1971

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Recommended Citation

Tebedge, N.; Alpsten, G. A.; and Tall, L., "Measurement of residual stresses-a comparative study of methods, August 1971 (72.-10)" (1971). *Fritz Laboratory Reports.* Paper 341.
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/341

First Day, Wednesday, 5th April

JOINT BRITISH COMMITTEE FOR STRESS ANALYSIS

CONFERENCE

on

"The recording and interpretation of engineering measurements"

5th, 6th and 7th April, 1972

at the Institute of Marine Engineers,
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72-10

MEASUREMENT OF RESIDUAL STRESSES — A COMPARATIVE STUDY OF METHODS

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In this paper some of the different techniques of residual stress measurements are investigated. Special attention is given to those methods applicable mainly to structural members.

Measurements of residual stresses are performed using the method of sectioning, a destructive method, and two different hole drilling methods, both semi-destructive. The methods are compared on a specimen having a uniform residual stress along its length.

The procedure of testing, preparation of specimen, the required tools and measuring devices, working conditions and similar relevant information are described.

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 since Kalakoutsky[1] performed such measurements in 1888. Several papers dealing with the various methods of residual stress measurement have appeared during the last few years. The variety of methods proposed shows that residual stress measurement still arouses considerable interest in technical circles.

In general, residual stresses tend to reduce the strength in fatigue, fracture, or stability; 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, as well as in smaller structural elements, are of great interest. Yet such methods are rather delicate, requiring much time, patience and expense.

The available methods of exploration fall into two categories; mechanical methods and physical methods.

The basic concept adopted by the mechanical methods is to release the residual stresses by appropriate removal of material. Since residual stresses form an internally balanced system of stress, removal of stressed material by cutting, drilling, or grooving will cause partial relaxation of stress. Thus, the mechanical methods do not measure the actual strain produced by the existing residual stress—what they do measure is the relaxed strain. Measurement of strain is basically the only manner in which stress can be determined, since stress is not a fundamental physical quantity like strain, but only a derived quantity.

The mechanical methods are either destructive or semi-destructive in nature. The destructive methods require a total destruction of the material before residual stresses are measured, whereas the semi-destructive methods produce only local damage which generally can be repaired, for example, by welding.

The physical methods are used to measure the existing residual stresses directly without requiring any destruction of the test specimen. Among these methods, the X-ray diffraction technique and the ultrasonic methods are the most important.

In general, the mechanical methods measure only macrostresses, the X-ray methods may superimpose the microstress on to the macrostress, and the ultrasonic methods provide information only on the difference between the principal residual stresses, and not on the absolute magnitude of these stresses. This leads to a situation seeking an answer to the familiar question, "what is actually being measured"?

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 14H202 shape¶, ASTM A36 steel builtup 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

The "sectioning method"[2] 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 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

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¶ The designation H refers to a wide flange section built up by welding component plates, as opposed to the designation W for rolled wide flange sections.

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 40 to 120 N/mm^2 in compression.(3) However, this localized surface stress will affect the measurements at the gauge points by less than 10 N/mm^2.(3,4)

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

Preparation of Test Specimen

The location of the test piece along the length of the material is the first step to be taken. 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(5).

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"(6,7) 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 fibres will always be linearly elastic.

