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Residual-stress Measurement by the Sectioning Method

A procedure for residual-stress measurements by the sectioning method is described. Two different hole-drilling methods were performed and the results are compared

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ABSTRACT—The measurement of residual stresses by the sectioning method has been used for decades to measure residual stresses in structural members. This method has proven itself adequate, accurate and economical if proper care is taken in the preparation of the specimen and the procedure of measurement. However, a standard procedure to carry out such measurement does not exist in the published literature. In this paper, a detailed description is presented on the procedure of testing, preparation of specimen, the required tools and measuring devices and working conditions.

For a specific comparison of results, measurements of residual stresses were performed on a specimen having a uniform residual-stress distribution along its length. On the same specimen, two different hole-drilling methods were also performed to investigate application and comparison of different methods. Other methods of residual-stress measurement which may be of general interest are discussed in brief.

Introduction

One of the major problems associated with the use of metals at present is that created by the presence of residual stresses. Many schemes and methods have been devised in the past and several papers dealing with the various techniques of residual measurement have appeared during the last few years.

In general, residual stresses tend to reduce the strength in stability, fatigue and fracture; in some situations, however, their presence may improve the strength. The various phases of the manufacturing processes causing residual stresses are too involved generally to permit more than an approximate prediction of the magnitude and distribution of them based on theoretical considerations. It is natural, therefore, to resort also to experimental means for their determination.

Residual stresses in small laboratory specimens may not reproduce the actual state of residual stresses in full-size structures. Hence, practical methods with sufficient accuracy and applicable to the measurement of residual stresses in full-scale members are of great interest. Insofar as structural-engineering applications are concerned, the destructive "method of sectioning" has shown itself to be the best method.

For the purpose of comparison, residual-stress measurements using the method of sectioning and two different hole-drilling methods were carried out on a single specimen having a uniform residual-stress distribution along its length. The selected work piece was a H14×202 shape, ASTM A36 steel, built up from flame-cut plates with fillet welds. The procedure of testing used, as well as the test results, are discussed in the following sections.

The Method of Sectioning

In the year 1888, Kalakoutsky[1] reported on a method of determining longitudinal stresses in bars by slitting longitudinal strips from the bar and measuring their change in length. This method, known as the "sectioning method", is based on the principle that internal stresses are relieved by cutting the specimen into many strips of smaller cross section. The method is best applied to members when the longitudinal stresses alone are important.

The stress distribution over a cross section can be determined with reasonable accuracy by measuring the change in length of each strip and by applying Hooke's Law. The analysis is further simplified by

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assuming that the transverse stresses are negligible, and the cutting process alone produces no appreciable strains. In practice, however, transverse stresses may exist, but the lower the transverse stresses the more accurate the results will be. Residual stresses formed due to sawing alone depend, among many other factors, on the spacing of the saw cuts, the plate thickness and the speed of sawing. For one particular set of parameters, the local stress at the saw-cut edge was observed to be of the order of 0.5 to 1.5 ksi in compression.[2]

The residual-stress distribution through the thickness of a plate can be determined from changes of strain readings after "slicing" of the sawed pieces. The steps in the sectioning and slicing process are illustrated schematically in Fig. 1.

The sectioning method has been used for decades to measure residual stresses in structural-steel members. It has proven itself adequate, accurate and economical if proper care is taken in the preparation of the specimen and the procedure of measurement.

