the use of the more refined prediction of the maximum strength. Furthermore, a comparison of column strength for built-up sections composed of plates center-welded with different welding parameters was a major purpose of this investigation. Therefore, this investigation studied the tangent modulus load-carrying capacity of the simulated flame-cut welded column 24H428, built-up with different investigated center-welded plates.

Extensive testing on heavy welded columns can be performed only at great expense, and findings established in the past have to be taken into consideration. Thorough experimental investigations of the residual stress distribution in small and medium-size rolled and welded built-up sections have been conducted by different investigators.[5,11,19,21] In these studies it was found that a welded built-up shape may be considered as equivalent to the separate component plates with simulated welds, provided that the sizes of the parent plates, as well as the heat inputs, are nearly the same. Thus, from the knowledge of the residual stress distribution in the welded component plates, the complete pattern of residual stresses in a built-up section may be deduced, see Fig. 17. With this as basis, the residual stress distribution in the structural shape was used below in the prediction of its behavior under compressive load.

Such an approach was used here to study the effect of the welding parameters on the strength of a welded built-up section 24H428, see Fig. 17. This shape was simulated from the different plate specimens as mentioned above. This welded section built up from two flanges of 24" x 2" and a web of 20" x 1½", composed from the separate plate specimens which were investigated, and for which residual stress patterns were discussed earlier in Sect. 3.

No measurement on the simulated edge-welded plate corresponding to the web of the 24H428 shape has been performed. Figures 18 and 19 present the results of the procedure which was followed to determine the distribution and magnitude of residual stresses. From the pattern of the initial stresses existing in a flame-cut plate 20" x 1½", Fig. 18a, the residual stress modification created by the welds deposited at the four edges of the plate has been computed, and compared with the experimental results available for a similar edge-welded flame-cut plate 9" x $1\frac{1}{2}$".[14] The temperature distribution was evaluated from the study made by Rosenthal.[1] The coefficient of heat losses was chosen as 85% which gives a good agreement with the result experimentally found for the plate 9" x $1\frac{1}{2}$".[22] In other words, 85% of the heat generated is effective in causing thermal stresses in the plate 20" x $1\frac{1}{2}$" in order to obtain stresses comparable to those found experimentally. The other variables, amperage voltage, speed of welding were taken from prior experience,[12] and the thermal properties of the plate used were those suggested in Ref. 17. Figure 19 shows the residual stress distribution assumed in the web plate, and developed from the results of Fig. 18B by including the residual stresses due to slicing, as obtained from the data collected in similar plates.

A numerical method utilizing a digital computer was used to compute the tangent modulus load, taking into account the measured residual stress distribution and material properties discussed above. Two sets of non-dimensionalized tangent modulus column curves (P/P_Y versus λ) were computed for both axes of the simulated section. The first set of curves correspond to the average residual stress through the thickness as obtained after complete sectioning, Figs. 6 through 11. The second set of curves was computed for the actual through-thickness variation of residual stresses as indicated in Figs. 13 through 16.

The numerical computation was accomplished by dividing the section into a number of finite area meshes, Fig. 20. The computation was based upon the following assumptions:

- Plane sections remain plane before and after application.
- The stress-strain relationship in any fiber is an ideal elastic-perfectly-plastic diagram.
- The residual stress distribution is symmetrical with respect to both axes. The experimental residual stress distributions were replaced by symmetrical diagrams obtained by averaging the distribution of the left and right parts of the plate.
- The geometrical properties of the section are constant along the beam.
- The column is perfectly straight.

4.2 Analysis of Results

A comparison between Figs. 21 and 22, or 23 and 24 indicates that the influence of residual stress is more pronounced for column buckling about the weak axis, than about the strong axis. This result is to be expected from theoretical predictions.[8]

A closer look at Figs. 21 and 23 reveals that there is no discernible variation due to effect of the welding conditions in the tangent modulus curves with respect to the strong axis buckling. The greatest difference in magnitude of residual stresses in component plates occurs mainly at the edges of the plate, and thus their influences upon the tangent modulus load with respect to the strong axis bending are less pronounced than for the weak axis bending.

The variation of residual stresses across the thickness of the plate, (those released by the slicing procedure), is of a large magnitude only in the region locally affected by a steep cooling temperature gradient as discussed in Sect. 3.3. Except for these areas, the variation through the thickness of the plate is not important for the plate dimensions studied here. Consequently for columns composed of wide plates, the tangent modulus curves computed from the average of the surface readings of the residual stress distributions and from the complete stress distribution through the thickness do not show a distinct difference, as would be the case for thick, relatively narrow plates. In the case where the isostress diagram is needed, it might be sufficient to slice only some elements taken in the vicinity of the flame-cut edges and the weld region, with some additional strips taken from the non-heat-affected zone in order to determine the entire stress distribution.

Figures 21 and 22 indicate the great influence of the manufacturing procedure on the column strength, that is, for welded H-shapes composed of universal-mill plates (plate specimen UM-2) and flame-cut plates. The existence of compressive residual stresses at the edges of a universal-mill plate is detrimental as far as column strength is considered, when compared to the welded built-up shape with flame-cut plates of the same sizes. The fabrication of built-up columns from flame-cut plates results in stronger columns; it is also economically feasible, as well as technically possible, by the use of motorized gantry-type burning machines which usually handles plates from 4 inches up to 15 inches thick and up to 160 inches wide.[23]

These figures also show clearly the favorable effect of the stress-relieving process on the strength of the column; however, such a process is expensive and, in general, impossible for large structural components. In any event, the absence of residual stress is the most favorable condition for column strength.

Examination of Figs. 22 and 24 indicates that only a small difference exists between the column curves of the shapes built up with the plate specimens CW-1 and CW-2. The column curve for specimen CW-1 is slightly higher than the column curve for the shape built-up from the plate specimen CW-2, but this is probably not of general significance. Thus, it appears that the number of passes is not a critical factor in producing residual stresses. As found analytically[5] the major portion of the stresses are caused by the first pass. Also, the influence of reducing the speed of welding, which was also a welding condition imposed on the specimen CW-2, is negligible; the change expected theoretically in terms of this welding condition has proven to be very small.

Comparison of column curves in the case of the weak axis buckling of the simulated built-up section with plates CW-1 and CW-3, (reflecting the difference in pre-heating temperature, that is, 200°F and 400°F), does not exhibit any significant difference (see Figs. 22 and 24). Thus, the effect of increasing the pre-heating temperature from 200°F to 400°F, has practically no influence on the buckling strength of the section studied. It was discussed in Sect. 3.4 that the residual stresses measured were similar for plates CW-1 and CW-3; as will be pointed out in Sect. 5.2, the mechanical properties of the material do not reveal a significant improvement.

Contrary to the two previous comparisons, the deviation in column strength between the specimens designated as CW-1 and CW-4 is more pronounced. Specimen CW-1 pre-heated uniformly indicates a more favorable column strength than specimen CW-2 which was locally pre-heated.

5. VARIATION OF MECHANICAL PROPERTIES

5.1 Tensile Tests

The flame-cutting or welding process leave high tensile residual stresses in the heat-affected region. These tensile stresses have a much higher magnitude than the yield strength of the parent material.

A systematic investigation of the longitudinal mechanical properties, through the thickness and across the width of the plate, was conducted to clarify why such peaks of tensile stress can be greater than the yield strength of the parent material.

Values of the static yield strength, ultimate strength, percent elongation, and reduction of area, were obtained from tension tests on small size specimens taken at different locations of the cross section as shown in Fig. 25. Standard test specimens with an 8 inch gage length were also made to check the results of the small size tension specimens. The testing procedure and technical terms adopted conform to those described in reference 24. All 2 inch gage length specimens were loaded similarly at two strain rates. Up to the onset of strain-hardening the rate of straining was set at 0.18 ipm and in the strain-hardening range the speed of loading was raised to 0.45 ipm.

The 2 inch gage length tensile specimens were taken from the two heat-affected zones and in the intermediate position. One specimen, location 11 in Fig. 25, contains a part of the weld.

The same distribution of the tensile test specimens, through the thickness and along the width of the cross section as indicated in Fig. 25, was kept for all 24" x 2" flame-cut plates designated as AM-1, CW-1, CW-2, CW-3, CW-4, CW-5. The reference number of a tensile specimen is composed of two digits which indicates the "level" and the "position" of the specimen in the plate as described in Fig. 25. The numbering was adopted to help the discussion of the results, and the difference between "position" and "level" is clearly defined in Fig. 25.

Figures 26, 27 and 28 show in a graph form and for each level, the variation of the static yield strength and the percent elongation of the 2 inch gage length tensile specimen for each plate. Tabulated details of static yield strength, modulus of ealsticity, ultimate strength, percent reduction of area, and percent elongation in gage length, are presented in Reference 25.

5.2 Discussion of Results

There is a discrepancy observed between the values of the yield strength of the material as given by the mill test report, Table 1, and the results of tension tests carried out on the same material;[25] much of this is due to the effect of the strain rate.[26]

Figure 26 indicates that, for the plate specimens CW-1, CW-2, CW-3, CW-4, the weld and a part of the adjacent heat-affected base metal had a significantly higher yield strength, a somewhat higher ultimate strength, and a lower elongation and reduction of area than the unaffected base metal (tension specimen 11). The tensile residual stresses obtained at the weld for all center welded plates, except for the stress-relieved specimen, is around 63 ksi; the yield strength of the material containing a part of the weld was lower than the value previously given.

There is, for the stress-relieved specimen CW-5, an important decrease of the static yield strength for specimen location 11, containing the base metal and a part of the weld, see Fig. 26. Due to the stress-relieving process the base metal has a somewhat lower yield strength, and higher ductility than the non-heat-treated specimen.

For the tension specimens, excluding CW-5, whose locations are 12, 22, and 32, no significant effect of the heat transmitted from the steep rate of cooling during the flame-cutting or welding process is noticed. In other words the high temperature gradient has only a local influence on the yield strength, and hence on the magnitude of residual stress.

The differences in mechanical properties of the parent material for the tension specimens taken in the vicinity of the flame-cut edges such as 13, 23 and 33 are less accentuated. Specimens in location 33 show a significantly higher static yield strength than the parent plate material, Fig. 28. Probably, this is due mainly to the fact that the specimens were cut from a region directly influenced by the flame.(11) This fact has been verified by observing the line markings produced by the liquid particles in fusion on the cut surface.

Reference 27 notes very high values of the Rockwell hardness in the area located in the immediate vicinity of the cutting flame. The difference of the Rockwell hardness through the thickness is explained by the difference of microstructure of the cut surface. This confirms the high magnitude of tensile stresses found in the heat-affected area. These deviations are more important than those experimentally observed, because the average behavior measured over the cross section of the tension specimen does not give a full indication of the mechanical properties in the immediate vicinity of the flame-cut surface.

