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Fritz Engineering Laboratory Report No. 249.18

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ABSTRACT

This report summarizes the results of an extensive investigation on residual stresses in welded built-up shapes.

Plates of various sizes were welded to form small and medium size shapes, simulating the conditions in a built-up shape. Basic shapes like L, T, H, and square Box were studied and the experimental residual stress distributions were compared with predictions. Similar residual stress distributions were obtained for similar shapes. With these results, it is possible to estimate the residual stress distribution in welded built-up shapes. A knowledge of the residual stress distribution in a structural shape helps in the prediction of its column strength.

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<div align="center">CONTENTS</div>

1. INTRODUCTION

Purpose and Scope

In the last decade, the importance of residual stress was fully recognized as one of the principle factors influencing the strength of centrally loaded steel columns. An extensive research project on "The Influence of Residual Stress on Column Strength" was conducted at Lehigh University under the guidance of Task Group 1 of the Column Research Council. This group was assigned the task of determining the relationship between material properties and the strength of columns[1]. More recently, the task group has been concerned with the strength of welded built-up columns. This paper presents the results of the study of the residual stress distribution in some welded shapes of small and medium cross section.

Euler defined the buckling load of a column by the equation

$$\frac{P_{cr}}{A} = \sigma_{cr} = \frac{\pi^2 E}{(\frac{kL}{r})^2} \tag{1}$$

where σ_{cr} is the buckling stress in a column, E is the Young's modulus, L is the total length of the pinned-end column, and kL/r is the effective slenderness ratio. Euler's buckling formula is applicable to column sections which remain elastic throughout the loading. Most practical columns fail in the inelastic range and the strength of columns buckling in the inelastic range is obtained from the tangent modulus concept by replacing E by E_t in the Euler equation[1]; thus,

$$\frac{P_{cr}}{A} = \sigma_{cr} = \frac{\pi^2 E_t}{(kL/r)^2} \tag{2}$$

where E_t is the tangent modulus. E_t is given by

$$EI_e = E_t I \tag{3}$$

where I_e is the moment of inertia of the elastic part of the yielded cross

section and I is the moment of inertia of the entire cross section.[2] E_t

is less than E above the limit of proportionality of the stress-strain curve

for a cross section containing residual stresses. The corresponding tangent

modulus load for a column is less than that given by the Euler curve or the

yield strength of the material. This reduction can be attributed to the

presence of residual stresses in the shape.

Residual stresses are the stresses that remain in a material as a

result of plastic deformations. These are caused by the uneven cooling of

the material after hot rolling, welding, or flame cutting and by various

fabrication methods such as cold bending and cambering.[3,4]

Welded built-up columns of small and medium cross section contain high

compressive residual stresses which reduce the carrying capacity of the

column; the reduction in strength may be considerable if these compressive

residual stresses are in critical sections of the shape, such as the tips of

the flange of an H-shape bending in the weak direction. For this reason a

knowledge of the magnitude and distribution of residual stresses in welded

shapes is important. With the proper proportioning and choice of the shape

of the cross section, the effect of the residual stresses may be minimized.

This is accomplished by choosing a shape such that the compressive residual

stresses develop in less critical areas of the shape. In some instances,

the method of fabricating the shape may also be considered as an influencing

factor. The importance of the nature of residual stress distribution is

illustrated as follows:

The typical distributions of residual stresses in a medium size welded H-shape and a welded Box-shape is shown in Fig. 1. As can be seen in this figure, the compressive residual stresses are contained at the center portion of the plate elements in the box, which for column strength is a less critical location than at the extremeties of the flanges as in the welded H-shape.[5,6] Tests have shown that the welded box-shape gives better column strength than a corresponding welded H-shape mainly because of this difference in the nature of the residual stress distribution. Thus, by reversing the normal residual stress distribution in an H-shape, the column strength of the cross-section can be improved. Such a reversal in the residual stress distribution is obtained for example by depositing a weld bead at the tips of the flanges[7] or by welding a cover plate to the flanges of an H-shape.[8]

Various shapes can be built-up by welding plates together. Figure 2 shows that the conditions in welded H- and Box-shapes can be submitted in center welded and edge welded plates. The aim of the investigation was to determine the residual stress distribution in plates and basic shapes like L's and T's and to show that the residual stress distribution in H- and Box-shapes can be obtained approximately by superposition. The experimental study reported here includes a wide range of plates, L-shapes, T-shapes, H-shapes, and Box-shapes of various sizes. The material of all the specimens tested were universal mill plates of A7 steel. However, the results of the study are applicable directly also to A36 steel.

Influencing Factors

Residual stresses can be considered as the cumulative sum of thermal stresses set up in a heated plate or shape during cooling.[4] Thermal stresses in shapes built-up by welding depend on the temperature distribution due to the heat input. The temperature distribution is in turn a function of the geometry of the component plates, the heat input, the material, heat losses from the shape, and the thermal properties of the material.[3,6,9] It has been shown that the geometry of the component plates is the main factor influencing the magnitude and distribution of residual stresses[4].

The width of the plate has a negligible influence on the behavior of the material in the vicinity of the weld. However, it does influence the general rise in temperature after welding.[10] Heat flow is one of the important factors which influences the formation of residual stresses. Consider the welding of a web plate to a flange plate, the heat produced by the weld travels in three directions the proportions depending upon the geometry of the plates.

Each plate in a welded shape has some restraining effect on the other. It may be expected that this effect depends very largely on the relative sizes of the two elements: for instance, for plates which are of a similar size and which are welded together it would be expected that the effect of restraint is smaller than when a very small plate is welded to a very large plate. For the cross-sections with which this study is concerned, all the plates may be regarded as similar in size, so that it was expected that the effect of restraint would be a minimum.

2. DESCRIPTION OF TESTS

The tests for the determination of the residual stress distribution in shapes were conducted in two stages. The residual stresses were measured first in welded plates and then in welded shapes. The component plates were of the various sizes which would be expected to be used generally in the fabrication of welded shapes of small and medium size.

Residual Stresses in Welded Plates

The investigation on the plates is reported in an earlier paper.[11] The plates were welded along either Single or Double V grooves in the center, or along an edge so as to simulate conditions prevailing in actual built-up shapes. To simulate the welds on Box sections, some plates were welded on both edges. Figure 3 shows the details of welds in the plates.

Generally, the welds were deposited in several passes as would be the case for built-up shapes. However, on one plate, single-, double-, and triple-pass welds were laid to observe the cumulative effect on the residual stress distribution.[11] The plates were welded manually in the flat position by professional welders and all welding standards were adhered to. The plates were clamped to heavy structural shapes. There was no precambering.

Residual Stresses in Structural Shapes

The structural shapes tested are given in Table 1. First, simple structural shapes such as L- and T-shapes were fabricated from plates ranging in width and thickness from 6" to 10" and 1/4" to 1" respectively, and the residual stresses were measured. Next, Box- and H-shapes were built up from similar plates and the residual stresses in these shapes were measured.

In fabricating these shapes, tack welds were made manually and, in addition, for the 10" by 10" Box-shape the first pass at the root was deposited manually; the major part of the welding was done by automatic welding machines. Table 1 shows also the sizes of the plates and the sizes of welds used in fabricating these shapes. The plate thickness varied from 1/4" to 3/4".

Although flame cutting is used usually in preparing plates for fabrication into shapes, the process introduces heat into the plates and this may affect the final residual stress distribution due to welding. To isolate the effect of welding on the residual stress magnitudes, two sets of Box-shapes were fabricated - one made up of plates prepared for welding by flame cutting and the other made up of machined plates.[5]

Another type of built-up shape considered was a cover-plated rolled H-shape studied in connection with tests on the strength of reinforced columns. An 8WF31 shape was reinforced by welding 7" x 3/8" cover plates on the flanges and the residual stress in the reinforced shape was measured.[8]

The plates and shapes used were sufficiently long so that a uniform state of stress would exist at the portion where the residual stresses were measured. Residual stress measurements were made on a gage length of 10", both the ends of which were at a distance from the cut edge more than the width of the plate. In experimental and theoretical studies on rolled shapes[2,3] this arrangement has been shown to satisfy the requirements at the end for the effect of boundary conditions.

The variation of residual stresses along the length of a shape was studied by taking the measurements at more than one section. Such an arrangement is shown in Fig. 4. The "method of sectioning" described in Reference 12 was used to measure residual stresses. A typical test section for measuring residual stresses is shown in Fig. 5. This method gives the longitudinal residual stress only, although by inference the lateral residual stresses may be obtained for thin plates.

Direct measurements of strain inside the box shape were not possible so that an indirect method was used to estimate the residual stress distribution of the inside face of the column. Two sets of residual stress specimens were taken each from fabricated pieces No. C11 and No. C12. Figure 6 shows the sections used in the study. Section E and F were taken from piece No. C11 and sections G and H from piece No. C12. The sections were cut into L shapes according to the detail shown in the figure. Additional gage holes were laid out on the inside faces of the L shape before final sectioning was done. Measurements were made prior to each cutting operation. It was hoped that the effect of edge condition would be small in this arrangement.

Coupon Tests

Tension coupons were tested to observe the effect of welding on the material properties. Figure 7 shows a typical lay-out of coupons cut from plates. The dimensions of coupons were in accordance with ASTM Specifications.[13] However, to check the yield strength* of the material at the weld, tension tests

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* Yield Strength - The stress at which a material exhibits a specified
                   limiting deviation from the proportionality of stress
                   to strain (ASTM E6-60T)

were made on coupons of non-standard size. The non-standard coupons consisted

entirely of weld metal or material in the heat affected zone. For purposes of

comparison, tension tests were conducted on non-standard coupons made up of

parent material.

3. TEST RESULTS AND DISCUSSION

The results of the tests are classified into three groups, those on:

1. Plates,

2. L- and T-shapes,

and 3. H- and Box-shapes.

Plates

The typical residual stress dsitribution in welded plates are shown in Fig. 8. The results of the test program on welded plates are discussed in detail in Reference 11. Based on the study, the following were some of the conclusions made:

1. The residual stress distribution in plates whether due to cooling from rolling of the unwelded plates or due to cooling after welding is approximately parabolic in shape, except at the weld itself. This is true for welded plates up to about 16 in. in width.

2. There is no great variation of residual stress in welded plates between successive passes, and the first pass causes the major portion of the residual stress. At the weld, however, the effect of succeeding passes of weld is marked.

3. Where the welding conditions are uniform along a plate, the residual stresses are also uniform along the length of the plate.

4. Plates greater than 1/2 in. in thickness show some difference between the longitudinal residual stresses on both faces. This shows that there is a limitation to the thickness of a plate for which the residual stress distribution may be considered as two dimensional in the plate.

This study has made it possible to predict approximately the residual stress magnitude and distribution in welded plates. For this purpose the plate sizes have been divided into three groups--(a) less than 8 in., (b) 8 to 14 in. and (c) 16 to 20 in.--called "narrow", "medium" and "wide" plates, respectively. Average experimental values of residual stresses are shown as predicted values for each of these groups in Table 2. The values given in this table can be considered as an estimate of expected values. As an example, for a medium plate with a weld at the center, the residual stress would be about 52 ksi tension at the center and about 23 ksi compression at the edges. Similar predictions can be made for other plates, both edge and center welded.

L- and T-shapes

The measured residual stresses in L- and T-shapes are shown in Figs. 9 through 16. The residual stresses are shown for both sides of each leg of the shapes. The residual stress magnitudes are given in Table 3 as ratios of the yield stress of the material. It is to be noticed that the residual stress distribution is quite similar for all the T-shapes. The tensile residual stress at the weld varies from 20 ksi to 65 ksi, however, for the T-shape made of 16 in. x 1 in. plates with 5/8 in. welds on both sides of the joint, the surface away from the weld showed that it was free from tensile residual stress (Fig. 14). At the free edge of the stem of the shape, the stress magnitude was low, except for the 16 in. x 1 in. T-shape in Fig. 14. This stem had shear cut edges. Shear cutting of edges introduces residual stresses of considerable magnitude. The nature of the residual stress is tensile on one face and compressive on the other face; this can be

explained as due to the presence of bending action at the instant of shearing of the edge. The residual stress magnitude at the sheared edge is about 30 ksi on each face of the plate; the average value approaches zero. At the weld the tensile stress is about 62 ksi. For the L- shape shown in Fig. 12, the residual stress distribution is symmetrical about the weld. At the weld the tensile stress is about 62 ksi and the maximum compressive stress is about 25 ksi. At the free ends the residual stress magnitude is about 3 ksi.

From a knowledge of the residual stress distribution in welded plates the residual stresses in welded shapes can be predicted. If a comparison of the measured residual stress is made with the residual stresses obtained from the prediction table (Table 2), a good agreement in the values for T-shapes can be seen. The only difference exists in the residual stress of the free arm of the T-shapes, which contains residual stresses of very small magnitude away from the weld. For example, consider the shape T-7 (Table 3). The flange of the shape (corresponding to a center-welded plate) has σ_{ro} = 63 ksi, σ_{re} = 25 ksi, z = 0.20. The web of the shape (corresponding to an edge-welded plate) has σ_{rt} = 63 ksi, σ_{rm} = 9 ksi (with small values for σ_{rn} and σ_{re}), z_3 = 0.23. From Table 2 under medium plates the corresponding values are: center welded, σ_{ro} = 52 ksi, σ_{rc} = 23 ksi, z = 0.19 and edge-welded, σ_{rt} = 55 ksi, σ_{rm} = 23 ksi, z_1 = 0.12.