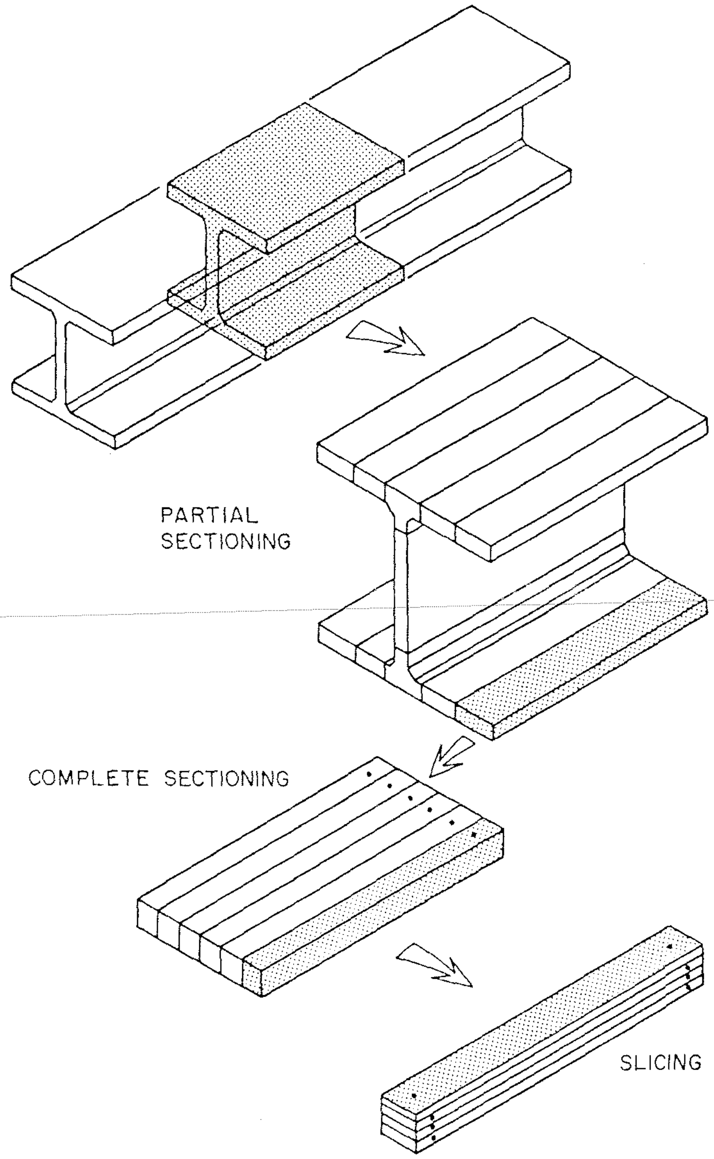

Fig. 1—Steps in the sectioning method

Preparation of Test Specimen

Location of Specimen

The location of the test piece along the length of the material is the first step to be performed. To reduce end effects, the test section must be far enough from the ends. A distance of 1.5 to 2.0 times the lateral dimension is recommended, though theoretically a ratio of 1.0 is sufficient.

Preparation of Gage Holes

It is important to prepare the gage holes with care since the accuracy in the readings depends mainly on the type of gage holes. The gage holes may be centrally located using a standard 10-in. punch in order to reduce variations in gage lengths. The hole and gage-point details for the steel specimen used in this study are shown in Fig. 2(a). The drill bit used was capable of making the hole in a single operation. For different metals, such as aluminum, different forms of gage points may have to be prepared. Gage holes at edges or corners, though not difficult to prepare, may give unreliable readings since the holes may have different alignments, and the extensometer cannot usually be made stable while taking measurements.

Sectioning Locations

The number of longitudinal strips to be cut depends on the variation of the residual stresses. Steep gradients in residual stresses, for example, would require closer spacings for longitudinal cuttings. To determine residual stresses with a lesser number of longitudinal cuts, the method of "partial sectioning" may be utilized. This method requires a prior knowledge of the pattern of residual-stress distribution. In order to make proper cutting locations, a fair estimate of the pattern rather than the magnitude of the stresses would be of importance. The location of a cut for partial sectioning is so determined that it lies near or at the transitions of residual-stress gradients. The sequence of cuttings has no influence on the final results, since unloading of the fibers will always be linearly elastic.

Measuring Technique

Mechanical extensometers have been found to be particularly suitable for the sectioning method since the device is not attached to the specimen and will not be damaged during the sectioning, and can be used to measure repeatedly. In this study, strain measurements were taken over a 10-in. gage length