Examination of Figs. 26, 27, and 28, for the test results performed on specimen AM-1, does not indicate any significant variation of the mechanical properties along the width of the plate. The only difference observed, that is, a higher static yield strength, was for tension specimens coming from the neighborhood of the flame-cut edges.

6. SUMMARY AND CONCLUSIONS

The investigation described in this report was concerned with the effect on residual stresses and column strength of the welding condition, pre-heating, post-heating, temperature, number of passes, and speed of welding. The experimental work was carried out on 24" x 2" flame-cut and universal-mill plates of A36 steel. This study was a part of a major research program intended to determine the residual stresses in thick welded plates and shapes and to relate this to the load-carrying capacity of compression members.

The influence of the welding conditions was studied in two separate steps. Firstly, the evolution and differences of the magnitude and distribution of the longitudinal residual stresses were investigated. Secondly, the effect of these different patterns of residual stress on the load-carrying capacity of simulated column shapes built-up from flame-cut plates was analyzed. Special attention was paid to the variation of mechanical properties of these specimens subjected to different heat input during their fabrication.

From these investigations carried out in this phase of the research program, the results found may be summarized as follows:

(1) The variation of residual stresses across the thickness of a plate was found to be significant in the heat-affected zone, but in the regions more than 2" distant from the flame-cut edges and the weld area, this variation is greatly reduced.

(2) Whatever the pre-heating and welding conditions of the plate, the maximum tensile residual stress created in the weld area reaches the yield strength of the weld material.

(3) In the regions of the parent material subjected to a very steep gradient of cooling temperature, as in the case of cutting or welding processes, it was found that the residual tensile stresses in these regions are equal to the yield strength of the weld metal, or, for metal affected by flame-cutting, the local yield strength, which is higher than the yield strength of the unaffected parent material.

(4) A higher pre-heating temperature of 400°F, as compared to the normal of 200°F, has no significant effect on the formation of

residual stresses, and consequently, no real improvement of the tangent modulus load was observed.

(5) Annealing reduces the magnitude of residual stresses to a negligible value. The mechanical properties of the parent material and the weld are also affected by the heat treatment. A lower static yield and ultimate strength and an improvement in the ductility properties were noticed.

(6) For relatively wide and thin plates, the variation of longitudinal stresses through the thickness has almost no influence on the tangent modulus load.

(7) The tangent modulus load computed with respect to the weak axis buckling is more sensitive to variations of welding conditions.

(8) The manufacture and fabrication conditions play an important role in column strength. Welded shapes made of universal-mill plates have an unfavorable column curve compared with the column curves computed for a welded built-up section made of flame-cut plates.

(9) The number of passes and the speed of welding

have almost no influence on the column strength of welded built-up sections.

(10) The weld and part of the adjacent heat-affected base metal, has a significantly higher yield strength, and slightly higher ultimate strength, whereas the ductility properties of the material are reduced compared to those of the base metal.

(11) Meaningful differences are observed for the mechanical properties between the tension specimens cut in the vicinity of the flame-cut surface, and the tension specimens taken from the unaffected base metal.

7. ACKNOWLEDGEMENTS

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8. TABLES AND FIGURES

Table 1 Mill Report of Mechanical and Chemical Tests

Plate No.	Yield(1) Strength (ksi)	Tensile Strength (ksi)	Elongation % (2)	C %	Mn %	P %	S %	Si %
24x2	39	71	29	.18	1.00	.012	.020	.25
20x1½	44	71	36	.20	1.00	.008	.019	--

(1) As given by a dynamic test

(2) The gage length was 8 inches

Table 2 Typical Mechanical Properties*

Electrode Name	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2" %
E7018	72 - 79	60 - 66	24 - 31

*Conforms to Test Requirements of AWS-A5.1 & ASTM-A233. Low figures give the minimum AWS requirements of the as-welded material.

Table 3 Welding Parameters and Residual Stress Specimens

Flame-Cut Plates, A36 Steel

Specimen Number	Preheat Temp. °F	Postheat Temp. °F	First Pass Velocity ipm	First Pass Current A	First Pass Voltage V	Second Pass Velocity ipm	Second Pass Current A	Second Pass Voltage V
Plates 24" x 2"								
AM-1*								
CW-1	200		16	410	32	32	410	32
CW-2	200		8	410	32			
CW-3	400 uniform		16	410	32	30	410	32
CW-4	400 local at weld	Annealing Process, see Sect. 3.1	16	410	32	30	410	32
CW-5	200		16	410	32	30	410	32
Plate 20" x 1½"								
H 428 FC W1*								

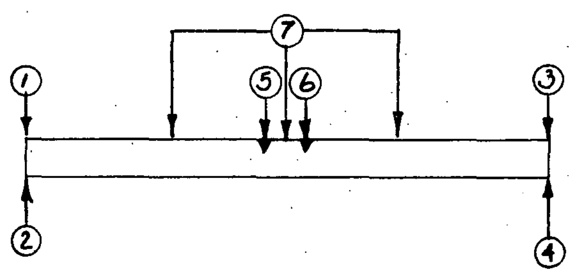
*Plates as-manufactured

Table 4 Residual Stresses Magnitude at Different Location Across The Plate Width

(ksi)

Location	Plate Specimen Designation (FC)						(UM)	
	AM-1	CW-1	CW-2	CW-3	CW-4	CW-5	UM-1	UM-2
1	32.1	28.0	22.4	5.4	4.1	1.6	-18.7	-24.0
2	35.1	41.3	28.1	14.5	14.5	-.1	-17.8	-15.1
3	37.2	28.1	7.4	4.1	13.4	-.8	-18.0	-21.1
4	39.1	39.5	18.2	11.0	22.9	-2.3	-18.7	-17.0
5	-.1	62.1	62.8	61.6	61.6	2.5	7.4	61.9
6	-.9	64.4	60.1	65.7	63.0	3.0	7.4	65.3
7*	-	38.2	42.8	36.2	39.1	-	-	42.3

*Values obtained by averaging the experimental results relative to the elements adjacent the elements containing the weld.