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

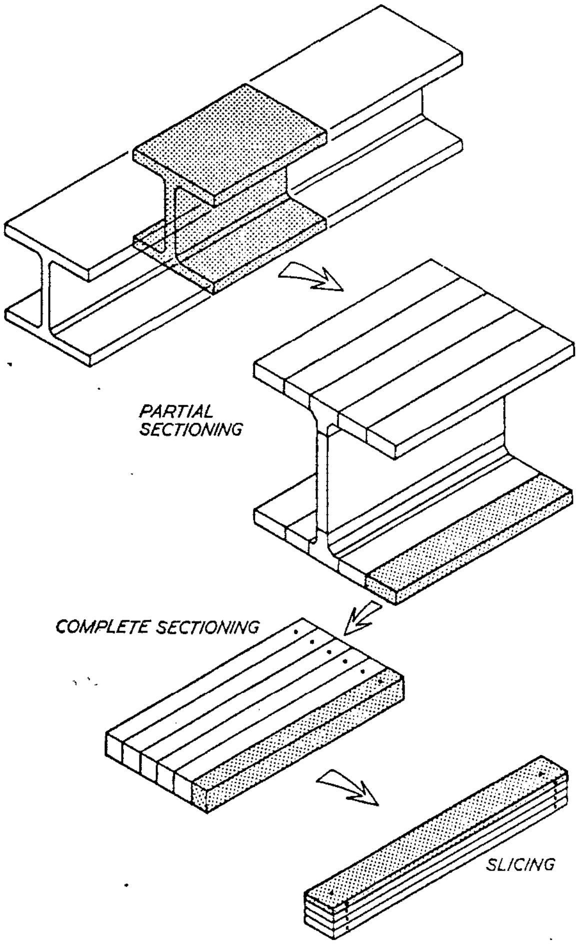

FIG. 1—*Steps in the sectioning method*

It is important to prepare the gauge holes with care since the accuracy in the readings depends mainly on the type of gauge holes. The hole and gauge point details for the steel specimen used in this study are shown in Fig. 2. The drill bit used was capable of making the hole in a single operation. For different metals, such as aluminium, different forms of gauge points may have to be prepared.

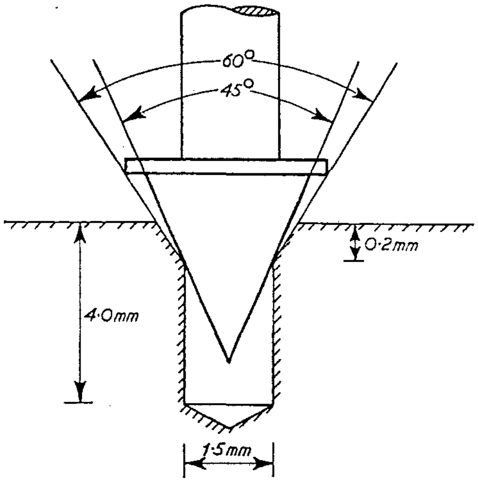

FIG. 2—*Detail of gauge point and gauge hole for the sectioning method*

Measuring Technique

For the sectioning method mechanical extensometers have been found to be particularly suitable since the device will not be damaged during the sectioning and also the same device can be used to measure repeatedly. In this study strain measurements were taken over a 254 mm (10 in) gauge length using the Whittemore Strain Gauge* (0·0025 mm sensitivity). The Whittemore gauge is a self-contained instrument consisting essentially of two coaxial tubes connected with a pair of elastic hinges and an accurate dial gauge.

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 reference 8 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:

a) cleaning the gauge holes using cleaning solution and air blast before taking any measurement,
b) taking three sets of measurements for each gauge length unless great variation persists in which case making a new set of holes would be advised,
c) taking intermediate readings on a temperature reference bar if the number of gauge hole readings, exceeds, say, 10,
d) protecting the gauge 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, and inaccurate seating of the gauge holes. Temperature changes during readings may practically be 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

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*U.S. Patent No. 1638425-2177605.

to the actual variation, while a big specimen responds with less fluctuation and 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 gauge length. Using the offset and the change in chord length as the measured quantities, the true strain may be approximated as:

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

where $\Delta L/L$ = strain measured by extensometer
δ/L = ratio of offset to gauge 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 gauge point do not coincide. These errors may be minimized if more readings are made for each gauge length. In general, three cyclic readings are sufficient for each gauge length. For three measurements, an accuracy of about 7 N/mm² with a confidence level of 99 per cent could be obtained.