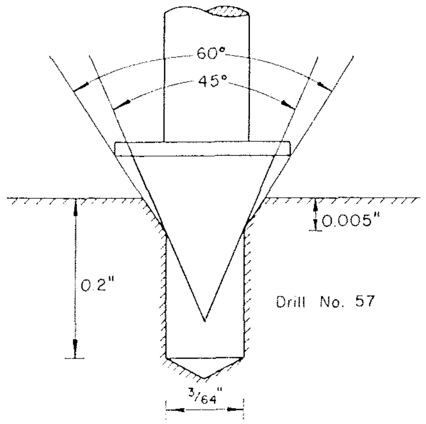

Fig. 2(a)—Detail of gage point and gage hole

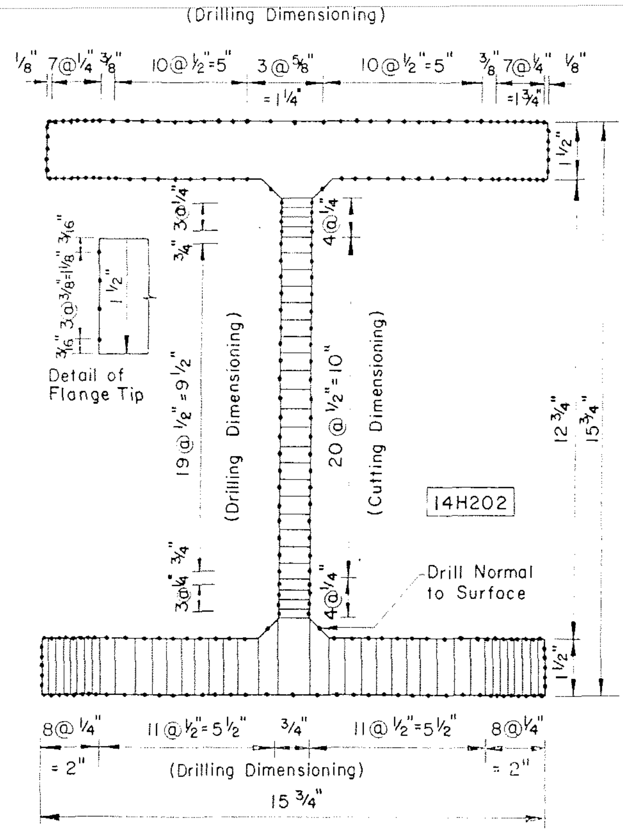

Fig. 2(b)—Gage-hole location and sectioning detail

using the Whittemore strain gage* (1/10,000-in. sensitivity). The Whittemore gage is a self-contained instrument consisting essentially of two coaxial tubes connected with a pair of elastic hinges and an accurate dial gage. Since the gage is intended for repeated measurement at a series of stations rather than for fixed mounting at one station, consideration must be given to controlling accidental longitudinal forces which might be applied by the operator.

For strain measurements, the contact points are inserted into the drilled holes which are 10 ± 0.02 in. apart. Motion between the two frame members is measured directly with a dial indicator. A handle, serving doubly as a shield against temperature change and as an aid to uniform seating of the points, is attached to the gage by means of two elastic hinges. These hinges prevent application of excessive longitudinal forces. A force of about 5 lb is recommended for properly seating the points in the drilled holes.

Seating the gage is one of the chief sources of error. It is suggested that a positioning angle be used to maintain the Whittemore gage in a perpendicular position to the surface of the specimen being measured.

Procedure of Measurement

When performing the experimental work, it is recommended that a carefully designed testing procedure be established and followed. In this study, the procedure described in Ref. 3 is followed.

First of all, attention should be given to the importance of obtaining a good set of initial readings, since these cannot be duplicated after the specimen has been cut. Some relevant items to be taken into consideration are:

—cleaning the gage holes using cleaning solution and air blast before taking any measurement;
—taking three sets of measurements for each gage length unless great variation persists, in which case making a new set of holes would be advised;
—taking intermediate readings on a temperature reference bar if the number of gage-hole readings exceeds, say, 10;
—protecting the gage holes from damage (such as by covering with tape) which may occur during moving, handling, sawing, etc.

Accuracy of Measurements

The main sources of error result from temperature changes. Temperature changes during readings may be practically eliminated by using a reference bar of the same material as the test member. To stabilize the reference-bar temperature to the environment of the test member, the reference bar is put on the test member for at least one hour ahead of time. Measurements are performed where the temperature is kept fairly uniform in order to maintain experimental accuracy. This is because the responses of the members and the reference bar may not be identical for the same variation of room temperature. The reference bar responds fairly closely to the actual variation, while a big specimen responds with less fluctua-

* U. S. Patent No. 1658125-2177605.

tion and with considerable time lag.

Strips sliced at regions of high stress gradients, observed close to flame-cut and welded edges of plates, will be curved considerably. Thus, the change in length measured by the extensometer is the change in the chord length rather than the change in arc length which represents the actual strain. Whenever large offset is observed, correction must be made to the strain computation. On a curved strip, the measurement that can be taken with ease is the offset of the arc over the gage length. Using the offset and the change in chord length as the measured quantities, the true strain may be approximated as:

$$\bar{\epsilon} = \frac{\Delta L}{L} + \frac{(\delta/L)^2}{6(\delta/L)^4 + 1} \tag{1}$$

where $\Delta L/L$ = strain measured by extensometer

δ/L = ratio of offset to gage length

It is noted that the correction component does not have significant influence on the strain calculation until δ/L exceeds 0.001. For almost all practical cases, the correction term is smaller than the experimental inaccuracy of the method of measurement.

Further experimental errors may be attributed to inaccuracies in the mechanism of the extensometer, the dial system, effects of lost motion when the motion is in the opposite direction, and whenever the axes of the drilled hole and the conical gage point do not coincide. These errors may be minimized if more readings are made for each gage length. In general, three cyclic readings are sufficient for each gage length. For three measurements, an accuracy of about 0.2 ksi with a confidence level of 99 percent could be obtained.

