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Department of Civil Engineering
Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania

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ABSTRACT

This report presents the results of an experimental investigation of the magnitude and distribution of residual stresses in heavy plates, which was carried out in conjunction with other phases of the research project "Residual Stresses in Thick Welded Plates".

A total of twenty-six plates was included in the study, of which twenty had flame-cut (FC) edges, the other six being universal mill (UM) plates with as-rolled edges. The width of the plates varied from 9 to 24 inches, and the thickness from $\frac{1}{8}$ to 6 inches; thus, the plate sizes covered the practical limits of component plates used today for heavy welded built-up columns. Some of the plates were studied in the as-manufactured condition, whereas others had weld beads placed along the center or along the edges, so as to simulate the component plates of welded built-up shapes. The results thereby could be compared with those of a parallel study on residual stresses in heavy welded shapes.

It was found that for as-manufactured universal mill plates with as-rolled edges, the maximum compressive
residual stress could be determined by means of a width-factor \( \beta \), a measure of the rate of cooling after rolling. The results showed that the maximum compressive stress increased as the size of the plate increased. The distribution of the residual stress in such plates generally exhibited a parabolic form, with some deviations from this in plates with large width/thickness ratios. Approximately one quarter of the plate width from either edge was subjected to compression, and the remainder of the plate exhibited tensile stresses. Comparison with theoretically predicted residual stress distributions showed very good correlation between experiment and theory.

Measurements to detect the variation of the residual stress through the thickness showed that the variation would be negligible in plates with thickness less than or equal to one inch, and that considerable variation could be expected in thicker plates.

It was found that the heat input created by the flame-cutting operation, together with the subsequent rapid cooling, had caused a change in the material properties within a very narrow region adjacent to the edge. The tensile residual stresses at the flame-cut edges therefore often were
considerably higher than the yield strength of the original material of the plate.

The welding at the plate center was found to have major effects only in a relatively narrow region around the weld. The influence became increasingly far-reaching as the size of the plate decreased. Similar results were found for the edge-welded plates, where it was shown also that the residual stress distribution in the heaviest plates very closely resembled that of the corresponding as-manufactured plates. The tensile residual stresses at the welds were usually significantly higher than the yield strength of the base metal of the plate, due to the changed material properties at the weld.

By comparison with the residual stress distributions found by measurements on welded built-up (FC) shapes, it was shown that the center-welded (FC) plate represented the flange of an H-shape, and the as-manufactured (FC) plate represented the web. Thus the residual stresses in built-up shapes may be found by assembling the data from the appropriate single plates.
1. INTRODUCTION

Over the past twenty years a number of investigations on the distribution and magnitude of residual stresses in steel plates and shapes have been carried out, and the results have contributed significantly to the understanding of the behavior and loading-carrying capacity of various types of structural components. The results have had a major impact on the formulation of design rules of many specifications, in particular the criteria governing the design of compression members such as columns.

Most of the research conducted previously was concerned with members of small or medium size, and the information on the residual stresses in such elements may be regarded as essentially complete. In recent years, however, increasingly heavier columns have been utilized in steel structures,\(^1,2\) prompting the question as to whether light and heavy columns actually exhibit similar patterns of residual stress and structural behavior. Previous investigations\(^3,4\) did indeed indicate that important differences might be expected, thus emphasizing the need for a study of these problems.
The investigations that are described in this report formed part of a research program with the aim of studying the residual stresses both in heavy plates and shapes. One of the heaviest rolled shapes presently in use was included, but most of the effort was directed towards studying welded shapes and their component plates. This was due to the fact that the largest shapes are exclusively welded, that is, built-up from plates, or in some instances from plates and rolled shapes, by welding, since the very process of rolling automatically limits the practical and economical size of rolled columns. The plates studied were all component plates of heavy welded shapes; some were examined in the as-manufactured condition, and the rest simulated actual conditions by having weld beads placed at the appropriate locations. A detailed description of the investigation, outlining the parameters and effects to be studied, is given in Chapter 2.
2. SCOPE OF INVESTIGATION

Major attention was paid to the investigation of various types of plates, each representing a component plate of a built-up shape. Thus, instead of having a number of different shapes manufactured, for each of which a time-consuming series of measurements would be required, it was intended to find whether measurements taken on a single plate would represent the state of residual stress present in an identical plate when it formed part of a shape. A plate with two centrally located weld beads, as illustrated in Fig. 1a, may therefore be thought of as the flange of an H-shape, whereas the edge-welded plate in Fig. 1b simulates the web of an H-shape or the plates of a box-section.

Within the same research program were also studied five complete heavy welded built-up H-shapes and one heavy welded box-shape. (5,6) A direct comparison between the measurements on the single plates and on the plates forming part of a shape was therefore possible.

All plates were manufactured from only one steel grade, ASTM A36. This was on the basis of previous results, (3,7)
which had indicated that the grade of steel had very little effect on the magnitude and distribution of residual stresses in a shape. ASTM A36 has also been shown to be the steel grade most frequently used for heavy columns in actual structures.\(^1\)

The effects of the following parameters on the residual stress distribution in a plate were studied:

1. plate geometry (width and thickness)
2. manufacturing method (plates with flame-cut or as-rolled edges)
3. welding (location, size of weld, and welding parameters).

In order to separate the effects of the welding, some plates were investigated in the as-manufactured condition, that is, without any weld beads.

The influence of varying the welding parameters was studied in another phase of the same overall research program.\(^8\) The welding parameters included were the speed of welding, the number of passes, the voltage of the welding current, and the temperature and extent of preheating. One plate was also annealed, to compare the effects of this type of treatment.
Table 1 gives the appropriate data for all the plates included in the investigation. A total of twenty-six plates was studied, their sizes covering the practical limits of the plates used today for heavy built-up columns. The thickness varied from 1\frac{1}{2} to 6 inches, and the width from 9 to 24 inches. Twenty of the plates had flame-cut (FC) edges, and the other six were universal mill (UM) plates with as-rolled edges.

