Control of Shrinkage and Distortion

1. WELDING FACTORS THAT CAUSE MOVEMENT

In making a weld, the heating and cooling cycle always causes shrinkage in both base metal and weld metal, and shrinkage forces tend to cause a degree of distortion. Designers and engineers must anticipate and provide control of this shrinkage to achieve the full economies of arc-welded steel construction. Suggested solutions for correction or elimination are based on both theoretical analysis and the practical experience of fabricating shops.

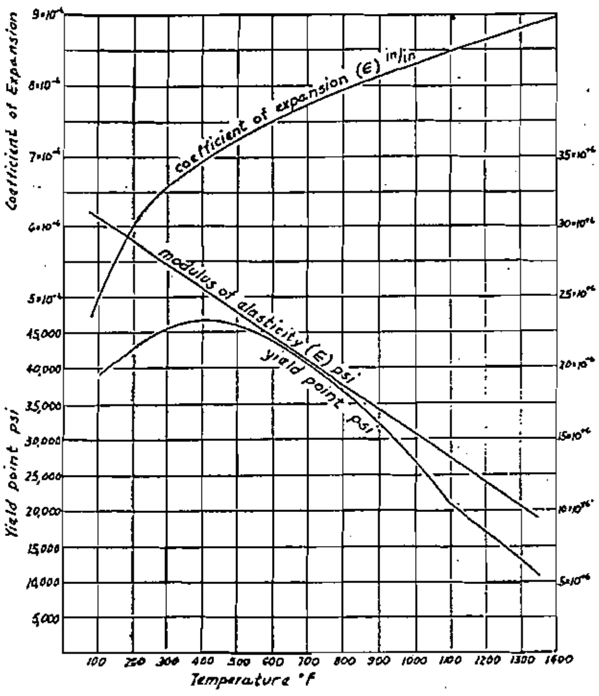

FIG. 1 Properties of a metal change at elevated temperatures, complicating the analysis of weld shrinkage. Graph is for mild steel.

The enormous temperature differential in the arc area, creates a non-uniform distribution of heat in the part. As the temperature increases, such properties as yield strength decrease, the modulus of elasticity decreases, the coefficient of thermal expansion increases, the thermal conductivity decreases, and the specific heat increases. See Figure 1. To anticipate the movement of material from a straightforward analysis of heat is difficult.

Restraint from external clamping, internal restraint due to mass, and the stiffness of the steel plate itself also must be considered. All these factors have a definite influence on the degree of movement.

Finally it is necessary to consider the factor of time as it affects the rapidly changing conditions. The period of time during which a specific condition is in effect controls the importance of that condition.

These variable conditions are further influenced by the welding process itself. Different welding procedures, type and size of electrode, welding current, speed of travel, joint design, preheating and cooling rates—all these bear significantly on the problem.

It is obvious that distortion cannot be analyzed

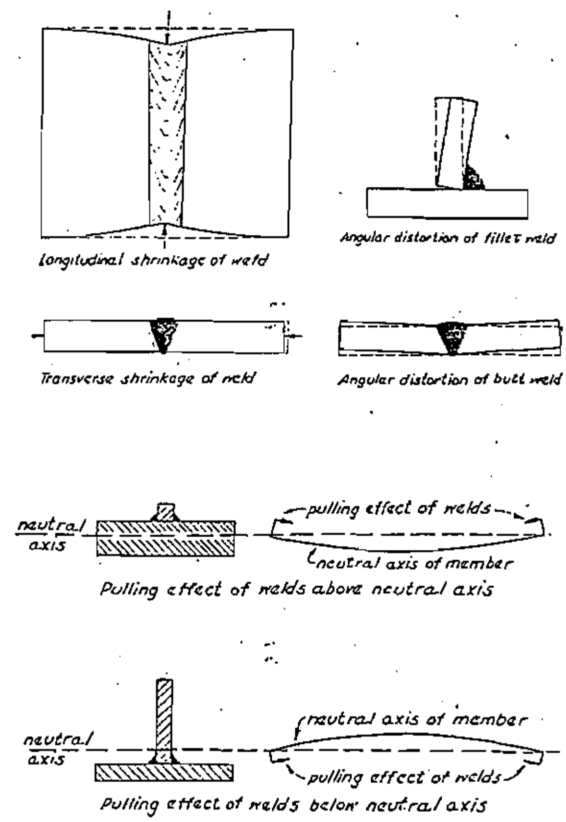

FIG. 2 An unbalance of forces resulting from shrinkage of weld deposit tends to cause angular distortion or bowing.

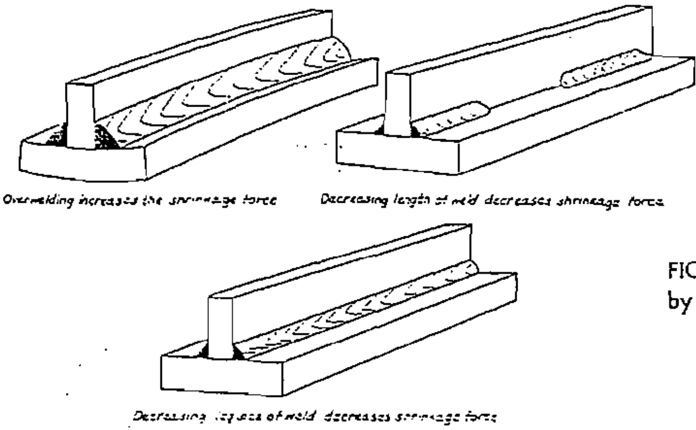

FIG. 3 Excessive distortion is frequently caused by overwelding.

by viewing each one of these factors separately. A solution based on correcting the combined effect is the only practicable approach.