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 gauge length. For each gauge length,

$$\bar{L} = \frac{1}{n} \sum_{j=1}^{n} L_j \qquad (2)$$

where n = number of readings for one gauge 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 gauge length and L_f the final measured gauge length. Then the total strain due to relaxation and temperature change is:

$$\varepsilon_0 = \left[\frac{L_i - L_f}{\bar{L}}\right]_{\text{Specimen}} \qquad (3)$$

The strain due to temperature change is:

$$\varepsilon_T = \left[\frac{L_i - L_f}{\bar{L}}\right]_{\text{Ref. bar}} \qquad (4)$$

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

$$\varepsilon_r = \varepsilon_0 - \varepsilon_T \qquad (5)$$

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

$$\varepsilon_r = \bar{\varepsilon} - \varepsilon_T \qquad (6)$$

where $\bar{\varepsilon}$ is evaluated from equation (1).

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

$$\sigma_r = -E\varepsilon_r \qquad (7)$$

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:

$$\sigma = -E\frac{\varepsilon_T + \varepsilon_b}{2} \qquad (8)$$

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(9). 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 gauge 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 gauge hole and cutting locations used on the 14H202 test piece are shown in Fig. 3. The total number of cuts for partial sectioning is only 12 compared to 109 required for the complete sectioning. Fig. 4 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.

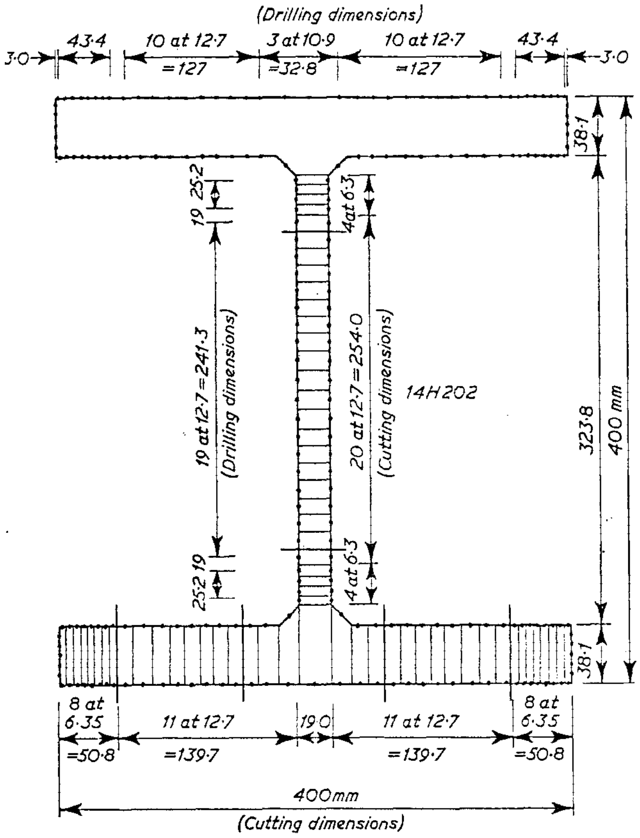


FIG. 3—*Gauge hole location and sectioning detail (dimensions originally in inches)*

The residual stress distribution for the complete section 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 the integration of the stresses over the whole section must be zero. For this particular case a difference of 5 N/mm² in compression is com-