Some typical examples of shapes where some of the plates have been, or might be, utilized are also indicated in Table 1. All of these shapes were fabricated for the research project.

It might be noted that four additional plates 24" x 2" (FC) were used for the welding parameter study. The total number of plates included in the project was therefore thirty (24 FC and 6 UM plates).

The sectioning method was employed for the measurement of the residual stresses, utilizing a Whittemore mechanical extensometer with a nominal sensitivity of 0.0001 inches. The accuracy in the stress recording is of the order of \( \pm 1 \) ksi.
3. RESULTS FROM RESIDUAL STRESS MEASUREMENTS

3.1 Residual Stresses in Universal Mill Plates

Figures 2 through 8 show the residual stress distributions for the six universal mill plates with as-rolled edges, and Table 2 shows a compilation of the most important data for these plates. All plates were measured in the as-manufactured condition, except one of the 24" x 2" plates, which was center-welded.

The five as-manufactured plates all exhibit the typical features of the residual stress distribution in universal mill plates: compressive residual stress occurs in the outer portions, and tensile residual stress in the center region. The open and closed circles in the diagrams represent the stresses found on the two faces of the plates, and it may be noted that the points lie close together for all the plates measured. This is an indication of the accuracy of the results obtained, and that the plates have cooled uniformly after rolling. A third curve, representing the average values of residual stress in each plate, has been included in the diagrams.
The magnitude of the maximum compressive residual stress in the as-manufactured universal mill plates varies from a low of -16 ksi in the 12" x 2" plate, to a high of -28.5 ksi in the 24" x 6" plate. Maximum tensile residual stresses vary from 8 ksi in the 24" x 2" plate to 13.5 ksi in the 24" x 6" plate. The distribution of residual stress across the plate width essentially is parabolic.

Figure 4 illustrates the isostress diagram for the 12" x 3\( \frac{1}{2} \)" plate, which provides an indication of the amount of variation of the residual stress through the thickness of the plate. The data for the isostress diagram are obtained by slicing the plate horizontally in addition to the regular sectioning procedure.\(^9\) It may be noted from Fig. 4 that the maximum difference between the surface stresses and the interior stresses amounts to approximately 6 to 7 ksi (in a small part of the center region). In most of the plate, however, the variation through the thickness never exceeds 3 ksi.

Slicing of the plates with thickness less than 3\( \frac{1}{2} \) inches was not performed, since it could be expected that the through-thickness variation in these plates would be smaller than in the thicker 12" x 3\( \frac{1}{2} \)" plate. Although
the data from the slicing operation of the two heaviest plates are not yet available, previous investigations\(^{(4,10)}\) have indicated that a significant variation of the residual stress will occur through the thickness of the plate when it is as large as 6 inches. The isostress-data for the 24" x 3\(\frac{1}{2}\)" plate will be comparable to those of the 12" x 3\(\frac{1}{2}\)" plate, shown in Fig. 4, even though a more accentuated variation through the thickness probably will prevail in the larger plate, due to the increased width.

The residual stress distribution in Fig. 8 for the center-welded universal mill plate exhibits a feature that is typical for all welded plates, regardless of manufacturing method. This is the very high tensile residual stresses that occur in the region around the welds. Also notable is the difference between the values of the residual stresses measured on the two faces of the plate. This is due to the fact that the welds are located only on one side of the plate, which causes an uneven and very localized distribution of the heat input from the welding process; it has a major effect only on the stresses in the relatively small area around the welds. The welding has also enlarged the proportion of the plate subjected to compression, as compared to the as-manufactured plate, and it occurs so that overall equilibrium of the residual stresses in the plate is maintained.
The high tensile residual stresses in the welds are accounted for by the fact that the weld electrodes used were of the grade E7018,\(^{(2)}\) with a specified minimum yield strength of 70 ksi.\(^{(11)}\) The heat input due to the welding, together with the depositing of the higher strength electrode metal, give rise to material properties in the zone around the welds that are different from the base material of the plate.\(^{(8)}\) An increased yield strength in this zone is one of the results, which thus explains why the residual stresses are higher than the yield strength of the parent material (ASTM A36).

3.2 Residual Stresses in Flame-Cut Plates

The results from the measurements on plates with similar manufacturing method will be described together, to focus attention on particularities relating to the manufacture. The plate categories are therefore (1) as-manufactured plates, (2) center-welded plates, and (3) edge-welded plates.

1. As-Manufactured Flame-Cut Plates

Figures 9 through 17 show the residual stress distributions for the eight as-manufactured flame-cut plates included in the study, and Table 3 summarizes the most important data for these plates.
The residual stress distributions reveal properties that are typical for all flame-cut plates, namely, a high tensile residual stress at the flame-cut edge which decreases very rapidly with increasing distance from the edge. The stress at the edge is usually substantially higher than the yield strength of the parent material of the plate, because the flame-cutting has caused a change of the material properties of the plate in a narrow region close to the edge. The rapid cooling of this region after cutting accounts for a fine-grained material with high hardness and yield strength, and this has been substantiated by the results from tension tests with small specimens cut from the edges of flame-cut plates. (8)

The width of the heat-affected region at the edge is very small, a fact which is further illustrated by the high gradient of the residual stress in this area. The data in columns 7 and 11 of Table 3 indicate that the width is less than 3 to 10 percent of the plate width, depending on the plate geometry, the heat input created by the flame-cutting operation, and the residual stresses that existed in the plate prior to the cutting. For example, Fig. 10 shows that for the 12" x 2" plate the residual stress has decreased to a value less than the yield strength of the base material of the plate at a distance of about 1/8 inch from the edge.
The magnitude of the average tensile residual stress at the edge varies from 30.5 ksi to 63 ksi, and the average maximum compressive residual stress from -7.5 ksi to -16 ksi. Columns 5 and 6 of Table 3 indicate that the maximum compression occurs at a distance from the plate edge between approximately 7 and 19 percent of the plate width. The distance depends on the same factors that control the width of the heat-affected zone at the plate edge.