That the size of the weld plays a small role in the magnitude and distribution of residual stresses may be seen from a comparison of Fig. 10 and 15. The free arm of the T-shape has markedly similar residual stress distributions in both cases, with only an increase of about 15% tensile residual stress at the weld due to a doubling of the weld size. A comparison

of the flanges indicates the effect of geometry, in that the residual stress patterns on both sides of the plate vary markedly for the thicker plate. The average residual stress distribution, however, is much the same in both cases.

It may be said, therefore, that experimental results for L- and T-shapes indicate that the residual stress distributions can be estimated reasonably well from those of the separate welded plates which may be regarded as the component parts of the built-up shapes. The only reservation is that the free arm (or web) of T-shapes contains residual stresses of very small magnitude away from the weld. What follows from this conclusion is that restraint may be neglected as a factor contributing to residual stress—welded plates have approximately the same residual stress magnitude and distribution whether they are component parts of built-up shapes or not (the distribution being independent of the weld size) unless the welds are very heavy.

H- and Box-shapes

Residual stress distributions in H- and Box-shapes are shown in Figs. 17 through 23. The residual stress distribution in the H-shapes resembles that of rolled H-shapes, but the magnitudes are comparably greater because of the heat of welding. The residual stresses shown are the average of the measurement on two faces for the H-shapes, whereas for the Box-shapes it is the magnitude on the outer face.

As can be seen from Fig. 17, at the flange tips of the H-shapes the compressive residual stress varies from 20 ksi to 35 ksi. The maximum tensile residual stress in the middle of the flanges is about 30 ksi. The webs themselves have a maximum compressive residual stress of about 18 ksi.

The residual stress distribution for box sections indicate approximately uniform compressive residual stresses at the center portion of the component plates, changing rapidly to tensile residual stresses at the edges. The compressive residual stress is about 30 ksi and the tensile residual stress at the welds is about 38 ksi. Residual stress measurements at three different sections along the length of a 10 in. x 10 in. Box-shape show insignificant variation in the residual stress distribution. Figure 18 shows the residual stress distribution of three sections A, B and C super-imposed on one diagram. The two 10" x 1/2" plates show uniform compressive residual stress of 28 ksi, the 9" x 1/2" plates have a somewhat parabolic residual stress distrbution with a high compressive residual stress of 36 ksi. The tensile residual stress at the welds is about 35 ksi. These values represent the magnitudes on the outer face.

Measurements on the inside face of the Box-shapes are shown in Fig. 22. There is only a slight variation in the magnitude of residual stresses measured on the outside and on the inside face. In Fig. 23 are shown residual stress distribution for Box-shape C12 cut along diagonals 1-3, and 2-4. It is to be noticed that away from the cuts, the residual stress magnitudes are not affected. The indirect method of measuring residual stresses inside a Box-shape appears to be satisfactory. Since the thicknesses of the plates are 1/2 in. or less and no great thermal difference exists across the thick-ness during welding, the residual stresses could be expected to be uniform over the thickness.

As illustrated for the L- and T-shapes, the effect of restraint may be considered negliglible when the component plates are similar in size. A study of the residual stress distribution in welded Box-shapes gives further verification to this conclusion. In Fig. 24 the predicted residual stress distribution for a 10 in. x 10 in. Box-shape is shown superimposed on an actual distribution. This figure shows that although it is not possible to predict the exact magnitudes of the residual stresses, a close approximation to the actual distribution can be obtained. This prediction is valid because of the negligible effect of restraint. It follows that from a knowledge of the residual stress distribution in welded plates, the residual stress distribution in a welded shape can be estimated by considering each component plate either as an edge-welded or as a center-welded plate.

The method of edge preparation of the plate had little effect on the residual stress distribution of the Box-shape in that the specimens showed very negligible differences between the residual stress distribution of the specimen fabricated from machined plates and the specimen fabricated from flame-cut plates.

Interesting results were obtained from the measurement of residual stresses in reinforced WF shapes. The residual stress distribution in a rolled 8WF31 shape and two 7 in. x 3/8 in. plates before welding are shown in Fig. 25. The residual stress distribution in the 8WF31 is as expected from earlier tests, with compressive residual stress of 12 to 14 ksi at the flange tips and tensile residual stress of 6 to 8 ksi at the flange centers.[12] In the web the residual stress is compressive and of an average value of 6 ksi.

The residual stress magnitude varied from 5 ksi tension at the center to 11 ksi compression at the edges of the plates. Figure 26 shows the residual stress distribution in the 8WF31 after the two 7 in. x 3/8 in. plates were welded to the flanges.

It is to be noticed that the residual stress distribution in the flange has reversed after welding, and at the flange tips the magnitude is 25 to 30 ksi tensile and that the compressive residual stress is no longer at the flange tips and is quite low, being 7 ksi. From this type of residual stress distribution, the shape could be expected to be stronger than a corresponding rolled shape.

Tension coupon test results are shown in Table 4. Small coupons containing weld metal indicate yield strengths higher than that of the parent material. The heat of the welding may change the structure of the parent-material in the vicinity of the weld and act as a heat treatment. This can increase the yield strength of the parent material, because of the higher strength weld metal contained in the electrode. This is also the reason for tensile residual stresses of magnitudes being much higher than the yield strength of the plate material.

4. SUMMARY

This section summarizes the results of an experimental investigation into the magnitude and distribution of longitudinal residual stresses arising in structural shapes built-up by welding. The results of this study are useful in the determination of the influence of residual stress on the strength of welded built-up columns.

The component plates are of ASTM designation A7 structural carbon steel. Plates, L- and T-shapes were welded manually, whereas H- and Box-shapes were welded automatically.

1. The results of the study on welded plates make it possible to estimate the residual stress magnitude and distribution for welded plates of medium size and thickness (see Table 2).

2. The residual stress in a welded shape may be estimated approximately from the residual stress distributions of the separate welded plates which may be regarded as the component parts of the built-up shapes. (The only reservation is that the free arm, or web, of T-shapes contains residual stresses of very small magnitude away from the weld).

3. It appears that longitudinal restraint may be neglected as a factor contributing to residual stresses in welded built-up shapes, provided the component parts are similar in size.

4. Shear cut plates show considerable residual stress in the vicinity
    of the edge on the two faces; however, the average residual stress
    is almost zero. (Fig. 14)

5. Welded H-shapes have residual stress distributions similar to
    those in rolled H-shapes, but larger in magnitude. Welded
    Box-shapes have high tensile residual stresses at the corners
    and compressive residual stresses distributed over a wide area of
    the mid portion of the component plates.

6. Residual stresses are uniform along the length of a shape welded
    under identical conditions. For shapes having medium size plates
    less than 1/2 in. in thickness, there is only a slight variation
    in the magnitude of residual stresses measured on the inside and
    on the outside faces. (Figs. 18 and 22)

7. Edge preparations such as machining or flame cutting have little
    effect on the final residual stress distribution of the welded
    Box-shapes, since the welding operation has the greatest influence
    in the formation of residual stresses.

8. The welding of cover plates to rolled H-shapes reverses the
    existing residual stress distribution to a favorable one and thus
    may increase the load carrying capacity of the shape. (Fig. 26)

9. Welding heat increases the yield strength in the vicinity of the
    weld, but creates no adverse effects elsewhere for structural
    strength. (Table 4)

5. NOMENCLATURE

A	=	cross-sectional area
b	=	width of the plate
E	=	Young's modulus of elasticity
E_t	=	tangent modulus
I	=	moment of inertia
I_e	=	moment of inertia of elastic part
L	=	total length of a pinned-end column
L/r	=	slenderness ratio
kL/r	=	effective slenderness ratio
P_{cr}	=	critical load on a column
r	=	radius of gyration
t	=	thickness of plate
T	=	depth of weld
z_1, z_2, z_3, z_4 z_5, z_6, z_7	=	parameters in terms of b used to express the distances of points of zero or maximum residual stresses
σ_{cr}	=	applied average maximum stress on a column
$\sigma_{cr}, \sigma_{cr1}, \sigma_{cr2}$	=	compressive residual stress
σ_{re}	=	residual stress at the edge
σ_{rm}, σ_{rn}	=	significant residual stress in the interior of a plate
σ_{ro}	=	residual stress at the center of a center welded plate
σ_{rt}	=	tensile residual stress

6. ACKNOWLEDGMENTS

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7. <u>TABLES AND FIGURES</u>

Table 1. Schedule of Welded Shapes
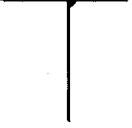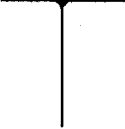
No.	Shape	Plate Size (in.)	Weld Size (in.)
1		6 x 1/4	3/16
2		8 x 1/4	3/16
3		6 x 1/2	5/16
4		10 x 1/2	3/8
5		10 x 1/2	5/16
6		16 x 1	5/8
7		10 x 1/2 8 x 1/4	3/16
8		6 x 1/2 6 x 1/4	3/16

Table 1.   (Continued)
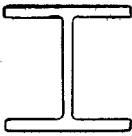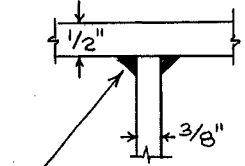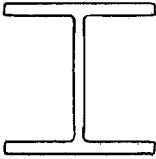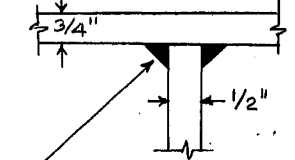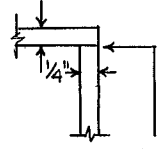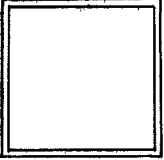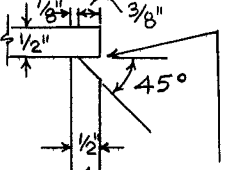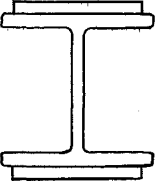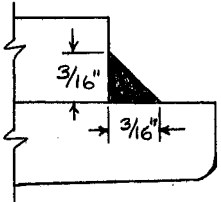
No.	Shape	Plate Size (in.)	Weld Size (in.)
9		6 x 1/2 6 x 3/8	1/2" 3/8" 3/16 Fillet weld both sides
10		9 x 3/4 9 x 1/2	3/4" 1/2" 1/4 Fillet weld both sides
11		6 x 1/4 5-1/2 x1/4	1/4" Minimum Reinforcement 1/16"
12		10 x 1/2 9 x 1/2	1/8" 3/8" 1/2" 45° 1/2" Minimum weld Reinforcement 1/16"
13		8WF31 7 x 3/8	3/16" 3/16"

Table 2. Average of Experimental Values of Residual Stress

Distribution in Welded Plates
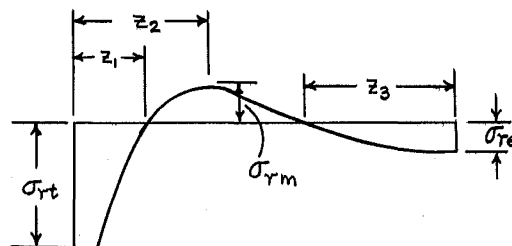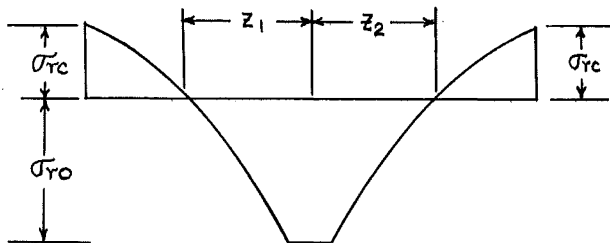
Center Welded Plates

	Nos. of Measurements	σ_{ro} (ksi)	σ_{rc} (ksi)	Distance from $\mathcal{C}$ of Plate to Zero Residual Stress (Mean of z_1 and z_2)
Narrow Plates	22	44	22	0.19
Medium Plates	22	52	23	0.18
Wide Plates	7	58	7	0.13

Edge Welded Plates

	Nos. of Measurements	σ_{rt} (ksi)	σ_{rm} (ksi)	σ_{re} (ksi)	Positions of Zero and Maximum Compressive Residual Stress		
					z_1	z_2	z_3
Narrow Plates	6	46	19	5	0.12	0.26	0.13
Medium Plates	5	55	23	7	0.10	0.23	0.41
Wide Plates	8	41	14	7	0.07	0.14	0.57