2. EVIDENCES AND CAUSE OF DISTORTION

When distortion occurs, it appears as a shortening of the weld area. This generally can be cataloged as longitudinal shrinkage and transverse shrinkage, Figure 2. Further, if transverse shrinkage is not uniform throughout the thickness of the weld, angular distortion will result. When longitudinal shrinkage acts in a direction that is not along the neutral axis of the member, the result is bowing or cambering (also shown in Fig. 2).

Distortion results when a condition of non-uniform expansion and contraction is created. Distortion can be anticipated by evaluating the following factors:

1. The weld along with some adjacent metal contracts on cooling, producing a shrinkage force, F.

2. The shrinkage force acts about the neutral axis of a member. The distance between the center of gravity of the weld area and this neutral axis represents the moment arm, d.

3. The moment of inertia of the section, I, resists this contraction. The I of a section also resists straightening, should it be necessary.

3. THE INFLUENCE OF OVERWELDING

Overwelding increases the shrinkage force, F, and the tendency to distort. Anything that reduces the amount of welding such as decreasing the leg size, reducing the weld length, or using intermittent welding techniques, will minimize this condition. See Figure 3.

Overwelding can be caused inadvertently by a chain of events. The designer may specify the next larger weld size because of a lack of confidence in welding. When the part reaches the shop floor, the shop foreman, wishing to play it safe, marks the piece up for the next weld size. The weldor, having just been criticized for making undersize welds, makes real sure that these welds are still larger. The result—a ¼″ fillet has become a ½″ weld. These men usually do not realize that weld metal increases as the square of the leg size. The apparently harmless ¼″ increase in the leg size has increased the amount of weld metal deposited, the weld shrinkage and the weld cost by 4 times.

4. CONTROL OF WELD SHRINKAGE

One technique used to control weld shrinkage involves prebending the member or presetting the joint before welding. In this way the net effect of weld shrinkage pulls the member or connection back into proper alignment (Fig. 4).

Whenever possible, welding should be balanced around the neutral axis of the member. This makes the moment arm, d, equal to zero. Even though a shrinkage force, F, does exist, the shrinkage moment ($d \times F$) becomes zero (Fig. 5).

Frequently the neutral axis of the member is below

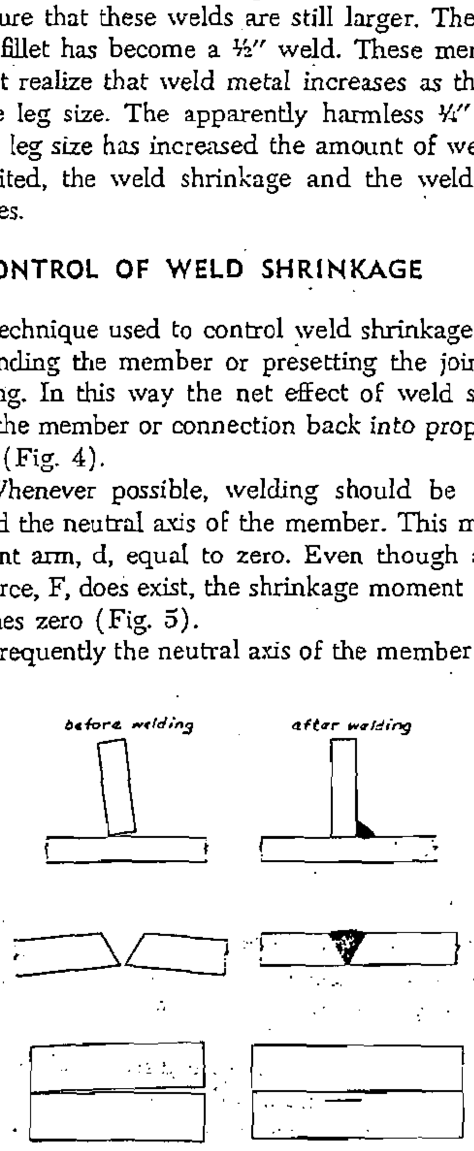

FIG. 4 Parts are often present so that weld shrinkage will pull them back into correct alignment.

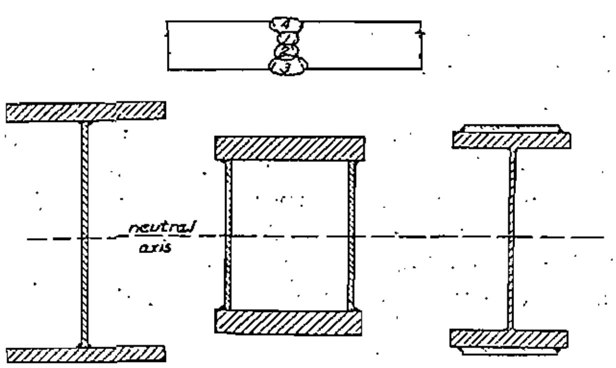

FIG. 5 Balancing welds or weld beads about the neutral axis of the member, reduces angular distortion to zero.

the center of gravity of the welds as shown in Figure 6. By making the welds with the submerged-arc automatic welding process, the deep penetration characteristic of this process further lowers the center of gravity of the weld deposit and reduces the moment arm, thereby reducing the shrinkage moment.

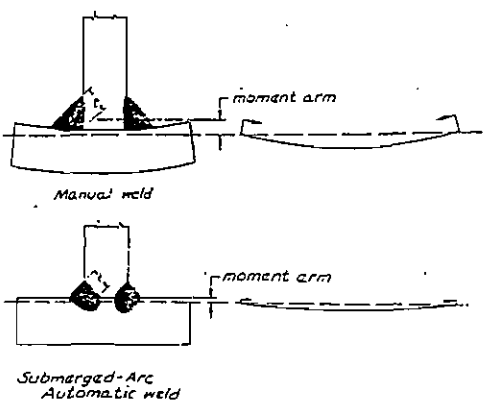

FIG. 6 Deep-penetration welding processes and procedures places the weld closer to the neutral axis, reducing moment arm and net effect of shrinkage forces.