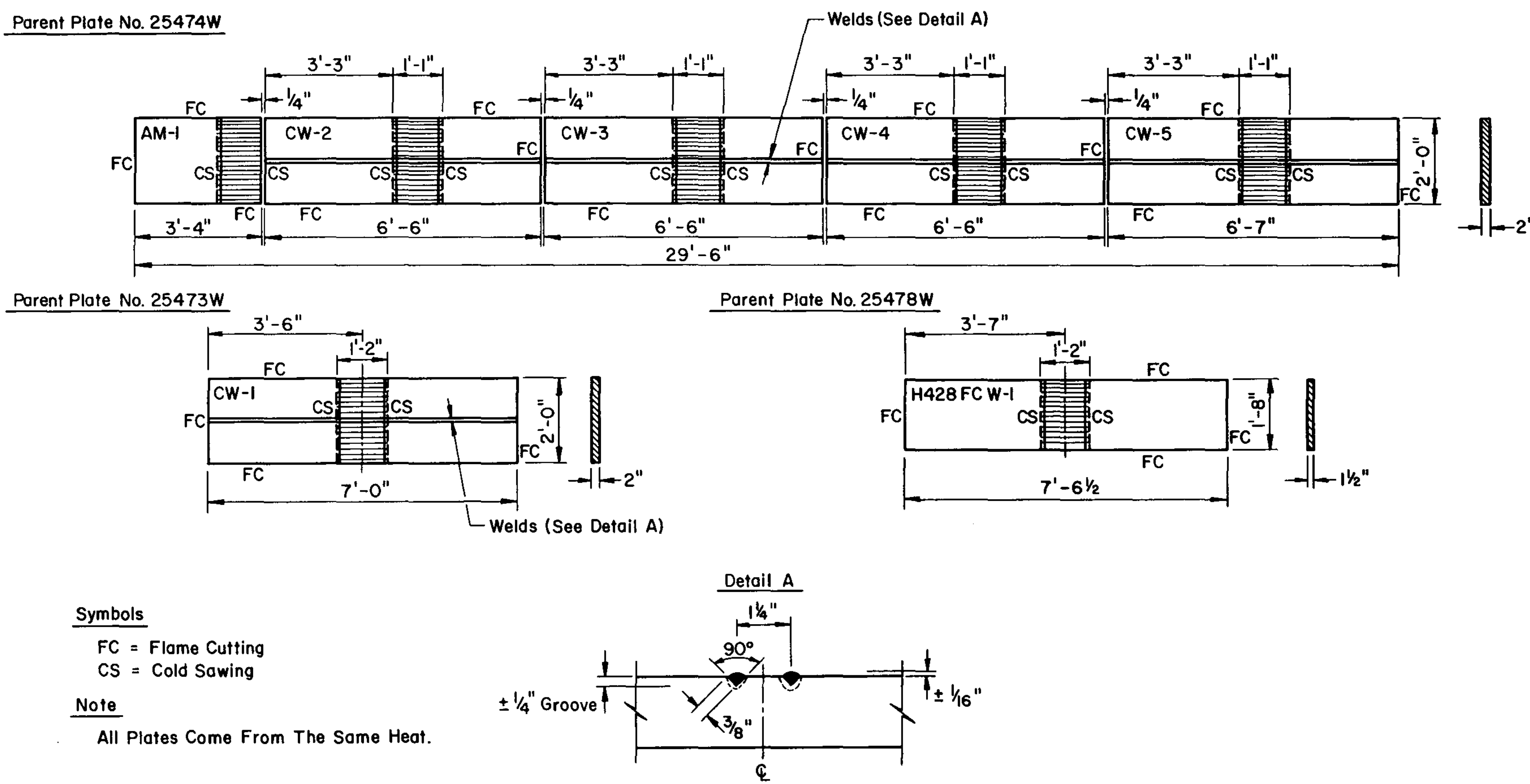


Fig. 1 Residual Stress Specimen Preparation

Fig. 2 Temperature Measurement

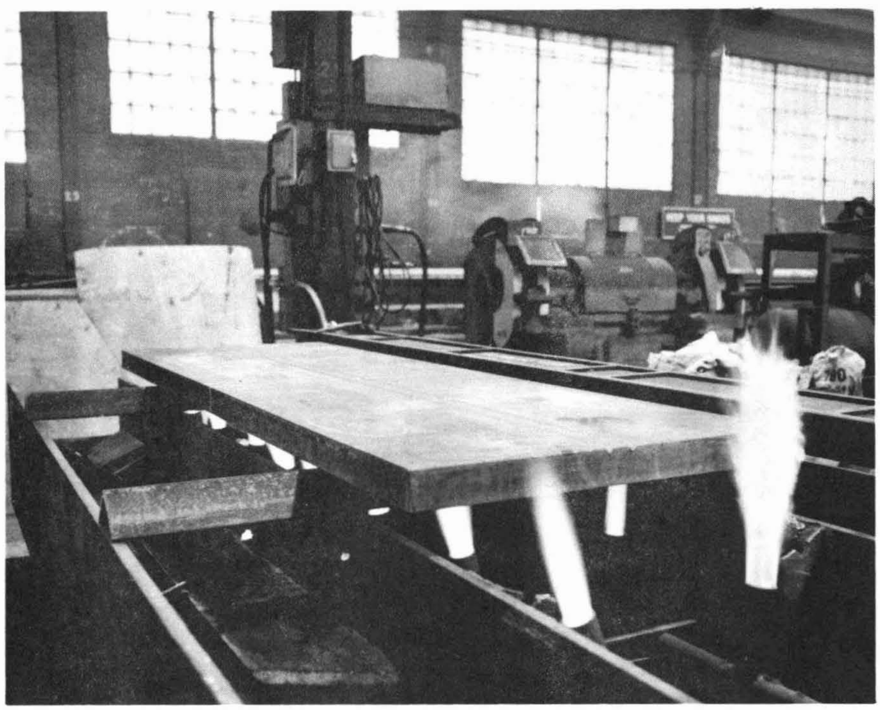


Fig. 3 Set-Up for Preheating

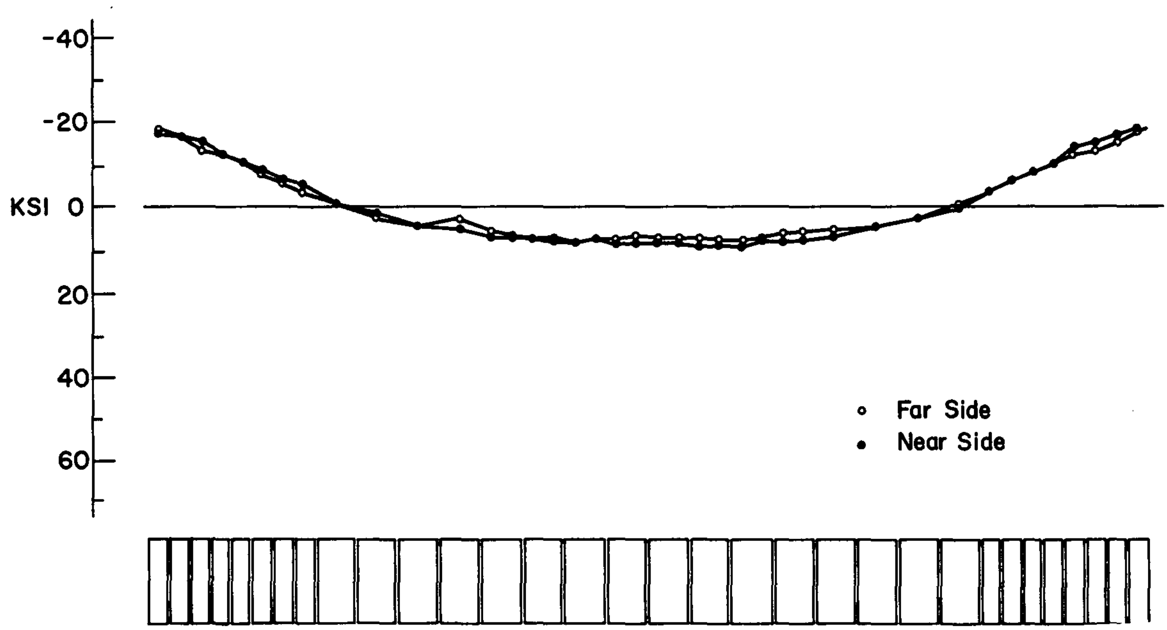


Fig. 4 Longitudinal Residual Stresses in a Universal-Mill Plate 24" x 2"

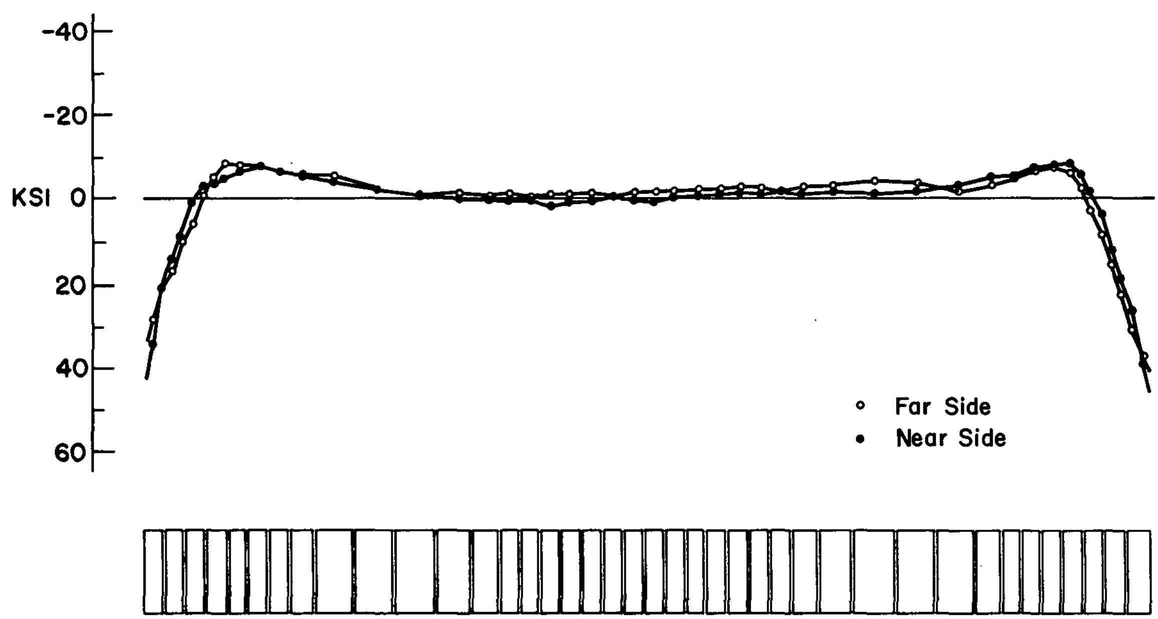


Fig. 5 Residual Stresses in a Flame-Cut Plate 24" x 2"

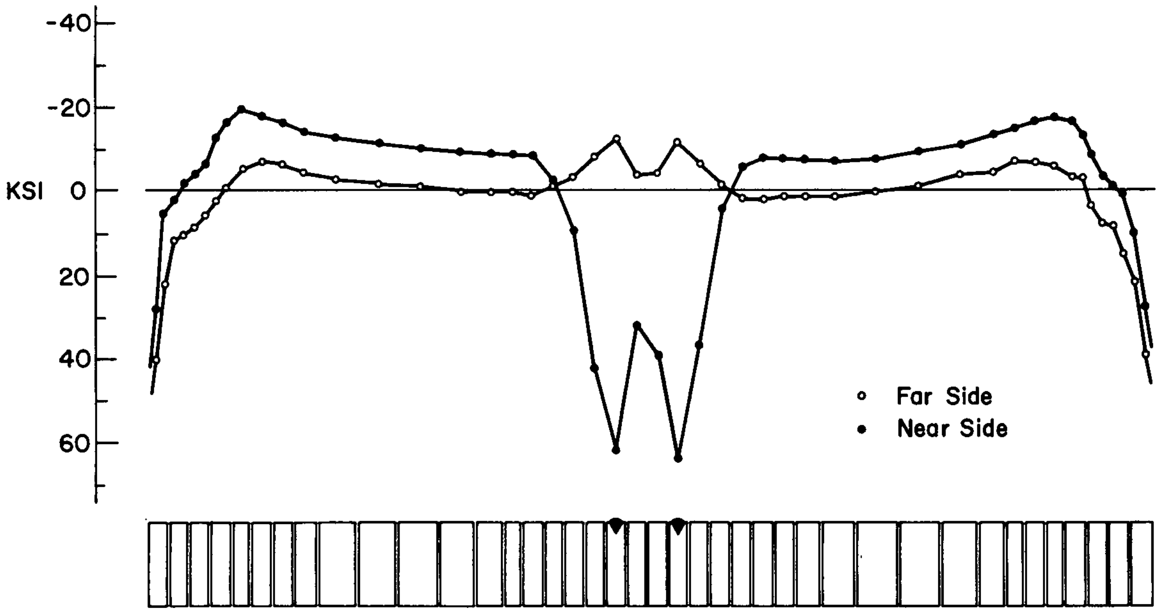


Fig. 6 Residual Stresses in a Flame-Cut Plate 24" x 2" Center Welded - Reference CW-1, (200°F Preheat, 1 Pass)

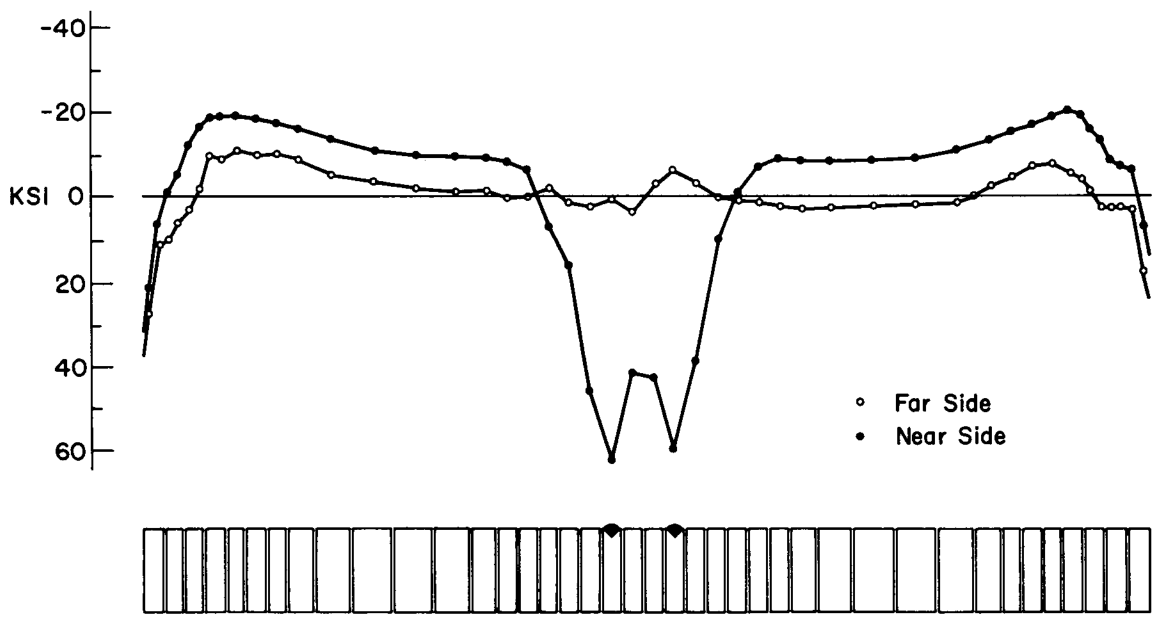


Fig. 7 Residual Stresses in a Flame-Cut Plate 24" x 2" Center Welded - Reference CW-2 (200°F Preheat, 1 Pass)