Table 3. Residual Stress Distribution in Welded T- and L- Shapes

$\sigma_y = 33$ ksi
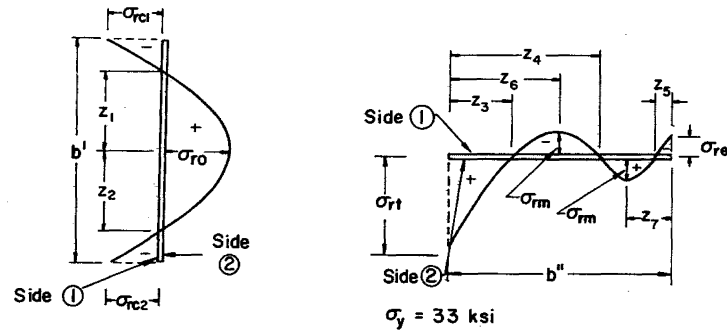
Shape No.	Shape	Weld Size (in)	Side	RESIDUAL STRESS COEFFICIENTS							CO-ORDINATES OF ZERO AND MAXIMUM STRESSES						
				$\dfrac{\sigma_{rc1}}{\sigma_y}$	$\dfrac{\sigma_{rc2}}{\sigma_y}$	$\dfrac{\sigma_{ro}}{\sigma_y}$	$\dfrac{\sigma_{rt}}{\sigma_y}$	$\dfrac{\sigma_{rm}}{\sigma_y}$	$\dfrac{\sigma_{rn}}{\sigma_y}$	$\dfrac{\sigma_{re}}{\sigma_y}$	z_1/b'	z_2/b'	z_3/b''	z_4/b''	z_5/b''	z_6/b''	z_7/b''
1	T	3/16	1	1.27	0.94	1.30	1.57..	0.26	0.00	0.06	0.19	0.13	0.20	0.83	0.17	0.23	0.17
			2	1.15	1.06	--	1.36	0.24	0.08	0.09	0.21	0.14	0.21	0.58	0.11	0.33	0.25
2	T	3/16	1	0.97	0.52	1.60	1.51	0.33	-0.13	0.10	0.20	0.08	0.16	0.75	0.10	0.27	0.13
			2	1.09	0.61	--	1.51	0.24	0.09	0.00	0.21	0.07	0.16	0.68	0.00	0.21	0.17
3	T	5/16	1	1.15	0.70	0.60	1.44	0.42	--	0.27	0.09	0.09	0.19	--	0.00	0.35	0.00
			2	1.27	0.94	--	1.35	0.18	0.33	-0.33	0.09	0.10	0.21	--	0.00	0.23	0.00
4	L	3/8x1/2	1	I Leg			1.73	0.79	0.14	-0.09			0.12	0.65	--	0.23	0.17
			2				2.03	0.73	0.26	-0.15			0.13	0.59	--	0.24	0.17
			1	II Leg			1.73	0.82	0.09	0.08			0.12	0.67	0.07	0.24	0.26
			2				2.03	0.64	0.29	-0.12			0.15	0.53	--	0.24	0.26
5	T	5/16	1	0.84	0.88	0.94	1.64	0.30	0.24	0.33	0.15	0.16	0.14	0.42	0.20	0.20	0.40
			2	0.97	1.21	--	0.78	0.19	0.20	0.41	0.20	0.12	0.14	0.41	0.21	0.20	0.39
6	T	5/8	1	0.30	0.76	0.00					0.08	0.07					
			2	0.61	0.48	--					0.22	0.25					
7	T	3/16	1	1.17	1.11	0.80	1.88	0.15	0.05	0.09	0.31	0.30	0.25	0.59	0.15	0.26	0.25
			2	0.48	0.26	--	1.91	0.36	0.00	0.27	0.12	0.08	0.20	0.63	0.25	0.26	0.25
8	T	3/16	1	0.95	0.67	0.64	1.55	0.40	0.00	0.00	0.12	0.18	0.18	1.00	0.00	0.29	0.00
			2	0.14	0.18	--	1.76	0.22	0.15	0.00	0.06	0.09	0.27	0.54	0.00	0.36	0.17

Table 4. Yield Strength of Some Typical Coupons

Before Welding		After Welding	
Coupon No.	σ_{ys} (ksi)	Coupon No.	σ_{ys} (ksi)
a) Welded Plates			
T-13-1	35.6	T-2-A2	34.5
-2	34.2	-A5	54.8[a,b]
-3	35.7	-A8	34.6
		T-2-3-1	36.6[c]
		-3	43.4
		-5	35.7
b) Welded Shapes			
		C71	37.3
These are for shape C7		C72	37.6
shown in Fig. 19		C73	37.0
		B10	34.6[b]
These are for shape C8		B21	47.2[a,b]
shown in Fig. 20		B30	37.2[b]
		B39	48.3[a,b]

a. Contains large proportion of weld metal

b. Small coupons

c. Contains weld metal
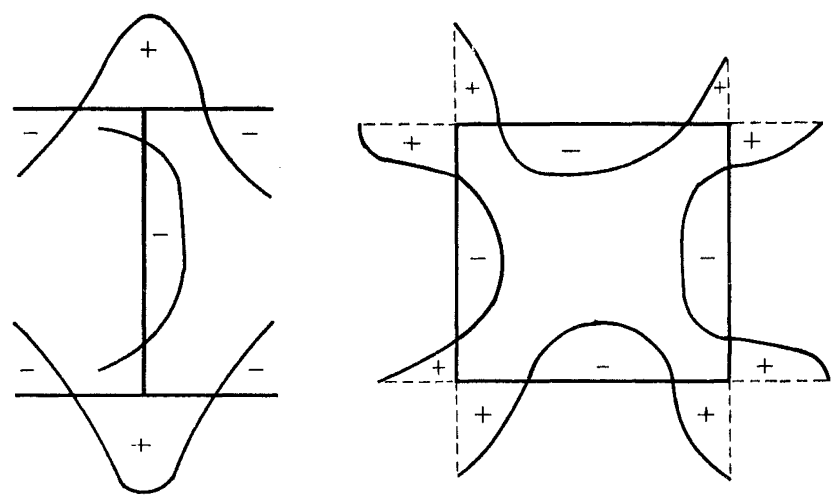
Fig. 1   Residual Stress Distribution in Welded H- and Box-Shapes
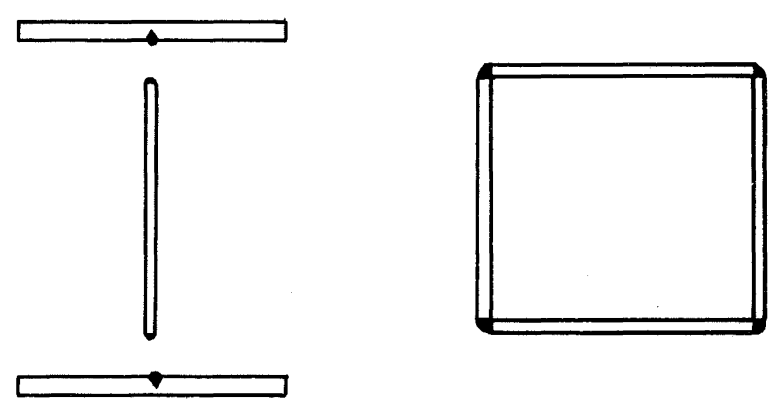
Fig. 2   Welded H- and Box-Shapes Considered as Center
Welded and Edge Welded Plates

Center Welded Plates
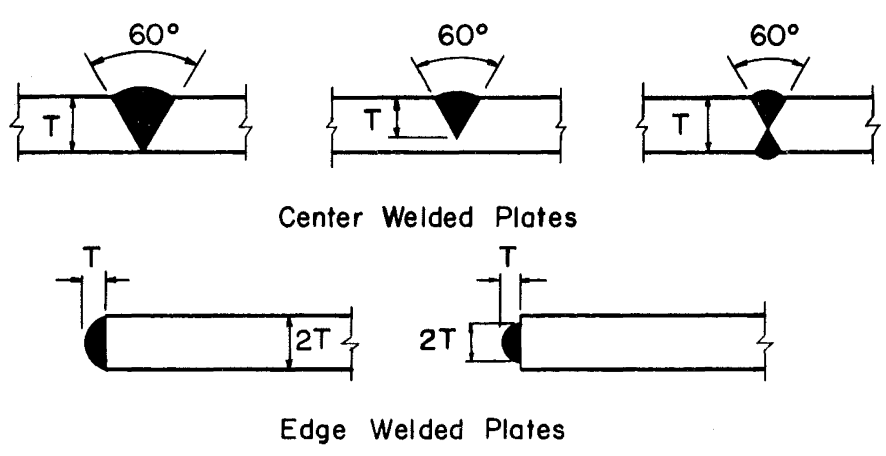
Edge Welded Plates

Fig. 3   Types of Welds Used In Welded Plates

(FROM FABRICATED PIECE NO.5)

Section A   Section B   Section C

|←1'8½"→|←11"→|←—— 4'5" ——→|←11"→|←—— 4'5" ——→|←11"→|←1'8½"→|

|←——————————————— 15'0" ———————————————→|

COLUMN C5
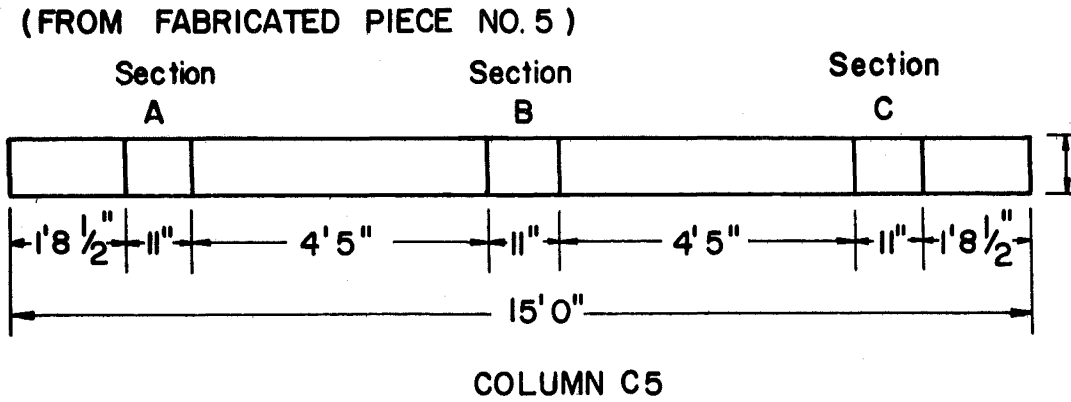
Fig. 4 Layout for Residual Stress Measurements at Different Sections

(FABRICATED PIECE)

|←11"→|←—— b ——→|

DETAIL A

HOLES FOR WHITTEMORE STRAIN GAGE

DETAIL A

11"

10"

b

½"
½"
½"

SAW CUTS

½" STRIPS
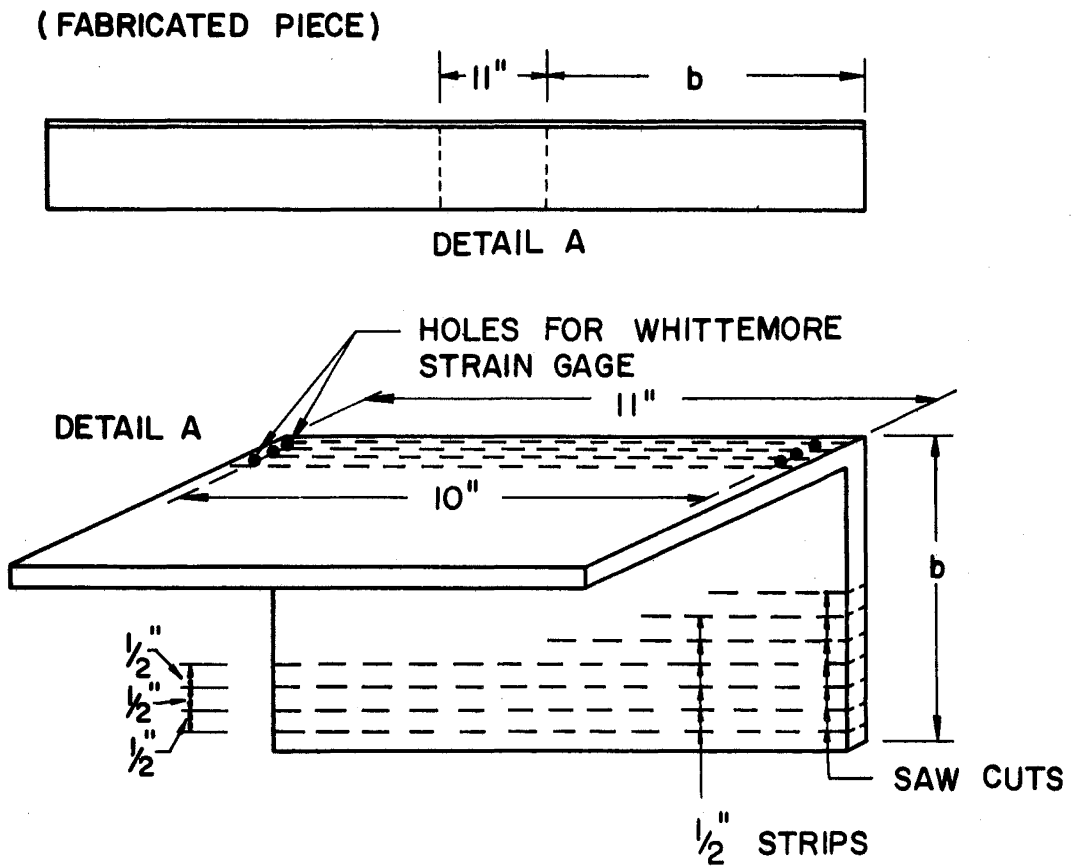
Fig. 5 Layout for Sectioning
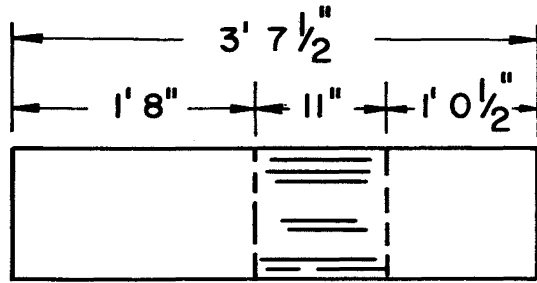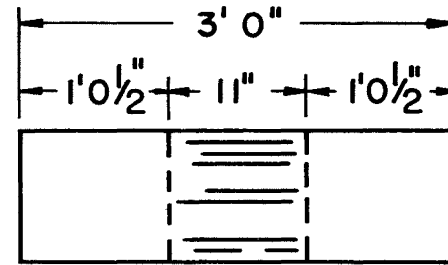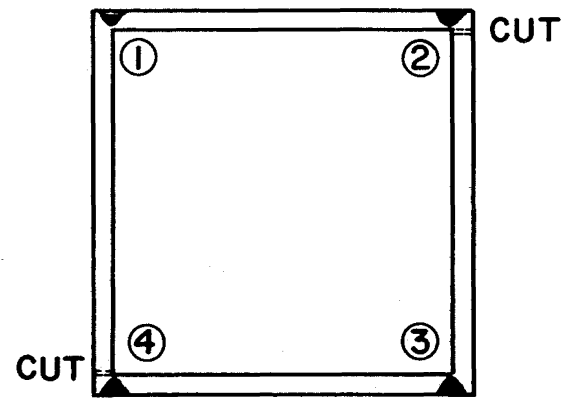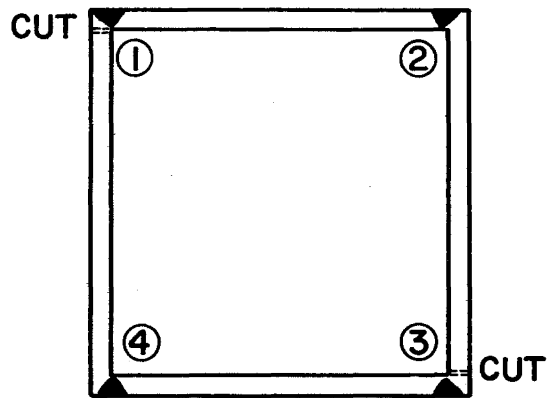
Fig. 6 Layout of Sections in Box-Shapes

