DISCUSSION PRÉPARÉE • VORBEREITETE DISKUSSION • PREPARED DISCUSSION

Prediction of Thermal Residual Stresses in Hot-Rolled Plates and Shapes of Structural Steel

Evaluation des tensions résiduelles thermiques dans les tôles et les profiles d'acier

Berechnung der thermischen Eigenspannungen in warmgewalzten Stahlplatten und Stahlprofilen

GÖRAN A. ALPSTEN
Dr. Techn., Docent
Sweden

INTRODUCTION

Residual stresses can play an important role in determining the strength of structural steel members, in particular with respect to the stability of compressed members, see review papers on this subject [1,2]. Much effort has been devoted to experimental studies of residual stresses in structural steel members. However, since such experiments are tedious and very expensive, it has been possible to test only very few out of a vast number of existing shapes with different geometry, manufactured under various conditions, of several steel grades with different thermo-physical and mechanical properties etc. For the same reason, it is natural that most experimental work in this area has been deterministic rather than statistical in nature [3].

This paper presents a theoretical computerized method for determining thermal residual stresses ("cooling stresses") in structural steel plates and shapes produced by hot-rolling. Plates are included here because they are components of welded shapes. Investigations have shown that the initial residual stresses existing in the plates prior to welding may be more important than the welding stresses [4,5]. The paper summarizes some particular aspects of the results of a more general study previously discussed in a research report in Swedish [6]. Reference is made to that report for fuller details of the theoretical method, and to [7] for an extensive discussion of the technical results with respect to residual stresses in structural steel members.

The method presented may be useful for illustrating the mechanism of formation of residual stresses, for identifying the important variables, and for studying the influence of these variables on the resulting residual stresses. An experimental study of this kind would not be feasible since it is practically impossible to separate the different variables. Another important application of the theoretical method is predictions of residual stresses, for instance, for revised manufacturing conditions or for a new steel grade -- apart from the experimental measurement being of the order of 100 times more expensive than a theoretical determination, the manufacturing of the test specimen may be excessively expensive at that investigative stage. Finally, the computer method is well suited for simulations of the statistical scatter of thermal residual stresses as influenced by scatter in the relevant variables.

The study is based upon an evaluation of the non-stationary thermal history and the thermal stress-strain state during the manufacturing process. A finite-difference solution was developed and the numerical computations wereperformed on a digital computer. Plastic and viscous deformations were considered, including the effect of variable properties with temperature.

The method of analysis is applicable also to studies of several other thermal stress problems, such as determining the temperature-time field and thermal stresses for a structural steel member exposed to fire [8], or calculating the temperature, cooling rates, and thermal strains and stresses in a quenching process, in a post-heat treatment, or in any other thermal process involved in the manufacture and fabrication of steel plates and shapes.

METHOD OF TEMPERATURE ANALYSIS

An analytical analysis of the non-stationary heat flow in cooling - with complicated boundary conditions and variable thermo-physical coefficients of the steel - is practically impossible. For this reason, a finite-difference solution of the Fourier heat conduction equation was applied. The solution is based upon the implicit alternating direction (IAD) method. The cross section is divided into a mesh with variable spacing, see Fig. 1. The governing finite-difference equation for interior mesh points may be written on the form

$$\frac{T_{ijk+1}-T_{ijk}}{\Delta t} = \frac{1}{\rho_{ijk+1/2}\, c_{pijk+1/2}} \left[\frac{\lambda_{i+1/2\,j\,k+1/2}\dfrac{T_{i+1\,jk+1}-T_{ijk+1}}{\Delta x_i} - \lambda_{i-1/2\,j\,k+1/2}\dfrac{T_{ijk+1}-T_{i-1\,jk+1}}{\Delta x_{i-1}}}{\dfrac{\Delta x_i+\Delta x_{i-1}}{2}} + \frac{\lambda_{i\,j+1/2\,k+1/2}\dfrac{T_{ij+1\,k}-T_{ijk}}{\Delta y_j} - \lambda_{i\,j-1/2\,k+1/2}\dfrac{T_{ijk}-T_{ij-1\,k}}{\Delta y_{j-1}}}{\dfrac{\Delta y_j+\Delta y_{j-1}}{2}} \right]$$

where T is temperature, t is time, ρ is density, c_p is specific heat, λ is thermal conductivity, and x and y are coordinates. The subscripts i and j refer to location in the cross section and k is the order of the time interval. For every second time step, the direction of integration is altered so that subscripts k and (k+1) of the temperatures T are exchanged in the right member of the equation. Similarly, a finite-difference equation may be formulated for the surface mesh points, based upon the equation

$$-\lambda \frac{\partial T}{\partial n} = h\left(T - T_{amb.}\right)$$

where n is a coordinate normal to the surface and h is the surface coefficient of heat transfer. The detailed derivation of the finite-difference equations employed is given in [6].

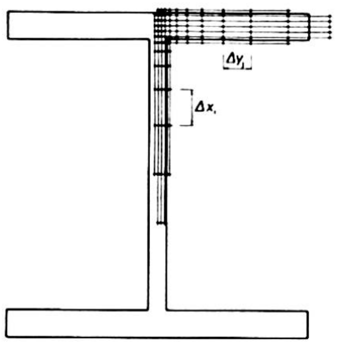


Fig. 1 Subdivision of an H-shape for finite-difference solution

The variable thermo-physical coefficients of structural steels as summarized from measurements in the literature were applied in the solution. A further complication results from the development of latent heat in the phase transformation of the steel around 727 °C. This effect was treated formally as a fictitious addition to the latent heat [6].

Results of calculations performed on a digital computer are shown in Fig. 2 as cooling

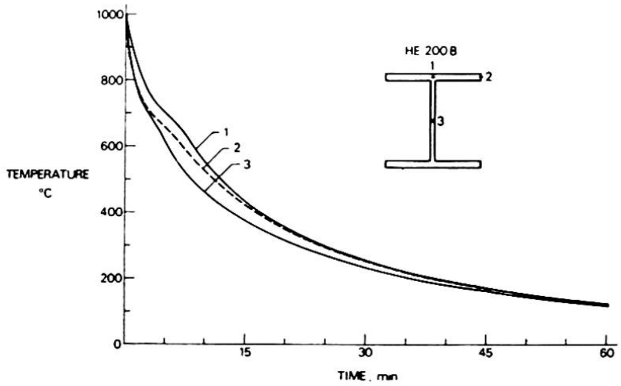


Fig. 2 Predicted cooling curves for an H-shape HE 200 B

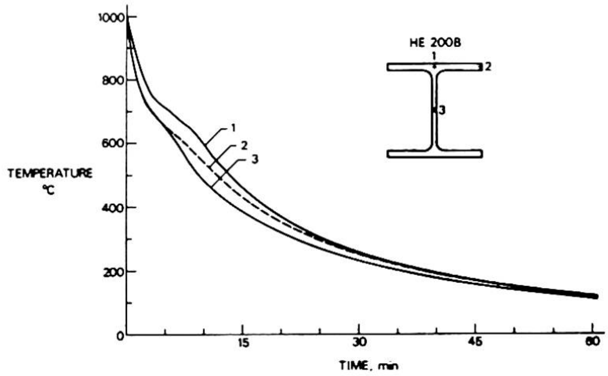


Fig. 3 Measured cooling curves for an H-shape HE 200 B

curves for three points on the cross section of an H-shape HE 200 B. This diagram may be compared with experimental cooling curves as given in Fig. 3. There is a good agreement between theory and experiment as evidenced by this comparison. Several such experimental temperature measurements were carried out and compared with calculations. For reasons which will be explained further below, a diagram of temperature differences over the cross section as a function of temperature will give a relevant representation of the cooling behavior. Figure 4 is such a diagram based upon the theoretical prediction of Fig. 2 and three repeated measurements on an HE 200 B shape. Considering the experimental scatter, and the fact that the prediction was based upon nominal average material coefficients, the agreement between prediction and measurements is most satisfactory.