Adjacent Base Metal

Shrinkage of weld metal alone is not sufficient to account for the amount of shrinkage sometimes actually encountered. The heat of welding causes the metal just adjacent to the weld deposit to expand. However, this metal is restrained by the relatively cooler sections of the remainder of the plate. Almost all the volume expansion must take place in thickness. On cooling, this heated section undergoes volume contraction, building up shrinkage stresses in the longitudinal and transverse direction, and this adjacent base metal tends to shrink along with the weld metal.

Effect of High Welding Speeds

The volume of this adjacent base metal which contributes to the distortion can be controlled by welding procedures. Higher welding speeds through the use of powdered-iron-type manual electrodes, semi-automatic and fully automatic submerged-arc welding equipment, or vapor-shielded automatic welding equipment reduces the amount of adjacent material affected by the heat of the arc and progressively decreases distortion.

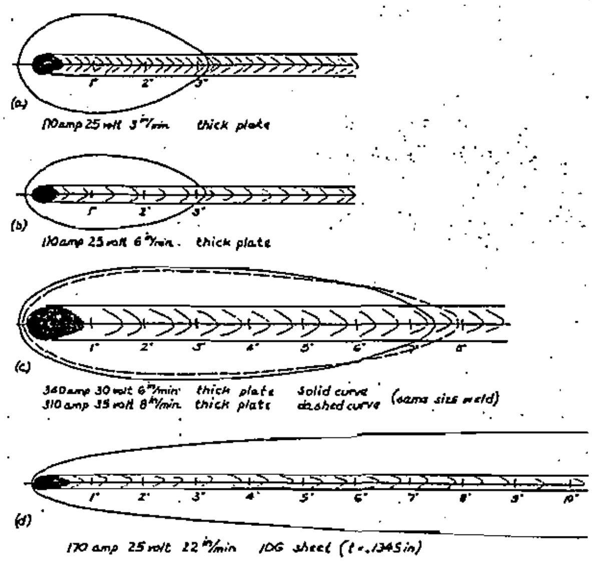

FIG. 7 Variance of welding technique. In each case, surface isotherm of 300°F is shown surrounding welding source.

The effect of welding current and arc speed on adjacent base metal is illustrated in Figure 7. Approximately the same weld size was produced with procedures (a) and (c). The important difference lies in the fact that the higher-speed welding technique produced a slightly narrower isotherm, measuring outward from the edge of the molten pool. The width of this isotherm of 300°F can be used to indicate the amount of adjacent metal shrinkage along with the weld, and therefore distortion; this helps to explain why in general faster welding speeds result in less distortion. This slight difference is also evident in a comparison of the quantity of welding heat applied to the plate.

For (a),

$$\frac{E\,I\,60}{V} = \frac{(25\text{ v})(170\text{ amp})(60)}{3''/\text{min}}$$

$$= 85{,}000 \text{ Joules/linear in. of weld}$$

For (c),

$$\frac{E\,I\,60}{V} = \frac{(35\text{ v})(310\text{ amp})(60)}{8''/\text{min}}$$

$$= 81{,}000 \text{ Joules/linear in. of weld}$$

Another condition can be observed by using conditions (a) and (b) of Figure 7. Two butt joints were made, one in the vertical position and the other in the horizontal position, using a multiple-pass groove weld. The same welding current (170 amps) was used in both joints. The vertical joint used a vertical-up weaving procedure, 3 passes at a speed of 3"/min., procedure (a). The horizontal joint used a series of 6 stringer passes at a speed of 6"/min., procedure (b). The faster welding of (b), 6"/min., produces a narrower isotherm. However, it required 6 passes rather than 3 of procedure (a), and the net result is an over-all cumulative shrinkage effect greater than that for (a).

This helps to explain why a given weld made with more passes will have slightly greater transverse shrinkage than one made with fewer passes. The transverse shrinkage can be reduced by using fewer passes. A further reduction can also be achieved by using larger electrodes.

In the weld on sheet metal, Figure 7 (d), it is noticed that a greater portion of the adjacent base metal is affected as compared to the weld itself. This, combined with the fact that the thin sheet metal is less rigid than the thick plate (its rigidity varies as its thickness cubed), helps to explain why sheet metal always presents more of a distortion problem.

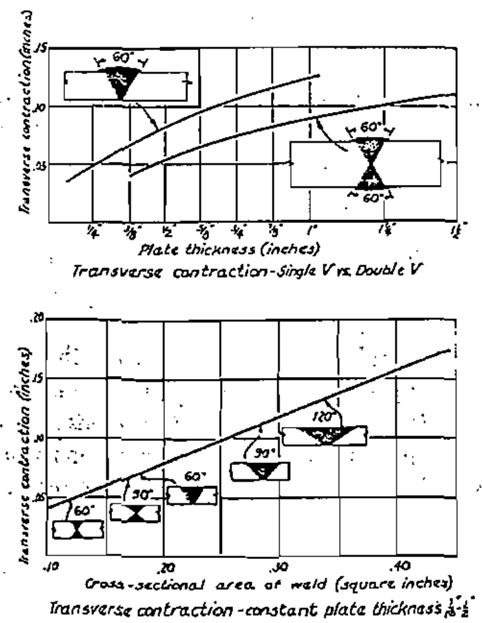

FIG. 8 Transverse shrinkage varies directly with amount of weld deposit.