STANDARD COUPONS
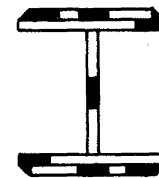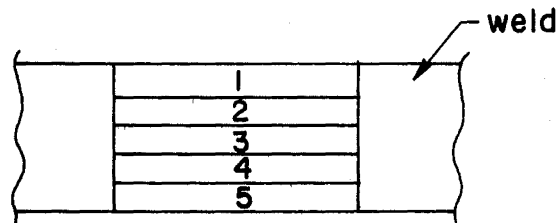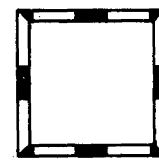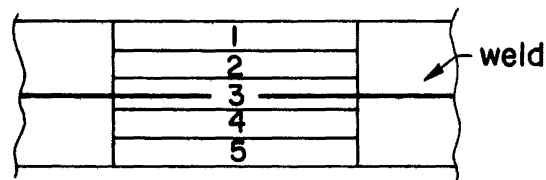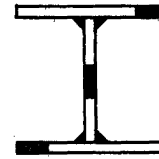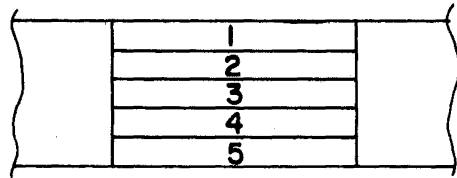
(a) PLATES

(b) SHAPES

NON - STANDARD COUPONS
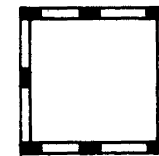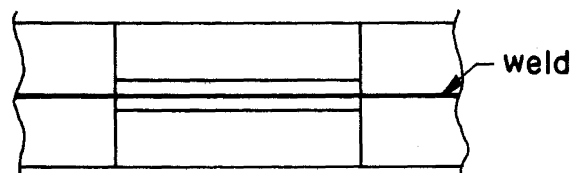
(c) PLATE

(d) SHAPE

Fig. 7 Layout for Coupons
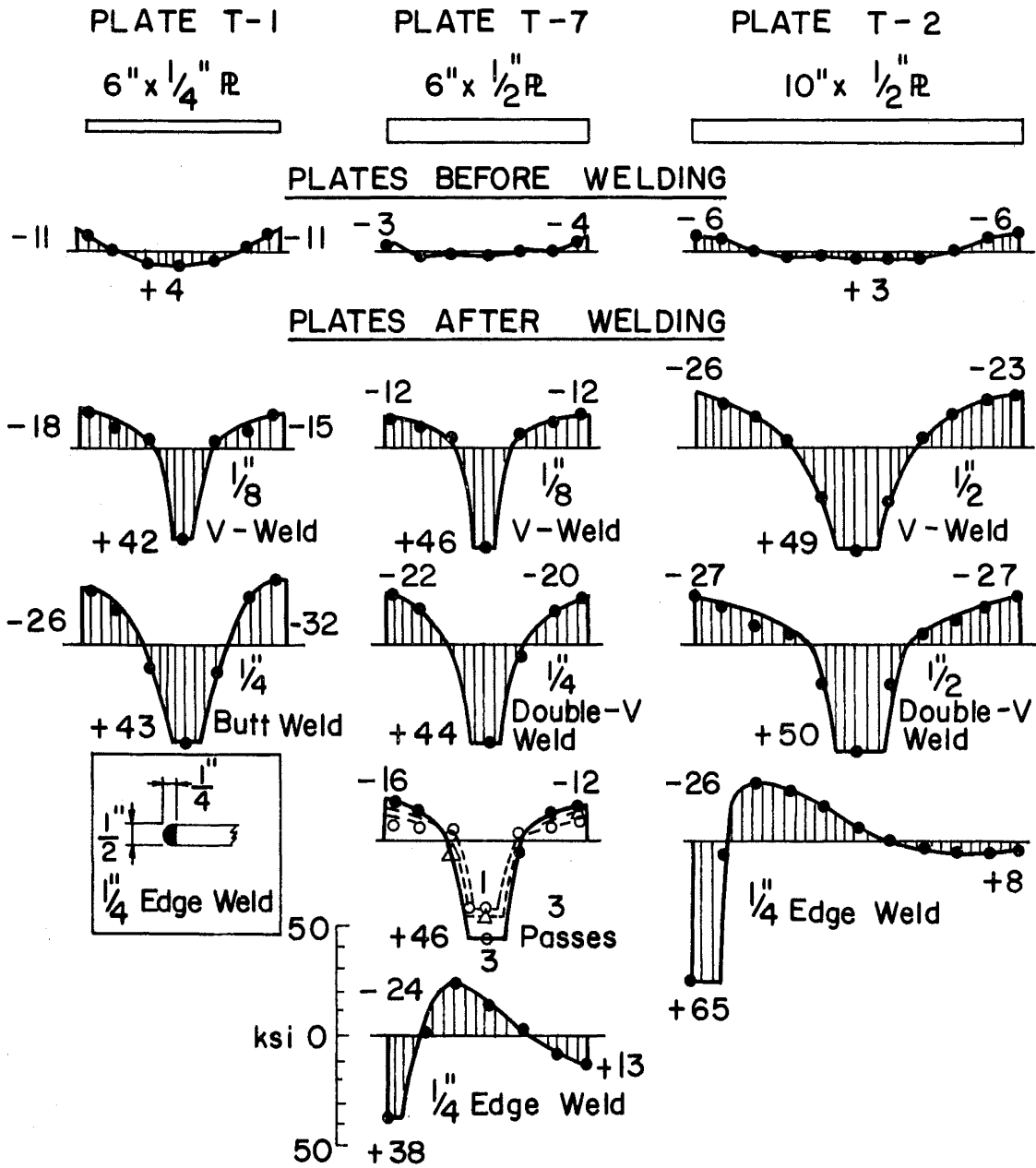
Fig. 8 Typical Residual Stress Distributions in Welded Plates