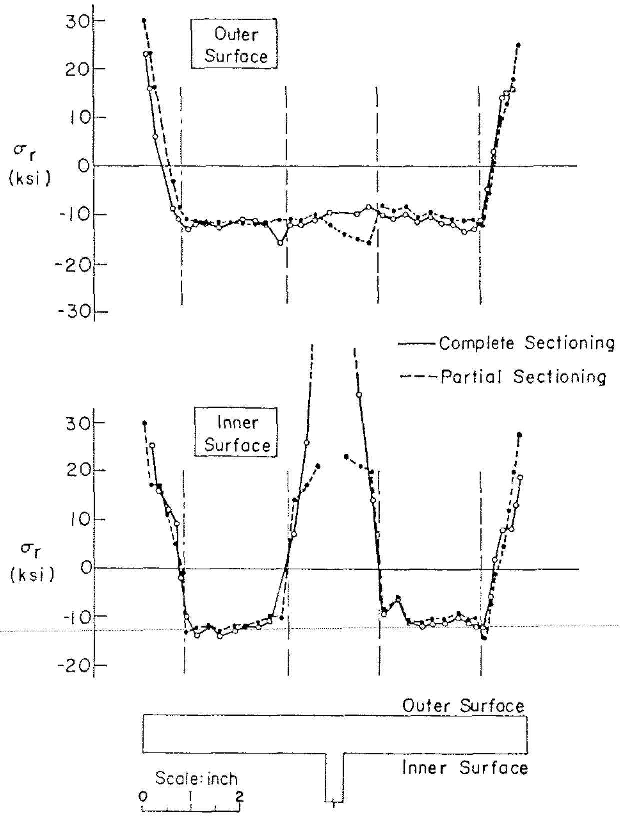

Fig. 3—Comparison of results from partial- and complete-sectioning methods

Evaluation of Data

The computation of relaxed stresses from measured strains is based on the assumption that the dimensional changes caused by the relaxation are purely linear elastic.

Since strains are read at top and bottom surfaces, evaluation of residual stresses at the respective surfaces are computed using experimental data.

Let $\bar{L}$ be the average value of the readings taken on one gage length. For each gage length,

$$\bar{L} = \frac{1}{n} \sum_{j=1}^{n} L_j \tag{2}$$

where n = number of readings for one gage length, usually three

L_j = measured value for each cycle

Similarly, for each interval of reference readings, the average values are evaluated. The strains due to temperature and the sectioning process are then evaluated.

Let L_i be the initial measured gage length and L_f the final measured gage length. Then the total strain due to relaxation and temperature change is:

$$\epsilon_0 = \left[\frac{\bar{L}_i - \bar{L}_f}{\bar{L}} \right]_{\text{Specimen}} \tag{3}$$

The strain due to temperature change is:

$$\epsilon_T = \left[\frac{\bar{L}_i - \bar{L}_f}{\bar{L}} \right]_{\text{Ref. bar}} \tag{4}$$

Thus, the net strain due to relaxation of residual strain will be

$$\epsilon_r = \epsilon_0 - \epsilon_T \tag{5}$$

Or, if a large offset due to curvature of sectioned strip is observed,

$$\epsilon_r = \bar{\epsilon} - \epsilon_T \tag{6}$$

where $\bar{\epsilon}$ is evaluated from eq (1).

Using Hooke's Law, the residual stress at the measured surface is:

$$\sigma_r = -E\epsilon_r \tag{7}$$

By virtue of the linear strain distribution postulated in the beam theory, the average axial stress σ in terms of top and bottom measured strains, ϵ_T and ϵ_b, is:

$$\sigma = -E\,\frac{\epsilon_T + \epsilon_b}{2} \qquad (8)$$

where E is Young's modulus.

The method of sectioning requires a very large number of measurements. Use of the digital computer will greatly reduce the amount of numerical work involved. Computer programs for such evaluations have been prepared and have been found to be versatile.[4] The programs are capable of computing and plotting the resulting residual stresses. In case of two-dimensional residual-stress distribution, plotting of the isostress diagram is also possible.

The possibility of automatic recording of the gage readings into a tape or cards by means of linear transducers has been considered. When completed, recording, computation and plotting using manual means will no longer be required.

Experimental Results

The dimensioning for gage hole and cutting locations used on the H14×202 test piece are shown in Fig. 2(b). The total number of cuts for partial sectioning is only 12 compared to 109 required for the complete sectioning. Figure 3 shows the comparison of the corresponding residual-stress distributions. It is observed that the results obtained from partial-sectioning readings are practically identical to those obtained after complete sectioning.

The residual-stress distribution for the complete section is shown in Fig. 4. Comparison of residual-stress measurement at the two ends is shown in Fig. 5. Using the measured residual stresses, the equilibrium condition for the whole section is checked. Theoretically, since no external forces exist, equilibrium requires that the integration of the stresses over the whole section must be zero. For this particular case, a difference of 0.7 ksi in compression is computed. This small difference may be attributed to the effect of saw cutting and accumulated experimental errors.

Applications to Heavy Shapes

Previous experimental research on residual stresses was related to small and medium-size shapes. As heavy shapes are currently being used rather extensively, it becomes necessary to determine the magnitude and distribution of residual stresses, not only along the cross section, but also through the thickness.

The variation of residual stresses through the thickness may be measured by employing the "slicing" technique. After the first set of saw cuts are performed (complete sectioning), additional gage points must be laid along the sides of the elements. New readings are then taken, followed by sawing the elements into strips across the thickness ("slicing"). In Fig. 6, this process is illustrated schematically. For a related research program[2], residual stresses were measured on a heavy welded shape H23×681 using the sectioning method. The results are shown in Fig. 7 where the residual-stress distribution is represented in the form of an isostress diagram, that is, contour lines for constant stress.