The stress at the center of the as-manufactured flame-cut plates may be either compression or tension, depending on the plate geometry, the flame-cutting heat input, and the prior residual stresses. Thus, four of the eight plates exhibit tension in a certain region around the center of the plate, indicating that the combination of flame-cutting heat input and plate geometry has not been such that the tensile residual stress, present before the cutting, could be reversed. For the other four plates, compressive residual stress prevails in this zone, but the magnitude of this stress is not more than -3.5 ksi. It is also interesting that for some of the plates, notably the 24" x 2" plate (Fig. 15), a condition of practically zero residual stress exists in a significant portion of the plate.
The isostress diagram for the 24" x 2" plate, shown in Fig. 16, further illustrates the high gradient of residual stress adjacent to the flame-cut edge. It also shows that the variation of the residual stress through the thickness in most of the plate is less than 2.5 ksi, and thus rather insignificant. Similar investigations on 16" x 2" and 24" x 3½" flame-cut plates have, however, indicated a much more pronounced variation through the thickness, illustrating the great importance of the plate geometry on this property. (10)

2. Center-Welded Flame-Cut Plates

Figures 18 through 24 show the residual stress distributions for the six center-welded flame-cut plates, and Table 4 gives a compilation of the most significant results.

Similar to the center-welded universal mill plate described above, these plates exhibit the typical high tensile residual stresses at the welds, and there is a marked difference between the stresses measured on the two faces of the plate. Average tensile stress in the welds (column 4, Table 4) vary between 11.5 ksi and 30 ksi, and the surface stresses in the welds attain values between 30 ksi and 63 ksi.
Due to the heat input created by the welding, the tensile residual stress at the plate edge in the center-welded plates is in most cases substantially lower than the edge-stress in the as-manufactured plates (cf. Tables 3 and 4). This is also the reason for the higher compressive residual stresses in the center-welded plates. Both of these changes have occurred in order that equilibrium of the stresses in the plate be maintained. The average tensile residual stresses at the edges vary from a low of 24.5 ksi to a high of 58 ksi, and the average maximum compressive stresses vary from -14 ksi to -18.5 ksi. The width of the region subjected to compression (columns 8 and 10, Table 4) amounts to 50 to 70 percent of the plate width; the smaller of the two values being applicable to the thicker plates.

Comparing the residual stress distributions for the six plates, it may be seen that the welding operation has the most significant effect on the plates whose thickness and/or width are small. An indication of this is illustrated by the decreasing difference between the residual stresses on the two faces of the plates for increasing size of plate. Thus, for the 24" x 6" plate the major changes are confined to a relatively small area around the welds; whereas for example for the 9" x 1\(\frac{1}{2}\)" and the 12" x 2" plate, the entire plate
has been subjected to severe alterations of the residual stress that existed prior to the welding. The decreasing influence of the welding as the plates become heavier can probably be attributed to the smaller ratio of heat-affected zone width to plate thickness.

The isostress diagram for the 24" x 2" plate shown in Fig. 23 further illustrates the high gradients of the residual stress in the zones adjacent to the flame-cut edges and the welds. The high gradient rapidly tapers off, however, and in most of the plate the variation of the residual stress through the thickness is less than 5 ksi.

3. **Edge-Welded Flame-Cut Plates**

Figures 25 through 30 show the residual stress distributions for the six edge-welded flame-cut plates included in the investigation, and Table 5 summarizes the most important data. It will be seen in general that, apart from smaller areas, the distribution in an edge-welded plate resembles very much that of an as-manufactured flame-cut plate.

The average tensile residual stress at the edge, that is, in the weld, varies from 40 ksi to 61 ksi. In all except two of the plates (12" x 2" and 12" x 3\(\frac{1}{2}\)"), these
stresses are higher than those exhibited by the corresponding un-welded plates. It is believed that the welding along the flame-cut edge has completely eliminated the effects of the cutting operation, although the two materials may resemble each other in grain structure and mechanical properties.

The maximum compressive residual stress attains values between -12.5 ksi and -16 ksi, and occurs at a distance of 10 to 20 percent of the plate width from the edge. The residual stress at the center of the plate is compressive for all the plates except the 24" x 6" plate. This indicates that the additional heat input due to the edge-welding has caused a reversal from tension to compression of the residual stresses that existed in the plate prior to the flame-cutting and the welding. This does not hold true for the heaviest plate, where evidently the volume receiving the heat input is large enough to prevent the welding from having a really significant effect. The data in column 4, Table 5, which illustrate the width of the region of the plate subjected to compression, support the conclusion that the welding has the most pronounced effect on the smallest plates.

The data-points in Figs. 25 to 30, representing the measurements on the two faces of the plates, lie relatively
close together. This is explained by symmetry; the welds are equidistant from the center of the plate, giving an even, although localized, heat input.

3.3 Measurements and Machining Time

A brief account of the number of measurements made and the time spent on the execution of the investigation may be of interest. A total of approximately 70,000 readings were taken with the Whittemore extensometer, and about 3,500 man-hours were spent, on all phases of the study. The 3,500 hours include approximately 2,400 hours machining time, that is, time needed by the machine-shop to cold-saw the plates for the sectioning and slicing operations. The remaining 1,100 hours were used for the actual measurements, the preparation of drawings, the evaluation of data, the preparation of specimens, and so on.

An example will be given by considering the time and number of measurements needed for the 12" x 3½" (UM) plate. The sectioning operation for this plate involved 400 measurements, and an additional 2600 measurements were needed for the slicing procedure, giving a total of 3000 measurements. The time for sawing the plate for sectioning was 50 hours and for slicing 51 hours,
leading to 101 hours machining time. Adding the time used for measuring, data evaluation, and so on, gives a final number of approximately 140 hours spent on this particular plate.
4. DISCUSSION OF RESULTS

4.1 Universal Mill Plates

Additional meaningful information may be obtained by considering together the various residual stress distributions in the as-manufactured plates. No such comparison can be made for center-welded universal mill plates, since only one is included in this study.