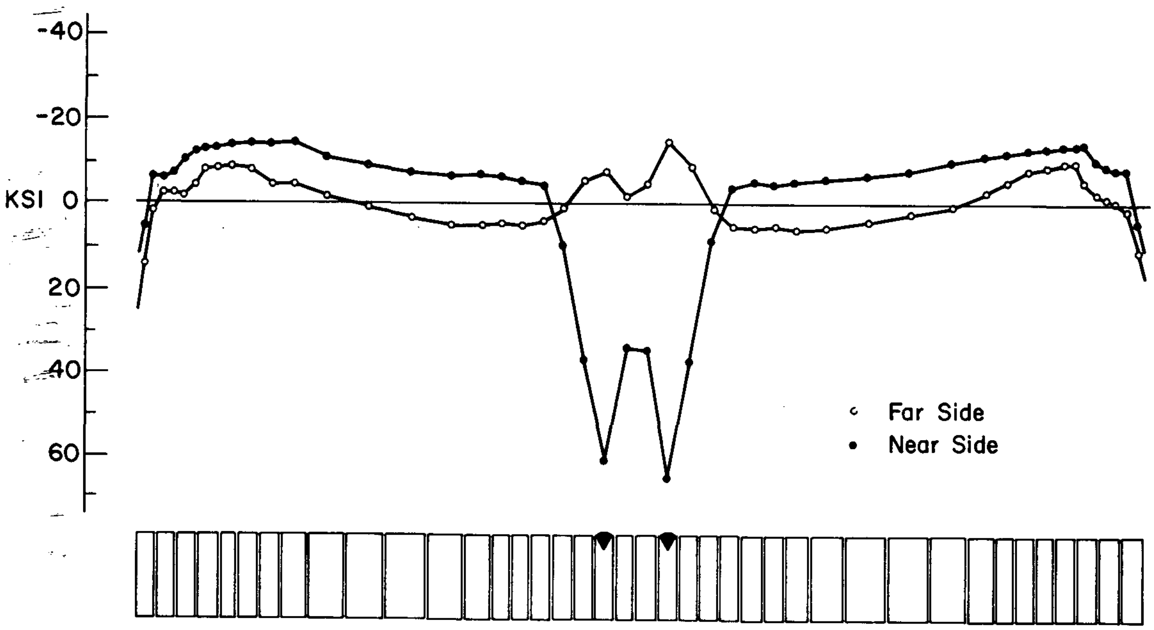


Fig. 8 Residual Stresses in a Flame-Cut Plate 24" x 2" Center Welded - Reference CW-3 (400°F Uniform Preheat, 2 Passes)

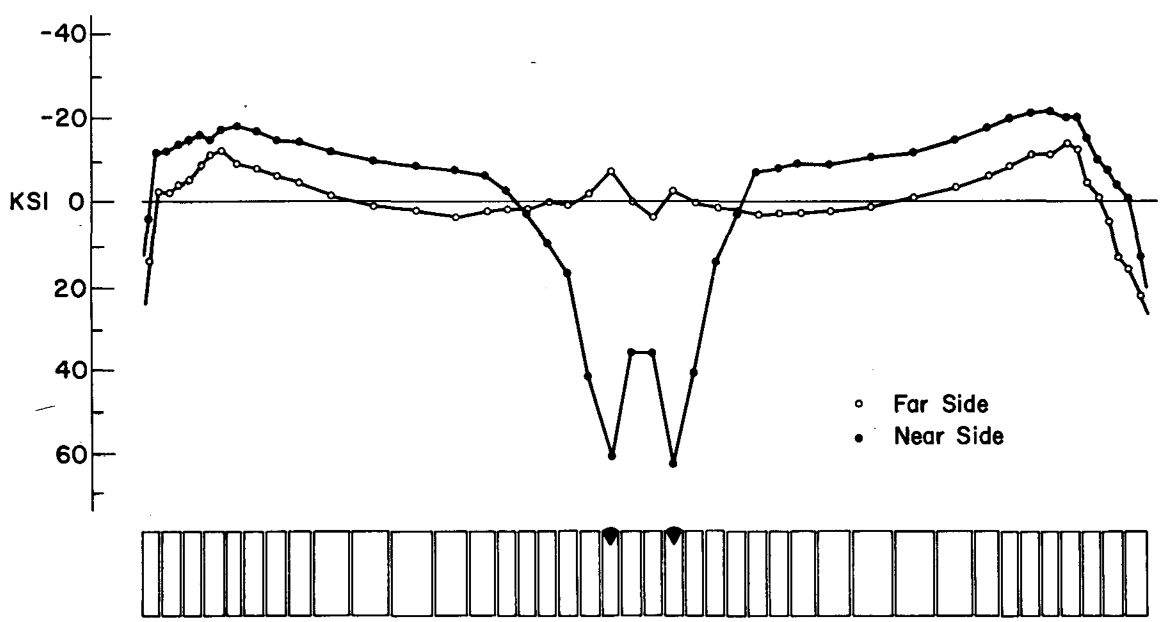


Fig. 9 Residual Stresses in a Flame-Cut Plate 24" x 2" Center Welded - Reference CW-4 (400°F Local Preheat, 2 Passes)

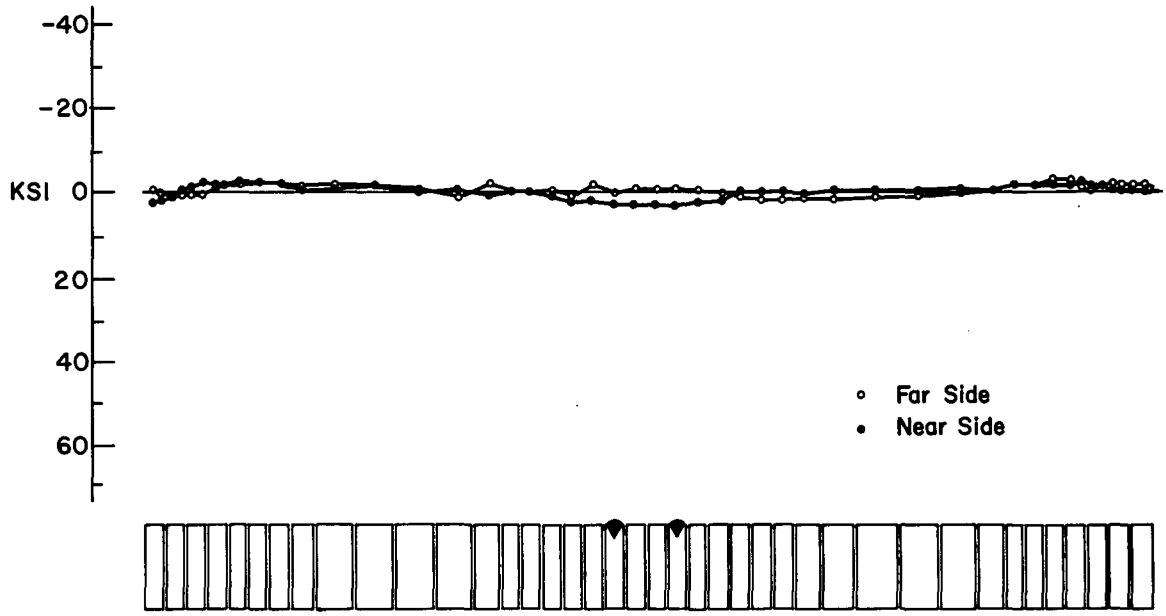


Fig. 10 Residual Stresses in a Flame-Cut Plate 24" x 2" Center Welded and Stress Relieved - Reference CW-5

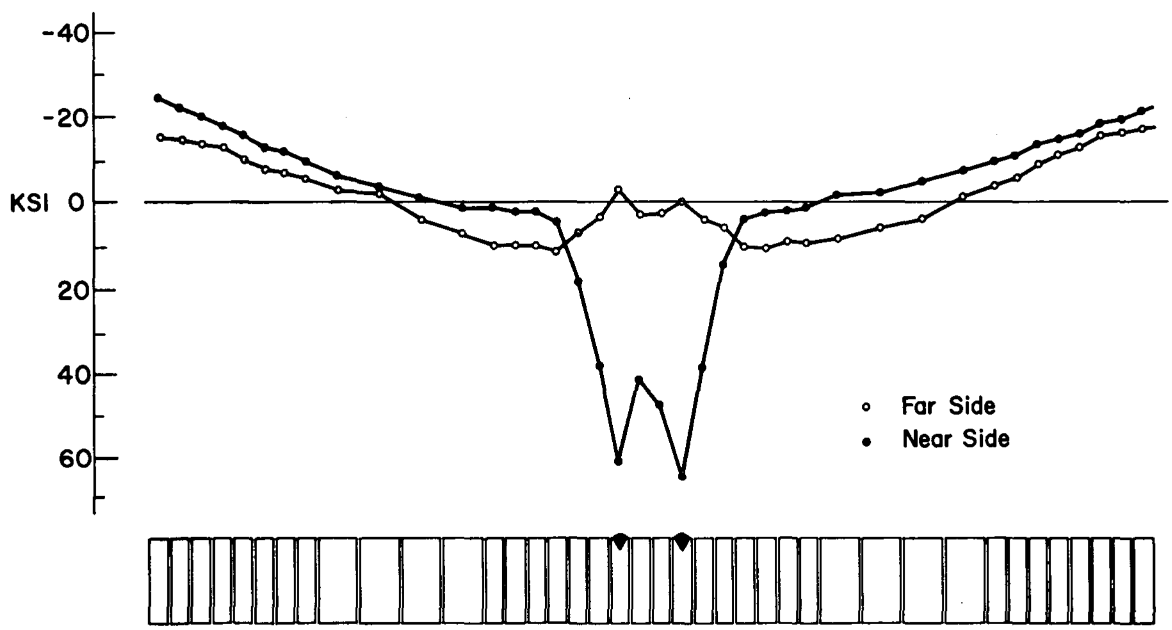


Fig. 11 Residual Stresses in a Universal-Mill Plate 24" x 2" Center Welded (200°F Preheat, 2 Welding Passes)

