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Prediction of Residual Stresses in Medium-Size to Heavy Welded Steel Shapes

Evaluation des tensions résiduelles dans les tôles d'acier soudées de dimensions moyennes et grandes

Berechnung der Eigenspannungen in geschweissten Stahlblechen mittleren und grossen Ausmasses

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Heavy welded steel shapes, that is, members built up of components ranging from 25 mm and up in thickness, are today commonly used in multistory buildings and other major structures. Figure 1 shows a few examples of medium-size to heavy welded steel columns as used in buildings in North America and Europe. While such members are commonplace in modern construction, their basic structural behavior had not been studied up to recently. The design rules for compression members of heavy steel shapes were merely extrapolated from the well-documented behavior of lighter members. This may not be a completely rational procedure, particularly when it is realized that such factors as mechanical properties and residual stresses are greatly influenced by the member geometry.

Thus, in order to develop rational design criteria for heavy welded steel columns there is a need for information on the magnitude and distribution of residual stresses in heavy fabricated members. Means for determining these stresses are experimental measurements and theoretical predictions. While experimental procedures are the only way to find the actual distribution of residual stresses in a single given member, such methods are often expensive and time-consuming. This is particularly true for heavy members. In addition, all methods for the measurement of residual stresses, except X-ray and ultrasonics measurement of surface residual stresses, require the destruction of the specimen, at least locally. Theoretical methods, on the other hand may be used for predictions which are sufficiently accurate for many purposes. Such methods appear particularly useful to study the effect of geometry, or the effect of various manufacturing and fabrication conditions on residual stresses. An experimental study of this kind would require several specimens and, if at all economically feasible, it would be complicated or even impossible to control all relevant variables.

This report presents briefly a theoretical study for predicting longitudinal residual stresses in medium-size to heavy welded plates and shapes. A full account of the investigation will be presented elsewhere [1]. The method of analysis differs from previous investigations of welding residual stresses in several respects. Some of these are:

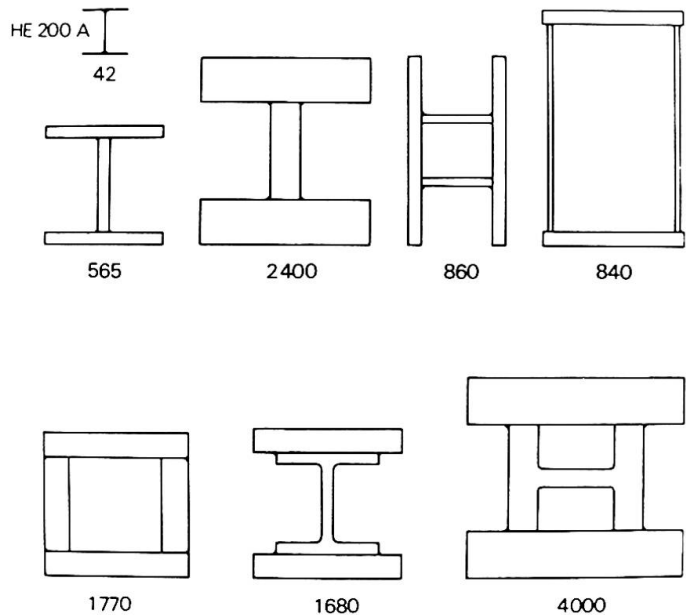


Fig. 1 Examples of heavy welded shapes used as columns in recent buildings (Numbers indicate weight in kg per linear meter; a rolled European standard shape HE 200 A is included for comparison)

1. The action of the complete member being welded is considered, not merely a separate plate with a weld bead.
2. The three-dimensional variation of temperature, and the resulting through-thickness variation of longitudinal stresses, are taken into account -- in thick plates, the through-thickness variation may be quite significant.
3. Most importantly, it is recognized that the initial residual stresses, that is, the residual stresses existing in the component plates prior to welding, may be of major importance in the formation of residual stresses in a welded shape [2] .

The welding residual stresses are generated by local plastic deformations occurring during the welding. These stresses are computed from an analysis of the temperature and the elastoplastic stress-strain history during welding. The analysis of heat flow is based upon the well-known theory for moving point heat sources as developed by Rosenthal [3, 4] and others. A review of some of the important earlier investigations concerned with welding residual stresses is given in [5] .