5. TRANSVERSE SHRINKAGE

Transverse shrinkage becomes an important factor where the net effect of individual weld shrinkage can be cumulative.

The charts in Figure 8 throw some light on transverse shrinkage. In the lower chart transverse shrinkage, for a given plate thickness, is seen to vary directly with the cross-sectional area of the weld. The large included angles only help to illustrate this relationship and do not represent common practice. The relative effects of single and double V-joints are seen in the upper chart. Both charts assume no unusual restraint of the plates against transverse movement. Calculations show that transverse shrinkage is about 10% of the average width of the cross-section of the weld area.

$$\Delta_{trans} = .10\,\frac{A_{weld}}{t}$$

$$= .10 \times \text{aver. width of weld}$$

Where the submerged-arc process is involved, the cross-section of the fused part of the joint is considered rather than simply the area of the weld metal deposited.

Problem 1

Estimate the transverse shrinkage to be expected after welding two 1" plates together if plates are free to pull in. Use a double-V groove weld, Figure 9.

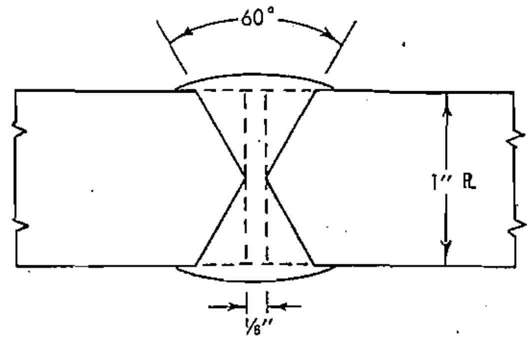

FIG. 9 Transverse shrinkage of this weld can be closely estimated from computed cross-sectional area of the weld.

area of weld:

$$(1/8'')(1'') = .125$$

$$2(1/2)(1/2'')(.58'') = .29$$

$$2(2/3)(1'')(1/16'') = \underline{.083}$$

$$A_w = .498 \text{ in.}^2$$

shrinkage

$$\Delta_{trans} = .10 \frac{A_w}{t}$$

$$= .10 \frac{(.498)}{(1'')}$$

$$= \underline{.05''}$$

Iron powder electrodes should reduce this shrinkage, and submerged-arc automatic welding should further reduce it. Also, a procedure resulting in fewer passes should reduce the shrinkage.

Notice that Figure 8 would indicate a transverse shrinkage of about .08″. However, in the above work, if the root opening were increased to ¼″ rather than the ⅛″ shown here and if the reinforcement were increased accordingly, the weld area would be increased to .75 in.^{2}. Thus the indicated shrinkage would increase to .075″. This shows good correspondence between Figure 8 and the above method of estimating shrinkage.

Use of Tables 6 and 7 in Section 7.5 (for weight of weld metal for various joints) makes it unnecessary to compute the cross-sectional area of the weld. Simply divide the weight of the weld (lbs/ft) by 3.4 to obtain the weld area in square inches.

For example, this 1″ double-V joint is equal to two ½″ single-V joints. From Table 6 (Sect. 7.5),

$$W_t = 2\ (.84\ \text{lbs/ft})$$

$$= 1.68\ \text{lbs/ft}$$

area of weld

$$A_w = \frac{(1.68)}{3.4}$$

$$= .494\ \text{in.}^2\text{, and from this}$$

transverse shrinkage

$$\Delta_{trans} = .10 \frac{(.494)}{(1.0)}$$

$$= \underline{.05''}\ \text{the same as before}$$

Problem 2

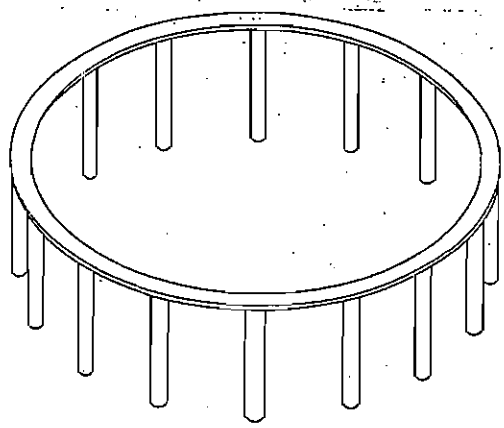

FIG. 10 Radial movement can be expected after welding large multi-segment ring as the cumulative effect of transverse shrinkage of each weld.

A steel tension ring, ½″ × 10″, is to support a dome of 136′ diameter. Each segment of this ring is to be groove welded to a steel insert plate directly over each of the 24 columns. See Figure 10. When fabricated, no allowance was made for the transverse shrinkage of these field welds. It was later found that the circumference of this ring had shrunk, causing each column to pull inward about ½″.

How should this have been estimated in order to open up the joints by this amount before welding?

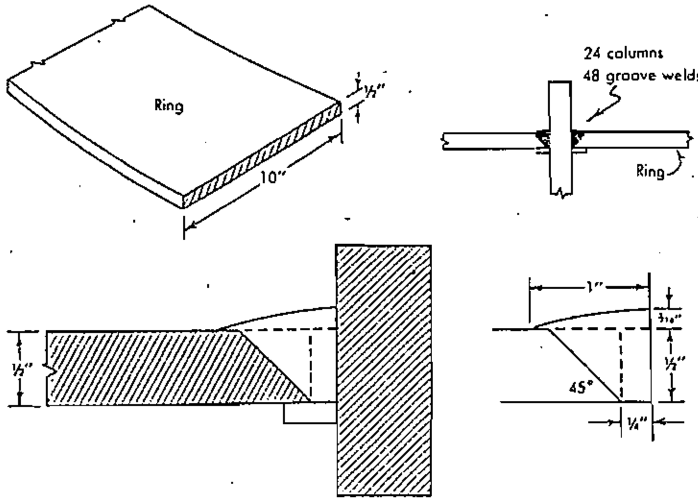

FIG. 11 Pull-in can be estimated readily.