Figs. 9 through 23

Residual Stress Distribution in Welded Shapes
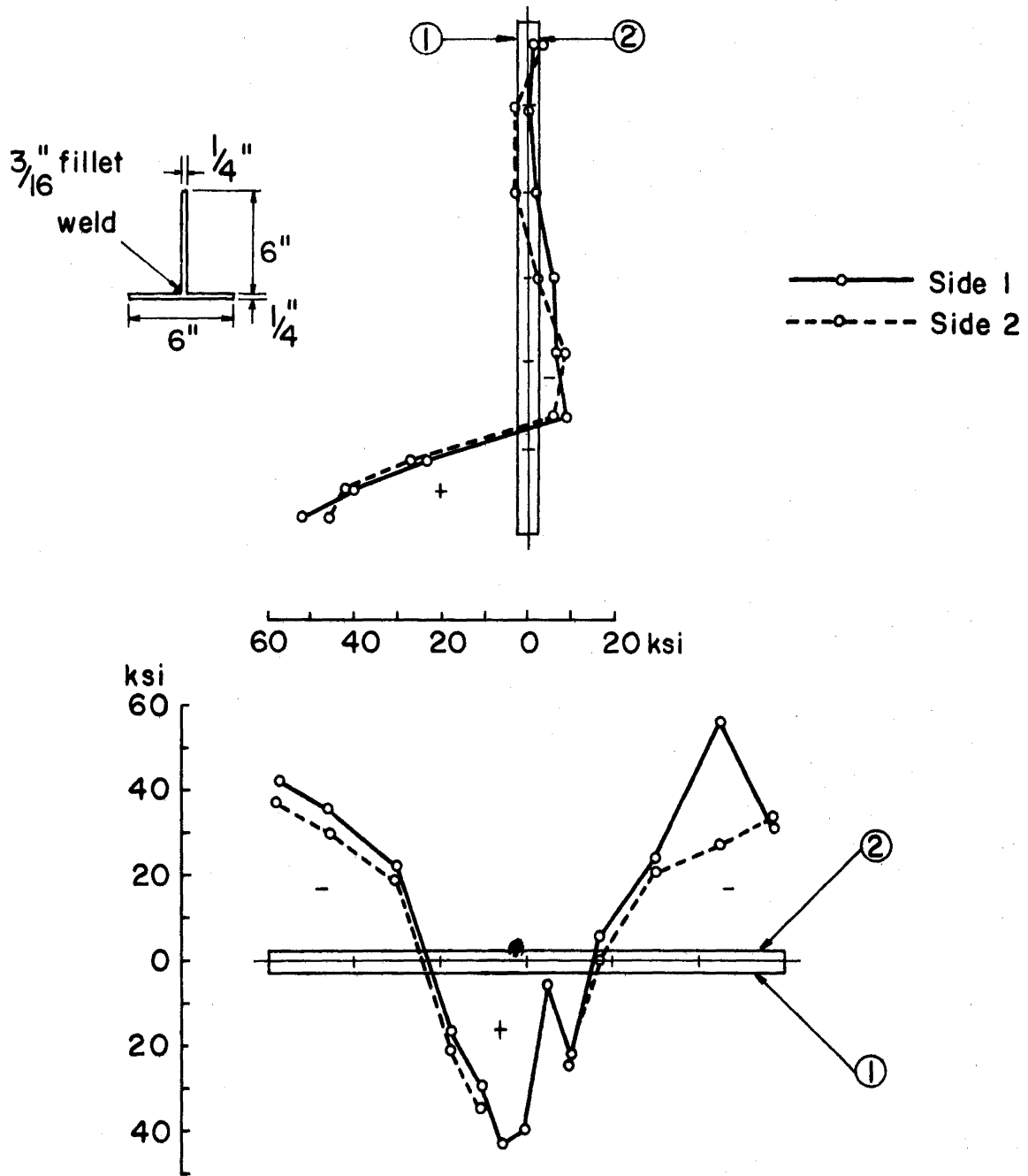
Fig. 9   Shape 1   Table 1
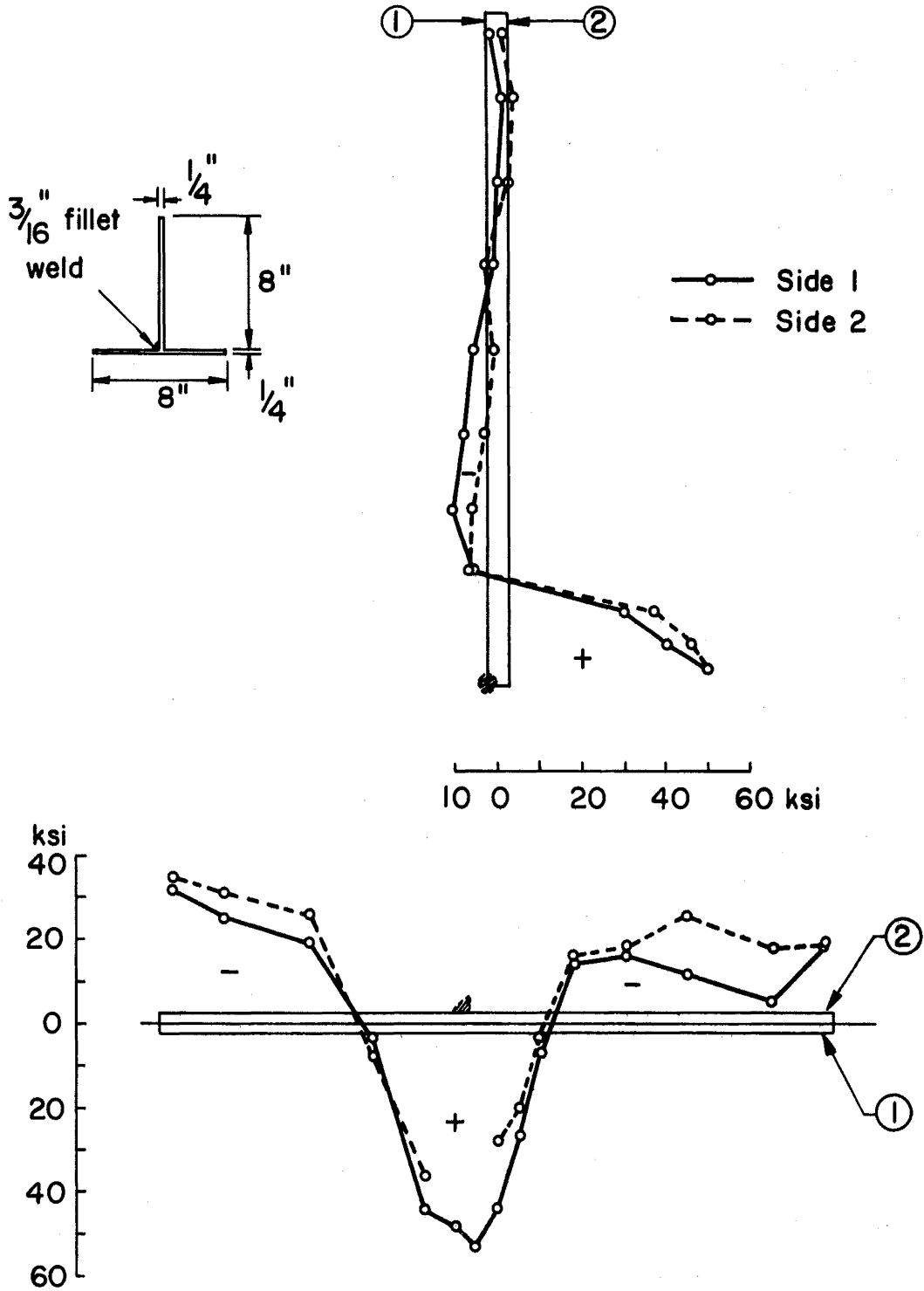
Fig. 10 Shape 2 Table 1
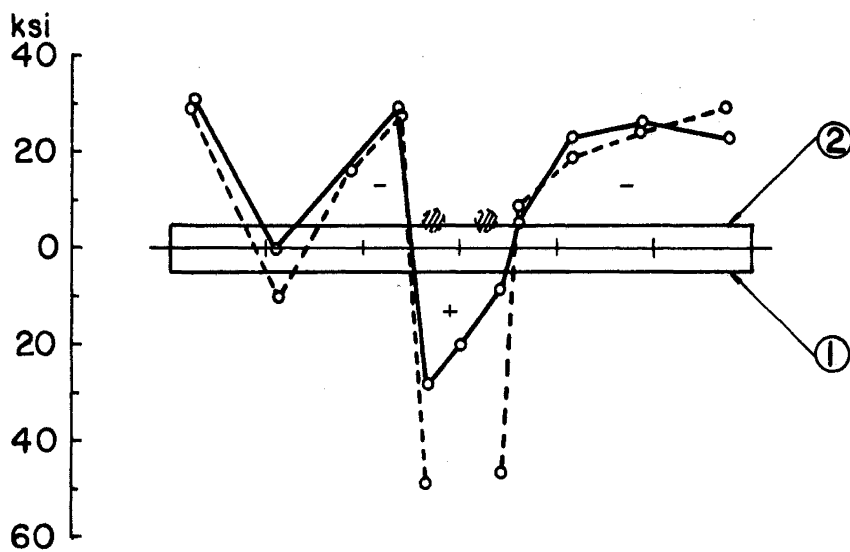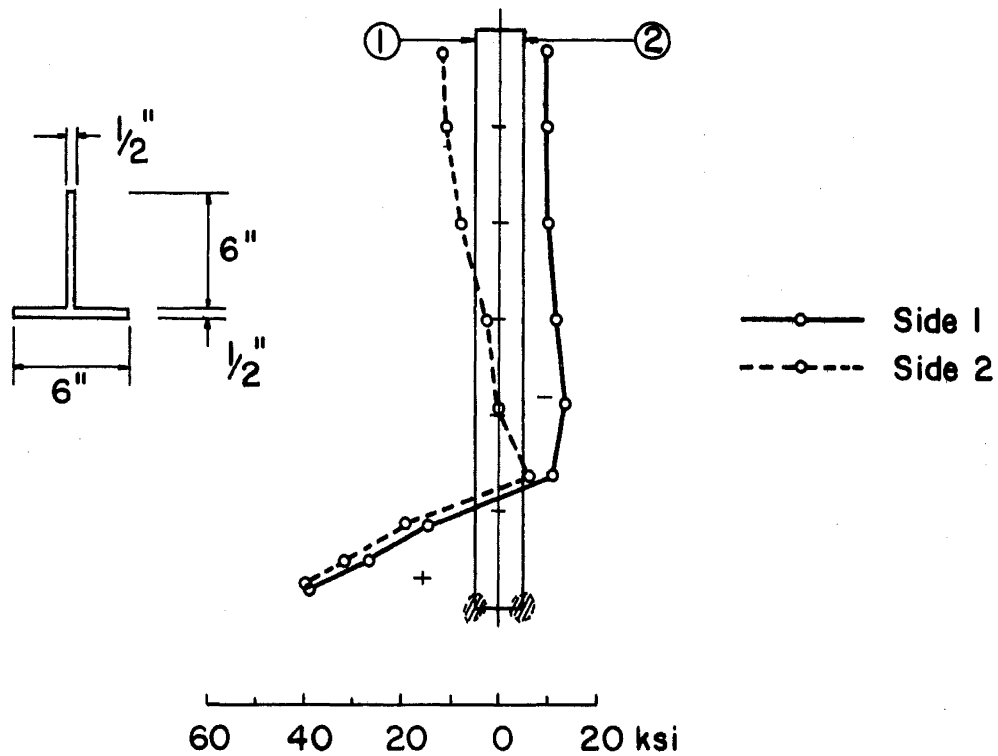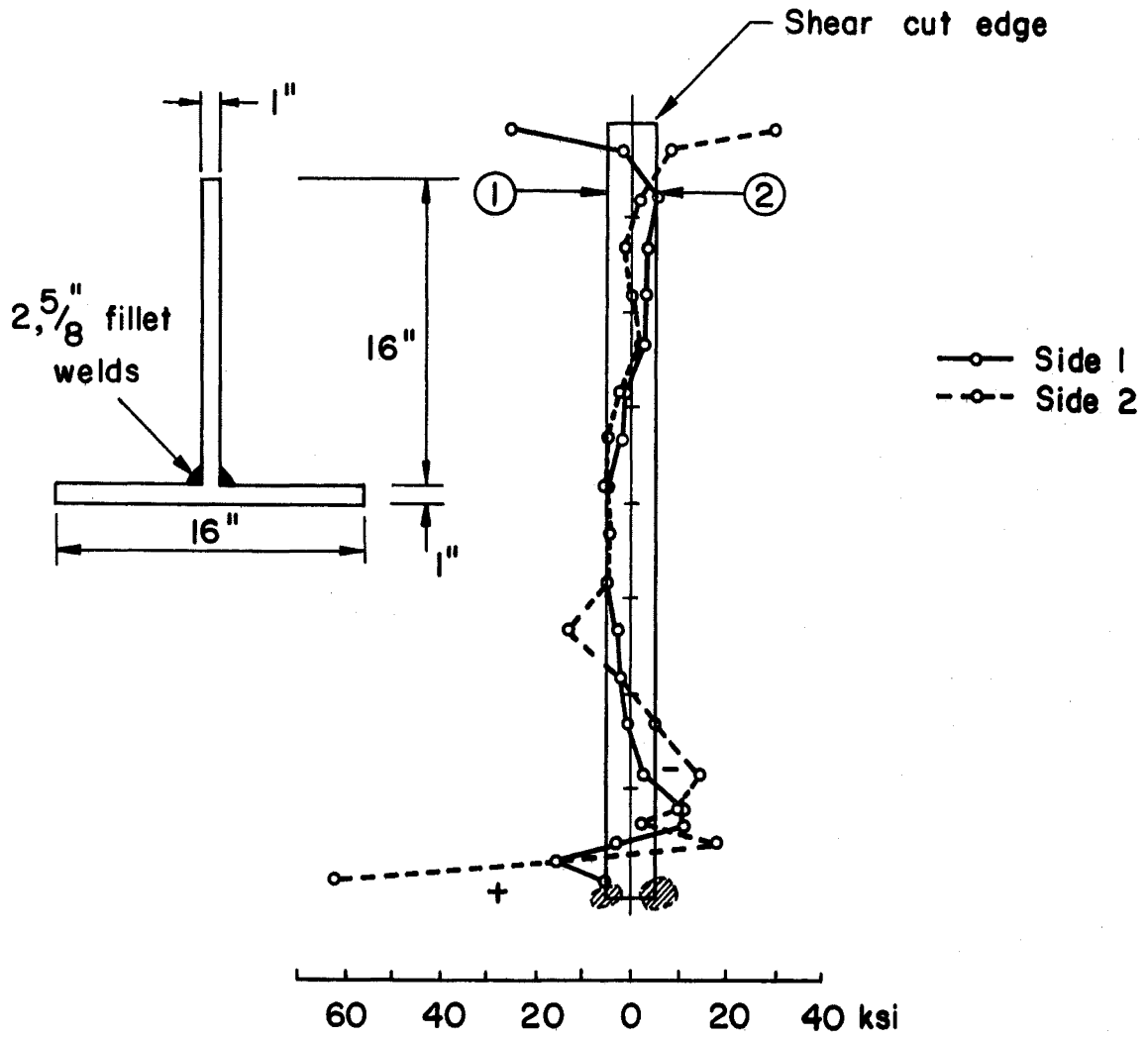
Fig. 11   Shape 3   Table 1