Figure 31 shows the residual stress diagrams for the five plates drawn to a common width. This illustrates that the maximum compressive stress, occurring at the edge of the plate, is directly dependent on the thickness of the plate. The 24" x 6" plate exhibits the highest compressive stress, and the magnitude of this quantity decreases in the order 24" x 3\(\frac{1}{2}\)", 24" x 2", 12" x 3\(\frac{1}{2}\)", and 12" x 2"; although the two smallest plates have practically the same residual stress distribution. This indicates that the width of the plate also has a significant influence.

A simple measure for the differences between the residual stresses in various as-manufactured universal mill plates is the width-factor \(\beta\). Denoting the following ratio
by \( \alpha \),

\[
\alpha = \frac{\text{Surface area per unit length of plate}}{\text{Volume per unit length of plate}} = \frac{2(b+t)}{bt} \quad (1)
\]

the width-factor is given by the expression

\[
\beta = \frac{\alpha}{b} = \frac{2(b+t)}{b^2t} \quad (2)
\]

where \( b \) denotes the width of the plate and \( t \) the thickness. \( \alpha \) is therefore given in units \((\text{length})^{-1}\), and \( \beta \) in units \((\text{length})^{-2}\). Table 6 gives the values of \( \alpha \) and \( \beta \) for the various plates.

The plate-factor \( \alpha \) is a direct measure of the rate of cooling of the plate after rolling, by considering the surface area through which the heat stored in the volume will dissipate. The width-factor \( \beta \) is a measure of the same, but it also takes into account the fact that the width has a substantially larger influence on the rate of cooling than the thickness.

Corresponding values of the maximum compressive residual stress, \( \sigma_{rc} \), and the width-factor have been plotted in Fig. 32. The solid line in the figure represents an empirical relationship between \( \sigma_{rc} \) and \( \beta \), which has been developed using a low-order polynomial of the form...
where $a_1$, $a_2$, and $a_3$ are constants. A piecewise continuous function has been fitted to the experimental data, giving the following empirical relationship between $\sigma_{rc}$ and $\beta$:

For $\beta > 0.1$:

$$\sigma_{rc} = \frac{2.85}{\beta} - \frac{0.135}{\beta^2}$$

and for $\beta \leq 0.1$:

$$\sigma_{rc} = 10.2 + \frac{0.566}{\beta} - \frac{0.0048}{\beta^2}$$

Note that a minus-sign should be attached to the value of $\sigma_{rc}$ found from equations (4) and (5), using the regular sign-convention with plus for tension and minus for compression.

The empirical equations have been compared with other test data\(^{(3, 12)}\) in order to include plates with high $\beta$-values. The points representing the maximum compressive residual stresses in plates 20" x 1", 14" x $\frac{1}{2}$", 10" x $\frac{1}{2}$", and 6" x $\frac{1}{2}$" are seen to fit well. Equations (4) and (5) should not be used for plates with $\beta$-value larger than approximately 1.0, because for these the width plays an even more dominant role in the cooling process than what is expressed in Eq. 2.
Observing the limitations of Eq. 4 and 5 as far as the magnitude of $\beta$ is concerned, and utilizing the knowledge that the residual stress distribution takes on the shape of a parabola (see Ch. 3.1), the complete distribution may be determined, knowing the width and the thickness, and maintaining equilibrium of the stresses.

A comparison between the theoretically determined values of $\sigma_{rc}$ (4), and the experimental results, is provided by the inclusion of the additional data points in Fig. 32. The dashed line gives the approximate theoretical relationship between $\sigma_{rc}$ and $\beta$. The fact that the theoretical predictions exhibit somewhat higher values of $\sigma_{rc}$ than the test results does not imply that the theory is erroneous. It rather emphasizes that the test results are based on one-specimen data only, and significant variations might be expected, (13) due to variations in the yield strength, thermal properties and cooling conditions.

The diagram in Fig. 33 underlines the fact that the test results will form a scatter band instead of indicating a mathematical curve. Both theoretical and experimental data are plotted in this figure, which relates $\sigma_{rc}$ to the width-thickness ratio b/t.
A more rational basis for the comparison of experiment and theory is provided by a study of the complete residual stress distributions for a plate. Such information is given in Figs. 34 through 38, where the experimental and theoretical residual stress distributions for the five plates are shown. It may be seen that in all plates, except the 24" x 2", the largest deviation between theory and experiment occurs at the plate edge. In the remainder of each of the plates, the correlation between experimental and theoretical results may be regarded as excellent.

An indication of the effect of the welding on the cooling residual stresses in universal mill plates may be seen from Fig. 39, where the distributions for the as-manufactured and the center-welded 24" x 2" plates are drawn in the same diagram. For this particular plate the only major changes have occurred in a relatively small area around the welds, and in the rest of the plate the differences in residual stress do not amount to more than about 2 to 3 ksi. It is expected that the changes will be more severe for smaller plates, and the opposite for heavier plates. These effects are considered in greater detail for the flame-cut plates, where it is possible to make several more comparisons.
4.2 Flame-Cut Plates

Figure 40 shows the residual stress distributions for the as-manufactured flame-cut plates, drawn in the same diagram on a non-dimensional basis for the plate width. The two smallest plates, that is, the 9" x 1\frac{1}{2}" and the 12" x 2" plate, exhibit the highest tensile residual stress at the edge, which indicates that the heat input due to the flame-cutting process has the greatest effect on the smallest plates. The smallest tensile stress at the edge occurs in the 24" x 6", the '24" x 2", and the 20" x 1\frac{1}{2}" plate. Whereas the 20" x 1\frac{1}{2}" plate has the highest tensile stress at the center of the plate, which was to be expected, the other two plates fall in the middle of the band of values for all plates. This shows that the heat input has been so large as to create a significant change of the stress at the center of the plate, but also important for the 24" x 6" plate is its large volume. Likewise, the 20" x 1\frac{1}{2}" plate by far exhibits the highest compressive residual stress, whereas all the other plates (except the 24" x 2") are very much alike. The low compressive stress in the 24" x 2" plate is consistent with its low values of tensile stresses at the edge and at the center.