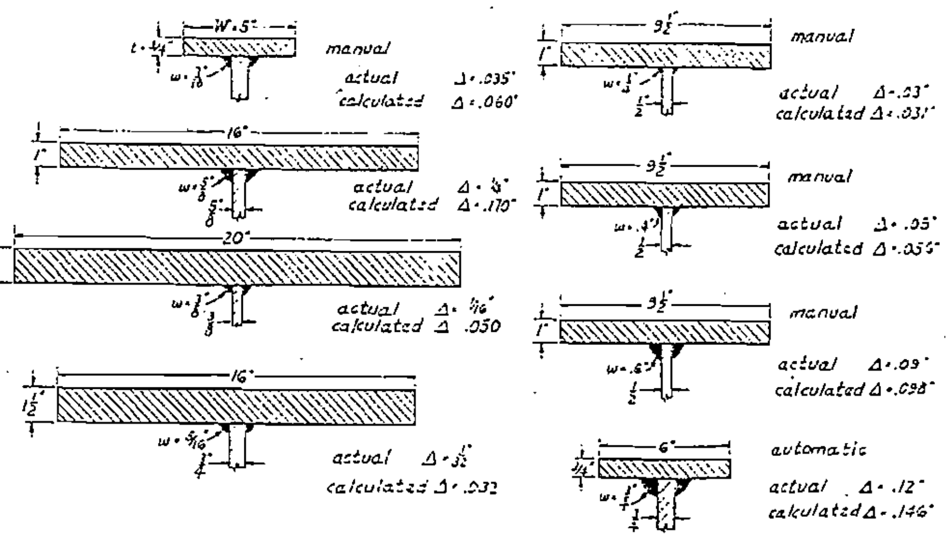

FIG. 12 Warpage varies directly with flange width and weld size, and inversely with plate thickness.

area of weld

$$\tfrac{2}{3}(1'')(\tfrac{3}{16}'') = .125$$
$$(\tfrac{1}{4}'')(\tfrac{1}{2}'') = .125$$
$$\tfrac{1}{2}(\tfrac{1}{2}'')(\tfrac{1}{2}'') = .125$$
$$A_w = .375'' \text{ in.}^2$$

average width of weld

$$\frac{.375 \text{ in.}^2}{\tfrac{11}{16}''} = .545''$$

transverse shrinkage

$$\Delta_{trans} = .10\ (.545'')$$
$$= .055'' \text{ estimated}$$

Since there are 24 columns or 48 groove welds,

overall shrinkage in circumference

$$\Delta_{circ} = 48\ (.055'')$$
$$= 2.64'' \text{ or a}$$

radial pull-in of columns

$$\Delta_{rad} = \frac{(2.64'')}{2\ \pi}$$
$$= .42''$$

Of course any poor fitup (increasing the root opening) or excessive weld reinforcement will greatly increase this transverse shrinkage.

6. ANGULAR DISTORTION

The formula for calculating warpage is—

$$\Delta = \frac{0.02\ W\ \omega^{1.3}}{t^2}$$

Figure 12 gives both the actual and calculated warpage for each of eight different flanges, fillet welded as indicated. The close agreement between the two values verifies the formula used. Only three exceed the American Welding Society allowable (½% of the width of the flange). It should be noted that these were overwelded.

7. BENDING OF LONGITUDINAL MEMBERS

Distortion or bending of longitudinal members results from development of a shrinkage force applied at some distance from the neutral axis of the member. The amount of distortion is directly controlled by the magnitude of the shrinkage moment and the member's resistance to bending as indicated by its moment of inertia.

Assuming no unusual initial stresses, the following formula indicates the amount of distortion or bending that will result from any longitudinal welding on a given member:

$$\Delta = 0.005\ \frac{A_w\ d\ L^2}{I}$$

where:

A_w = total cross-sectional area within the fusion line, of all welds, in.^{2}

d = distance between the center of gravity of the weld group and the neutral axis of the member, in.

L = length of the member, assuming welding the full length, in.

I = moment of inertia of the member, in.^{4}

Δ = resulting vertical movement, in.

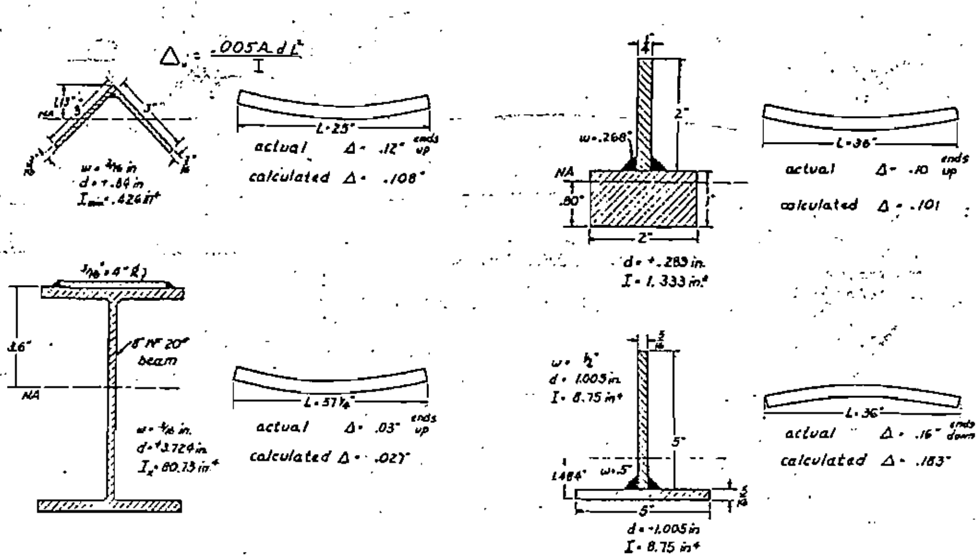

FIG. 13 Actual measured distortion corresponds well with calculated distortion, using the formula given.