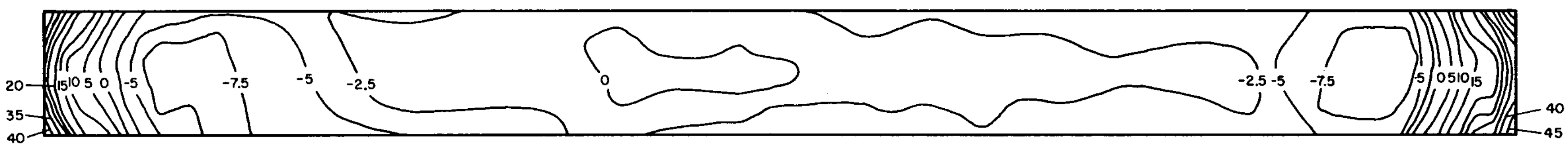


Fig. 12 Isostress Diagram of a Flame-Cut Plate 24" x 2"
Reference AM-1

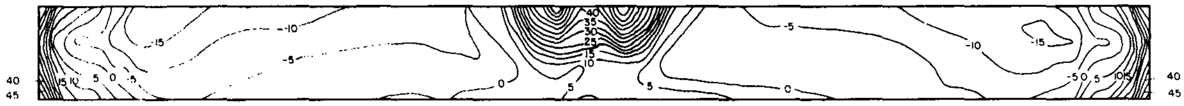


Fig. 13 Isostress Diagram of a Flame-Cut Plate 24" x 2" Center Welded - Reference CW-1, (200°F Preheat, 2 Welding Passes)

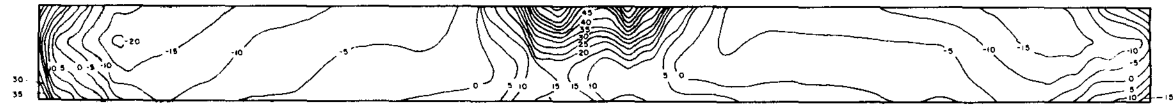


Fig. 14 Isostress Diagram of a Flame-Cut Plate 24" x 2" Center Welded - Reference CW-2, (200°F Preheat, 1 Welding Pass)

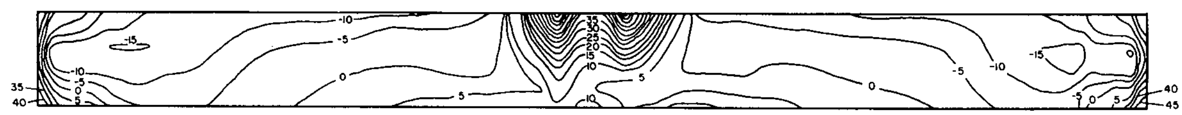
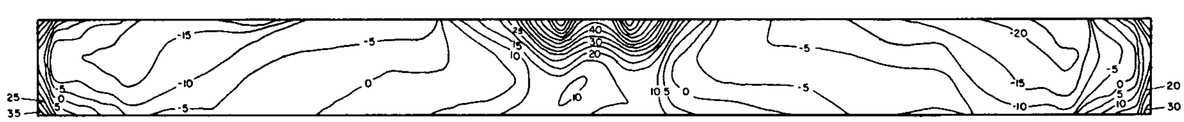


Fig. 15 Isostress Diagram of a Flame-Cut Plate 24" x 2" Center Welded - Reference CW-3, (400°F Uniform Preheat, 2 Passes)



24x2 - A36
H428 FC F-1 CW-4

Fig. 16 Isostress Diagram of a Flame-Cut 24" x 2" Center Welded - Reference CW-4 (400°F Local Preheat, 2 Passes)

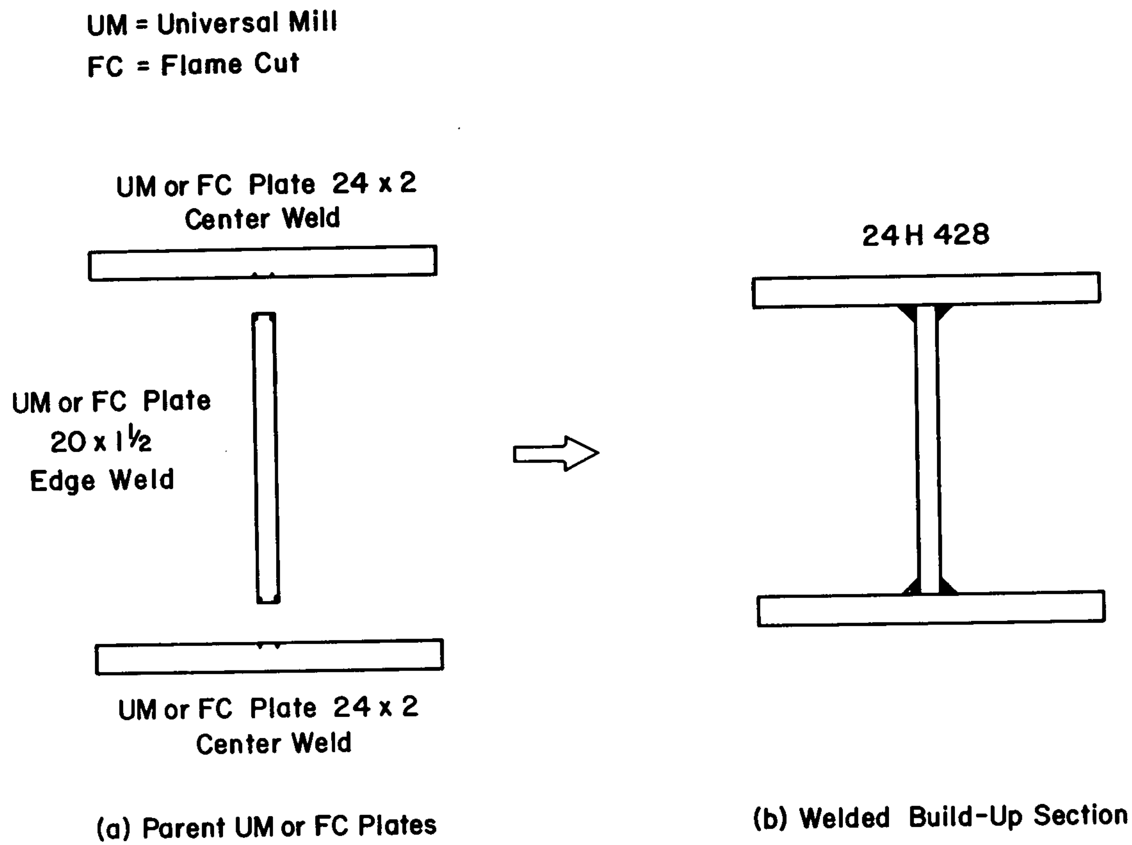
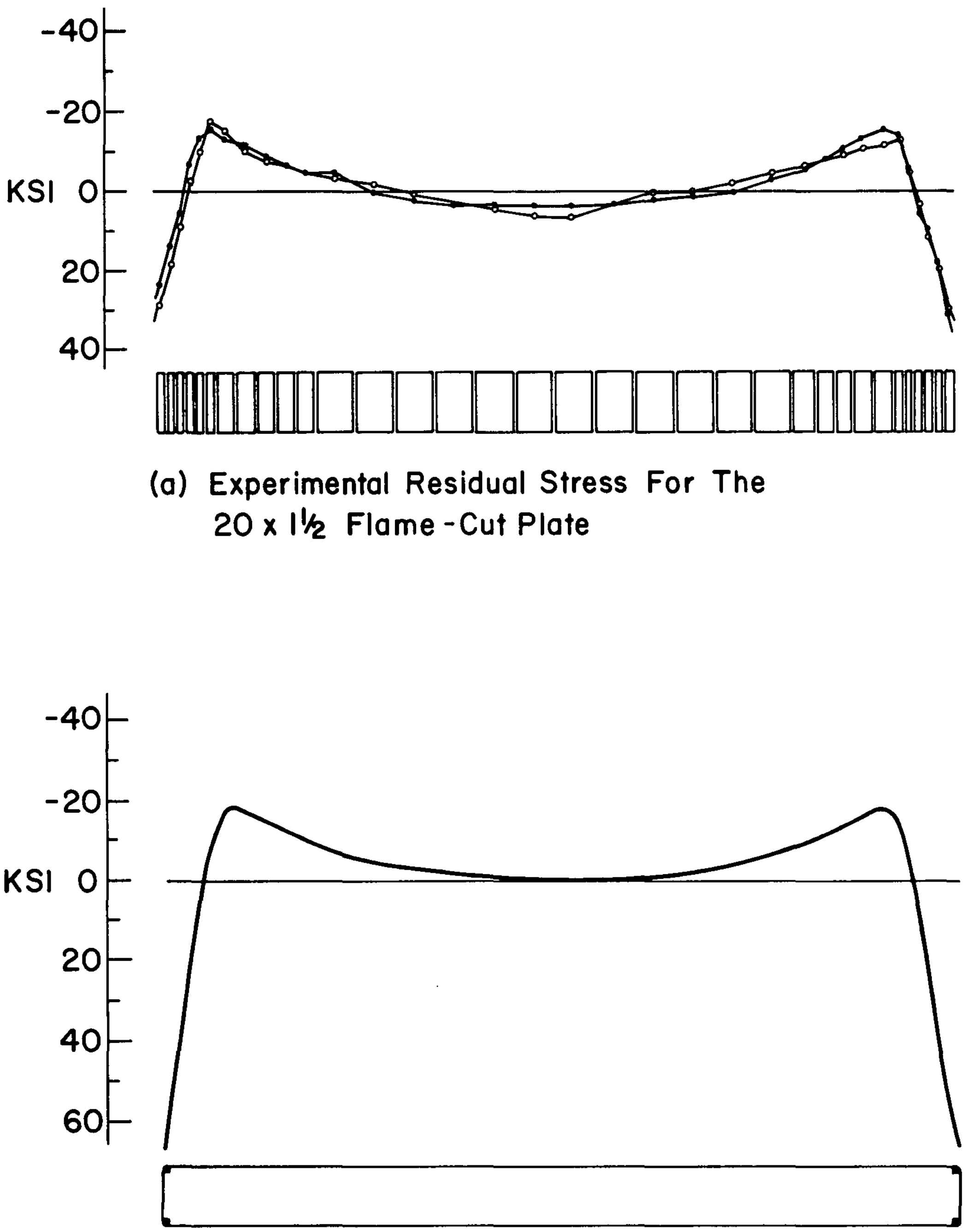


Fig. 17 Schematic Representation of a Simulated Section Built-Up From the Plate Specimens



(a) Experimental Residual Stress For The 20 x 1½ Flame-Cut Plate

(b) Computed Residual Stress Distribution For The 20 x 1½ Flame-Cut Plate With Edge Welds