METHOD OF THERMAL STRESS ANALYSIS

The thermal stress field at any instant during the cooling process may be calculated from the temperature field, considering the compatibility and equilibrium conditions. The longitudinal strain in a particular fiber (i, j) of the cross section can be written

$$\varepsilon_{ijk+1} = \Delta\varepsilon^{C}_{ijk+1/2} - \left(-\varepsilon^{E}_{ijk} + \Delta\varepsilon^{T}_{ijk+1/2}\right)$$

where ϵ^C is the strain increment due to compatibility conditions, ϵ^E is the elastic strain, and ϵ^T is the free thermal strain. The expression within parenthesis is the strain of a free fiber.

The formal addition of strains is represented graphically in Fig. 5, where $\Delta\epsilon$ equals $(\Delta\epsilon^C - \Delta\epsilon^T)$. Generally, the strain ϵ is composed of three parts

$$\varepsilon_{ijk+1} = \varepsilon^{E}_{ijk+1} + \varepsilon^{P}_{ijk+1} + \varepsilon^{V}_{ijk+1}$$

that is, an elastic, a plastic, and a viscous strain component. The elastic strain is the cause of stresses equal to

$$\sigma_{ijk+1} = E_{ijk+1}\,\varepsilon_{ijk+1}$$

where E is the modulus of elasticity. The plastic and viscous components are accumulated as remaining deformations in the fiber considered.

The method discussed here is formally somewhat different from similar computational procedures used previously for theoretical investigations of welding residual stresses [9]. The difference is exemplified in Fig. 6 (method B for adding strains is the method discussed above). Although the method of adding stresses will lead to physically impossible results for large increments of strains [6], the differences between

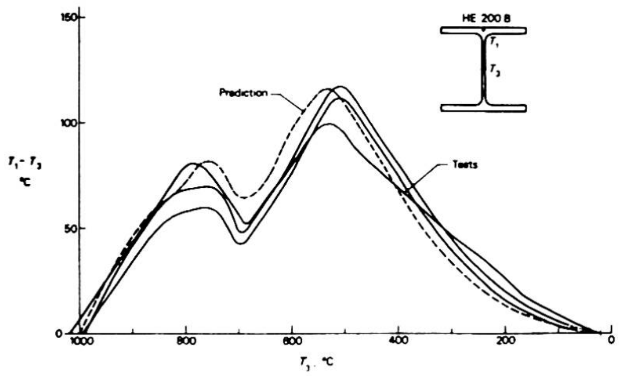


Fig. 4 Comparison betwen predicted and experimental cooling behavior

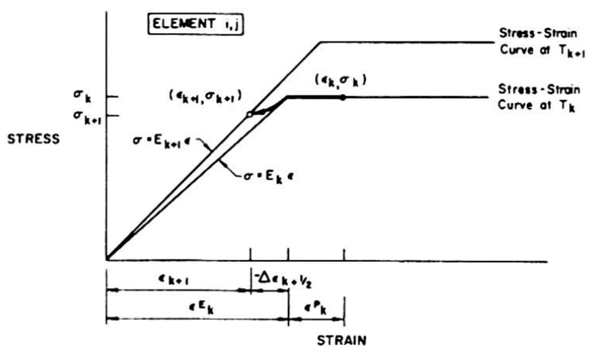


Fig. 5 Model for calculating thermal stresses at varying temperatures

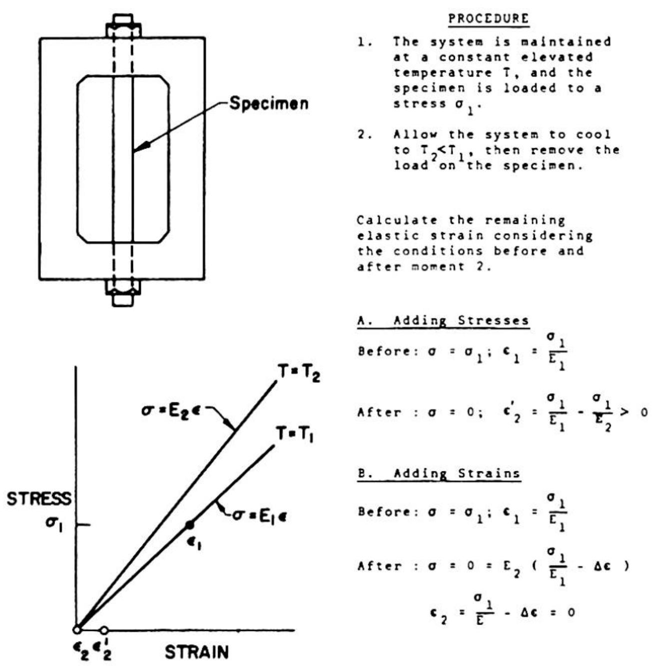


Fig. 6 Simplified model for comparison between calculation procedures

results obtained with the two methods are reasonably small for smaller strain increments.

In Fig. 5 the stress-strain curves were drawn as for elastic perfectly-plastic behavior. While this is a reasonable assumption for structural carbon steels at room temperature, real stress-strain curves at elevated temperatures are somewhat different as exemplified in Fig. 7. The dashed lines are elastic perfectly-plastic approximations fitted through the stress corresponding to 0.2 percent offset. Such approximations were applied in the present investigation. However, if sufficient mechanical data is available for a particular steel, the computational method discussed above is equally suited for a Ramberg-Osgood or some other parametric type representation of the stress-strain curve.

Figures 8 and 9 summarize limits of literature data for yield strength σ_F ($\sigma_{0.2}$ at elevated temperatures) and modulus of elasticity E of structural carbon steels. Also shown are the curves used for calculations. Results of both short-time tensile tests and creep tests are included in Fig. 8. In the present investigation, the viscous deformations were included in the plastic deformations. When curves for σ_F and E are adjusted appropriately, this leads to a reasonable approximation. Figure 10 shows the implications of this assumption. Comparative calculations for cooling processes of normal-size members, including a more detailed estimation of the viscous strains, indicated that the error of the above approximate method is negligible compared to the errors resulting from an inaccurate knowledge of the short time stress-strain curve at high temperatures. This conclusion may not be correct for a heating process, where high temperatures normally are maintained at longer duration of time, for instance, when applying the method for predictions of temperatures and thermal stresses in a member exposed to fire. For such cases a detailed

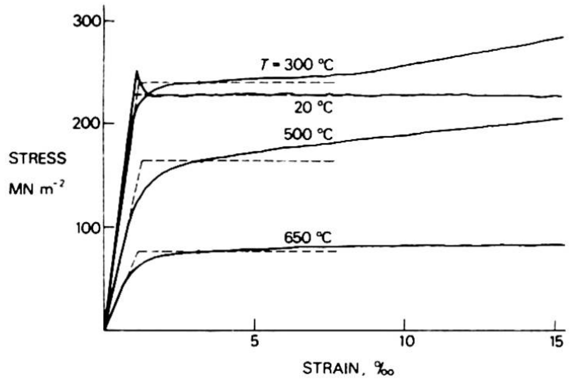


Fig. 7 Examples of stress-strain curves at different temperatures for a structural carbon steel