Measurements by the Hole-drilling Method

The hole-drilling method is based on the fact that drilling a hole in a stress field disturbs the equilibrium of the stresses, thus resulting in measurable deformations on the surface of the part, adjacent to the hole. This method has the advantage of removing a minimum amount of material which makes it the least destructive of the mechanical methods. Unlike other mechanical methods, residual stresses can be measured at what is essentially a point, a special application of which is the measurement of transverse residual stresses. The method, however, has a limitation of depth and is used to measure stresses very near to the surface.

The hole-drilling method, probably first proposed and applied by Mathar,[5] measures displacements between two points across the drilled hole using mechanical and optical extensometers. Replacing the mechanical extensometer with electrical-resistance wire strain gages, Soete and Vancrombrugge[6] eliminated the difficulties of measurements and improved the precision. Further work on measuring nonuniform residual stresses by the hole-drilling method was performed by Kelsey.[7] The method is empirical and depends on experimental calibration. Rendler and Vigness[8] reported on measuring residual stresses

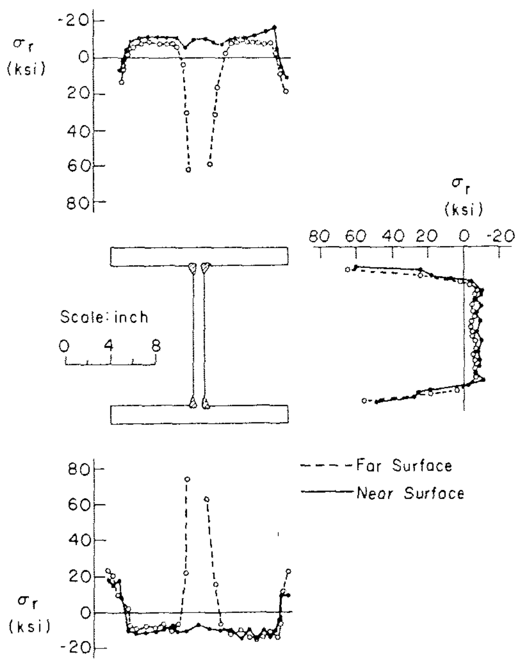

Fig. 4—Residual-stress distribution in H14X202 section at location A

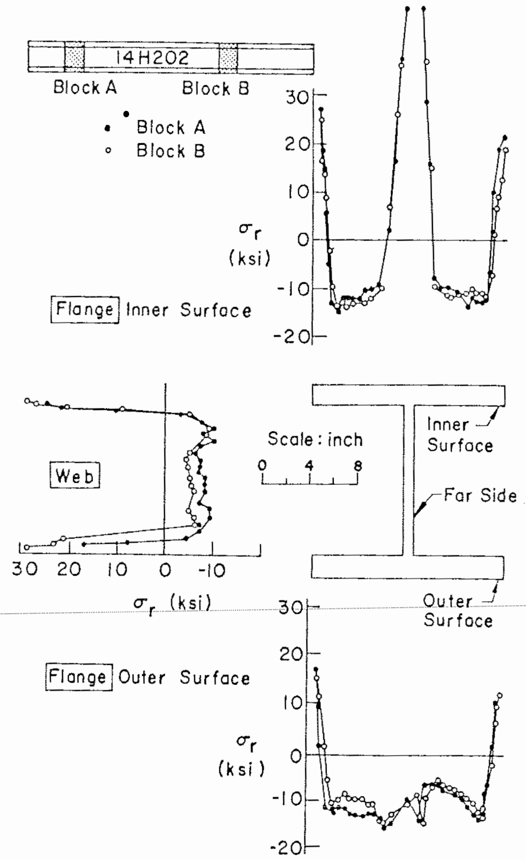

Fig. 5—Comparison of residual-stress measurement at two ends, A and B

using dimensions as small as 1/16-in. hole diameter and 1/16-in. strain gages. Recently, Bert *et al.*[9] reported on the applicability of the hole-drilling method to measure residual stresses in orthotropic materials.

In this study, two different hole-drilling methods were performed, namely, Mathar's[5] and Soete's[6] hole-drilling methods, to measure the residual stresses on the same specimen as used for the sectioning method. In Ref. 3, a detailed description is available on the measuring procedure of these methods.

Figure 8 shows the layout of the holes on one flange of the shape H14×202 where three holes were drilled to measure residual stresses by Soete's method. On the same flange, 14 holes were also drilled to measure residual stresses by Mathar's method.

The holes used for Mathar's method were 1/2-in. diameter drilled to a depth equal to the diameter. A Huggenburger extensometer with 20-mm gage length and nominal strain sensitivity of 0.001 mm (0.000030 in.) was used for the strain measurement. The residual stresses were determined by utilizing a calibration curve which was experimentally determined and verified theoretically.