The study of heavy welded shapes discussed in this report supplements the previous investigations of residual stresses as related to the strength of structural steel columns. Extensive studies of residual stresses were previously carried out for hot-rolled members [6, 7, 8, 9] , small welded plates [5, 10] , and shapes built up from universal-mill plates [11] . Recent or current experimental studies include also welded shapes of flame-cut plates [12] and heavy welded plates and shapes [2, 13, 14] .

The method of analysis discussed here is not only applicable to the welding residual stresses in medium-size to heavy welded columns. Other important applications include thermal stress effects in heavy steel installations exposed to local heat; residual stresses in heavy welded plates, for instance, as used in submarine hulls; or temperature and stress conditions in plates welded by modern methods producing a very localized heated zone, such as electron beam welding.

INITIAL STRESSES

Although the possible effect of initial stresses existing in the parent plates before fabrication of a welded member was pointed out as early as 1936 [15], it is surprising to note that this effect has not been investigated in previous studies. In fact, many experimental investigations of residual stresses purposely excluded this factor by stress-relieving the parent plates of the test specimens prior to welding. The results thereby obtained would barely have any practical value for medium-size to heavy welded members, since the initial stresses may be of greater importance than the stresses created by the welding process [2].

Component plates in medium-size to heavy welded members are either universal-mill plates with as-rolled edges ("UM plates") or oxygen-cut plates ("OC plates") taken from larger rolled parent plates. Initial residual stresses in UM plates may be predicted from the cooling procedure, using a theoretical method discussed elsewhere [7, 8, 9]. Such stresses alternatively may be estimated from recent measurements [14]. Similarly, residual stresses in OC plates may be predicted, for instance, by using the method reported below, or may be estimated from measurements [14]. When calculating residual stresses in OC plates, the thermal stresses produced by the oxygen-cutting have to be superimposed upon the cooling stresses existing in the rolled parent plates.

Figure 2 shows predicted residual stresses in two heavy UM plates with dimensions 356 x 64 mm and 254 x 38 mm, respectively (14 x 2 1/2 and 10 x 1 1/2 inch, respectively). These plates were chosen here because experimental results are available for comparisons [2]. In the prediction, the viscous deformations during the cooling process were considered specifically [9, 16] using viscous coefficients for structural steel as determined in the literature [17].

The compressive stresses at the plate edges of the larger plate (Fig 2 a) are up to 75 percent of the assumed yield strength, and balanced by tensile stresses in the center of the plate. The maximum compressive stress predicted for the smaller plate, Fig 2 b, is about half the yield strength.

The heat input introduced into a plate during oxygen-cutting may be treated as a moving linear heat source acting along the plate edge [3]. Mathematical expressions for this and several other heating cases have been conveniently summarized in Ref. 18.

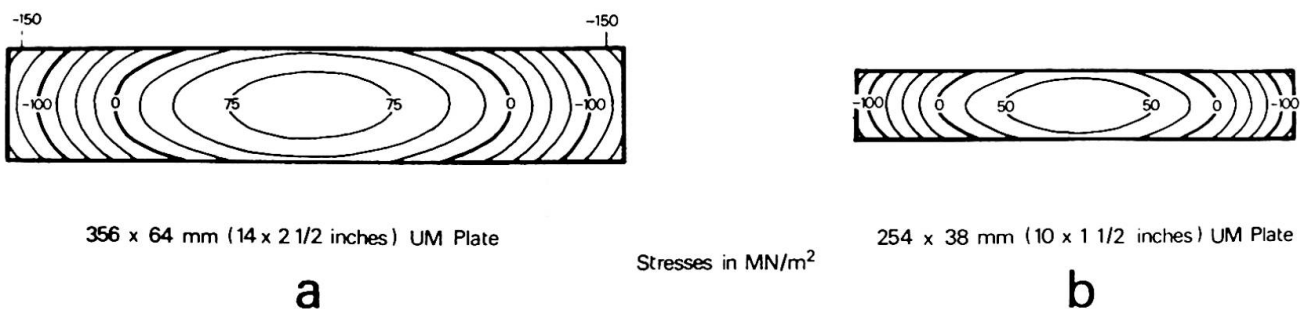


Fig. 2 Predicted residual-stress distributions in two thick universal-mill plates