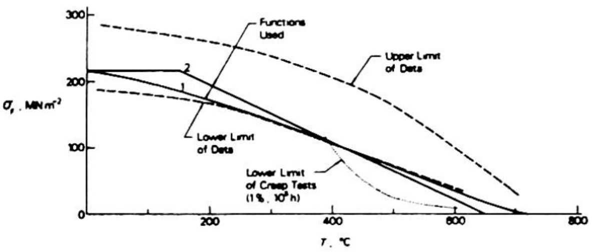


Fig. 8 Yield strength σ_F of structural carbon steels versus temperature

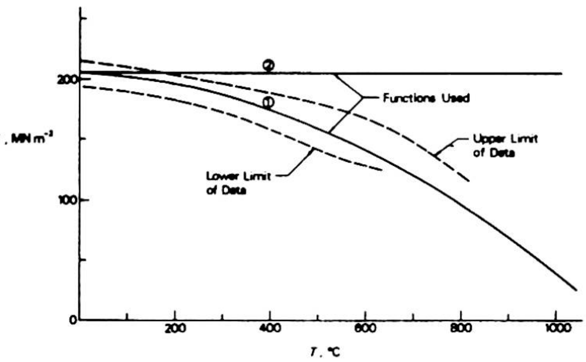


Fig. 9 Modulus of elasticity E of structural carbon steel versus temperature

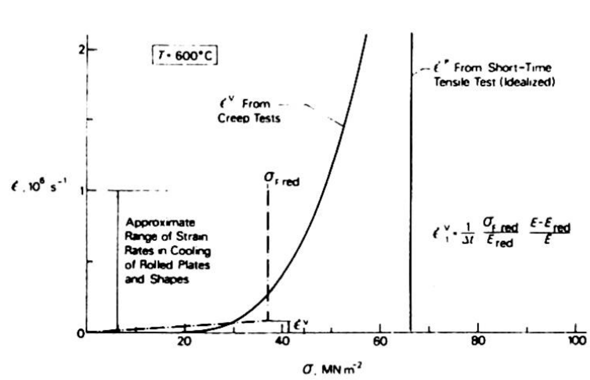


Fig. 10 Approximate method for calculating viscous strains (schematic)

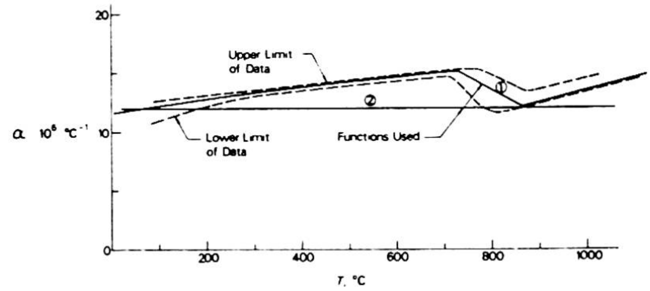


Fig. 11 Coefficient of linear expansion α of structural carbon steels versus temperature

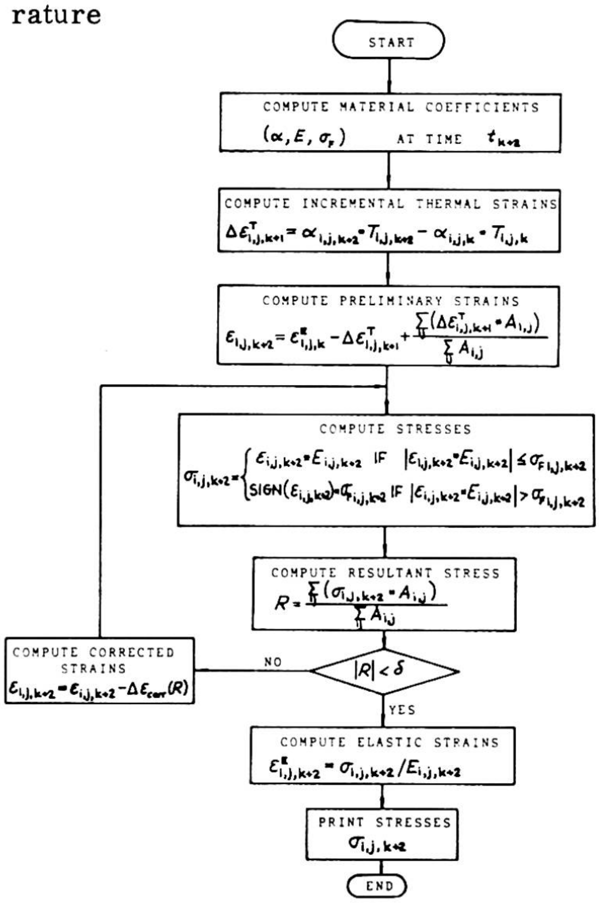


Fig. 12 Short flow diagram of subroutine for thermal stress analysis

account of the viscous deformations may become necessary. The computer procedure as discussed here (see also Fig. 12 above) has been revised to include a separate account of viscous strains. In the residual stress calculations, however, it was assumed that E_{red} in Fig. 10 is equal to E, which leads to negligible errors for normal-size shapes. For very heavy members, this assumption overestimates slightly the elastic strains and the resulting residual stresses.

A further mechanical property entering the stress-strain calculation is the coefficient of linear expansion α. Figure 11 shows the limits of literature data and the assumed functions. The relationship is influenced by the gradual phase transformation $\gamma \rightarrow \alpha$ which is accompanied by a volume expansion.

The various other conditions and assumptions involved in the calculation were discussed in detail in the original report [6]. The computer subroutine used for calculating thermal stresses is given in Fig. 12 (in this flow chart, viscous deformations are considered in σ_F but not in E).