Measurement of actual distortion verifies the formula for theoretical calculation of distortion, Figure 10.

In some instances when equal welds are positioned symmetrically around neutral axis of a member, a certain amount of distortion still occurs even though the magnitudes of the shrinkage moments are equal and opposite. It is believed some plastic flow or upset occurs in the compressive area next to the weld area after the first weld is made. Because of this upset, the initial distortion, from the first weld, is not quite offset by the second weld on the opposite side. Where multiple-pass welding is involved, this condition can be corrected, as illustrated in the groove-weld sequence, Figure 5. Here Pass 1 is on the top side. Pass 2, deposited on the opposite side, does not quite pull the plates back into flat alignment; therefore Pass 3 is added to the same side. The net result will usually pull the plate slightly beyond the flat position and Pass 4, on the top side, should bring this plate back into flat alignment. Frequently this problem is of no major importance since the sections to be welded are large enough in respect to the size of the weld to prevent the occurrence of this upsetting. As a result, on large sections the second weld on the opposite side is just as effective as the first weld.

In cases where the welds are not symmetrically balanced about the neutral axis of the section, advantage may be taken of this difference in distortion by first completing the joint nearest the neutral axis (it has the shorter moment arm) and then welding the joint on the side farthest from the neutral axis (taking advantage of its greater moment arm). See Figure 14, which illustrates a masonry plate welded to the bottom flange of a rolled beam. On the left, the welds are not symmetrical, so weld (a) was made first. Weld (b) follows since it has a greater moment arm. On the right, the wider masonry plate extends slightly on the left, and allows both welds to be made at the same time (since they are both in the flat position). The equal moment arms in this situation should result in no sweep of the beam. In both cases the welds will produce some camber but this is usually desirable.

Many long slender members are made by welding together two light-gage formed sections. Waiting until the first weld has cooled before making the second

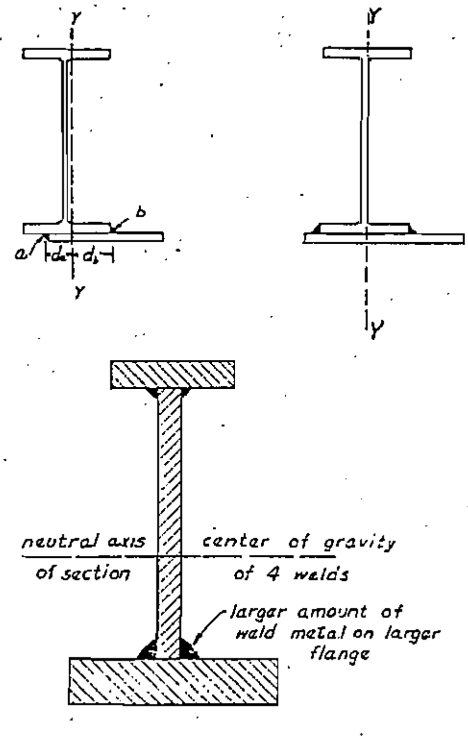

FIG. 14 Where welds are not balanced about the neutral axis of the section, distortion can be minimized by welding first the joint nearest the neutral axis and then the joint farthest from the neutral axis. Similarly, weld sizes may be varied to help balance forces.

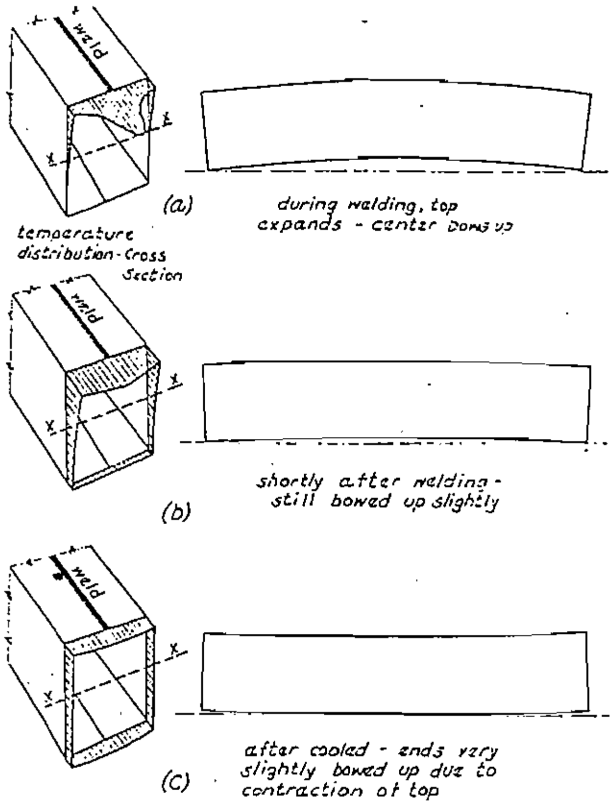

FIG. 15 To avoid bowing of long, thin box sections welded up from two channels, the first weld is protected against cooling until the second weld is completed. The two welds are then allowed to cool simultaneously.

weld on the opposite side, usually results in some final bowing since the second weld may not quite pull the member back, Figure 15. Notice (a) the heating of the top side of the member by the first weld initially causes some expansion and bowing upward. Turning the member over quickly while it is still in this shape and depositing the second weld, increases the shrinking effect of the second weld deposit and the member is usually straight after cooling to room temperature.