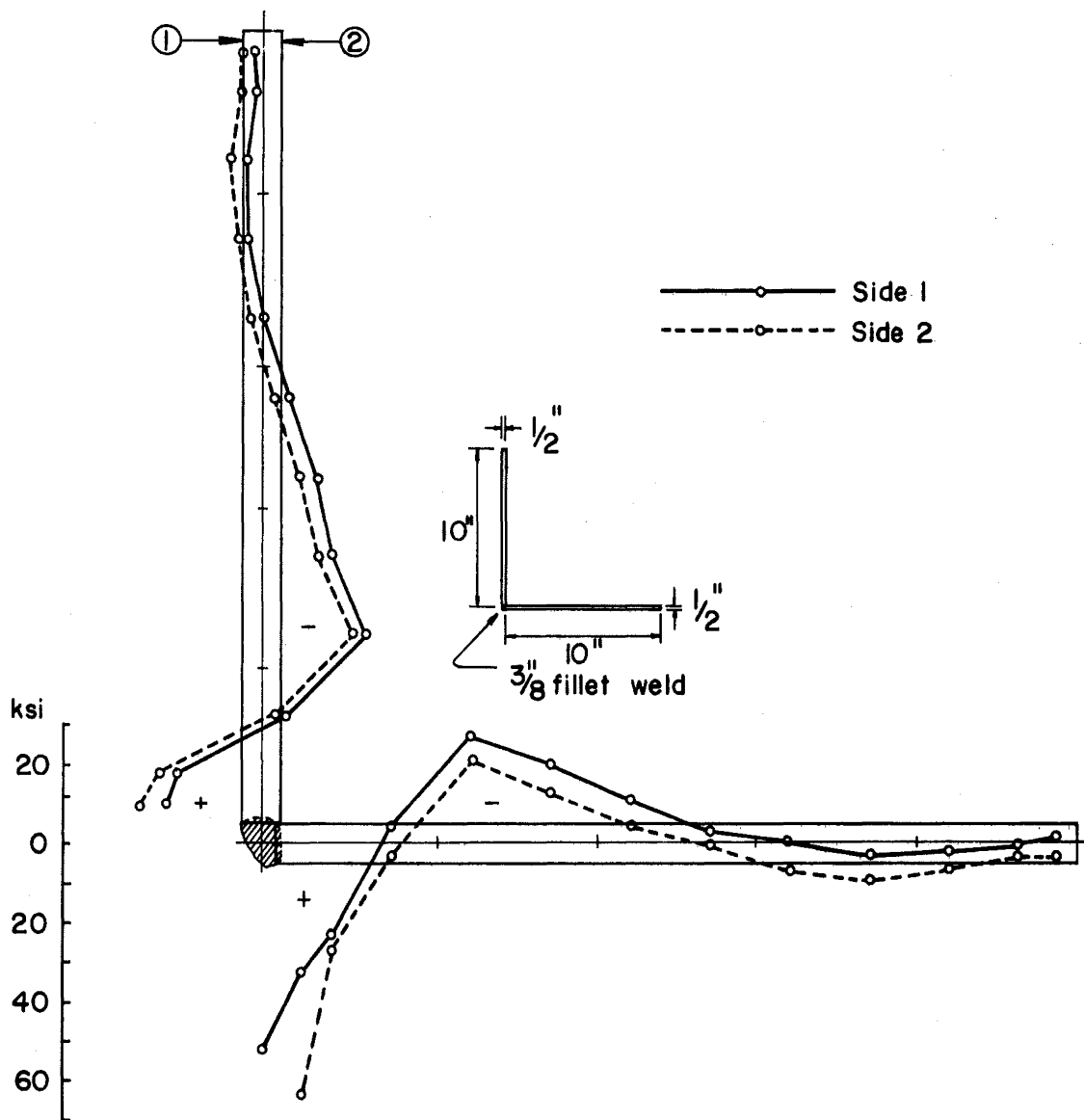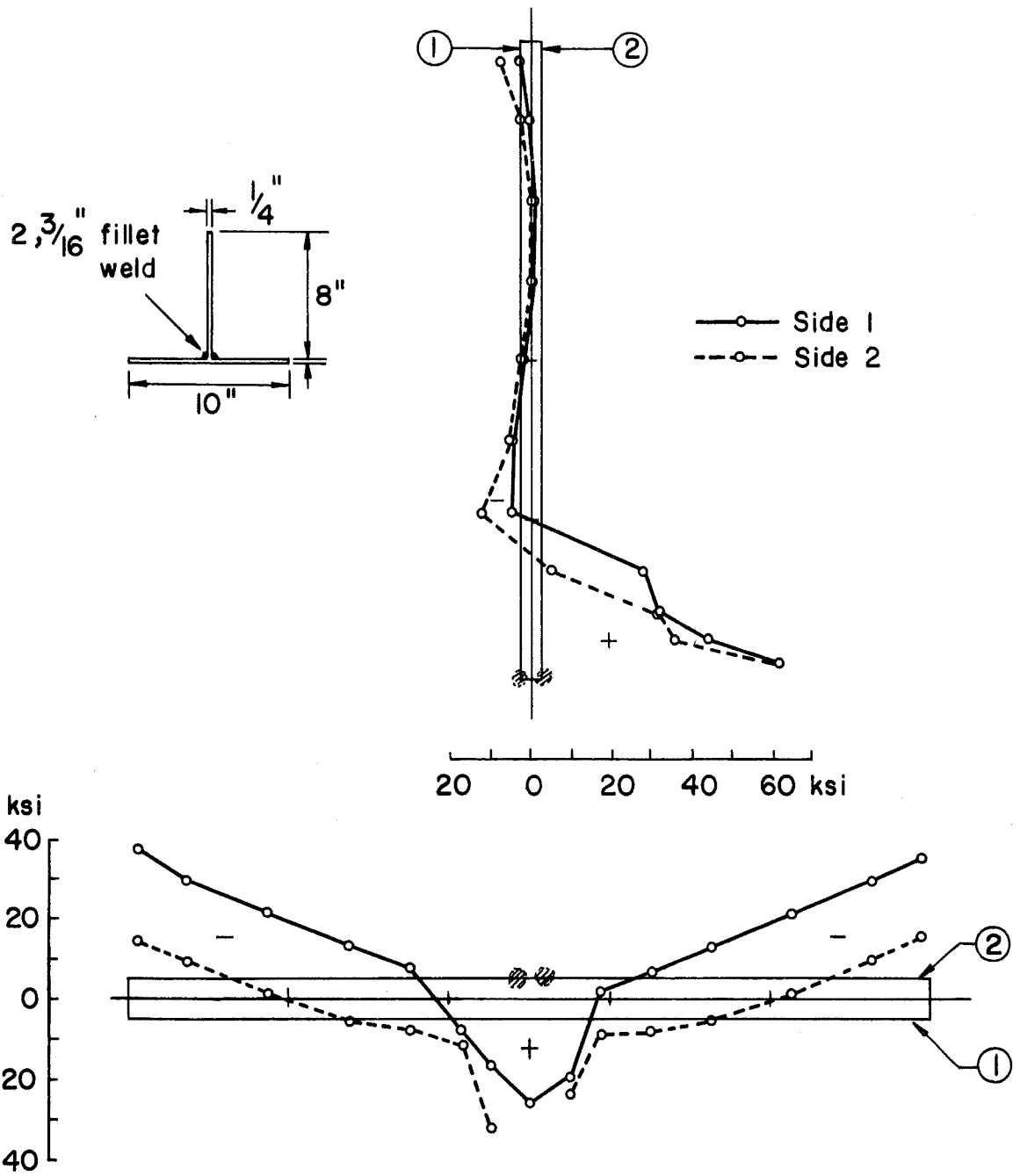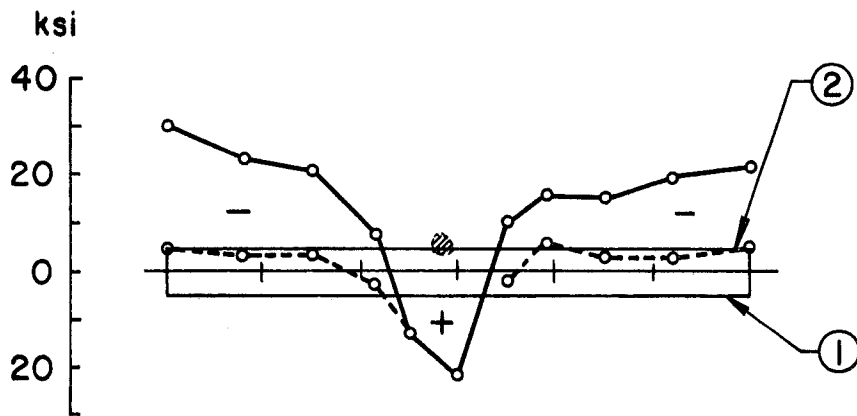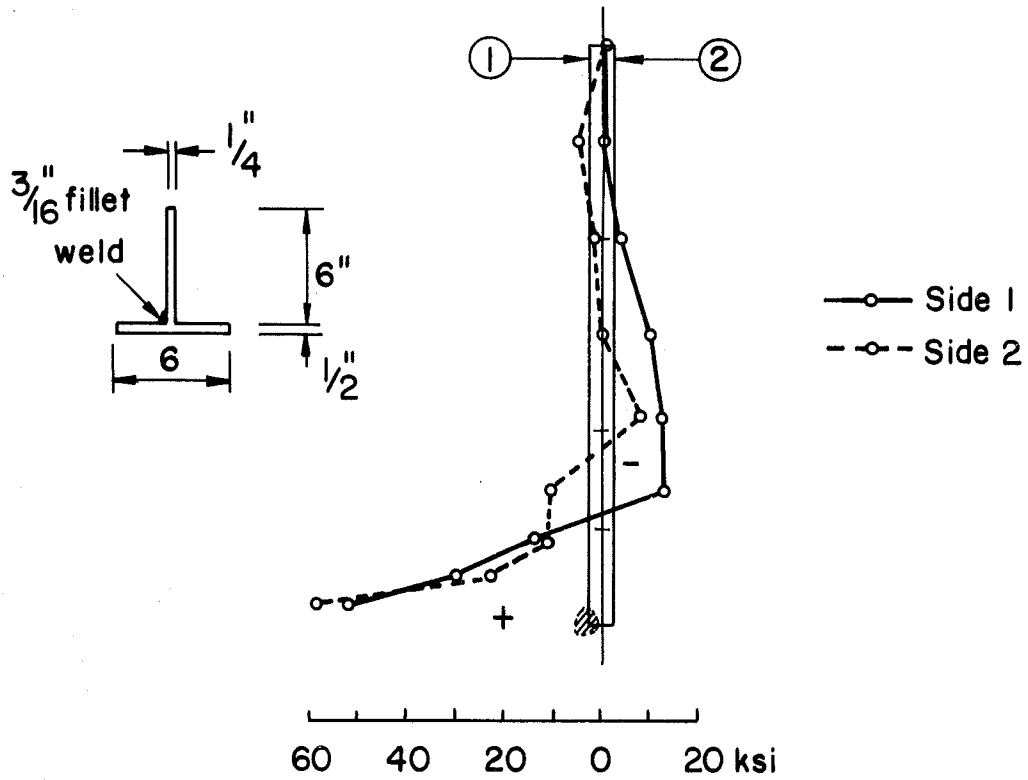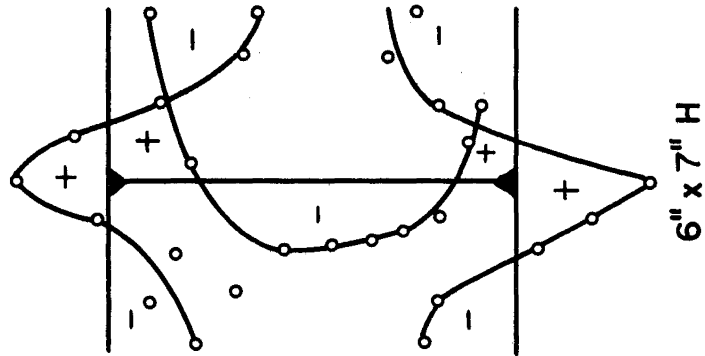
Fig. 12   Shape 4   Table 1
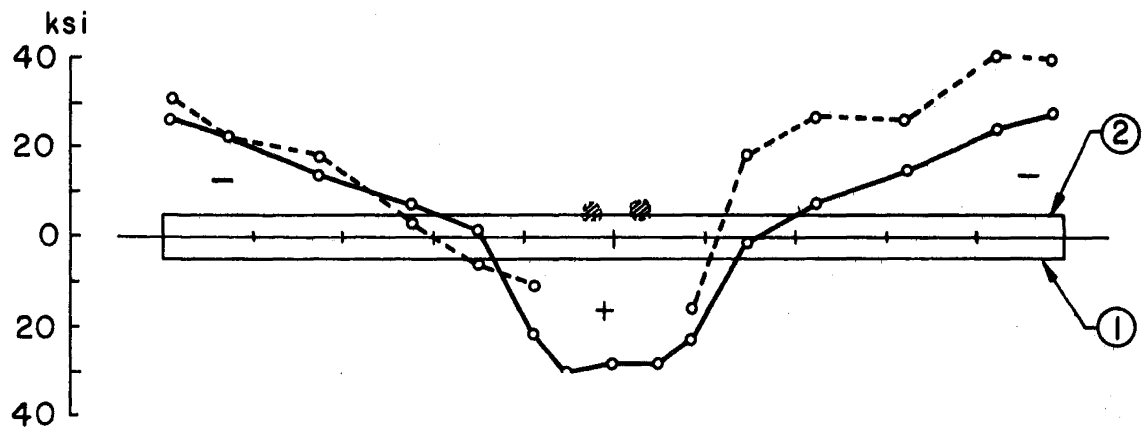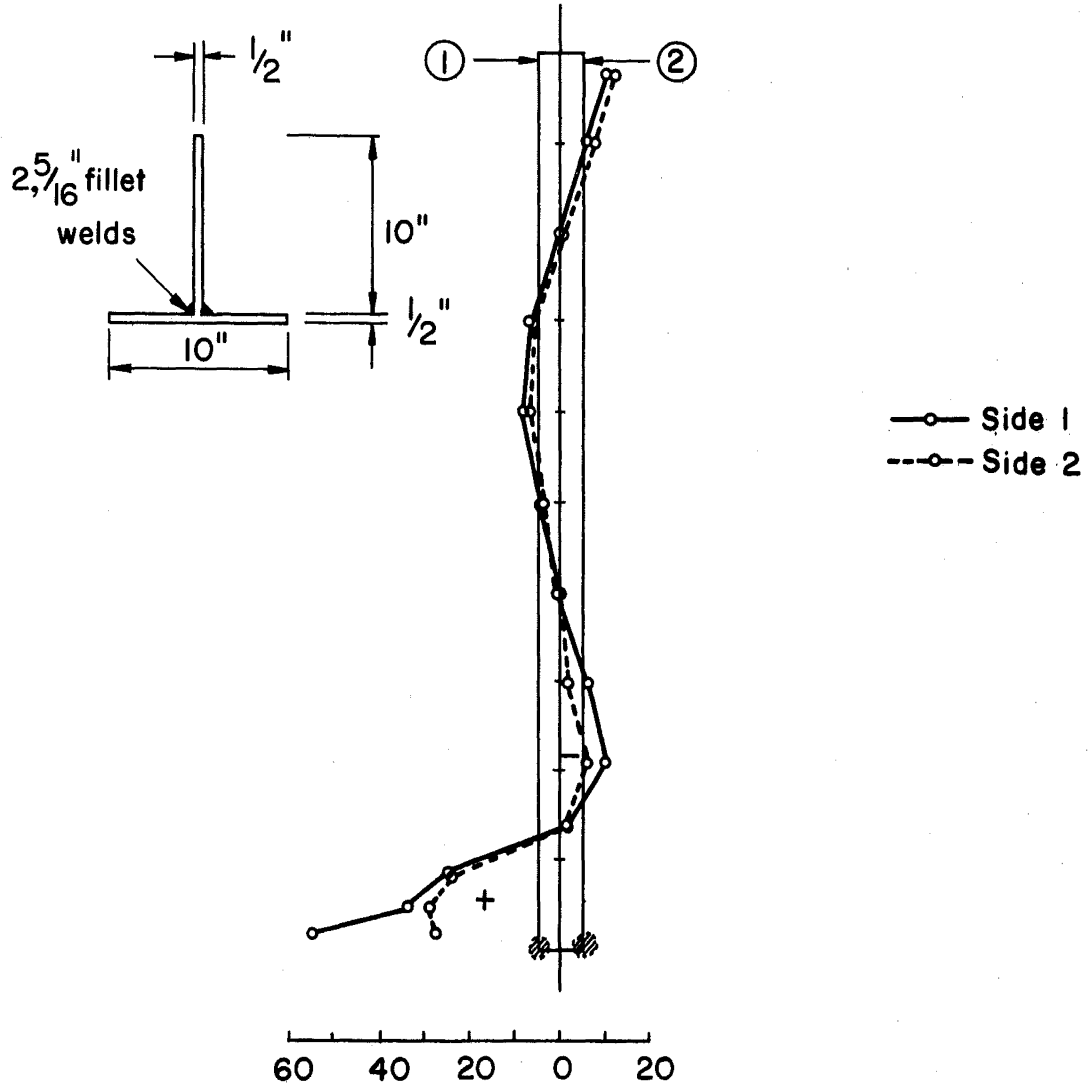
Fig. 13 Shape 5 Table 1