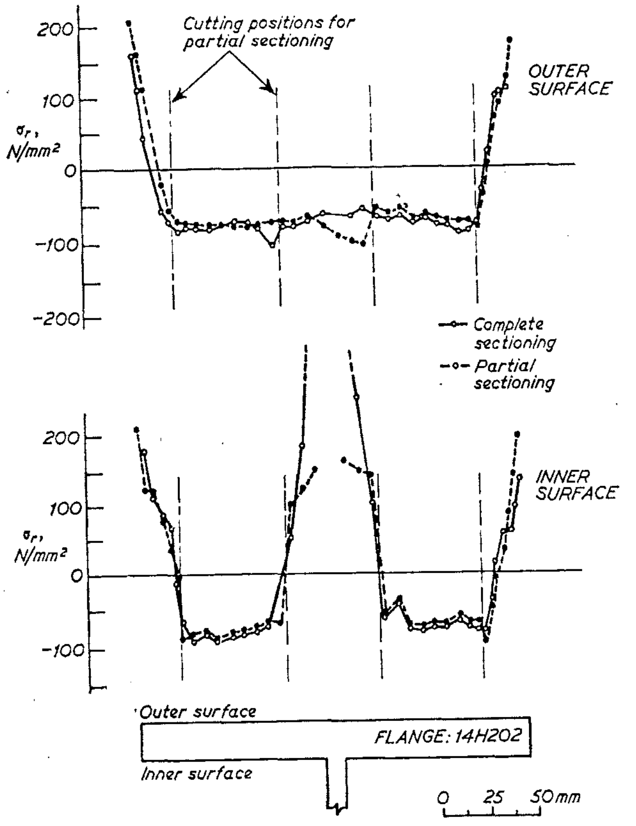


FIG. 4—*Comparison of results from partial and complete sectioning method*

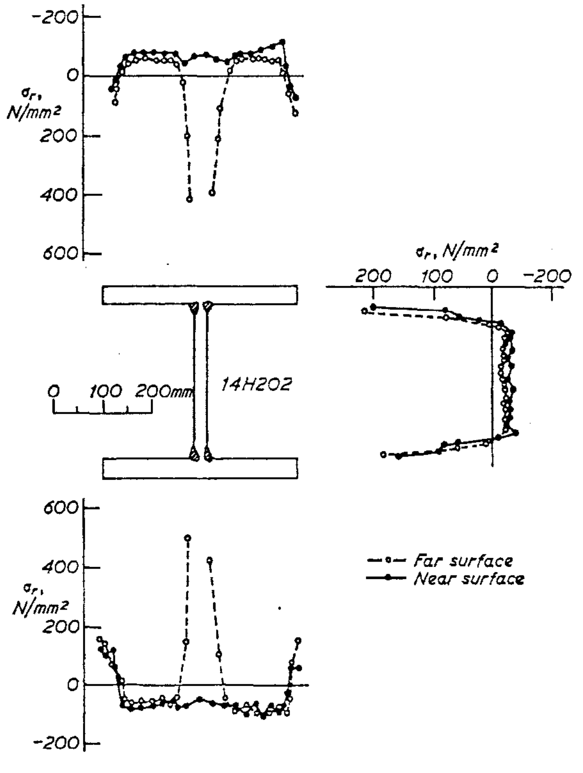


FIG. 5—*Residual stress distribution in 14H202 section (complete sectioning)*

puted. This small difference may be attributed to the effect of saw cutting and accumulated experimental errors.

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,(10) measures displacements between two points across the drilled hole using mechanical and optical extensometers. Replacing the mechanical extensometer with electrical resistance wire strain gauges, Soete and Vancrombrugge(11) eliminated the difficulties of measurements and improved the precision. Further work on measuring non-uniform residual stresses by the hole drilling method was performed by Kelsey(12). The method is empirical and depends on experimental calibration. Rendler and Vigness(13) reported on measuring residual stresses using dimensions as small as 1·5 mm hole diameter and 1·5 mm strain gauges. Recently, Bert *et al.*(14) reported on the applicability of the hole drilling method to measure residual stresses in orthotropic materials.

Mathar's Method

In order to explain the principle of the method, consider a specimen subjected to a uniaxial stress which is uniform through the thickness. If a circular hole is drilled between two gauge points, the hole will become elliptical and the gauge length will be changed. It is possible to establish a relationship between the change of the gauge length and the internal stress either by experimental means or by theoretical calculation.