For Soete's method, 1/8-in.-diam holes were drilled where the strains were measured using foil-strain-gage rosette, type EA-09-125E having a gage length of 0.125 in.

The results obtained for these two hole-drilling

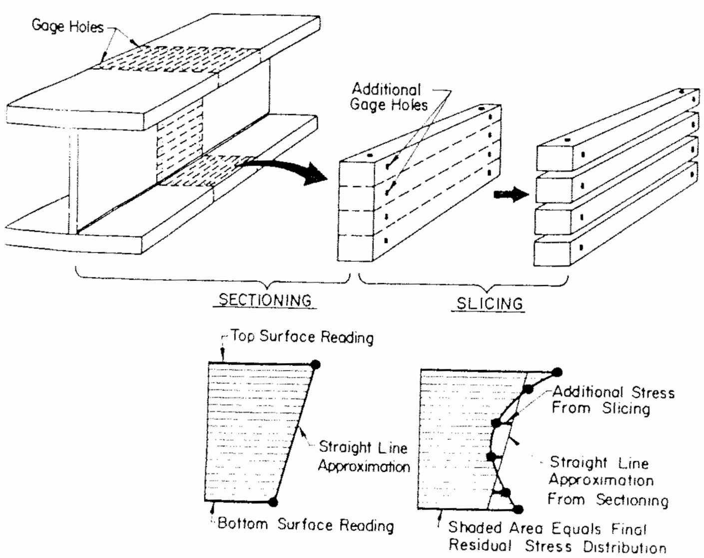

Fig. 6—Principle of the sectioning method for residual-stress measurements

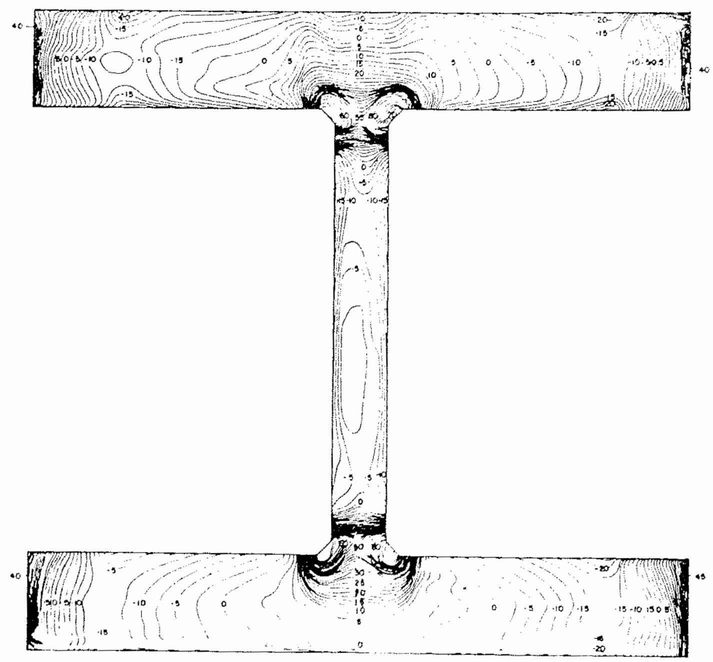

Fig. 7—Two-dimensional variation of residual stress in a welded shape H23X681. Flame-cut plates, A36 steel, ½-in. fillet welds

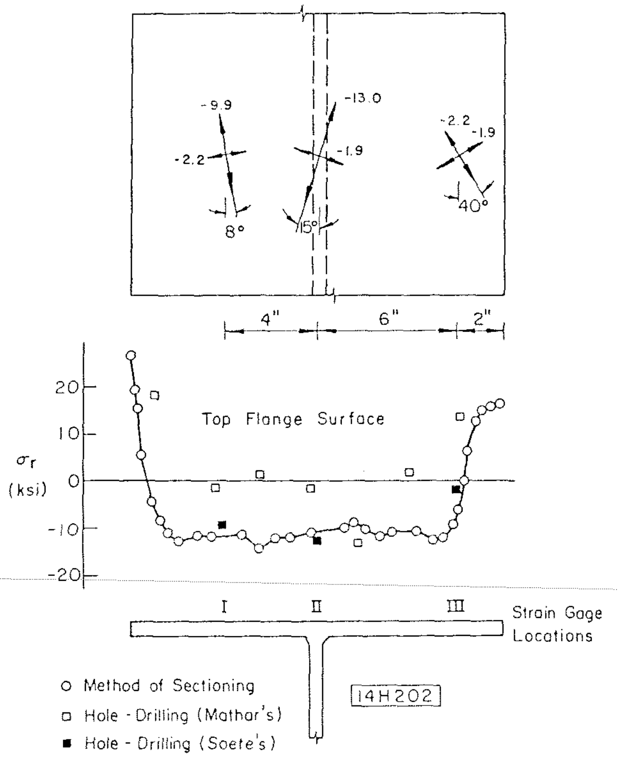

Fig. 8—Residual-stress measurement using the hole-drilling method (Soete's method) and comparison with the sectioning method

methods are compared with those obtained by the sectioning method as shown in Fig. 8. It is noted that the test results from Mathar's method do not compare well with those obtained for the sectioning method. This may be due to the gage points and the measuring device used for the test. To have meaningful results, it is necessary to prepare gage points which can stand severe test conditions. The results from Soete's method, however, show a close agreement to those obtained from the method of sectioning.