Fig. 18 Computed Residual Stresses Due to Welding in a 20" x 1½" Flame-Cut Plate

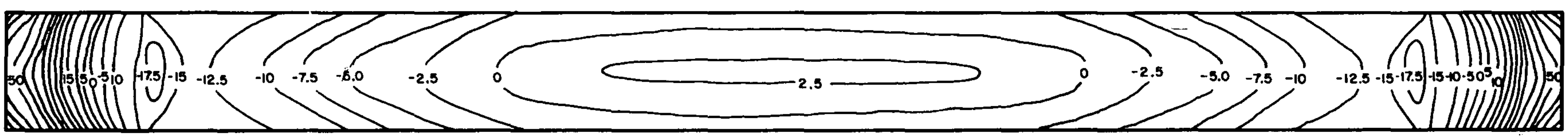


Fig. 19 Theoretical Isostress Diagram in an Edge Welded
20" x $1\frac{1}{2}$" Flame-Cut Plate

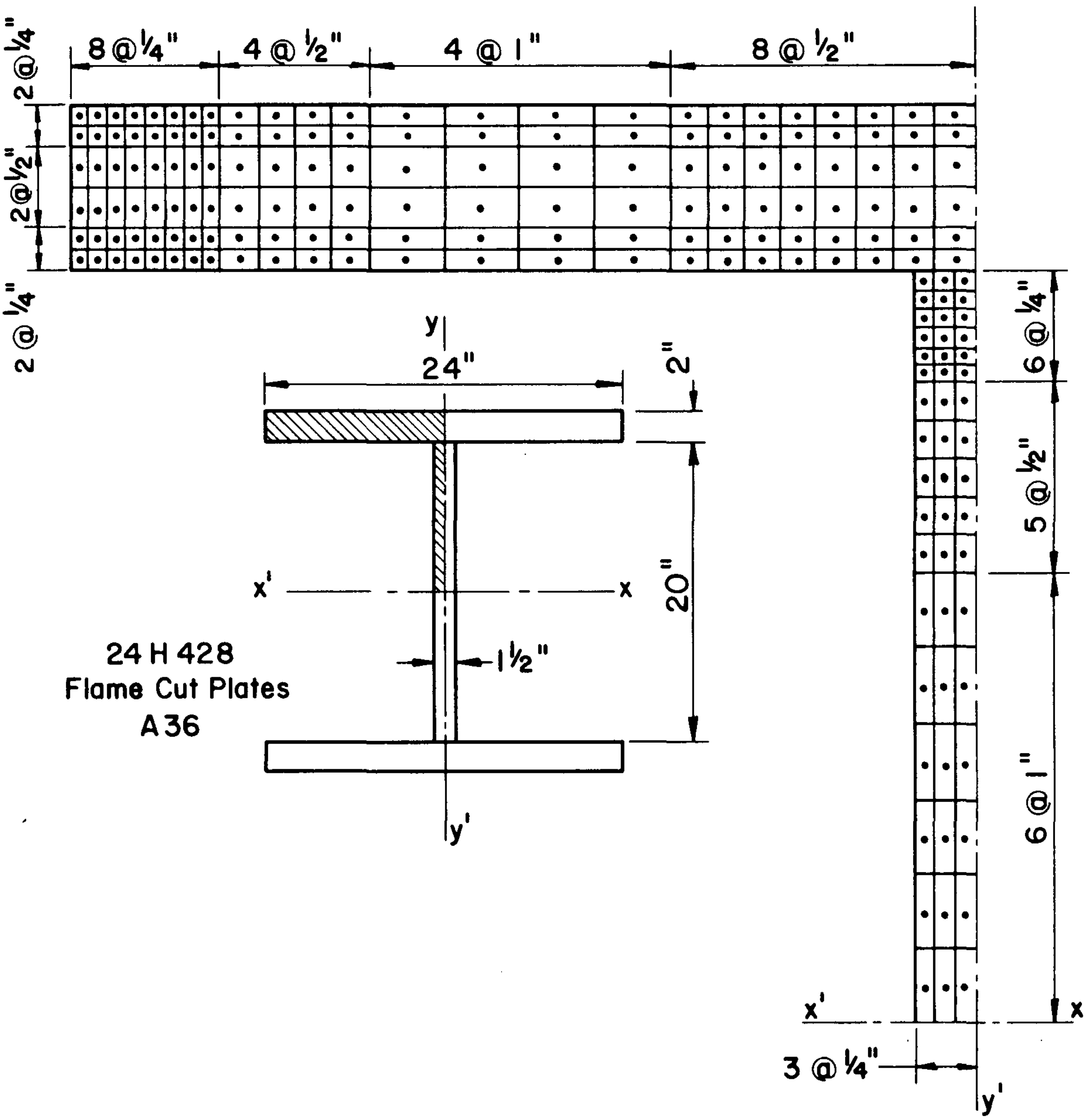


Fig. 20 Arrangement of Finite Area Elements

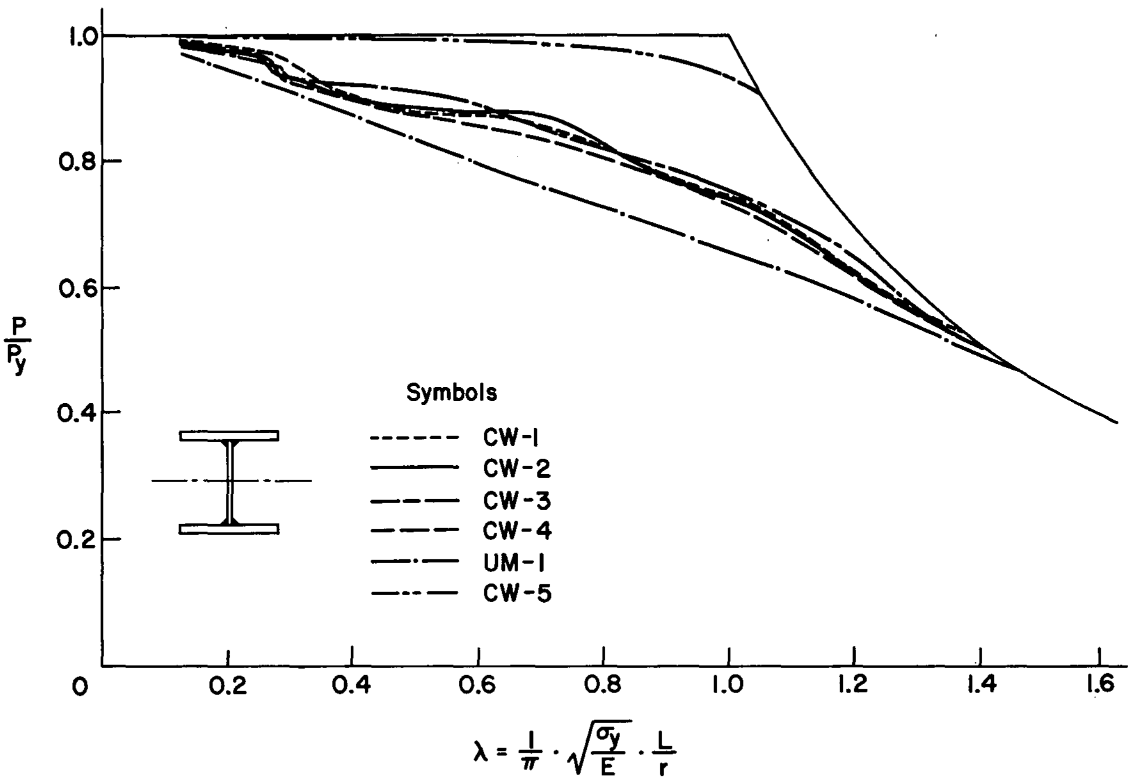


Fig. 21 Tangent Modulus Curves, Axis Bending, for the Average Residual Stresses Through the Thickness

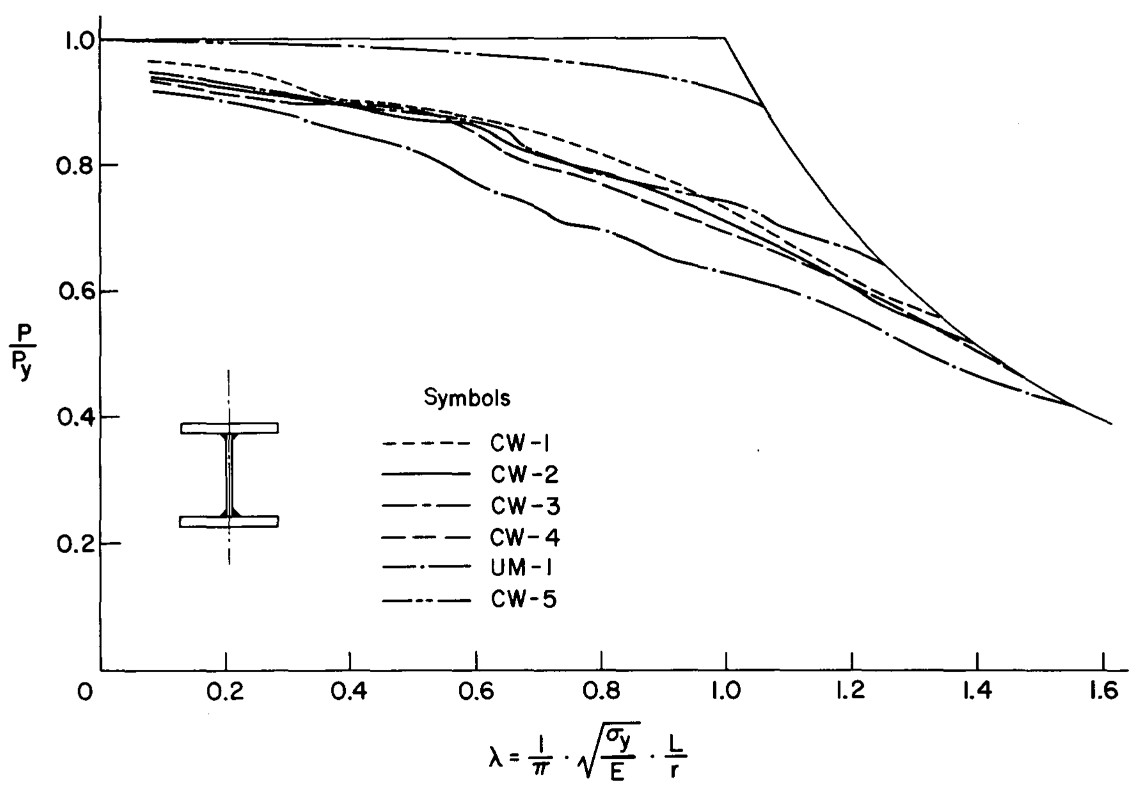


Fig. 22 Tangent Modulus Curves, Strong Axis Bending, Average Residual Stresses Through the Thickness