Fig. 14   Shape 6   Table 1

2,3/16" fillet weld

1/4"

8"

10"

Side 1
Side 2

20   0   20   40   60 ksi
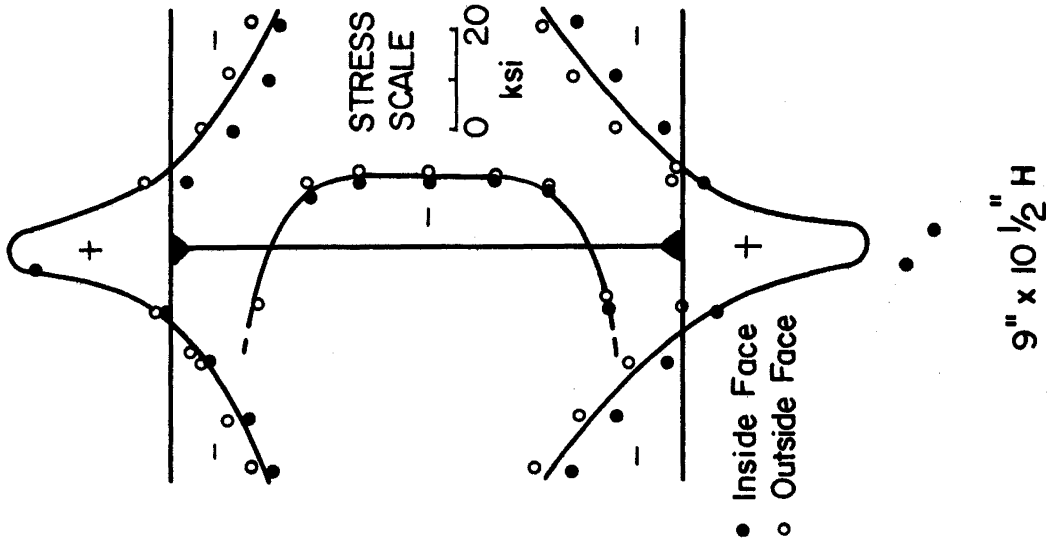
ksi
40
20
0
20
40
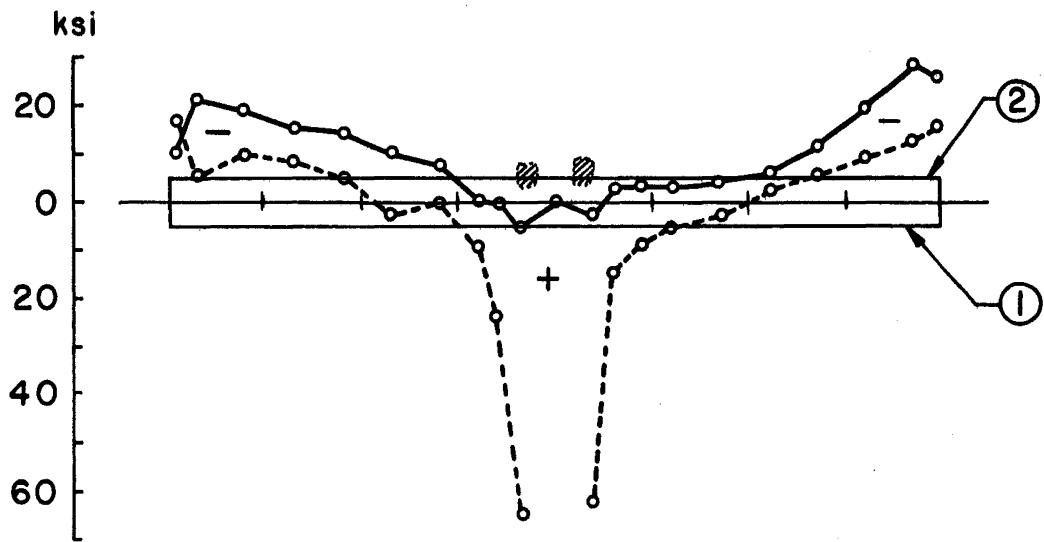
2
1

Fig. 15 Shape 7 Table 1

Fig. 16   Shape 8   Table 1

STRESS
SCALE

20

0   ksi

+

−

−

+

−

−

+

−

• Inside Face
○ Outside Face

9" x 10 ½" H
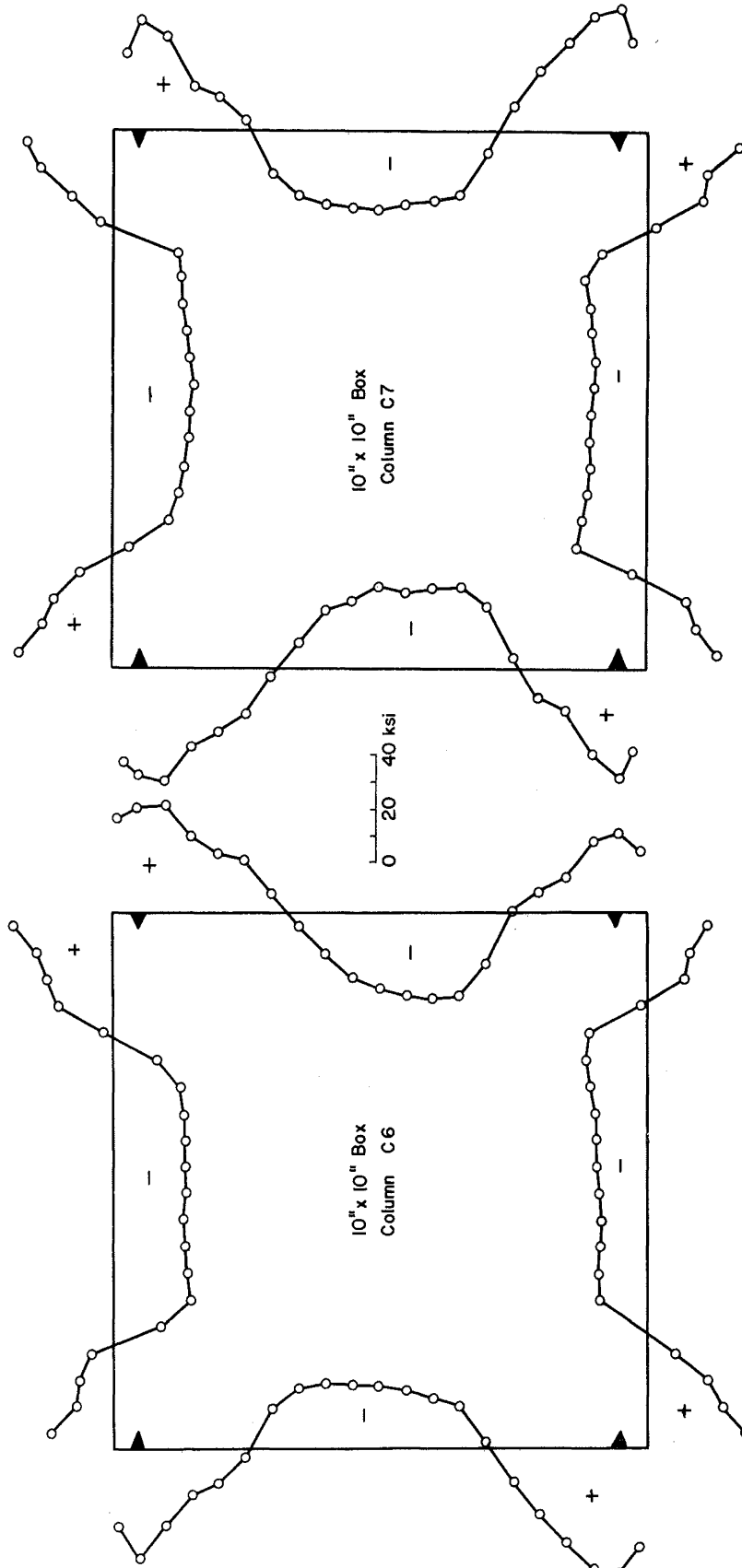
+

+

+

−

−

−

+

−

6" x 7" H

Fig. 17 Welded H-shapes

Fig. 18 Welded Box-shapes

Text labels in the left figure:
6" x 6" BOX
0   20   40 ksi

Text labels in the right figure:
9" x ½" ℞
9" x ½" ℞
STRESS SCALE
0   20   40 (ksi)
10" x 10" BOX
COLUMN C5
□ SECTION A
△ SECTION B
○ SECTION C

10" x 10" Box
Column C7

0
20
40 ksi

10" x 10" Box
Column C6

Fig. 19 Welded Box-shapes

10" x 10" Box
Column C9

10" x 10" Box
Column C 8

40 ksi
20
0

Fig. 20 Welded Box-shapes

10"x 10" Box
Column CII E

Inside O
Outside △

0 20 40 ksi

10" x 10" Box
Column CIIE

Fig. 21 Welded Box-shapes

10" x 10" Box
Column C11F

10" x 10" Box
Column C10

0 20 40 ksi

Fig. 22 Welded Box-shapes
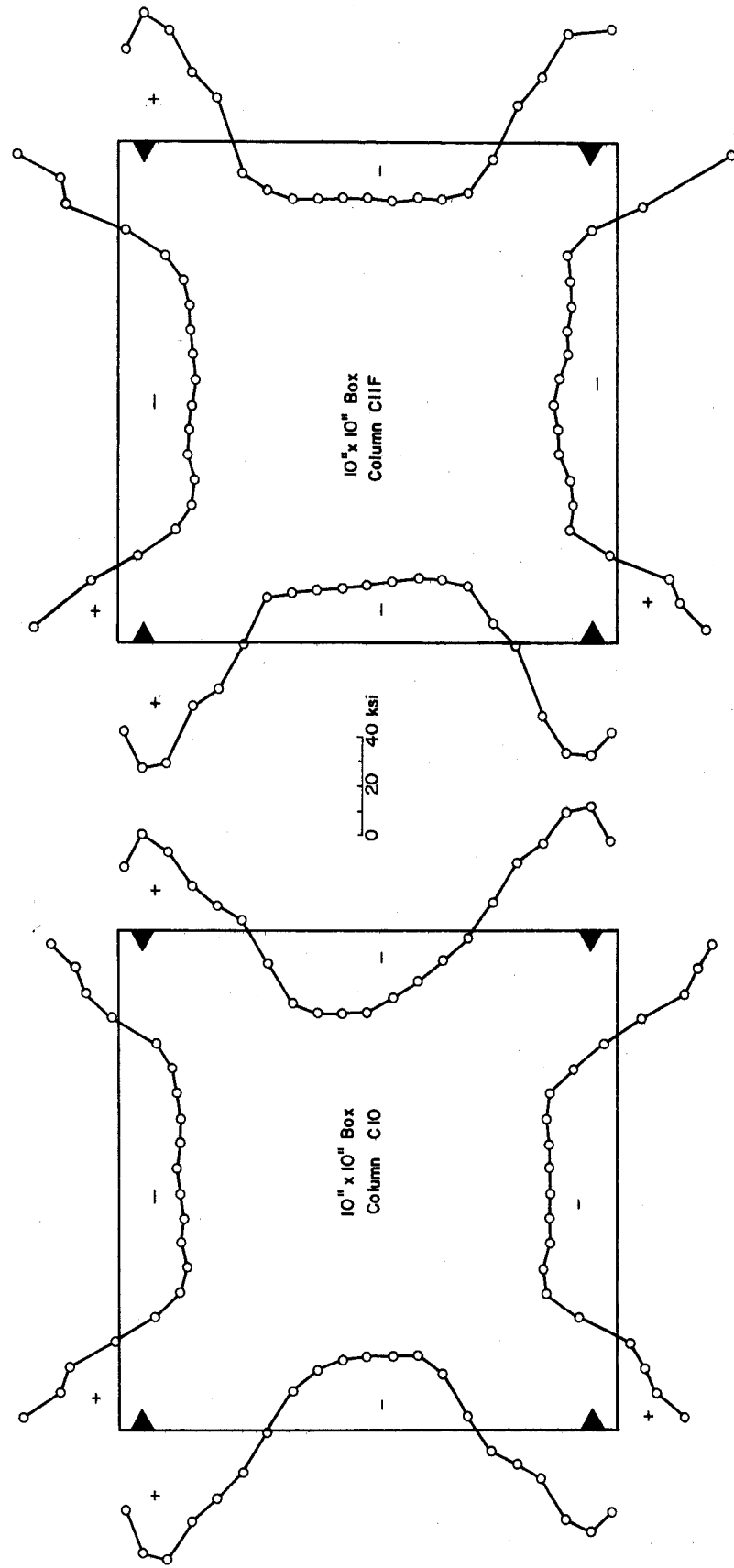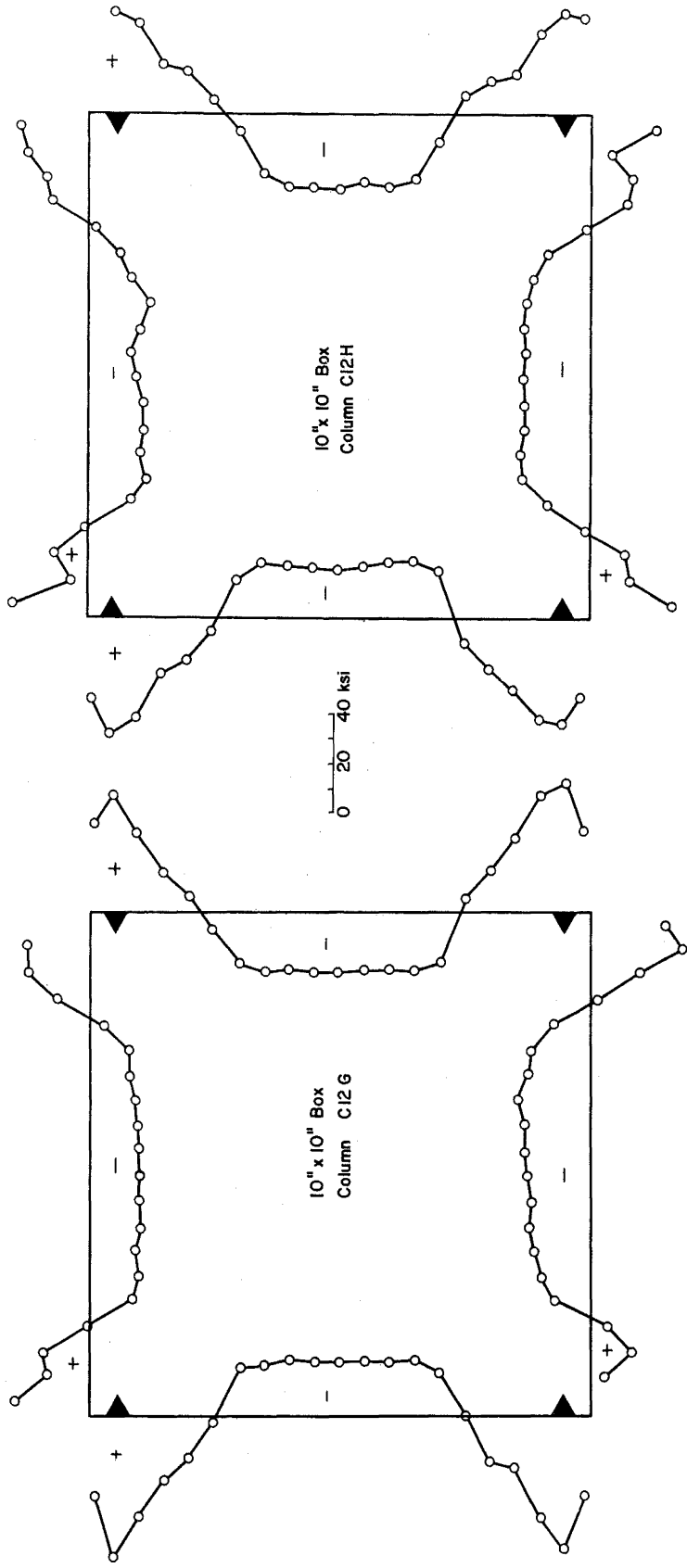
10" x 10" Box
Column C12H