Theoretical methods on which calibration could be based was first reported by Kirsch(15) who related the deformation of a hole in a member of infinite width in terms of the applied uniaxial stress. Willheim and Leon(16) extended it to members of finite width. Mesmer(17) generalized the formula for the case of plane stress distribution, under the assumption that the direction of the principal stresses were known. A further generalization was given by Campus(18), extending the formulae to the case in which the principal axes directions are unknown. Extensive work has been done in recent years to establish calibration for the case of uniform(11,19,20,21,22) and non-uniform(12,13,14,23) residual stress distribution through the thickness of the plate. In this study suggestion is made to apply the finite element technique whenever theoretical calibrations are required. The finite element method is a versatile and powderful tool, specially for problems that would be too complicated to achieve a closed-form solution. The method can be extended to materials with non-linear behaviour without introducing much complication. An application of the method is demonstrated at a later section where a problem pertinent to this study is used.

Experimental calibration is performed by subjecting a test piece to a desired level of stress and drilling in it a hole similar to that to be used for the actual residual stress measurement. Simultaneously, the changes in gauge length are measured as the drilling process is progressing. From these must be subtracted the corresponding increase in gauge length which would have occurred if the hole did not exist.

Calibration Test

In this study experimental calibration was conducted for a uniaxial stress state. The test specimen was designed to satisfy certain requirements for the available equipment. For comparison, a theoretical calibration was also made. In designing the calibration test specimen, it is necessary to consider and satisfy the following points:

i) The applied stress must be uniform throughout the cross-sectional area.

ii) The drilling process should produce a measurable strain.
iii) The hole must be small compared with the specimen dimensions in order to eliminate any boundary effects.
iv) The applied load must not produce plastic flow near the hole due to high stress concentration.

The calibration specimen used was 100 × 38 mm in cross section and 1·5 m in length. In order to obtain uniform stress (Requirement (a)) the specimen is aligned by monitoring the strain gauges mounted on all four sides of the specimen. Residual stresses that may have existed in the specimen are practically eliminated by heat-treatment such that no metallurgical changes are introduced.

In general, strain relaxations due to hole drilling are very small but this problem may be resolved (Requirement (b)) by increasing the applied load and also by increasing the hole size. A Huggenberger extensometer with 20 mm gauge length and sensitivity of 0·001 mm is used for strain measurement over a 12·7 mm, ($\frac{1}{2}$-in) hole.

Requirement (c) may be satisfied if a minimum width of ten times(11) the diameter of the hole is used. Also, calculations based on formulae given by Timoshenko(24) show that the longitudinal and transverse stresses four diameters from the hole axis in the longitudinal direction deviate less than 4 per cent and 1 per cent, respectively, from the longitudinal stress remote from the hole. To allow no plastic flow in the region of the hole (Requirement (d)) the internal stress must not be greater than 40 per cent(24) of the yield point.

Gauge Hole Preparation

To obtain reliable results, it is important to prepare the gauge points with care. Steel balls of 1·5 mm diameter are used as gauge points. The gauge points may be prepared in two different ways; punched gauge points using a special punch, and bonded gauge points using industrial adhesive.

In both cases care must be taken to make sure that the holes are not imbedded too deeply, to prevent the measuring gauge from seating properly; this is done by sinking the ball's "equator" slightly below the surface. The punched gauges seem to be more preferable since they are easier to install, and can be fixed strongly into position.

Drilling Technique

The location and alignment of the hole was controlled by the milling fixture. The hole was drilled using a 12·7 mm ($\frac{1}{2}$-in) high speed centre cutting end-mill. In order to avoid possible blemishes and tears, the end mills were kept sharp and were checked at appropriate intervals.

At the preliminary stage of this study a boring unit which included the end-mill, a speed reducing device and power drill was used. In Fig. 6 all the equipment used and the calibration specimen are shown. At a later stage a portable magnetic base press was used giving great ease and better efficiency. To minimize possible residual stress formation due to the drilling process, a cutting speed of less than 200 rev/min is considered sufficient.