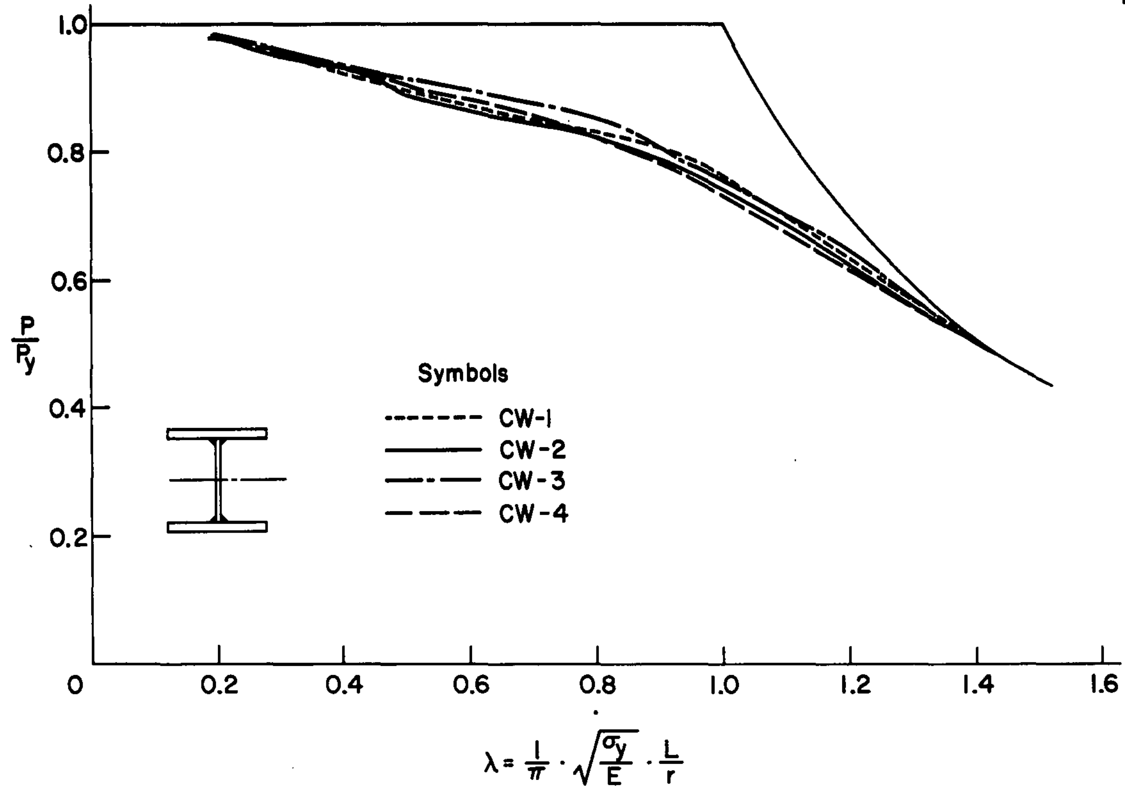


Fig. 23 Tangent Modulus Curves, Axis Bending, Actual Variation of Residual Stress Distribution Through the Thickness

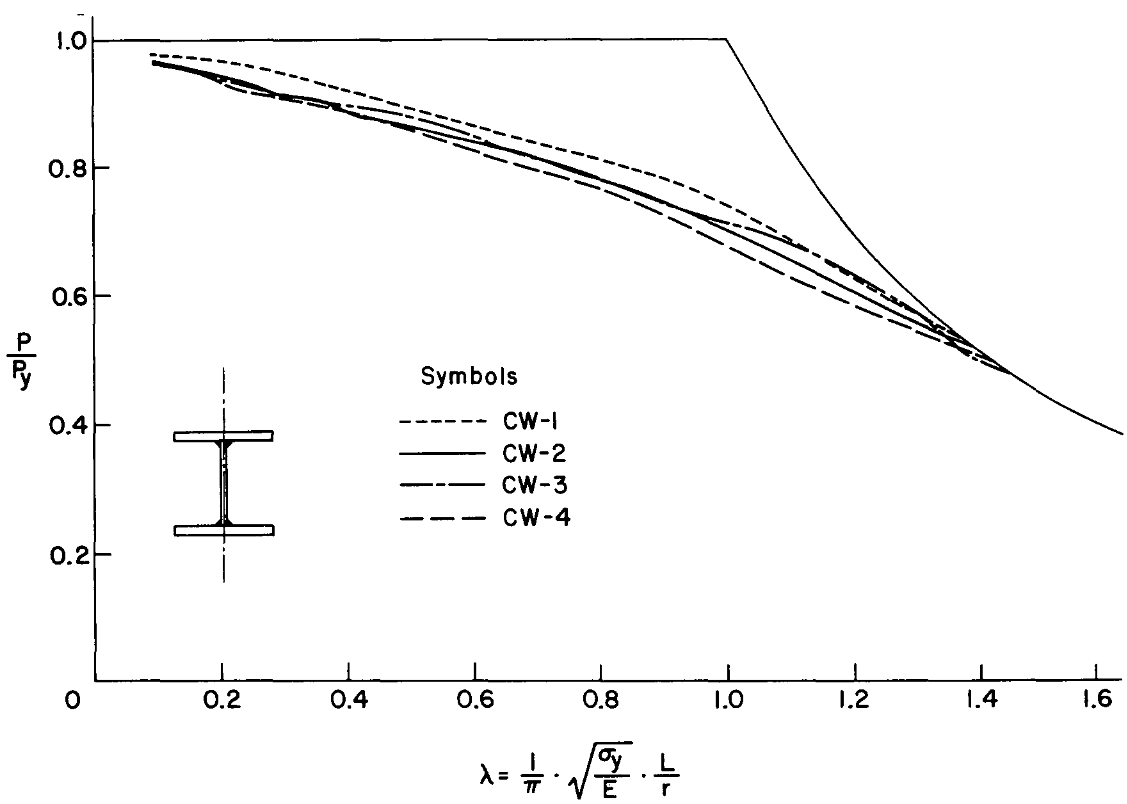
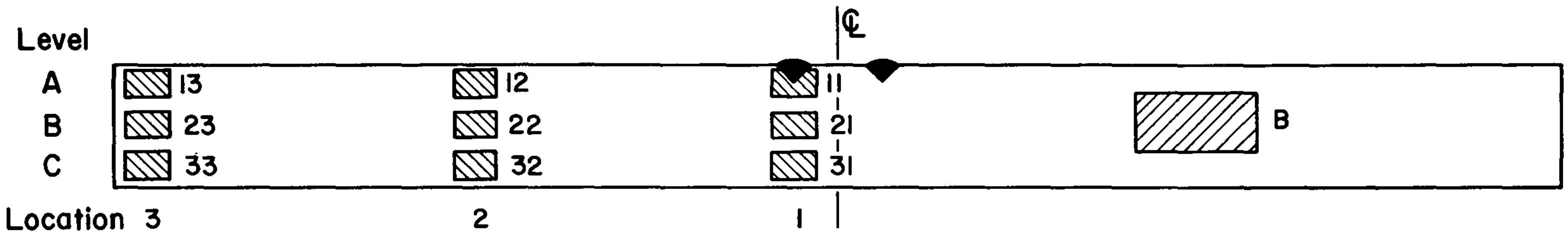
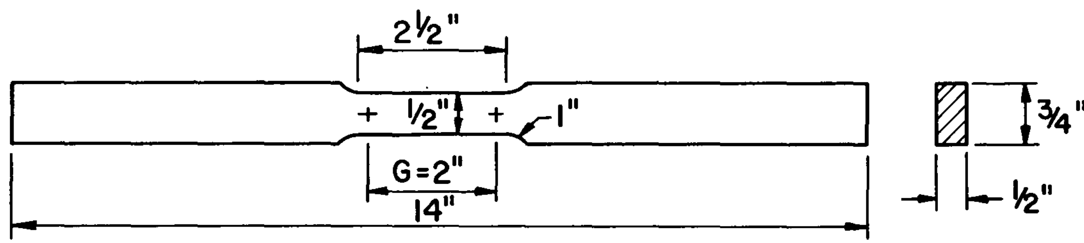


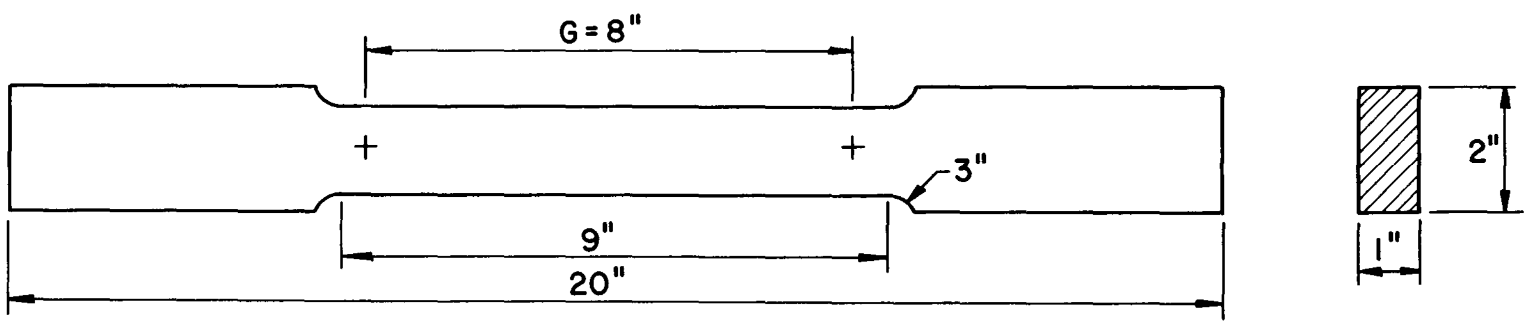
Fig. 24 Tangent Modulus Curves, Weak Axis Bending, Actual Variation of Residual Stress Distribution Through the Thickness



(a) Location of Test Specimens Across The Width and Thickness of a 20 x 2 (FC)



(b) Standard Test Specimen With a 2" Gage Length (ASTM A570)