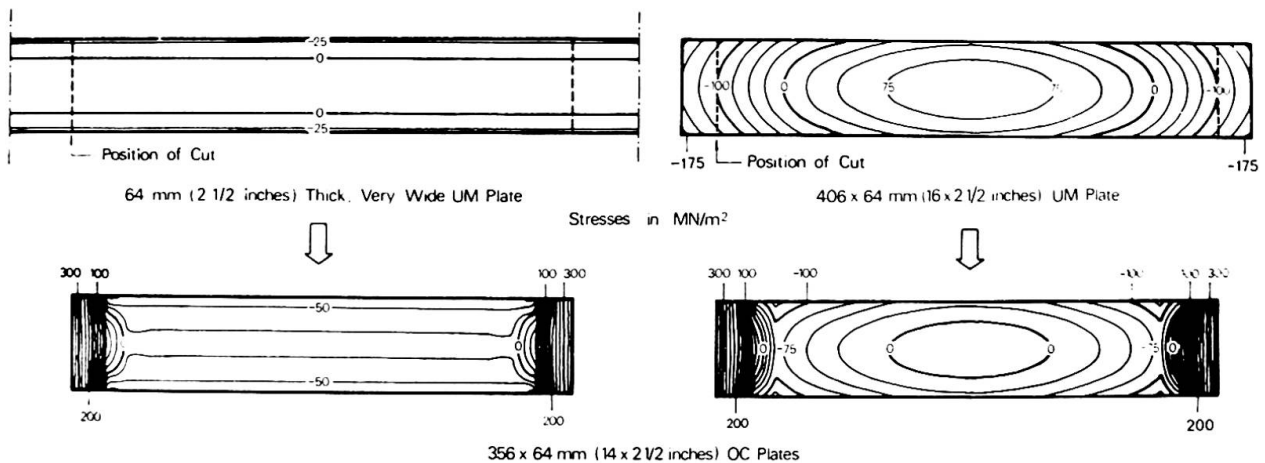


Fig. 3 Predicted residual-stress distributions in thick oxygen-cut plates taken from a very wide universal-mill plate and a narrower universal-mill plate

However, because the heat input may vary throughout the thickness, the heat source can also be treated numerically as a line of several moving point heat sources. The relative intensity of these point sources may be chosen to simulate the different heating conditions on the near and far side of the plate. The formal computations can be made using the same method as discussed below for the welding.

Residual-stress distributions predicted for an OC plate of the same size as in Fig. 2 a are seen in Fig. 3. Two distributions are given, one corresponding to a very wide parent plate, with initial stresses varying only across the thickness, and one corresponding to a narrower parent plate, the plate presumably being oxygen-cut only to obtain straight edges. The width of the parent plate in the second case was chosen arbitrarily to be 407 mm (16 inches). In this prediction, all point heat sources along the oxygen-cut edges were simply assumed equal, the total heat input given away to heat each plate edge being 16 kJ.