Other Methods—A Brief Survey

Nondestructive Methods

THE X-RAY METHOD—The fundamental theory of stress measurement by means of X rays is based on the fact that the interplanar spacing of the atomic planes within a specimen is changed when subjected to stress.

The basic expression when using the X-ray method can be derived using principles of theory of elasticity.[10]

$$\sigma_\phi = \frac{E}{1+\mu} \cdot \frac{1}{d_o} \cdot \frac{\partial d_{\phi,\psi}}{\partial \sin^2 \psi} \tag{9}$$

where ϕ = direction of measurement on the specimen surface
ψ = angle between diffraction planes and surface
E = Young's modulus
μ = Poisson's ratio
d_o = interplanar spacing in unstressed condition
$d_{\phi,\psi}$ = interplanar spacing in direction determined by ϕ and ψ.

X-ray strain measurements have frequently been shown to be useful in very different fields of applied and basic research. Up till now, however, the equipment necessary for accurate measurements has limited its use to small specimens. Furthermore, in some materials, such as with plastically deformed steel, interpretation of the results may be difficult.

ULTRASONICS METHOD—Of the several ultrasonics techniques studied, the one based on double refraction of shear waves has received the most attention for measuring residual stresses. The phenomenon of double refraction of shear wave is associated with the separation of the shear wave into two components which are transmitted through the medium on planes at right angles to each other. This birefringence of the wave will occur only if the medium is anisotropic and if the direction of the particle motion does not coincide with the principal axis. The method, therefore, may be utilized to measure residual stresses since an isotropic body when stressed becomes anisotropic when subjected to shear wave.

To date, the technique has been used only in the laboratory on specimens whose microstructures are well documented.[11] Furthermore, the technique is capable of providing information only on the difference between the principal residual stresses, and not the absolute magnitude of these stresses.

MAGNETIC METHOD—This method makes use of the fact that the magnetic properties of steel depend on the state of stress. Magnetic stress measurements, determined from inductance measurements at different frequencies, have been reported.[12] The method is limited to ferromagnetic materials, nickel and steel.

THE BRITTLE-LACQUER METHOD—The method employs the use of Stresscoat as an indicator of residual stresses. The brittle-lacquer coating forms characteristic crack patterns at right angles to the principal tension strain when the test part is loaded. The lacquer will crack first at regions where the residual and applied stresses add up to the yield strength of the test material.

INDENTATION METHODS—Several means of using hardness measurements for the determination of residual stress have been proposed, based on the principle that the hardness of metal parts depends on stresses acting on those parts. Investigations conducted on steel indicated that the relationship between stress and change of hardness is practically linear, as long as those stresses are within the linear range. Furthermore, the same tests indicated that the change of hardness is greater for tensile than compressive stresses.

Recent work[13] using the same principle utilizes the Knoop indentor to measure biaxial residual stresses. The change in hardness ΔH is defined as

$$\Delta H = \frac{H_s - H_o}{H_o} \tag{10}$$

where H_o = hardness of unstressed state

H_s = hardness of stressed state.

The biaxial residual stresses are determined from the equations

$$\sigma_1 = \frac{E}{2}\left[A(\Delta H_1 + \Delta H_2) + B(\Delta H_1 - \Delta H_2)\right] \tag{11}$$

$$\sigma_2 = \frac{E}{2}\left[A(\Delta H_1 + \Delta H_2) - B(\Delta H_1 - \Delta H_2)\right] \tag{12}$$

where A and B are empirically derived constants and the subscripts 1 and 2 indicate the principal-stress directions.

The hardness-test method is nondestructive and has a special application in the range of nonlinear material behavior. It is, however, limited to materials for which the initial hardness is known and its accuracy is dependent on numerous factors.

Semidestructive Methods

GUNNERT'S METHOD—In Gunnert's method, stress relieving is achieved by trepanning a groove round the gaging area by means of a core drilling.[14] The core drilling is guided by drilling a small hole in the center of the measuring surface and by using a spring guide.

The method has the advantage of evaluating local residual stresses close to the yield point such as residual stresses due to welding.

THE TREPANNING METHOD—The trepanning method accomplishes relaxation by removing a plug of metal containing gages by drilling a series of overlapping holes. If the directions of the principal stresses are not known, the strain gages are arranged in rosette form. Residual stresses are calculated based on the initial and final strain-gage readings and using principles of strength of materials. The method can be reliable when the stresses are fairly uniform over the area to be measured.