The sequence for automatic welding to produce the four fillets on a fabricated plate girder can be varied without major effect on distrotion. In most cases this sequence is based on the type of fixture used and the method of moving the girder from one welding position to another (Fig. 16). When a single automatic welder is used, the girder is usually positioned at an angle between 30° and 45°, permitting the welds to be deposited in the flat position. This position is desirable since it makes welding easier and slightly faster. It also permits better control of bead shape and the production of larger welds when necessary.

Permissible AWS tolerances for most welded

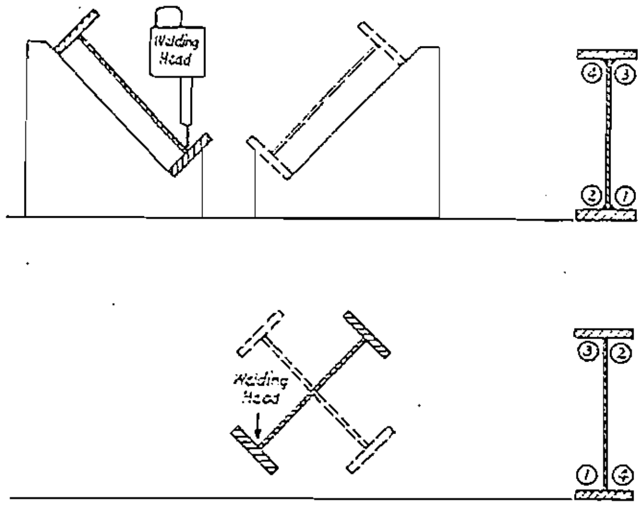

FIG. 16 Proper welding position and sequence for fabricotion when girder is supported by inclined fixture (top) or trunnion-type fixture (bottom).

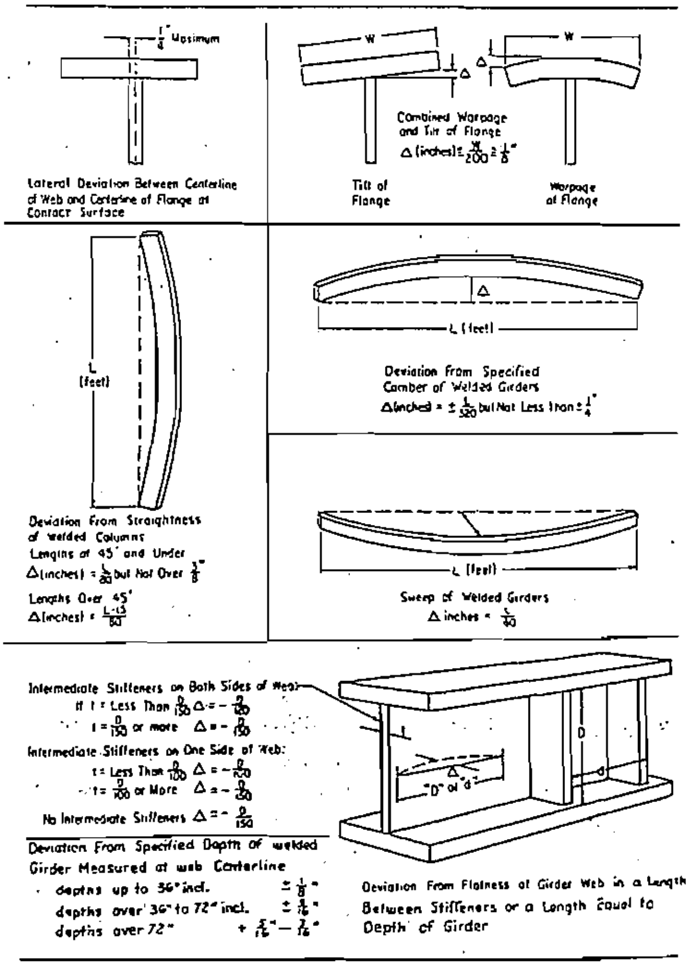

FIG. 17 AWS permissible tolerances for common welded members.

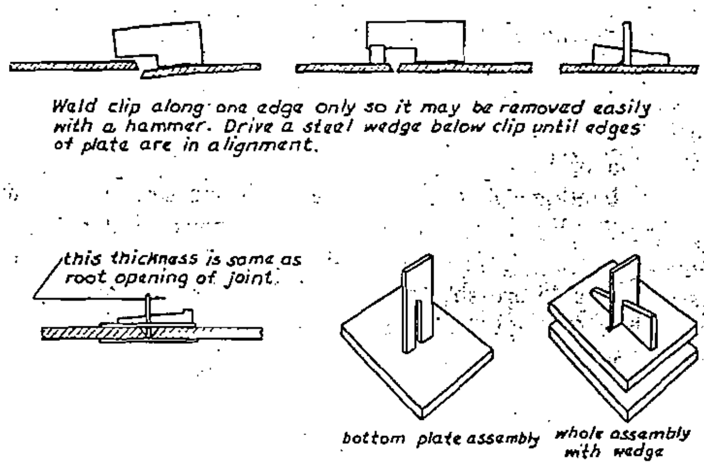

FIG. 18 Small clip angles and wedges can be used to economically maintain alignment of plates during welding. If clips are welded on one side only, they can later be knocked off with a hammer.

members are illustrated in Figure 17: (a) deviation between centerline of web and centerline of flange; (b) camber or sweep of columns; (c) at left, tilt of flange, and at right, warpage of flange; (d) deviation of camber of girders; (e) sweep of girders; (f) deviation from flatness of girder web.