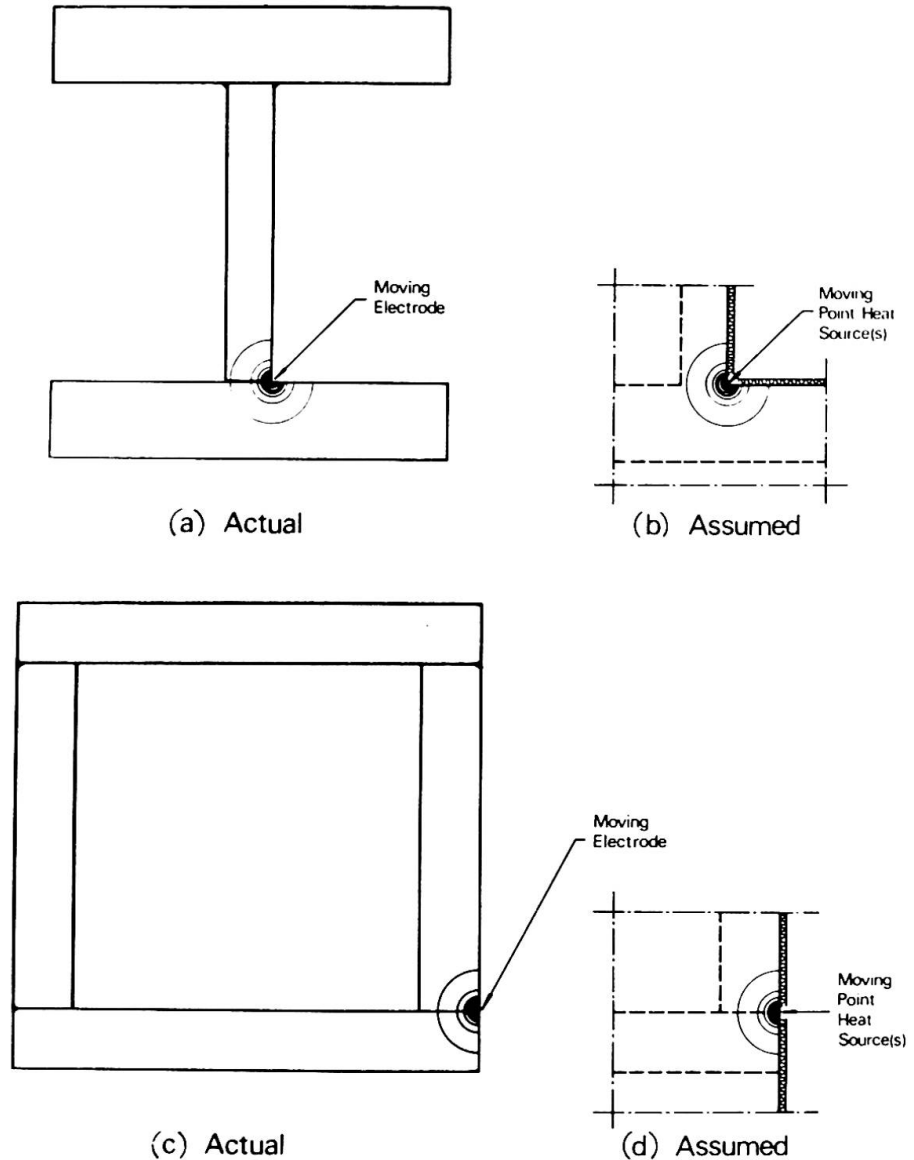
TEMPERATURE ANALYSIS IN WELDING

For the case of interest here, the heated zone around a weld is small compared to the thickness of the material. Under such conditions the actual geometry of the member being welded can be considered as a segment of a three-dimensional continuum. Different practical boundary conditions for heavy shapes may be approximated as shown in Fig. 4.

The heat input in welding normally is treated in the literature as the result of a moving point heat source [3, 4, 5, 13, 18] . However, because of the finite size of the molten pool, the high-temperature region around a real weld is much wider than obtained for a point heat source . To simulate the actual conditions, the weld may conveniently be approximated as an aggregate of heat sources, all located within the molten weld pool, the total heat input of the point sources being equal to the weld heat input.

Further details of the computational method and a derivation of the equations used may be found in the full report [1] . For calculating the temperatures during welding, the cross section is divided into a mesh of sectional points, these same points being used also for expressing the thermal stress-strain conditions.

Fig. 4 Theoretical boundary conditions simulating the actual conditions in heated heavy members



The temperature conditions may be studied in incremental time steps, see Fig. 5. However, since the welding stresses normally constitute only a small fraction of the final residual stresses in a fabricated member, it is reasonable to adopt a simple approximate method. Following suggestions advanced in the literature [13], only three instances will be considered here: the initial state corresponding to the preheat temperature (or ambient temperature if no preheat is applied), an intermediate state corresponding to the conditions at the maximum temperature envelope (see Fig. 5) and the final state after the completed weld run. The resulting "three-step method" may be considered a generalization of the previously developed "two-step method" [13]. In Fig. 6 is shown in a non-dimensional diagram the relationship between maximum temperature and distance from weld line for a moving heat source. The maximum temperature envelope may be obtained conveniently with the aid of the diagram.