There seems to be no simple means of predicting either the stresses occurring in a flame-cut plate, or the
way they are distributed. This is probably due mainly to factors such as local variations in the heat input during flame-cutting, variations in the material structure and properties, and the rate of cooling after cutting. For a plate with a large thickness, the cutting operation will not have effects similar to those in a thinner one, because the heat penetrates the plate to a much smaller distance from the edge. All these factors together constitute a very involved picture, which can not be interpreted by simple, independent observations.

Figure 41 compares the residual stress distributions for the center-welded flame-cut plates on a non-dimensionalized basis for the width. The weld generally reduces the tensile stresses at the flame-cut edge that existed prior to the welding, and this effect is more pronounced the smaller the plate, provided the size of the weld remains constant. The magnitude of the maximum compressive residual stress does not differ too much from plate to plate, such that the major changes occur in a relatively small area around the welds.

A comparison of the effects of center-welding and edge-welding on the residual stress distribution in flame-cut plates is provided by Fig. 42 through 47. The distributions
of each of the corresponding as-manufactured, center-welded, and edge-welded flame-cut plates have been drawn in the same diagrams, and thus make possible a direct evaluation of the effects of the welding.

It is quite evident that as the size of the plate increases, the changes in the residual stress distribution that are produced by welding at the center or at the edge, become less and less significant. For example, placing welds at the center of the 9" x 1\(\frac{1}{2}\)" plate changes the original tensile stress at the edge from approximately 48 ksi to 28 ksi, and welding at the edge of the same plate introduces changes of 10 to 15 ksi throughout the entire plate. On the other hand, the same operations for the 24" x 6" plate produce almost negligible alterations in the residual stress distribution. Note particularly that for this heavy plate the residual stress distributions for the as-manufactured and the edge-welded condition are practically identical, and also that the only notable changes for the center-welded plate occur in the weld-region.

4.3 Comparison with Results from Measurements on Shapes

So far the residual stresses found in the various plates have been related only to each other, but a problem
of major concern is whether these results are comparable to the data provided by measurements on complete, built-up shapes. Several investigators have studied the distributions of residual stresses in heavy shapes, \((3, 4, 5, 6, 7, 8, 10, 12)\) but no comparisons between the results from heavy plate and shape measurements have previously been done. However, the data provided by an investigation\((5)\) that was conducted within the same research program make such an evaluation possible here.

Figures 48 through 51 combine the residual stress distributions found in the single plates so as to simulate welded built-up shapes, and compare these results with those found in complete shapes with component plates of the same sizes. Figures 52 through 55 provide comparisons of the average residual stresses for the same shapes, based on shape- and plate-measurements.

In general, it may be said that the residual stress distribution in center-welded plates represents very well the distribution in the same plates when they form part of welded built-up shapes. The differences that arise are largest for the smallest shapes, which may be seen by comparing, for example, the results given in Fig. 52 and Fig. 55; and they are confined to the areas around the welds and very close
to the edges. For the largest shape (24H122), the residual stresses found by plate- and by shape-measurements are almost identical throughout the whole of the plates.

The residual stress distributions in the webs and the corresponding edge-welded plates (Figs. 52 and 55) exhibit larger differences than what is found for the flanges and the center-welded plates, although the deviation is smaller for the largest shape. The reason for the discrepancies is probably the fact that even if comparable amounts of heat have been produced by the welding of the shape and the plate, in the shape the heat is stored in a much larger volume, and the rate of cooling after welding therefore will be smaller than in the plates. The significantly higher compressive residual stresses in the edge-welded plates as compared to the webs are indications to this effect.

For two of the shapes (20H354, Fig. 53, and 24H428, Fig. 54) edge-welded plates of the same dimensions as the webs were not included in the investigation. The comparison in Figs. 53 and 54 is therefore based on the results for as-manufactured flame-cut plates. An interesting conclusion may be made, namely, that there seems to be better correspondence between the residual stress distributions in
the web and the corresponding as-manufactured plate, rather than between the web and the edge-welded plate. The proper simulation of the residual stress distribution in a heavy welded built-up shape therefore will be to assemble the diagrams for center-welded and as-manufactured plates, representing flanges and web, respectively.

The conclusions arrived at here are valid for shapes made from flame-cut plates. Further studies are necessary in order to substantiate whether or not they hold also for shapes with universal mill plates. It can be stated immediately, however, that the plate simulating the web in such a shape must have some form of edge welds (not necessarily one weld at each of the four corners), in order to introduce the appropriate tensile stresses at the flange-web junction of the simulated section.
5. SUMMARY AND CONCLUSIONS

The following conclusions may be drawn on the basis of the results presented in this report:

1. The larger the size of the plate, the larger will be the maximum compressive residual stress in as-manufactured universal mill plates with as-rolled edges. More specifically, the compressive stress increases as the value of the width-factor, \( \beta = \frac{2(b+t)}{b^2t} \), decreases. The width-factor is a measure of the rate of cooling after rolling, and expresses the ratio surface area per unit length of the plate, to volume per unit length times width. This quantity may be used together with the curve in Fig. 32 to determine the maximum compressive residual stress in such plates.

2. The distribution of residual stress in as-manufactured universal mill plates with as-rolled edges generally has the shape of a parabola. This information may be used to determine the complete distribution in
a plate given its width-factor $\beta$. Some deviations from the parabolic shape may be found for plates with high width/thickness ratios.