8. PROPER ALIGNMENT OF PLATES

Various methods have been used for pulling plate edges into alignment and maintaining this alignment during welding. The most widely used technique (Fig. 18) calls for welding small clips to the edge of one plate. Driving a steel wedge between each clip and the second plate brings both edges into alignment. Welding the clips on one side only, simplifies removal.

In the top part of Figure 19, pressure is applied by steel wedges whereas, in the bottom part of this figure, pressure is applied by tightening the strongbacks with bolts previously welded to the plate.

9. PEENING AND FLAME SHRINKING

Peening is used occasionally to control distortion. Since the weld area contracts, peening, if properly applied, tends to expand it. However, this expansion occurs only near the surface.

Upsetting or expansion of the weld metal by peening is most effective at higher temperatures where the yield strength of the metal is rather low. Unfortunately, most of the distortion occurs later at the lower temperatures after the yield strength has been restored to its higher value. For this reason, peening does not accomplish the desired results. An additional disadvantage of peening is that it work-hardens the surface of the metal and uses up some of the available ductility.

Flame shrinking or flame straightening is another method of correcting distortion, through localized heating with a torch. The heat causes the metal in this area to expand, and this expansion is restrained in all directions by the surrounding cooler metal. As a result, this

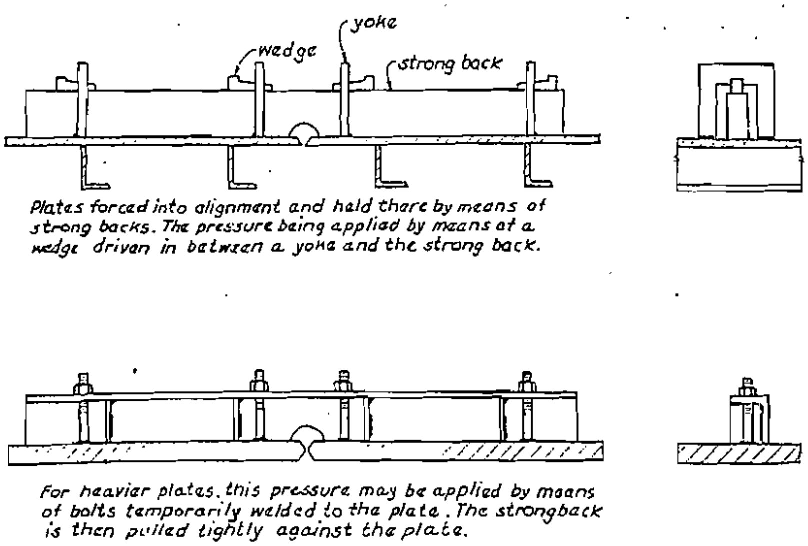

FIG. 19 Large plates can be aligned against strongbacks, the plates being pulled up by means of yoke and wedge combination; or, bolts are welded to the plates and run through the strongbacks to facilitate alignment.

area of the metal expands abnormally through its thickness and upon cooling tends to become shorter in all directions. The section so treated will become shorter and stressed in tension with each successive application of heat.

The bending of a member by welding and its straightening by flame shrinking is analogous to the case of a stool which will tilt to one side when the legs on one side are shortened but will again become erect when the opposite legs are also shortened the same amount.

10. SUMMARY AND CHECK LIST

Transverse distortion

1. Depends on restraint.
2. Is equal to about 10% of the average width of the weld area.
3. Increases with the weld area for the same plate thickness.
4. Increases with the root opening and the included angle.
5. Is directly proportional to the welding heat input per inch, that is, Joules per inch.

Angular distortion can be reduced by:

1. Use of a double bevel, V, J, or U for butt joints.
2. Alternating welds from side to side.
3. Beveling the web of a T-joint; this will reduce the moment arm of the weld and reduce the angular movement.
4. Use of the smallest leg size for fillet welds, since the distortion varies approximately with the 1.3 power of the leg size of such a weld.
5. Use of thicker flanges; distortion varies approximately inversely with the square of the flange thickness.

Bending of long members by longitudinal welds can be partially controlled by:

1. Balancing welds about the neutral axis of the member.
   a. Making welds of the same size at the same distance on the opposite side of the neutral axis of the member.
   b. For welds of different sizes—if at different distances from the neutral axis of the member—making the welds that are farther away smaller.
2. If the welding is not symmetrical, this result is achieved by:
   a. Prebending the member.
   b. Supporting the member in the middle and letting the ends sag, and for the opposite effect, by supporting the member at the ends and letting the middle sag.
   c. Breaking the member into sub-assemblies so that each part is welded about its own neutral axis.

Deflection is directly proportional to the shrinkage moment of the welds (weld area times its distance from the neutral axis of the member) and inversely proportional to the moment of inertia of the member. Although a high moment of inertia for the member is desired to resist bending, it also makes the member more difficult to straighten, once it has become distorted. Flame shrinking may be applied to the longer side if welding has bent the member.

Assembly procedures that help control distortion:

1. Clamp the member in position and hold during welding.
2. Preset the joint to offset expected contraction.
3. Prebend the member to offset expected distortion.
4. Before welding, clamp two similar members back to back with some prebending.
5. If stress-relieving is required, weld two similar members back to back and keep fastened until after stress relief.
6. Use strong-backs.
7. Use jigs and fixtures to maintain proper fit-up and alignment during welding.
8. Make allowances for contraction when a joint is assembled.
9. Arrange the erection, fitting, and welding sequence so that parts will have freedom to move in one or more directions as long as possible.
10. Use subassemblies and complete the welding in each before final assembly and welding together.
11. If possible break the member into proper sections, so that the welding of each section is balanced about its own neutral axis.
12. Weld the more flexible sections together first, so that they can be easily straightened before final assembly.