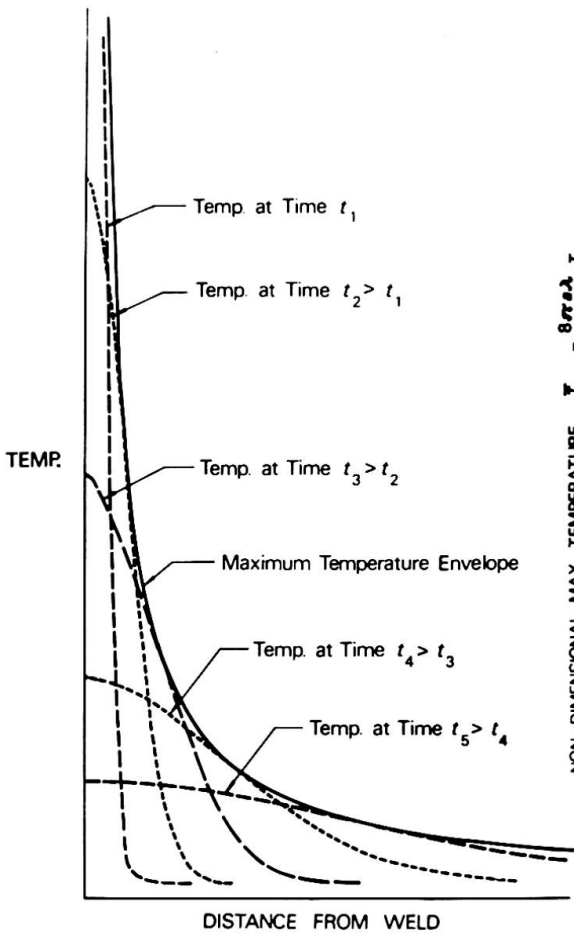


Fig. 5 Examples of temperature distributions at different times after onset of welding (schematic)

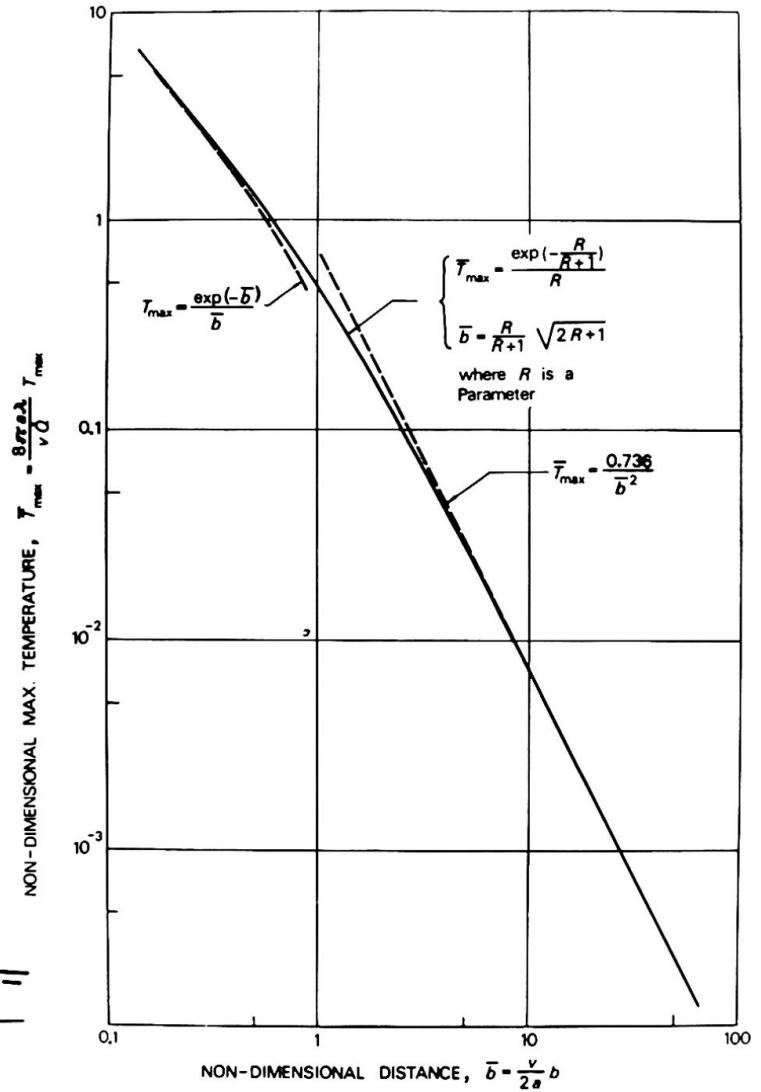


Fig. 6 Non-dimensional curves for the maximum temperature envelope around a point heat source moving in an infinite solid along a line with constant speed (solid line is theoretical curve, dashed lines are approximations, α = thermal diffusivity, λ = thermal conductivity, b = radial distance from weld, and \dot{Q} = rate of heat input)