SCHWAIGHOFER'S METHOD—Schwaighofer's method[15] requires that two grooves be cut around the gage area under consideration to achieve the desired stress release. Reproducibility of test conditions are found to be high when high-speed tools are used. For high-strength metals, chemical milling may be used.

The method is applicable to measure variation of stresses through the depth based on surface readings recorded during the progress of grooving.

THE BRITTLE-LACQUER METHOD—The method of using brittle lacquer in studying residual stresses is by relieving stresses. The relaxation of residual stresses about the hole brings out a crack pattern characteristic of the type of stresses existing on the surface. The main features of this method are its simplicity and its freedom of material limitations. This method, however, should be considered qualitative rather than quantitative.

Destructive Methods

STÄBLEIN'S METHOD—Stäblein's method[16] is based on the fact that removal of material on one side of a strip with residual stresses results in bending of the strip. By measuring the curvature of deflections at different stages the residual-stress distribution can be determined.

Considerable amount of work has been performed in the past using the same principle. For plate-like specimen, residual stresses are measured by measuring the curvature while thin layers are removed from the surface after grinding or milling.[17] The most recent contribution made to this method is to develop it into a simpler and computerized technique.[18] The method has a particular application for the determination of residual-stress distributions varying through the thickness.

SACHS' METHOD—For objects having rotational symmetry both in geometry and in stress distribution, such as in welded tubes or plates, the Sachs' method is suited to measure the residual stresses. In this method residual stresses are determined by removing concentric layers from a cylindrical rod or tube and measuring the resulting elongation or contraction. With sufficient number of steps, the longitudinal stress distribution is determined.

The method is, however, an approximation since only longitudinal stresses are considered. The presence of transverse and radial stresses that would be present in the general case are ignored. These limitations were recognized by Mesnager[19] wherein he proposed the removal of the material from the center of the cylindrical rod or tube and measuring the longitudinal and circumferential strains in the remaining portion. Sachs[20] greatly simplified the calculation and, today, the method is popularly known by his name.

Sachs' equations for the determination of the longitudinal, tangential and radial residual stresses in an axially symmetric cylinder are given by,

$$\sigma_L = \frac{E}{1-\mu^2}\left[(A_o - A)\frac{d\lambda}{dA} - \lambda\right] \tag{13}$$

$$\sigma_t = \frac{E}{1-\mu^2}\left[(A_o - A)\frac{d\theta}{dA} - \frac{(A_o - A)\theta}{2A}\right] \tag{14}$$

$$\sigma_r = \frac{E}{1-\mu^2}\left[\frac{(A_o - A)\theta}{2A}\right] \tag{15}$$

where E = Young's modulus

μ = Poisson's ratio

A_o = original cross section of cylinder

A = bored area
$\lambda = \epsilon_e + \mu\epsilon_t$
$\theta = \epsilon_t + \mu\epsilon_e$
ϵ_e, ϵ_t = strains in longitudinal and circumferential directions.

For specimens where machining is applied from the outside surface, the method can be applied by making appropriate modifications of the formulas.

Conclusions

The following recommendations and conclusions may be made for the measurement of residual stresses:

1. The method of sectioning is adequate, accurate and economical for residual-stress measurement in structural members when the longitudinal stresses alone are important. It is felt that this method is as accurate and more foolproof than any of the other measuring techniques.
2. The method of "partial sectioning" can be utilized to reduce substantially the total number of required longitudinal sectionings. Its use, however, requires a prior knowledge of the approximate variation in residual-stress distribution.
3. The best locations for partial sectioning are at transitions of residual-stress gradients. When using properly selected cutting locations, the results from partial sectioning usually are not significantly different from those obtained after complete sectioning.
4. To obtain satisfactory results with the sectioning method, it is important to perform a careful preparation of the test piece such as proper location of the test section, gage-hole locations and cutting positions and layout. Preparation of gage holes must be performed with care since unreliable readings can result if the holes are not prepared in a proper manner.
5. Temperature changes appear to be the major cause of errors introduced during residual-stress measurement. Measurement should be avoided whenever a frequent fluctuation in temperature is likely to occur.
6. The test results when using Mathar's method were found to be inaccurate due to the gage points and the measuring device used for the test. To have meaningful results, it is necessary to prepare gage points which can stand severe test conditions. Also, a dependable measuring device having a small gage length should be used.
7. The test results when using Soete's method were in very close correlation with those of the sectioning method. In addition, transverse residual stresses were measured.
8. The hole-drilling method has some advantageous features over the sectioning method. It is semidestructive, can have wider application, and the principal stresses can be measured at what is essentially a point. To use the method effectively, more work should be done on the drilling techniques, on establishing calibration curves, and on the interpretation of test results.

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