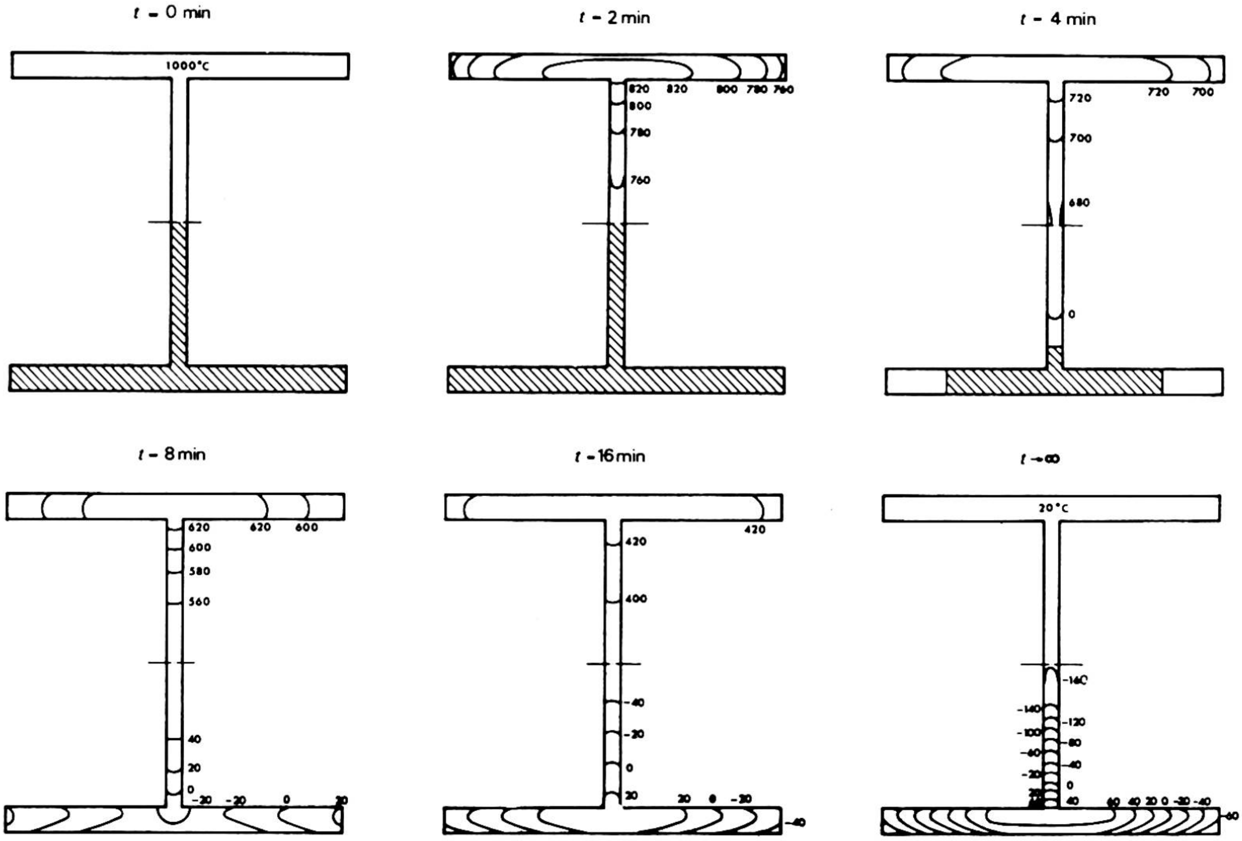


Fig. 13 Predicted cooling behavior and transient thermal stresses in an HE 200 B shape

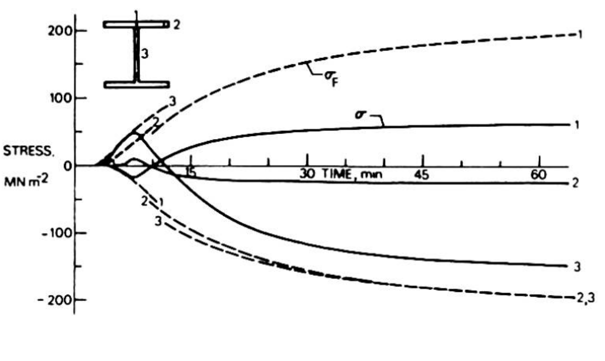


Fig. 14 Predicted thermal stress and associated yield strength as a function of cooling time, HE 200 B

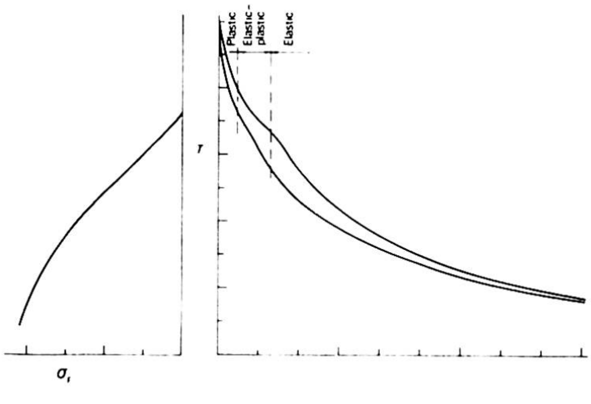


Fig. 15 Different regions of mechanical behavior during the cooling of an H-shape, HE 200 B

RESULTS

Figure 13 shows the computed temperature and thermal stress fields at different stages during cooling of an H-shape HE 200 B. A constant temperature of 1 000 °C was assumed for the initial state. The thermal stresses obtained when the member approaches the ambient temperature are the resulting residual stresses. As a rule-of-thumb, the regions cooling first will develop compressive residual stresses, balanced by tensile stresses in the remainder of the cross section.

The relative stress level at various stages of the cooling process may be studied in Fig. 14. It is interesting to note that the stresses are completely plastic and completely elastic, except for a short intermediate time interval. The three regions are indicated in Fig. 15. The intermediate elastic-plastic region is closely related to the temperature range where the yield strength approaches zero. The important implication is that temperature differences existing in this intermediate temperature range are the major cause of residual stresses to form after cooling to ambient temperature.

The influence of various assumptions on the residual stresses may be studied in Fig.16. In summary, the initial temperature state is not an important variable; constant thermophysical coefficients will lead to large deviations in the results, but reasonably small variations in the various coefficients will cause only small differences in the computed results; cooling conditions are most important in the formation of residual stresses.

In Fig. 17 is a comparison between predicted and measured residual stresses in two shapes, a light I-shape IPE 200 and a heavy H-shape W 14x426, weighing 22.4 and 632 kg per linear meter, respectively. The diagrams give an idea of the agreement between predictions and tests for two shapes towards the ends of the span of different existing rolled shapes. A comparison between Figs. 17 a and 17 b also gives an indication of the effect of geometry on the magnitude of residual stresses.

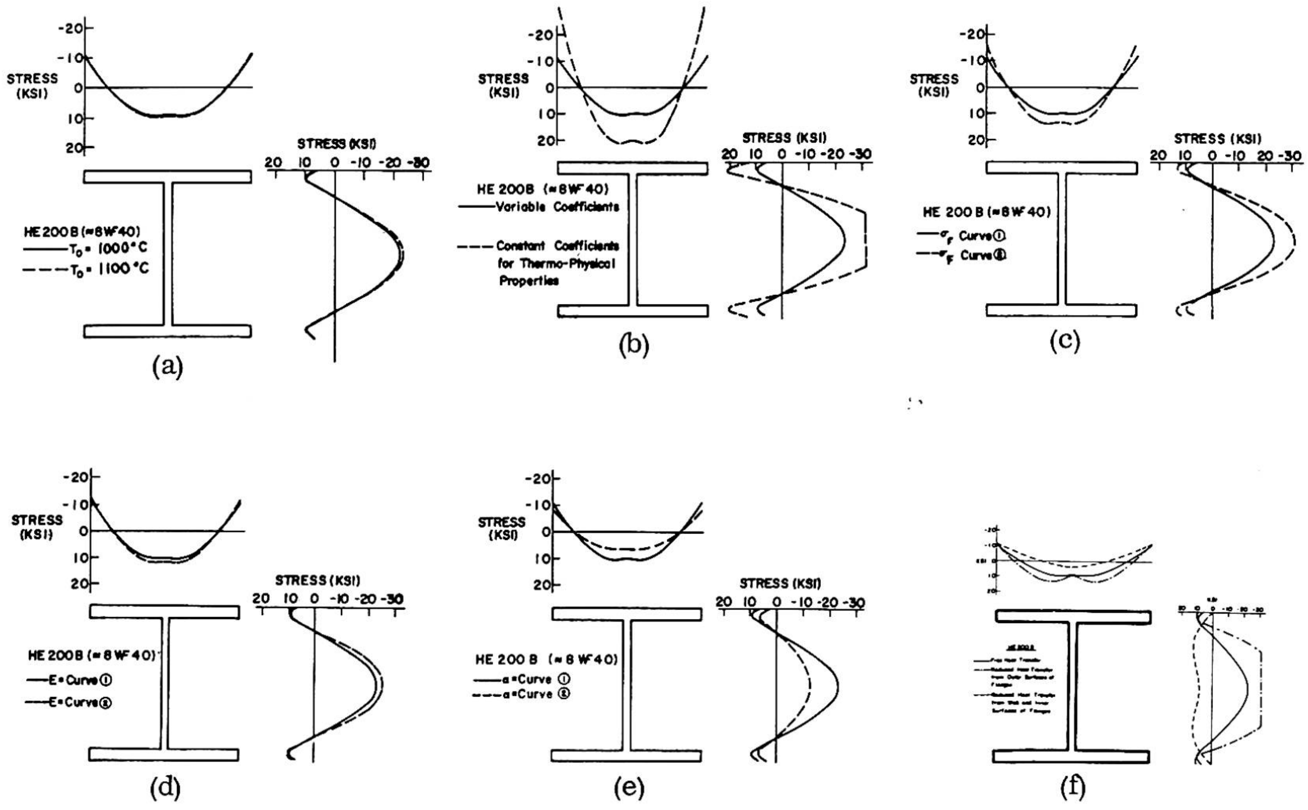
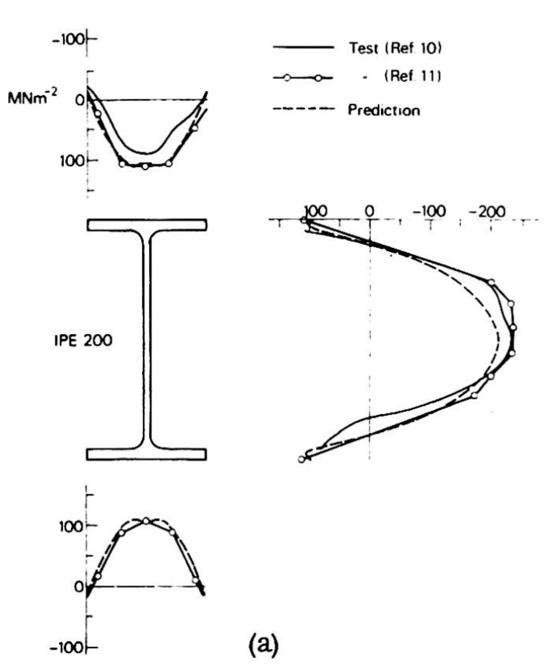