THERMAL STRESS ANALYSIS

A numerical method for the analysis of thermal stresses of an elastic-plastic material with temperature dependent coefficients, that is, modulus of elasticity, coefficient of linear expansion, and yield strength, was described previously [7, 8, 9] . In the three-step method discussed here, however, this comparatively complicated procedure is not justifiable, because of the more approximate nature of the temperature analysis. Thus, a less laborious method may be used here. First, the viscous strain components may be included in the plastic strain [4] . Further, the factor $E\alpha$ entering the thermal stress equations may be considered a constant. This appears to be a reasonable approximation because E tends to decrease and α to increase with increasing temperature.

For any fiber of the cross section the stress corresponding to the maximum temperature T_{\max} may now be calculated from

$$\sigma_t = \sigma_{\text{init}} - E\alpha(T_{\max} - T_{\text{init}}) + \sigma_{\text{eq}}$$

$$|\sigma_t| \leq \sigma_F(T_{\max})$$

where σ_{init} is the initial residual stress, T_{init} is the initial temperature, σ_{eq} is the "equilibrium stress", and $\sigma_F(T_{\max})$ is the yield strength corresponding to the maximum temperature. The equilibrium stress, being distributed along a plane for compatibility, is determined from the equilibrium equations.

The final residual stresses σ_r after completed welding and cooling to ambient temperature T_{amb} are computed from a similar equation as above, or

$$\sigma_r = \sigma_t - E\alpha(T_{\text{amb}} - T_{\max}) + \sigma'_{\text{eq}}$$

$$|\sigma_r| \leq \sigma_F(T_{\text{amb}})$$

The resulting equation systems may be solved by a straight-forward trial-and-error procedure. However, for the case studied here, with a highly localized temperature rise, the calculations can be simplified when applying an iterative computational scheme as described further in Ref. 1. In fact, the convergence is so fast that hand calculations may be used for a specific problem. The various calculations discussed here, including the plotting of results, were programmed for an electronic computer. The computer program can handle any type of shape built up of rectangular component plates.

The relationship between yield strength and temperature used in the predictions was an average curve of literature data for structural steels. A further factor to be considered is the increase in yield strength of the weld area, due to high cooling rates and the effect of higher strength electrode material. For welded structural steel members it was found experimentally [2, 11] that the yield strength of the weld region is of the order of 50 percent above the yield strength of the base material. Thus, in the computations the material that had become liquefied in the heating cycle was assumed to gain a 50 percent increase in yield strength at ambient temperature. For maximum temperatures between the melting temperature and the transformation temperature at approx. 727°C for carbon steel, the yield strength after cooling was assumed here to be linear with temperature.

SOME RESULTS

Results of calculations will be exemplified here only for one shape -- an H-shape composed of 356 x 64 mm (14 x 2 1/2 inches) flanges and 254 x 38 mm (10 x 1 1/2 inches) web. Iso-stress diagrams from predictions are given in Fig. 7 for a shape being built up of universal-mill plates and in Fig. 8 for the same shape but of oxygen-cut plates. The initial residual stresses in the parent plates were predicted as shown in Figs. 2 and 3.

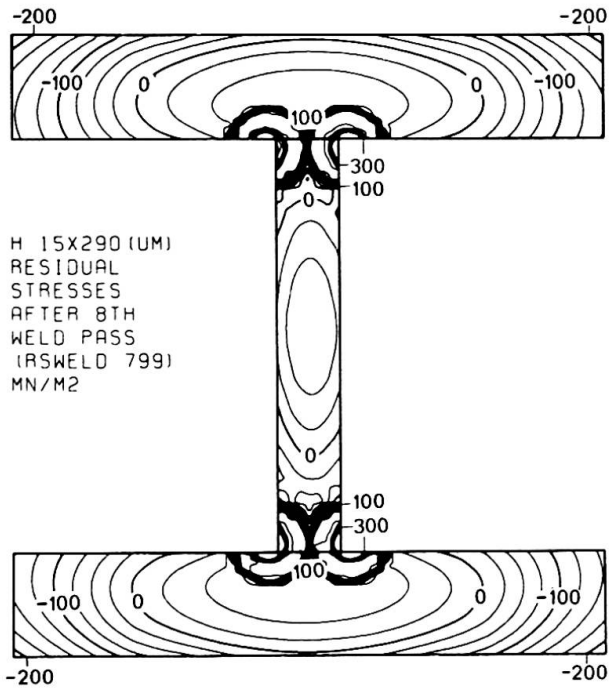


Fig. 7 Iso-stress diagram for predicted residual stresses in a heavy welded H-shape built up of universal-mill plates with as-rolled edges