10" x 10" Box
Column C12 G

40 ksi
20
0

Fig. 23   Welded Box-shapes
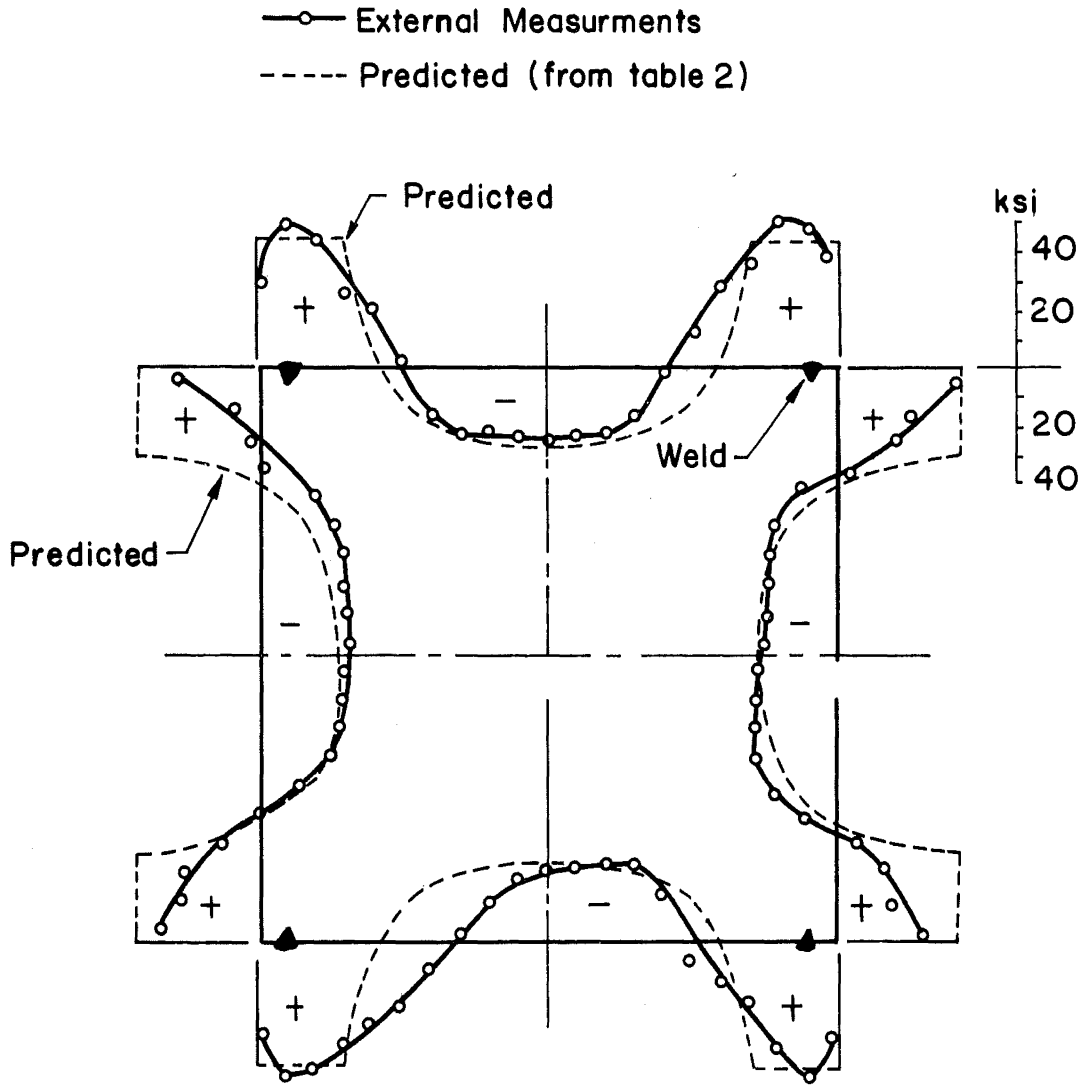
Fig. 24   Predicted and Measured Residual Stress
Distribution in a 10"x10" Box-shape

PLATE P-I

SIDE I- o
SIDE 2- △
MEAN- ----

PLATE P-2

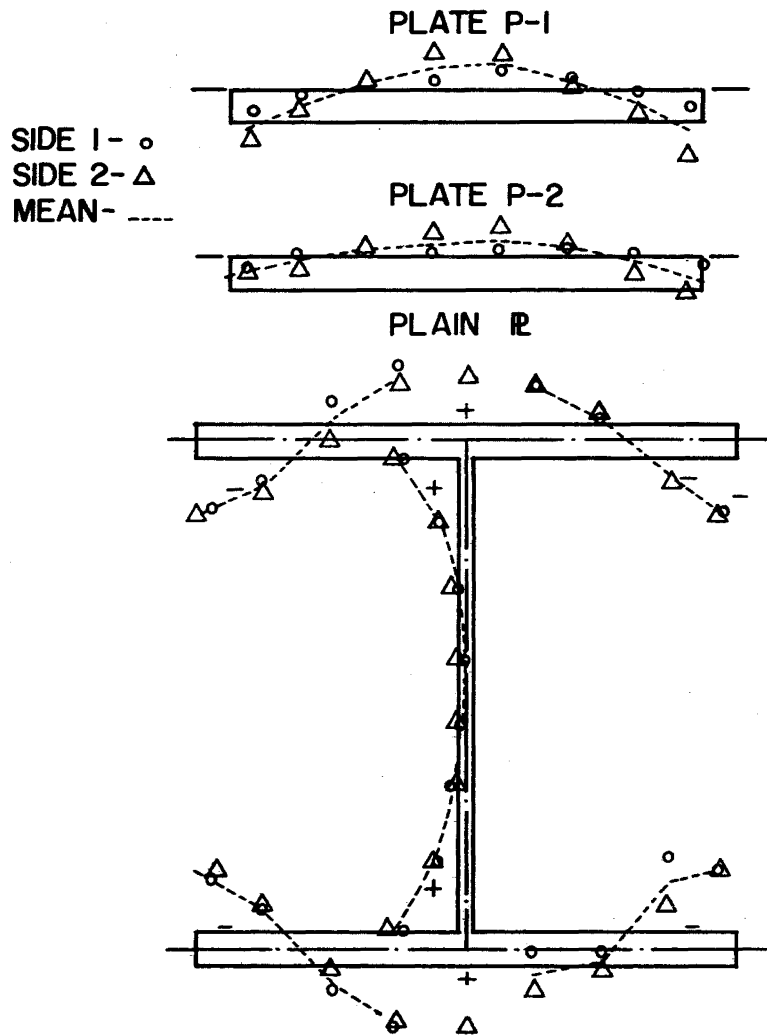PLAIN ℡

ksi
0

20

o INSIDE
△ OUTSIDE
---- MEAN

Fig. 25 Residual Stress Distribution in 8WF31
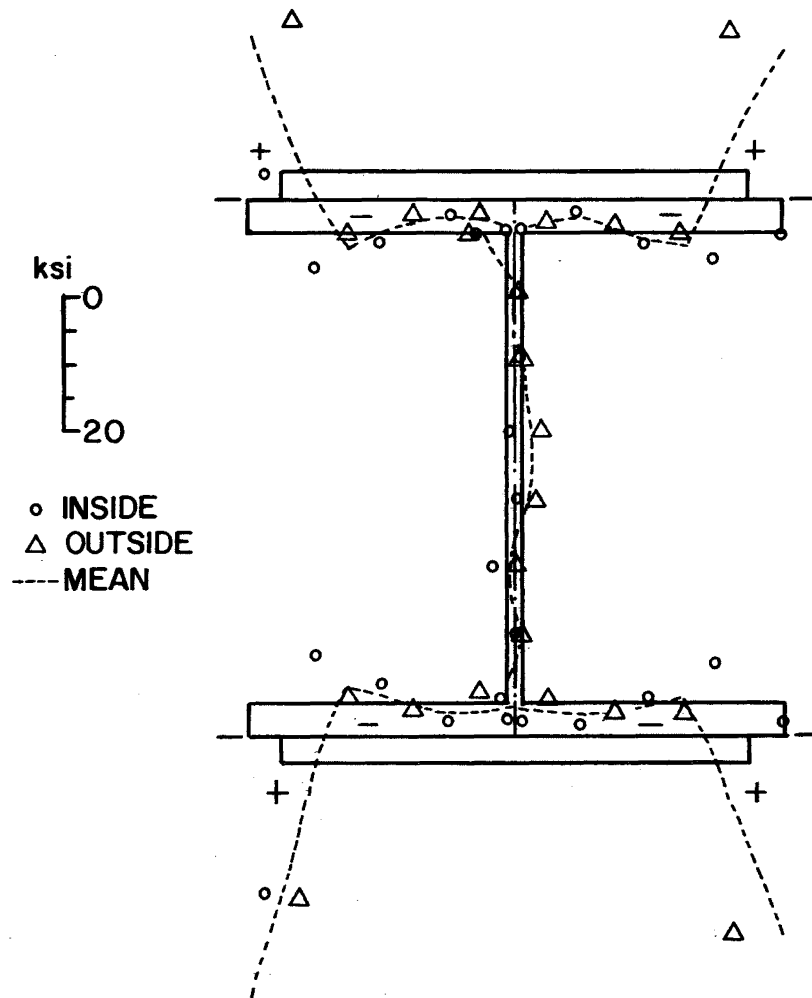and 7"x3/8" Plates Before Welding

Fig. 26 Residual Stress Distribution in
8WF31 With 7"x3/8" Plates Welded
to the Flanges

8. REFERENCES

1. Column Research Council
    THE BASIC COLUMN FORMULA, Technical Memorandum No. 1 (May 1952)

2. Beedle, L. S. and Tall, L.
    BASIC COLUMN STRENGTH, ASCE Proc. Paper 2555, 86(ST7), p. 139
    (July 1960)

3. Huber, A. W.
    RESIDUAL STRESSES IN WIDE-FLANGE BEAMS AND COLUMNS, Fritz
    Laboratory Report 220A.25, Lehigh University (July 1959)

4. Tall, L.
    RESIDUAL STRESSES IN WELDED PLATES - A THEORETICAL STUDY, Fritz
    Laboratory Report No. 249.11, Lehigh University, (July 1961).
    To be published in The Welding Journal.

5. Estuar, F. R. and Tall, L.
    EXPERIMENTAL INVESTIGATION OF WELDED BUILT-UP COLUMNS, The
    Welding Journal, 42(4), Research Suppl., 164-s to 176-s, (1963)

6. Tall, L.
    THE STRENGTH OF WELDED BUILT-UP COLUMNS, Ph.D. Dissertation,
    Lehigh University, (May 1961)

7. Fujita, Y.
    ULTIMATE STRENGTH OF COLUMNS WITH RESIDUAL STRESSES, Journal of
    the Soc. of Nav. Arch. of Japan, (January 1960)

8. Nagaraja Rao, N. R. and Tall, L.
    COLUMNS REINFORCED UNDER LOAD, The Welding Journal, 42(4),
    Research Suppl., 177-s to 185-s, (1963)

9. Timoshenko
    THEORY OF ELASTICITY, McGraw-Hill Book Co., (New York), (1951)

10. Rosenthal, D.
     MATHEMATICAL THEORY OF HEAT DISTRIBUTION DURING WELDING AND
     CUTTING, The Welding Journal, 20(5), Research Suppl., p. 220-s
     (1941)

11. Nagaraja Rao, N. R. and Tall, L.
     RESIDUAL STRESSES IN WELDED PLATES, The Welding Journal, Research
     Suppl., 468-s to 480-s (1961)

12. Huber, A. W. and Beedle, L. S.
     RESIDUAL STRESS AND THE COMPRESSIVE STRENGTH OF STEEL, The Welding
     Journal, 33(12), Research Suppl., 589-s to 614-s (1954).

13. ASTM Designation: E8-57T