Fig. 16 Influence of different assumptions on the predicted residual stresses, HE 200 B (Scales graded in ksi. 1 ksi=6.9 MN/m²)



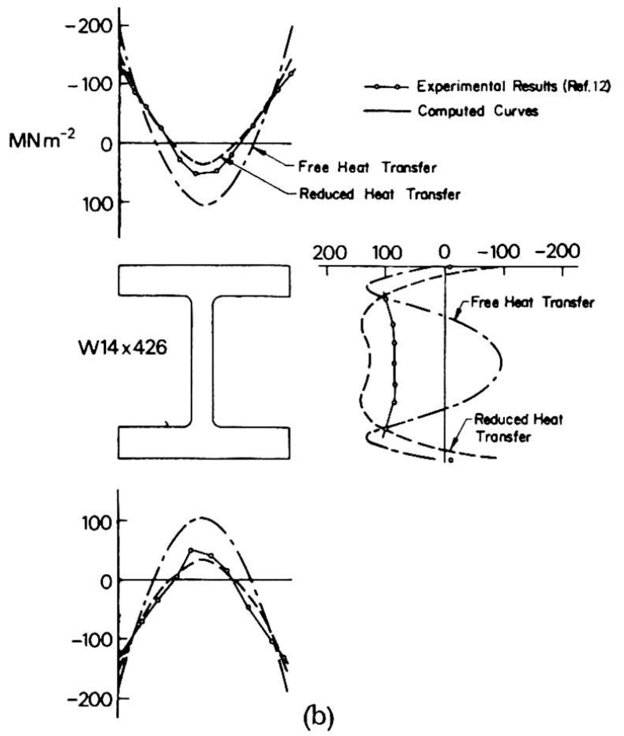


Fig. 17 Predicted and measured residual stresses in (a) a light I-beam IPE 200 and (b) a heavy H-shape W 14x426

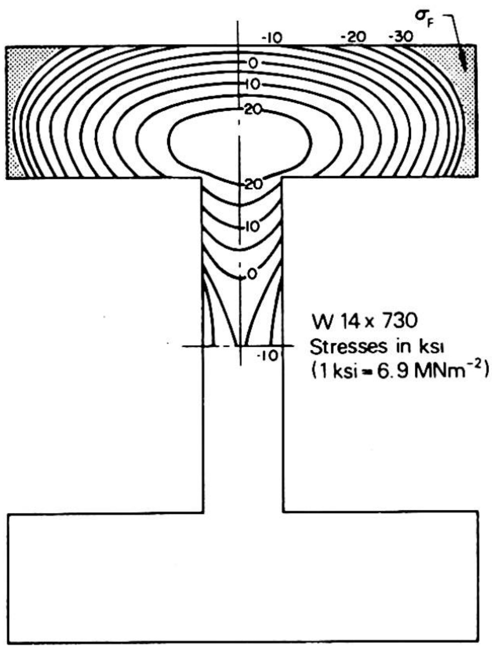


Fig. 18 Predicted two-dimensional variation of residual stresses in a "jumbo" shape W 14x730

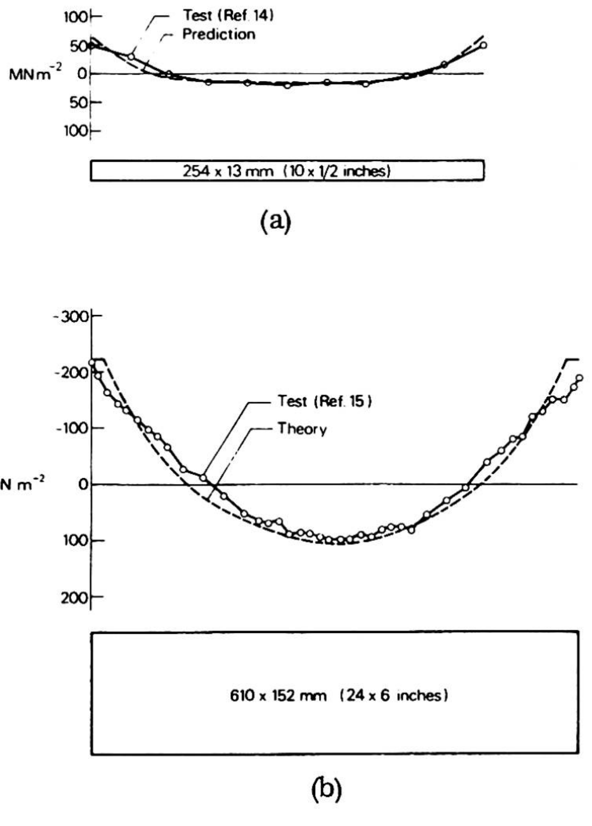


Fig. 19 Predicted and measured residual stresses in two universal-mill plates with as-rolled edges

Figure 18 shows the predicted two-dimensional variation of residual stresses in a still heavier H-shape W 14x730, that is the heaviest "jumbo" shape being rolled in the U.S. today. The calculated temperature differences in this extremely heavy shape (1 087 kg/m) are sufficient to cause residual stresses approaching the yield at the flange tips. Another important feature is the great through-thickness variation of residual stresses. Experimental measurements of residual stress have been carried out also for this "jumbo" shape [13]. The measured residual stresses were, however, much lower than predicted in Fig. 18, probably because the test member had been cold-straightened after cooling in the mill.

The effect of geometry on cooling residual stresses, as predicted by the theory [6,7], and as exemplified in Fig. 17, has been verified also by experiments on universal-mill plates with as-rolled edges [15]. Two examples are shown in Fig. 19. The compressive residual stress in the heavy plate is about three times greater than in the smaller plate. Thus, member size and geometry is one of the major variables affecting thermal residual stresses in hot-rolled plates and shapes.