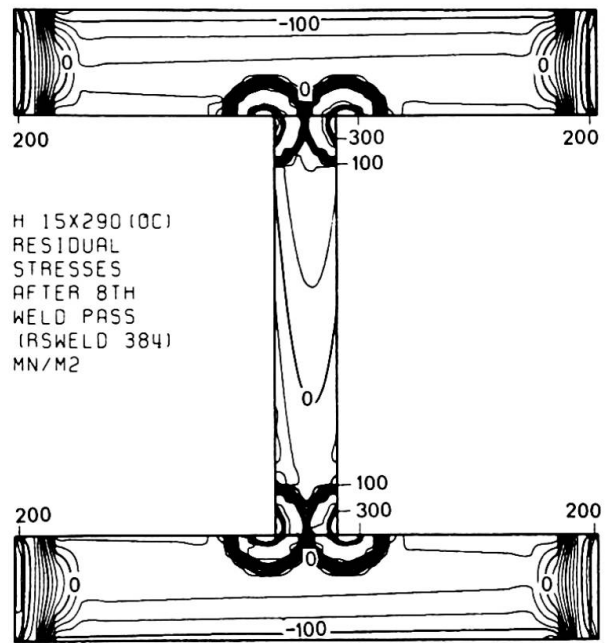


Fig. 8 Iso-stress diagram for predicted residual stresses in a heavy welded H-shape built up of oxygen-cut flange plates

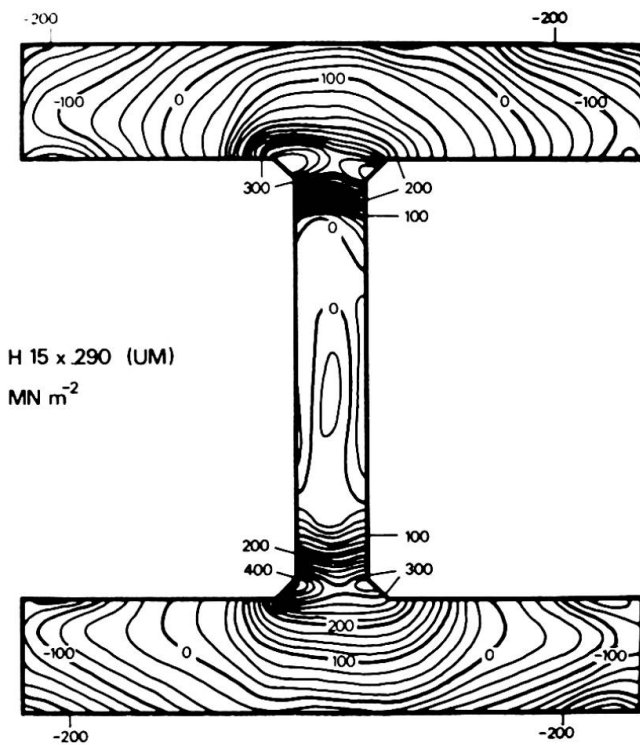


Fig. 9 Iso-stress diagram for measured residual stresses in a heavy welded H-shape built up of universal mill plates with as-rolled edges [2]