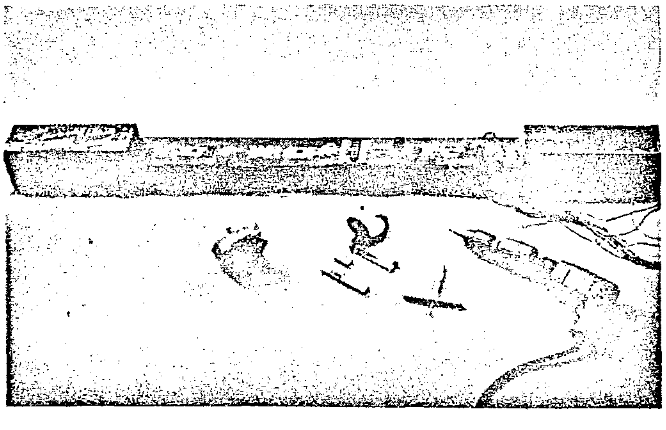


FIG. 6—*The calibration test specimen and tools*

Test Results

As drilling progressed, the relationship between the change in gauge length and the corresponding hole depth was determined by taking measurements at increments of 1 mm in the drilled depth. A plot of relaxed strain as a function of non-dimensional hole depth is shown in Fig. 7. The curve indicates that the surface strains increase rapidly up to a depth/diameter ratio of about 0·8 and do not change appreciably for greater hole depths. Thus, measurements based on a hole depth of one diameter makes use of the maximum released strain and is used as a standard depth.

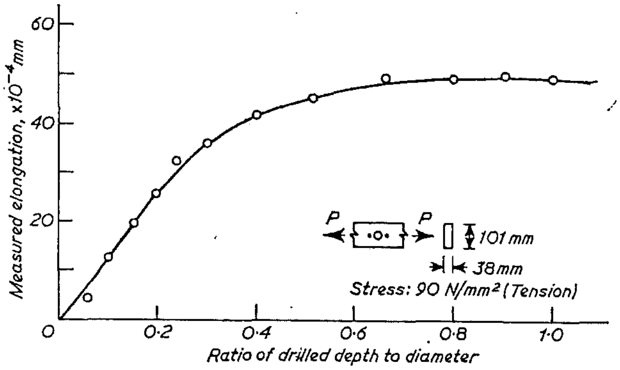
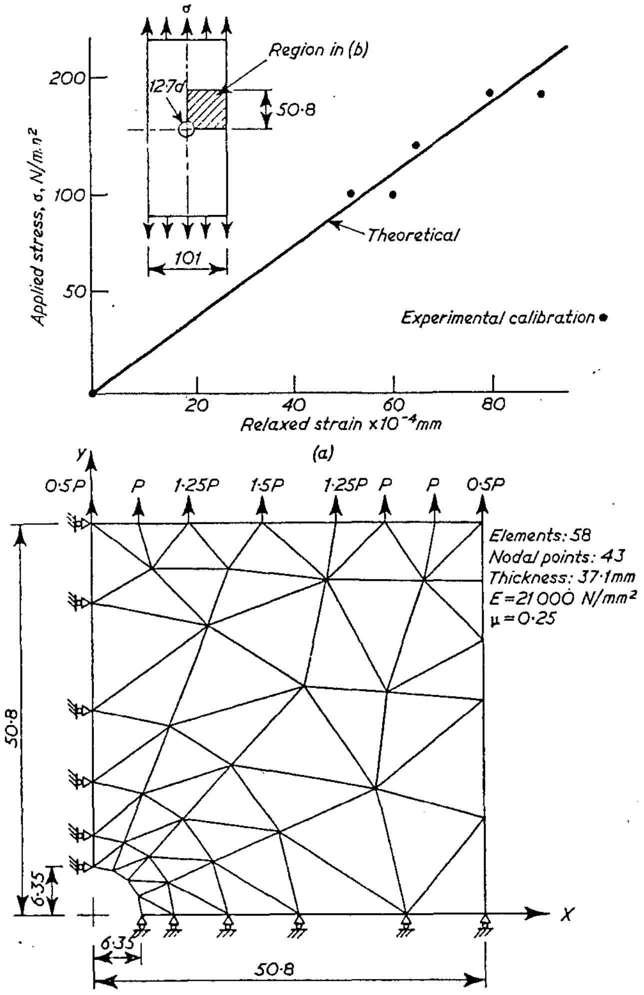