Residual stresses affect the strength of centrically loaded columns. The variation of residual stresses as caused by different shape size may reduce the maximum strength by as much as 30 percent [2,7]. Thus, it appears necessary that the detrimental effect of high residual stresses be considered in the design of steel columns. Alternatively, measures should be taken to limit such stresses below acceptable values. A controlled roller-straightening procedure could be used for this purpose [16]. Experimental studies of roller-straightened columns have shown that the column strength may be increased by 10 to 15 percent from the roller-straightening process, even for a shape HE 200 A with relatively small thermal residual stresses [17].

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SUMMARY

A computerized method for predicting thermal residual stresses in hot-rolled steel plates and shapes is presented. The procedure is based upon a finite-difference solution using an implicit alternating direction method for calculating the non-stationary heat flow. From the temperature field the transient thermal stress-strain conditions are evaluated, considering elastic, plastic, and (approximately) viscous strain components, and taking into account the variable mechanical coefficients of structural carbon steel. Predicted temperature-time curves and residual stress distributions agree well with experimental results. The method is applicable also to several other types of thermal problems.

RESUME

On présente ici une méthode, utilisant l'ordinateur, pour prédire les tensions thermiques résiduelles dans les plaques et les coques en acier laminé à chaud. Ce procédé est basé sur une solution aux différences finies utilisant pour calculer le flux thermique non-stationnaire une méthode implicite aux directions alternantes. On évalue les conditions transitoires d'allongement et de tensions thermiques à partir du champ des températures, considérant les composantes d'allongement élastiques, plastiques et (approximativement) visqueuses et tenant compte des coefficients mécaniques variables de l'acier de construction au carbone. Les courbes température-temps et les distributions des tensions résiduelles obtenues, concordent bien avec les résultats expérimentaux. La méthode est aussi applicable à d'autres types de problêmes thermiques.

ZUSAMMENFASSUNG

Es wird eine mittels Computer durchgeführte Methode zur Vorausbestimmung von Eigenspannungen in warmgewalzten Stahlblechen und Stahlprofilen vorgelegt. Der Vorgang stützt sich auf eine endliche Differenzenlösung unter Verwendung einer impliziten Methode zur Berechnung des nichtstationären Wärmeflusses. Aus dem Temperaturfeld werden die transienten thermischen Eigenspannungsbedingungen ausgewertet unter Berücksichtigung der elastischen plastischen und (annähernd) viskosen Spannungskomponenten und unter Berücksichtigung der variablen mechanischen Koeffizienten von Kohlenstoffstahl. Die vorausgesagten Temperatur/Zeit-Kurven und die Verteilung der Eigenspannungen stimmen mit den experimentellen Ergebnissen gut überein. Die Methode ist auch auf verschiedene andere Typen thermischer Probleme anwendbar.

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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

GÖRAN A. ALPSTEN
Dr. Techn., Docent
Sweden

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:

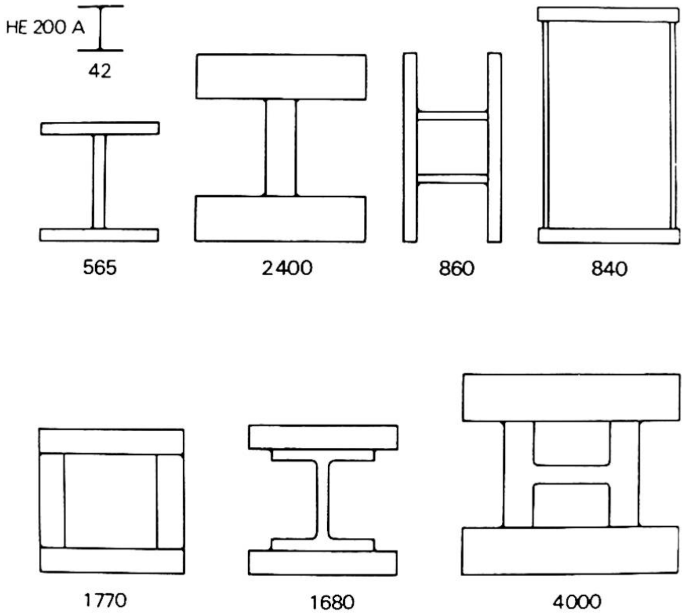


Fig. 1 Examples of heavy welded shapes used as columns in recent buildings (Numbers indicate weight in kg per linear meter; a rolled European standard shape HE 200 A is included for comparison)

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 occuring 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 that 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 my 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.

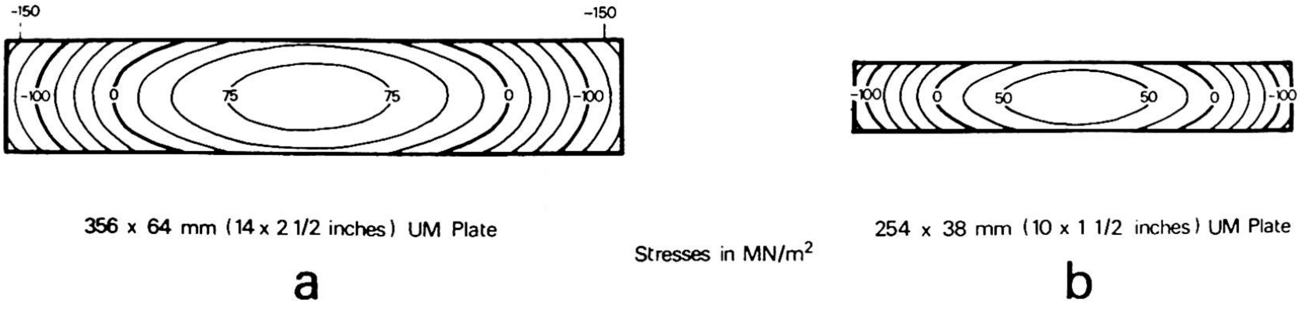


Fig. 2 Predicted residual-stress distributions in two thick universal-mill plates

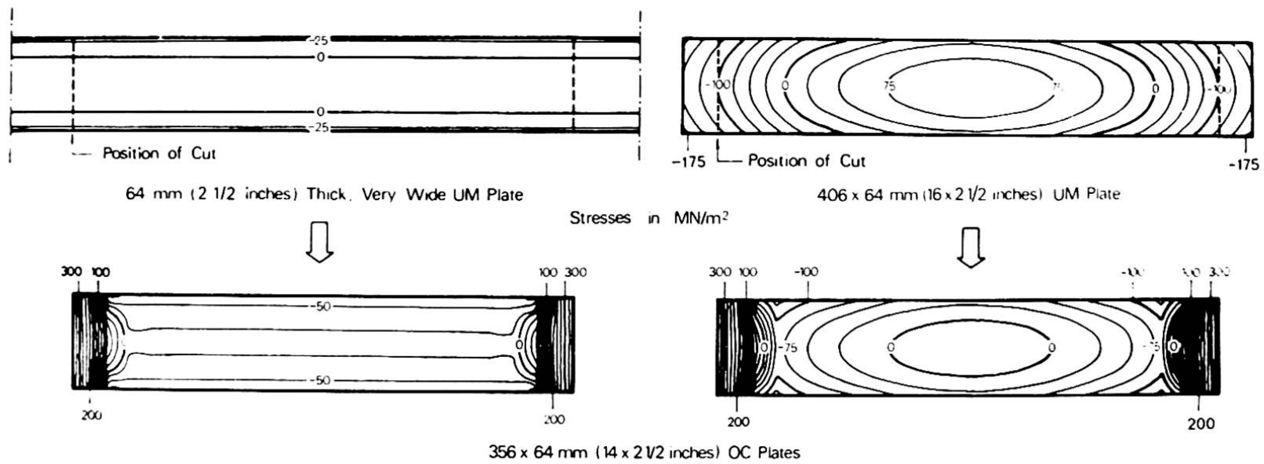


Fig. 3 Predicted residual-stress distributions in thick oxygen-cut plates taken from a very wide universal-mill plate and a narrower universal-mill plate

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.