3. Approximately one-half of the plate width, located centrally in as-manufactured universal mill plates, will be subjected to tensile residual stresses. The outermost one quarter of the plate on either side will exhibit compressive residual stresses.

4. The variation of the residual stress through the thickness normally is negligible in plates with thickness less than about one inch, but may be considerable in thick plates.

5. The heat input created by the flame-cutting operation causes a change in the material properties within a very narrow region adjacent to the edge, with yield strength significantly higher than that of the original material. The tensile stress at the edge, therefore, may become much higher than the yield strength of the plate material itself.

6. Welding at the center of a plate generally causes a reduction of the tensile stress at the edge prior to the welding. The residual stress in the welds
will be very high, and close to the yield strength of the electrode metal.

7. The welding of heavy plates usually has its primary effect on the stresses in a relatively small region around the welds, and does not drastically change the stresses in other parts. This effect will become more and more significant as the size of the plate decreases.

8. The residual stresses in the heaviest (24"x6") edge-welded flame-cut plate are very closely of the same magnitude and distribution as those found in its as-manufactured counterpart. The smaller the plate, however, the more extensive will be the changes in the residual stress distribution; in particular, the compressive stresses will increase significantly.

9. The correlation between theoretical predictions and experimental results may be regarded as excellent.

10. Comparison between the residual stresses measured in complete, built-up (FC) shapes and the corresponding single plates, reveal that the flange
is accurately represented by a similar, center-welded, plate. The differences in residual stress that do occur are small, and confined to small areas around the welds and very close to the edges. The differences decrease as the size of plate (shape) increases.

11. The residual stress distribution in the web of a built-up (FC) shape seems to be represented better by an as-manufactured plate than by an edge-welded one.

12. The residual stress distribution in a heavy welded (FC) H-shape can be well predicted by using a center-welded (FC) plate as the flange, and an as-manufactured (FC) plate as the web.
6. NOMENCLATURE

\( a_1, a_2, a_3 \) = constant coefficients, used in polynomials

\( b \) = plate width

\( t \) = plate thickness

\( x_1 \) through \( x_7 \) = various distances to important points in the plates, describing the residual stress distribution

\( \alpha \) = plate-factor, a measure of the rate of cooling after rolling, given by

\[
\alpha = \frac{2(b+t)}{bt}
\]

\( \beta \) = width-factor, also a measure of the rate of cooling after rolling, given by

\[
\beta = \frac{2(b+t)}{b^2t} = \frac{\alpha}{b}
\]

\( \sigma^c_r \) = residual stress at the center of a flame-cut plate

\( \sigma_{rc} \) = compressive residual stress at the edge of an as-manufactured universal mill plate with as-rolled edges

\( \sigma^m_r \) = maximum compressive residual stress in flame-cut plates

\( \sigma_{rt} \) = tensile residual stress at the center of an as-manufactured universal mill plate with as-rolled edges

\( \sigma^e_{rt} \) = tensile residual stress at the edge of a flame-cut plate

\( \sigma^w_{rt} \) = tensile residual stress in the welds of center-welded plates
7. ACKNOWLEDGEMENTS

This report presents the results of a major investigation on the residual stresses in heavy welded plates, forming part of the research project "Residual Stresses in Thick Welded Plates". The research program is being carried out at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania.

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The assistance of Miss Joanne Mies in typing the manuscript, and John M. Gera in preparing the drawings, is sincerely appreciated.
8. TABLES AND FIGURES
### TABLE 1

Summary of Data for Plates Studied

<table>
<thead>
<tr>
<th>Plate Size (in)</th>
<th>Manufacturing Method*</th>
<th>Welds Location†</th>
<th>Size (in)</th>
<th>Typical Shape in Study</th>
<th>Where Plate is Used**</th>
<th>No. of Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 x 1 1/2</td>
<td>FC</td>
<td>AM</td>
<td>1/4</td>
<td>-</td>
<td>12H210 (W)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CW</td>
<td></td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>EW</td>
<td>3/8</td>
<td>-</td>
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</tr>
<tr>
<td>12 x 2</td>
<td>FC</td>
<td>AM</td>
<td>-</td>
<td>-</td>
<td>12H210 (F)</td>
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<td></td>
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<td>-</td>
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</tr>
<tr>
<td>12 x 2</td>
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<td>-</td>
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<td>1</td>
</tr>
<tr>
<td>12 x 3 1/2</td>
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<td>AM</td>
<td>-</td>
<td>-</td>
<td>24H1122 (W)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>EW</td>
<td>1/2</td>
<td>-</td>
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</tr>
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<td></td>
<td>1</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
<td></td>
<td>1</td>
</tr>
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<td>AM</td>
<td>-</td>
<td>-</td>
<td>20H354 (F)</td>
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</tr>
<tr>
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<td></td>
<td>CW</td>
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<td>-</td>
<td>20H744 (&quot;W&quot;)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>EW</td>
<td>3/8</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 x 2</td>
<td>FC</td>
<td>AM</td>
<td>-</td>
<td>-</td>
<td>24H428 (F)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CW</td>
<td>1/4</td>
<td>-</td>
<td>24H744 (&quot;F&quot;)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>EW</td>
<td>3/8</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 x 2</td>
<td>UM</td>
<td>AM</td>
<td>-</td>
<td>-</td>
<td>24H428 (F)</td>
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</tr>
<tr>
<td>24 x 3 1/2</td>
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<td>AM</td>
<td>-</td>
<td>-</td>
<td></td>
<td>1</td>
</tr>
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<td>24 x 6</td>
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<td>-</td>
<td>24H1122 (F)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>CW</td>
<td>3/8</td>
<td>-</td>
<td>24H1122 (F)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>EW</td>
<td>1/2</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 x 6</td>
<td>UM</td>
<td>AM</td>
<td>-</td>
<td>-</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

*Method designation: FC = Flame-cut plate; UM = Universal mill plate with as-rolled edge