(c) Standard Test Specimen With a 8" Gage Length (ASTM A570) Ref. B

Fig. 25 Layout and Dimensions of the Tension Test Specimens

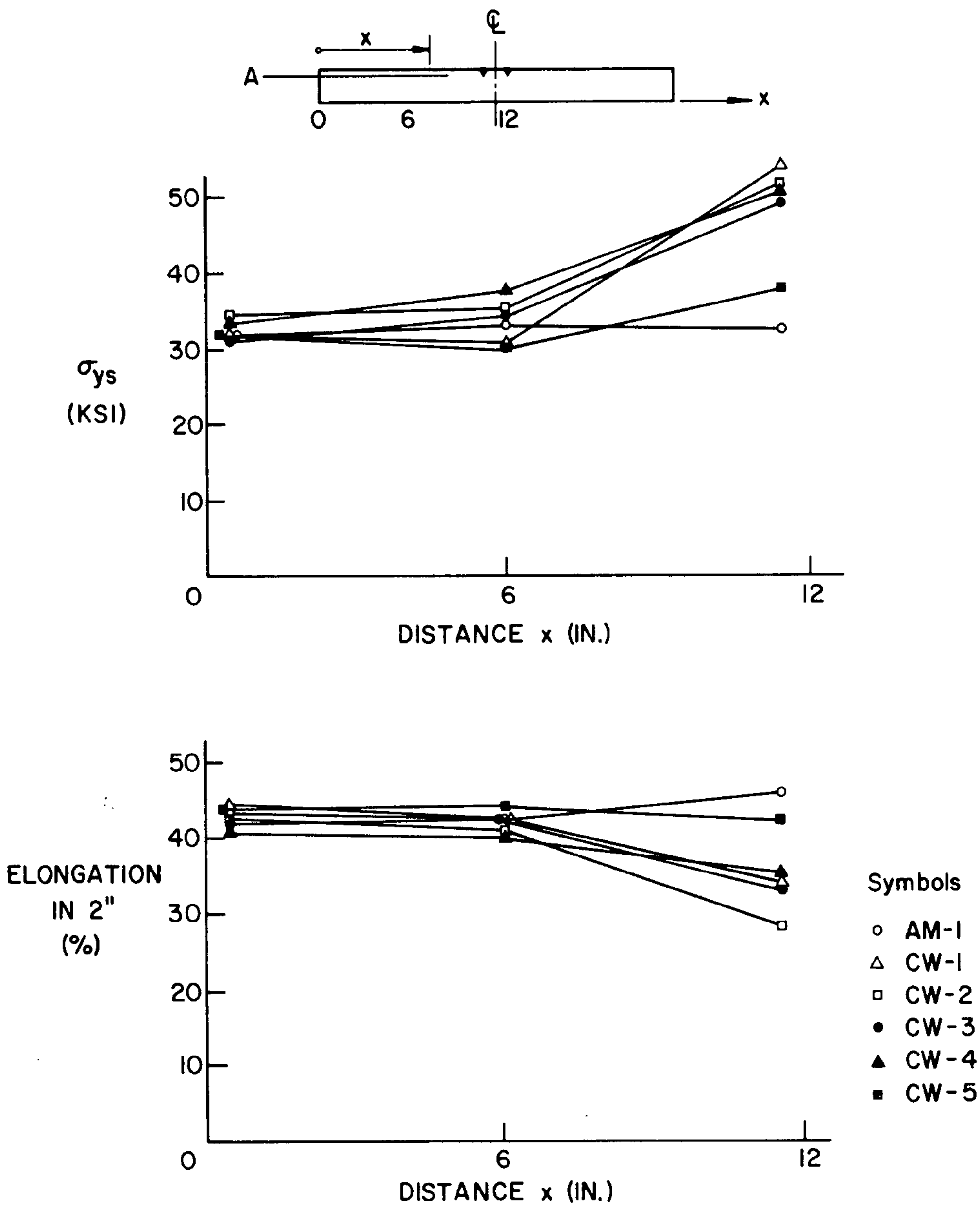


Fig. 26 Static Yield Strength and Percent Elongation Variation - Level A

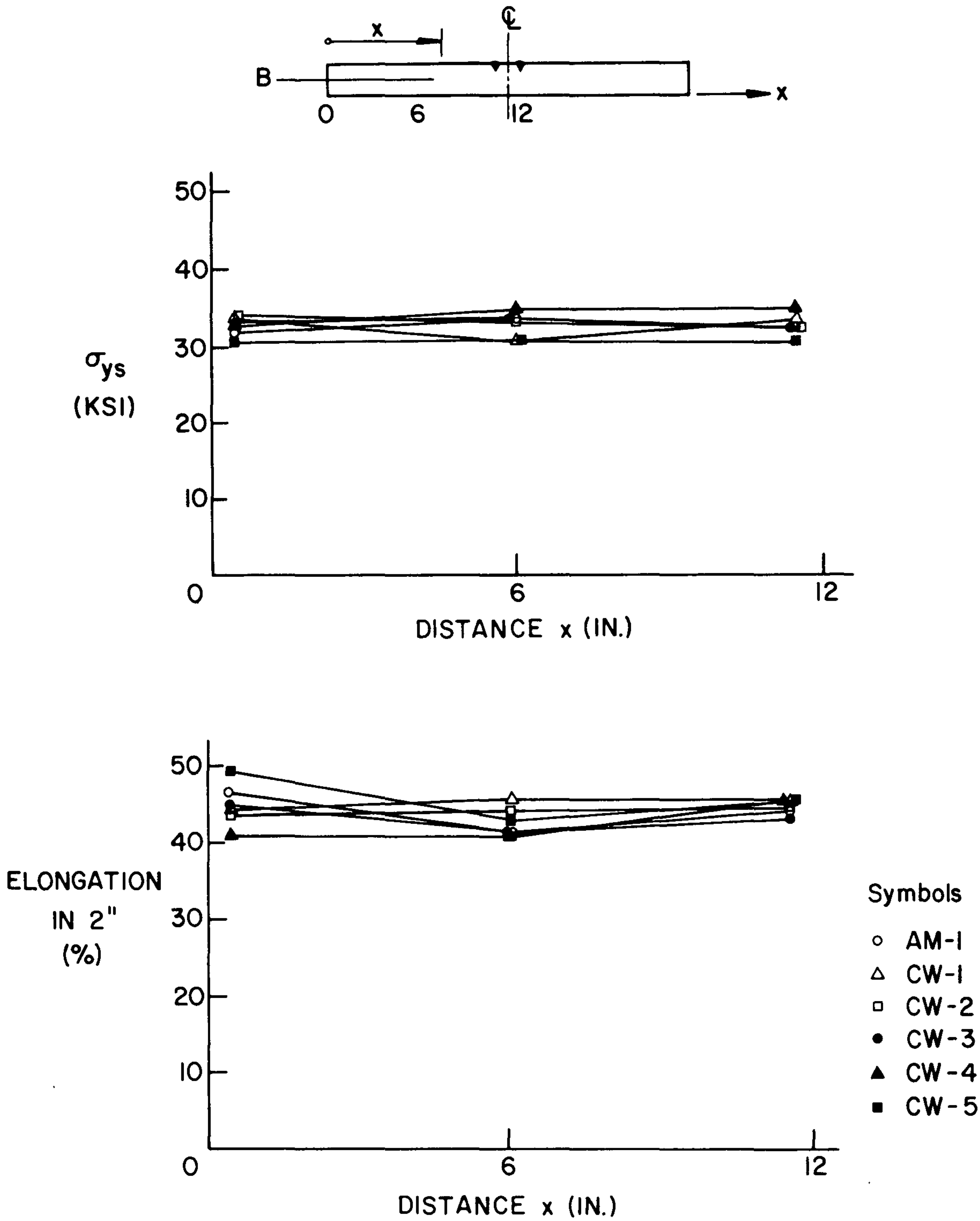


Fig. 27 Static Yield Strength and Percent Elongation Variation - Level B

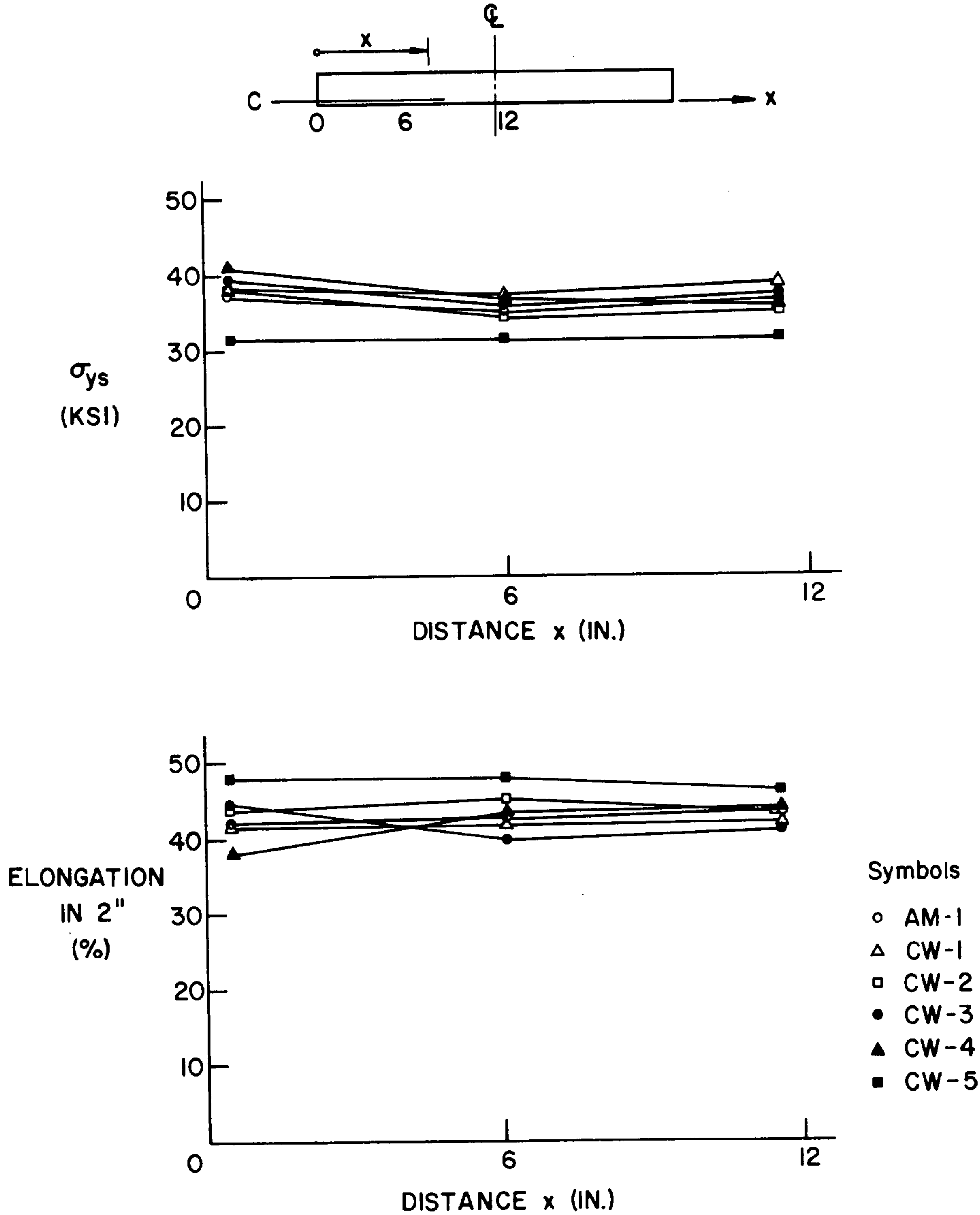


Fig. 28 Static Yield Strength and Percent Elongation Variation - Level C

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