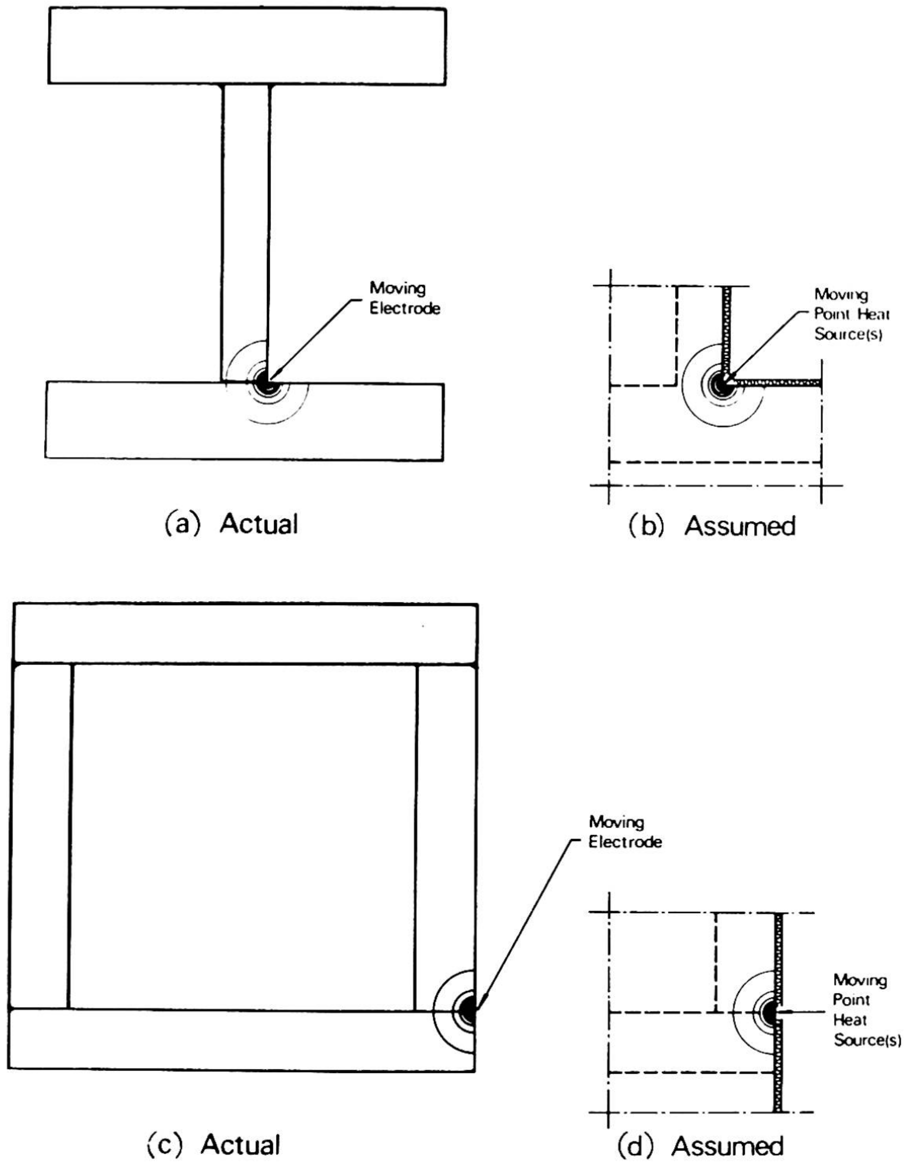
TEMPERATURE ANALYSIS IN WELDING

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.

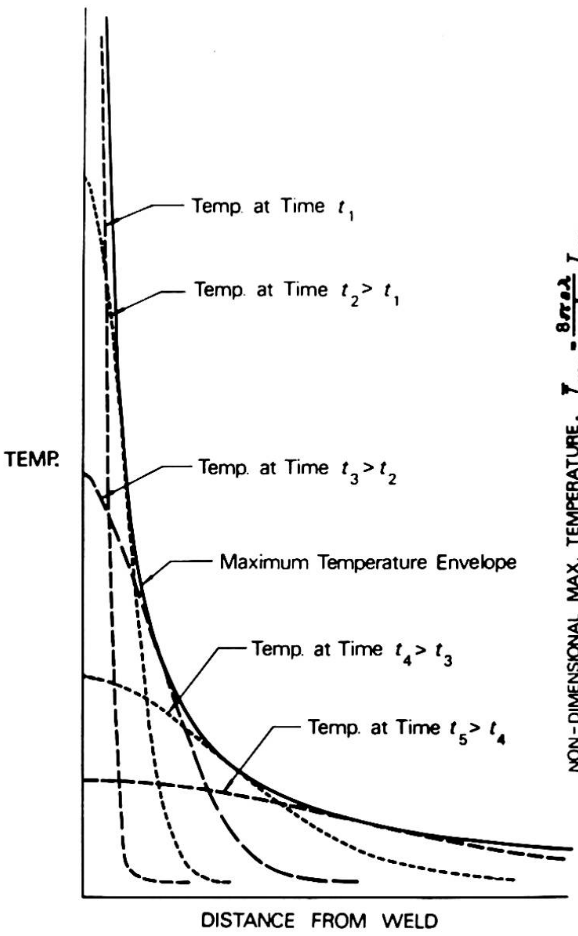


Fig. 5 Examples of temperature distributions at different times after onset of welding (schematic)

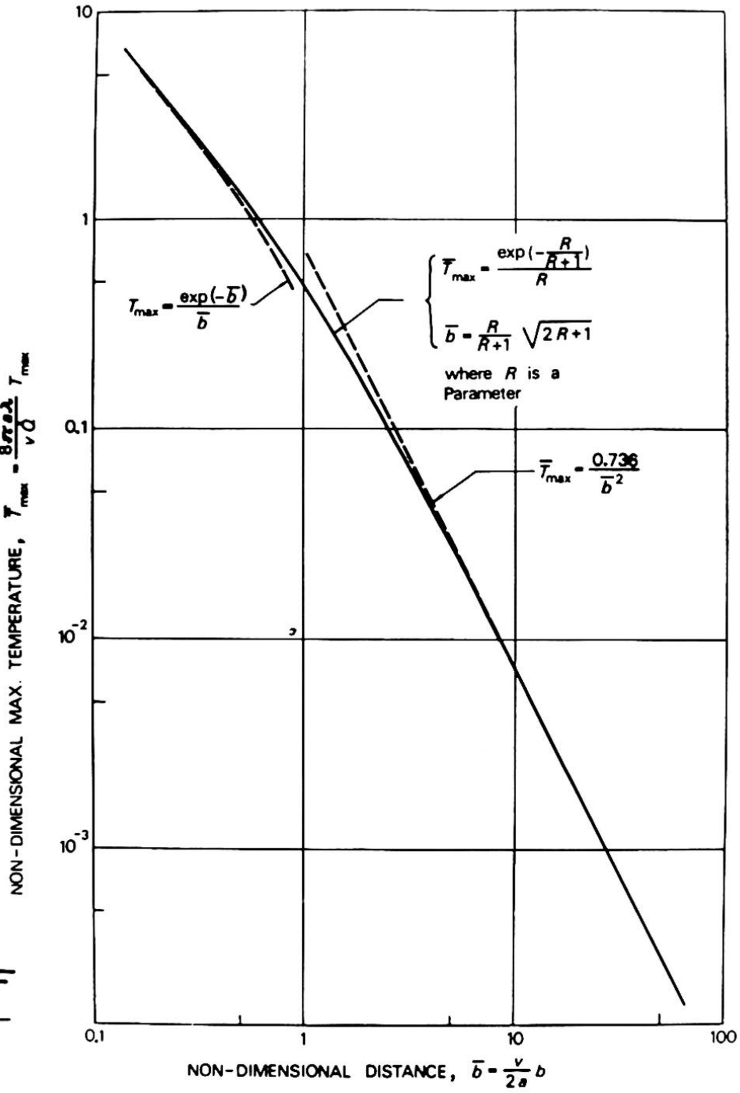


Fig. 6 Non-dimensional curves for the maximum temperature envelope around a point heat source moving in an infinite solid along a line with constant speed (solid line is theoretical curve, dashed lines are approximations, a = thermal diffusivity, λ = thermal conductivity, b = radial distance from weld, 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 Eα 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

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

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

where σ_{init} is the initial residual stress, T_{init} is the initial temperature, σ_{eq} is the "equilibrium stress", and σ_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

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

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

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 computional 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.