**F = Flange; W = Web

†AM = As-manufactured (no welds); CW = Center-welded; EW = Edge-welded.
TABLE 2

Average Residual Stresses in As-Manufactured Universal Mill Plates

<table>
<thead>
<tr>
<th>Plate Size (in)</th>
<th>Residual Stresses (ksi)</th>
<th>Non-Dimensionalized Distances, $x_i/b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{rc}$ $\sigma_{rt}$</td>
<td>$x_1/b$ $x_2/b$ $x_3/b$</td>
</tr>
<tr>
<td>12 x 2</td>
<td>-16.0 8.5</td>
<td>0.23 0.54 0.24</td>
</tr>
<tr>
<td>12 x 3 $\frac{3}{8}$</td>
<td>-16.0 10.0</td>
<td>0.23 0.53 0.24</td>
</tr>
<tr>
<td>24 x 2</td>
<td>-19.0 8.0</td>
<td>0.19 0.61 0.20</td>
</tr>
<tr>
<td>24 x 3 $\frac{3}{8}$</td>
<td>-23.0 12.5</td>
<td>0.20 0.58 0.22</td>
</tr>
<tr>
<td>24 x 6</td>
<td>-28.5 13.5</td>
<td>0.25 0.53 0.22</td>
</tr>
</tbody>
</table>

* Extrapolated value at plate edge; average of the two edges.
+ Taken at center of plate.
### TABLE 3

Average Residual Stresses in As-Manufactured Flame-Cut Plates

![Diagram showing residual stresses in plates]

<table>
<thead>
<tr>
<th>Plate Size (in)</th>
<th>Res. Stresses (ksi)</th>
<th>Non-Dimensionalized Distances, ( x_i/b )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \sigma_{rt} )</td>
<td>( \sigma_{rc}^m )</td>
</tr>
<tr>
<td>9x1( \frac{3}{4} )</td>
<td>48.0</td>
<td>-13.5</td>
</tr>
<tr>
<td>12x2</td>
<td>63.0</td>
<td>-14.0</td>
</tr>
<tr>
<td>12x3( \frac{3}{4} )</td>
<td>51.5</td>
<td>-10.5</td>
</tr>
<tr>
<td>16x1( \frac{3}{4} )</td>
<td>50.5</td>
<td>-11.5</td>
</tr>
<tr>
<td>20x1( \frac{3}{4} )</td>
<td>30.5</td>
<td>-16.0</td>
</tr>
<tr>
<td>20x2</td>
<td>49.5</td>
<td>-15.0</td>
</tr>
<tr>
<td>24x2</td>
<td>44.0</td>
<td>-7.5</td>
</tr>
<tr>
<td>24x6</td>
<td>46.5</td>
<td>-13.5</td>
</tr>
</tbody>
</table>

+ Extrapolated value at plate edge; average of the two edges.
* Taken at the center of the plate.
** \( x_i = x_4 + x_5 + x_6 \) in this case (compression over the entire region).
TABLE 4

Average Residual Stresses in Center-Welded Flame-Cut Plates

<table>
<thead>
<tr>
<th>Plate Size (in)</th>
<th>( \sigma_{\text{rt}} )</th>
<th>( \sigma_{\text{rc}} )</th>
<th>( \sigma_{\text{rt}} )</th>
<th>( x_1/\ell )</th>
<th>( x_2/\ell )</th>
<th>( x_3/\ell )</th>
<th>( x_4/\ell )</th>
<th>( x_5/\ell )</th>
<th>( x_6/\ell )</th>
<th>( x_7/\ell )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9x1( \frac{1}{2} )</td>
<td>24.5</td>
<td>-17.5</td>
<td>28.5</td>
<td>0.15</td>
<td>0.10</td>
<td>0.04</td>
<td>0.33</td>
<td>0.33</td>
<td>0.31</td>
<td>0.03</td>
</tr>
<tr>
<td>12x2</td>
<td>58.0</td>
<td>-18.5</td>
<td>22.0</td>
<td>0.13</td>
<td>0.16</td>
<td>0.06</td>
<td>0.31</td>
<td>0.27</td>
<td>0.29</td>
<td>0.09</td>
</tr>
<tr>
<td>12x3( \frac{1}{2} )</td>
<td>40.0</td>
<td>-17.0</td>
<td>11.5</td>
<td>0.16</td>
<td>0.19</td>
<td>0.08</td>
<td>0.25</td>
<td>0.35</td>
<td>0.24</td>
<td>0.09</td>
</tr>
<tr>
<td>20x2</td>
<td>49.0</td>
<td>-14.5</td>
<td>24.0</td>
<td>0.14</td>
<td>0.12</td>
<td>0.08</td>
<td>0.32</td>
<td>0.31</td>
<td>0.24</td>
<td>0.06</td>
</tr>
<tr>
<td>24x2</td>
<td>25.5</td>
<td>-14.0</td>
<td>30.0</td>
<td>0.10</td>
<td>0.10</td>
<td>0.04</td>
<td>0.36</td>
<td>0.21</td>
<td>0.38</td>
<td>0.02</td>
</tr>
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<td>24x6</td>
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<td>-14.5</td>
<td>13.0</td>
<td>0.14</td>
<td>0.16</td>
<td>0.05</td>
<td>0.27</td>
<td>0.34</td>
<td>0.28</td>
<td>0.06</td>
</tr>
</tbody>
</table>

* Extrapolated value at plate edge, average of two edges.
+ Average value of the residual stresses in the two welds.
TABLE 5