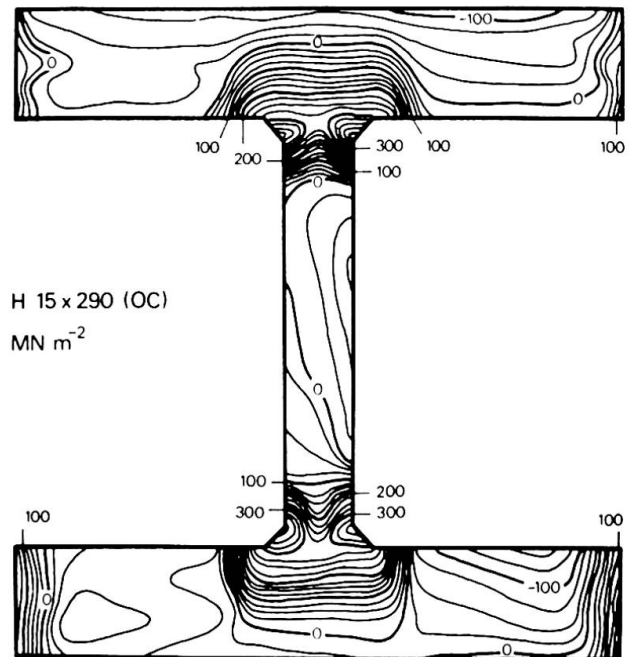


Fig. 10 Iso-stress diagram for measured residual stresses in a heavy welded H-shape built up of oxygen-cut plates [2]

The theoretical results in Figs. 7 and 8 may be compared with experimentally obtained results [2], see Figs. 9 and 10, respectively. There is a satisfying agreement between the predicted and the measured results.

It may be noted by comparing the predicted initial-stress diagrams (Figs. 2 and 3) and the predicted residual-stress diagrams (Figs. 7 and 8) that the effect of the welding is indeed rather small except for in the weld area. It may also be seen that there is a radical difference between the predicted residual-stress distributions in the two members shown in Fig. 7 and Fig. 8, differing only in the manufacturing procedure assumed to have been used for the component plates. These observations, substantiated by further predictions for other shapes [1], verify the same indications drawn from the experimental study [2].

The effect of the high compressive residual stresses in the flanges of Fig. 7 is to reduce column strength, while the tensile stresses at the flange edges of Fig. 8 are beneficial for the column strength of such a member. It appears reasonable that design criteria for heavy columns should recognize this basic difference in properties due to the manufacturing process of welded shapes. The method discussed here for predicting residual stress in such members should be useful for determining the effects of geometry as well as manufacture and fabrication procedures.

ACKNOWLEDGMENTS

The theoretical results in the paper were calculated on an IBM 360/75 at the Stockholm Computer Center with computer time provided by the Office of the Chancellor of the Swedish Universities. Experimental results quoted in the paper for comparison purposes were obtained at Fritz Engineering Laboratory, Lehigh University in an investigation of residual stresses in thick welded plates -- references to the original reports are given in the paper.

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SUMMARY

A method for predicting residual stresses in medium-size to heavy welded steel shapes is discussed, and some results are given. The prediction is based upon a three-step analysis of the temperature rise and thermal stresses. The welding stresses are caused by plastic deformations occurring during the welding cycle. The initial residual stresses existing in the parent plates prior to welding are considered in the predictions. These initial stresses are shown to be the major source of residual stresses in a heavy welded member. Predicted results show good agreement with experimental measurements.

RESUME

On discute une méthode pour prédire les tensions résiduelles dans les tôles d'acier soudées de moyennes et grandes dimensions et quelques résultats sont communiqués. La prédiction est basée sur une analyse à trois échelons de l'augmentation de la température et des tensions thermiques. Les tensions dues au soudage sont causées par des déformations plastiques pendant la marche de la soudure. Dans les prédictions on a tenu compte des tensions résiduelles initiales dans les tôles primitives avant le soudage. Ces tensions initiales forment, comme il est démontré, la source principale des tensions résiduelles dans une grande tôle soudée. Les résultats prédits montrent une bonne concordance avec les mesures expérimentales.

ZUSAMMENFASSUNG

Es wird eine Methode zur Vorausbestimmung der Eigenspannungen in geschweissten mittelgrossen und grossen Stahlblechen diskutiert und einige Ergebnisse werden mitgeteilt. Die Vorausbestimmung stützt sich auf eine Dreistufenanalyse der Temperaturerhöhung und thermischen Spannungen. Die Schweissspannungen werden durch plastische Deformationen während des Schweissvorganges verursacht. Die anfänglichen Eigenspannungen in den ursprünglichen Blechen vor dem Schweißen sind in den Vorausbestimmungen berücksichtigt. Diese Anfangsspannungen bilden nachweislich die Hauptquelle der Restspannungen in einem grossen geschweissten Blech. Die vorausgesagten Ergebnisse zeigen eine gute Uebereinstimmung mit den experimentellen Messungen.

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