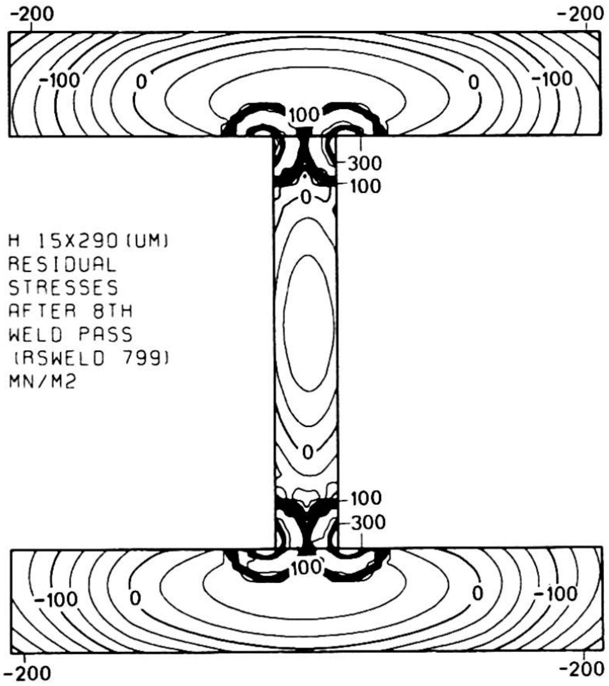


Fig. 7 Iso-stress diagram for predicted residual stresses in a heavy welded H-shape built up of universal-mill plates with as-rolled edges

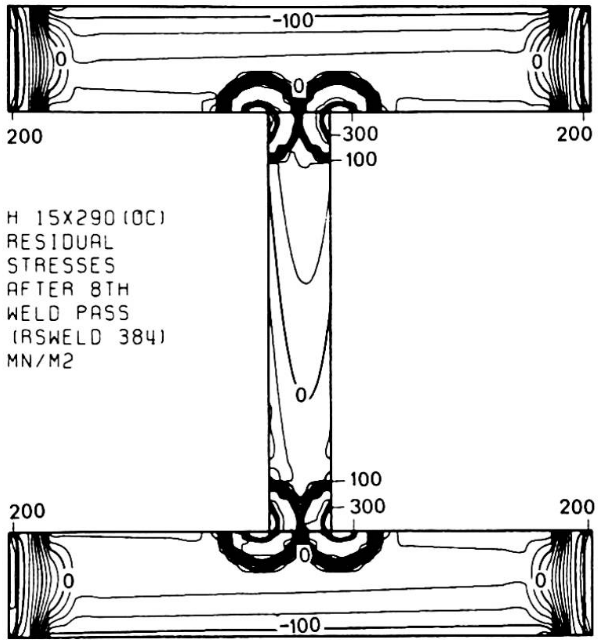


Fig. 8 Iso-stress diagram for predicted residual stresses in a heavy welded H-shape built up of oxygen-cut flange plates

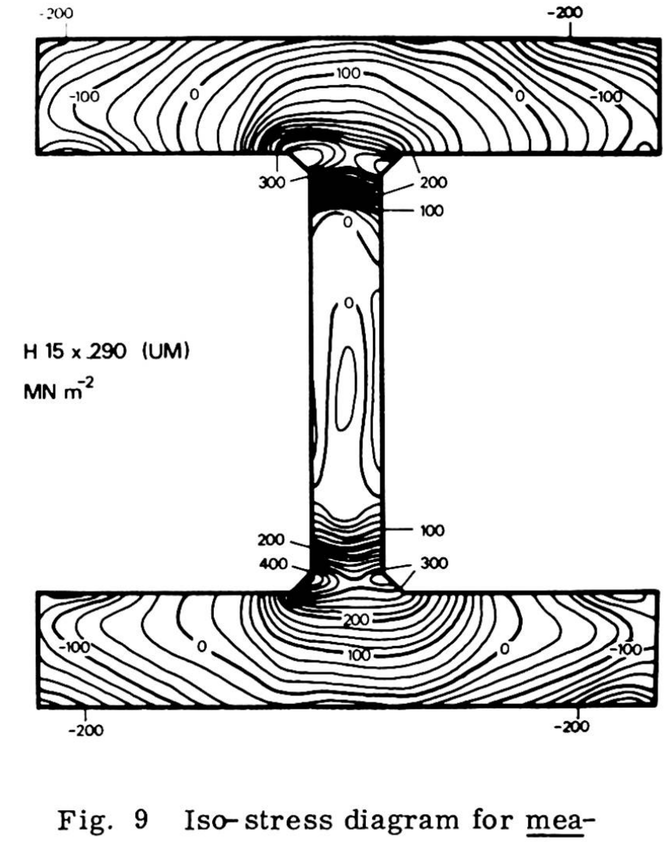


Fig. 9 Iso-stress diagram for measured residual stresses in a heavy welded H-shape built up of universal mill plates with as-rolled edges [2]

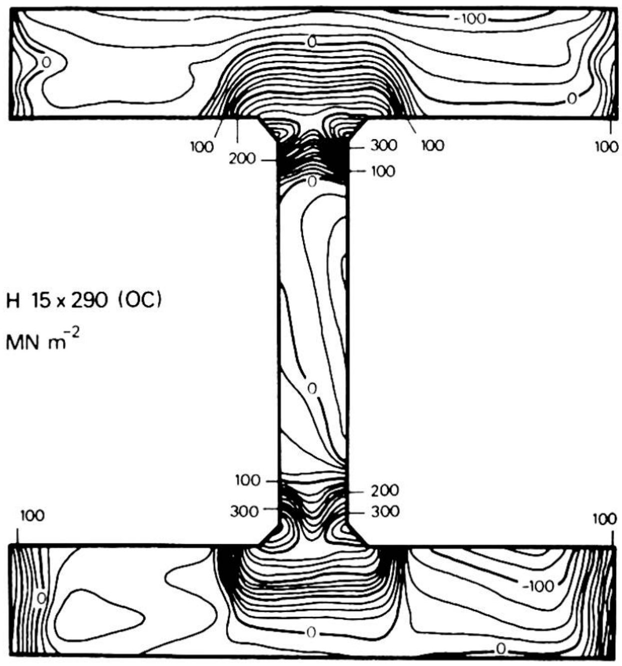


Fig. 10 Iso-stress diagram for measured residual stresses in a heavy welded H-shape built up of oxygen-cut plates [2]

The theoretical results in Figs. 7 and 8 may 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 occuring 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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