Average Residual Stresses in Edge-Welded Flame-Cut Plates

<table>
<thead>
<tr>
<th>Plate Size (in)</th>
<th>Res. Stresses (ksi)</th>
<th>Non-Dimensional Distances, $x_i/b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{et}$</td>
<td>$\sigma_{rc}$</td>
</tr>
<tr>
<td>9x1\frac{3}{2}</td>
<td>52.0</td>
<td>-16.0</td>
</tr>
<tr>
<td>12x2</td>
<td>57.5</td>
<td>-15.5</td>
</tr>
<tr>
<td>12x3\frac{3}{2}</td>
<td>40.0</td>
<td>-13.0</td>
</tr>
<tr>
<td>20x2</td>
<td>61.0</td>
<td>-12.5</td>
</tr>
<tr>
<td>24x2</td>
<td>58.5</td>
<td>-14.0</td>
</tr>
<tr>
<td>24x6</td>
<td>48.5</td>
<td>-13.5</td>
</tr>
</tbody>
</table>

* Extrapolated value at plate edge; average of the two edges.
+ Average value of maximum compressive residual stress, measured at the two locations given by $x_1$ and $x_2$.
** The entire region $x_4 + x_5 + x_6$ is subjected to compression.
### TABLE 6

Values of Plate-Factor $\alpha$ and Width-Factor $\beta$ for the Plates Studied

<table>
<thead>
<tr>
<th>Plate Size (in)</th>
<th>Plate-Factor* $\alpha$ (1/in)</th>
<th>Width-Factor $\beta = \frac{\alpha}{b}$ (1/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9x1 3/8</td>
<td>1.554</td>
<td>0.173</td>
</tr>
<tr>
<td>12x2</td>
<td>1.167</td>
<td>0.097</td>
</tr>
<tr>
<td>12x3 3/8</td>
<td>0.738</td>
<td>0.062</td>
</tr>
<tr>
<td>16x1 3/8</td>
<td>1.459</td>
<td>0.091</td>
</tr>
<tr>
<td>20x1 3/8</td>
<td>1.432</td>
<td>0.072</td>
</tr>
<tr>
<td>20x2</td>
<td>1.100</td>
<td>0.055</td>
</tr>
<tr>
<td>24x2</td>
<td>1.082</td>
<td>0.045</td>
</tr>
<tr>
<td>24x3 3/8</td>
<td>0.655</td>
<td>0.027</td>
</tr>
<tr>
<td>24x6</td>
<td>0.416</td>
<td>0.017</td>
</tr>
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</table>

* The plate-factor is given by

$$\alpha = \frac{\text{Surface Area per Unit Length of Plate}}{\text{Volume per Unit Length of Plate}} = \frac{2(b+t)}{bt} \ (1/\text{in})$$

where $b$ is the width of the plate, and $t$ the thickness.

+ The width-factor is given by

$$\beta = \frac{2(b+t)}{b^2t} = \frac{\alpha}{b} \ (1/\text{in}^2)$$
Fig. 1 Center- and Edge-Welded Plates, Simulating the Flange and the Web of a Welded Built-Up H-Shape.
Fig. 2 Residual Stress Distribution in a 12" x 2" Universal Mill Plate with As-Rolled Edges.
Fig. 3 Residual Stress Distribution in a 12" x 3½"
Universal Mill Plate With As-Rolled Edges.
Maximum Compressive Residual Stress = -18 ksi

Maximum Tensile Residual Stress = 11 ksi

Fig. 4 Isostress-Diagram for the Residual Stresses in a 12" x 3\(\frac{1}{2}\)" Universal Mill Plate With As-Rolled Edges (stresses in ksi).
Fig. 5 Residual Stress Distribution in a 24" x 2" Universal Mill Plate With As-Rolled Edges.
Fig. 6 Residual Stress Distribution in a 24" x 3½"
Universal Mill Plate With As-Rolled Edges.
Fig. 7 Residual Stress Distribution in a 24" x 6" Universal Mill Plate With As-Rolled Edges.
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Fig. 9 Residual Stress Distribution in a 9" x 1½" Plate With Flame-Cut Edges (Flame-Cut Plate).
Fig. 10 Residual Stress Distribution in a 12" x 2" Flame-Cut Plate.
Fig. 11 Residual Stress Distribution in a 12" x 3½" Flame-Cut Plate.
Fig. 12 Residual Stress Distribution in a 16" x 1\(\frac{1}{2}\)" Flame-Cut Plate.
Fig. 13 Residual Stress Distribution in a 20" x 1½" Flame-Cut Plate.
Fig. 14: Residual Stress Distribution in a 20" x 2" Flame-Cut Plate.
Fig. 15 Residual Stress Distribution in a 24" x 2" Flame-Cut Plate.
Fig. 16 Isostress Diagram of a 24" x 2"
As-Manufactured Flame-Cut Plate.
Fig. 17 Residual Stress Distribution in a 24" x 6" Flame-Cut Plate.
Fig. 18 Residual Stress Distribution in a 9" x 1\(\frac{1}{2}\)"
Center-Welded Flame-Cut Plate.
Fig. 19 Residual Stress Distribution in a 12" x 2"
Center-Welded Flame-Cut Plate.
Fig. 20 Residual Stress Distribution in a 12" x 3\(\frac{1}{2}\)"
Center-Welded Flame-Cut Plate.
Fig. 21 Residual Stress Distribution in a 20" x 2" Center-Welded Flame-Cut Plate.
Fig. 22 Residual Stress Distribution in a 24" x 2" Center-Welded Flame-Cut Plate.
Fig. 23  Isostress Diagram of a 24" x 2"
Center-Welded Flame-Cut Plate.
Fig. 24 Residual Stress Distribution in a 24" x 6" Center-Welded Flame-Cut Plate.
Fig. 25 Residual Stress Distribution in a 9" x 1 1/2"
Edge-Welded Flame-Cut Plate.
Fig. 26 Residual Stress Distribution in a 12" x 2"
Edge-Welded Flame-Cut Plate.
Fig. 27 Residual Stress Distribution in a 12" x 3½" Edge-Welded Flame-Cut Plate.
Fig. 28  Residual Stress Distribution in a 20" x 2" Edge-Welded Flame-Cut Plate.
Fig. 29 Residual Stress Distribution in a 24" x 2" Edge-Welded Flame-Cut Plate.
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