FIG. 7—*Strain relaxation as a function of non-dimensionalized hole depth for Mathar's method of hole drilling*



(a)

(b) FINITE ELEMENT MODEL

FIG. 8—*Comparison of experimental and theoretical calibration of Mathar's method*

Calibration tests were conducted for three different levels of stresses; 92 N/mm^2, 116 N/mm^2 and 138 N/mm^2. The complete history of strain changes during the loading-drilling-unloading operation were recorded for each test. Fig. 8(a) shows resulting test points from the calibration tests. A theoretical calibration curve is also shown. The curve was calculated by means of a finite element technique using constant strain triangles(25). The calibration specimen is idealized and integrated to form a finite element model illustrated in Fig. 8(b). Because of symmetry only one-quarter of the idealized specimen was solved. The theoretical curve falls closely to the arithmetic mean of the test points. Thus this curve may be used as the calibration curve for the testing technique applied.

A total of 28 holes for residual stress measurement were drilled on both flanges of the 14H202 shape following the same hole drilling procedure used during calibration. Fig. 9 shows the layout of the holes on one flange and the corresponding residual stress results are shown in Fig. 10.

It is noted that the test results do not compare well with those obtained from the sectioning method (Fig. 5). This may be due to the gauge points and the measuring device used for the test. To have meaningful results it is necessary to prepare gauge points which can stand severe test conditions.

Soete's Method

Soete's method of hole drilling is based on the same fundamental principle as that of Mathar's, except that in Soete's method electrical strain gauges are used to measure strains at what is essentially a point, rather than measuring displacements over a specific gauge length. Recent refinements in strain gauge manufacturing techniques have made it possible to obtain strain gauges of very small dimensions. Thus, a hole of a very small diameter and depth may be sufficient to measure residual stresses. Use of such small dimensions has a special application when used in regions with stress gradients as, for example, in weldings.

In this method also, the experimental approach requiring the determination of empirical constants was used to evaluate residual stresses from observed strains.

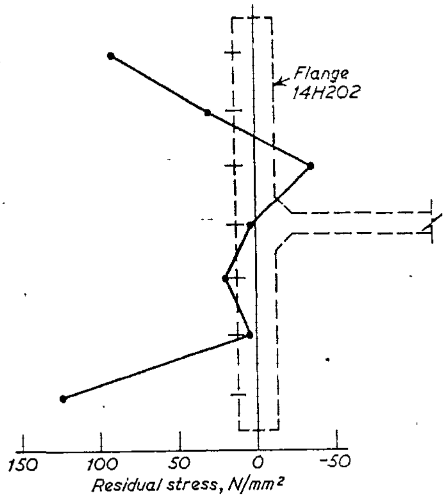


FIG. 10—*Residual stress measurement on outer surface of 14H202 flange using Mathar's method of hole drilling*

Calibration Test

The experimental calibration is simplified by subjecting the test specimen to uniaxial tension. Strains around the 3 mm diameter hole were measured with electric resistance SR-4 strain gauges. The strain gauges used are epoxy-backed, etched-foil Type EA-09-125RE, 3 mm in size and preassembled into a 45 deg rosette. With such preassembled gauges, the necessary operational skill is reduced to that of locating the cutter in the centre of the rosette.

Under a uniaxial condition, the calibration constants A and B may be determined from the formulae(13):

$$A = \frac{\varepsilon_1 + \varepsilon_3}{2\sigma} \tag{1}$$

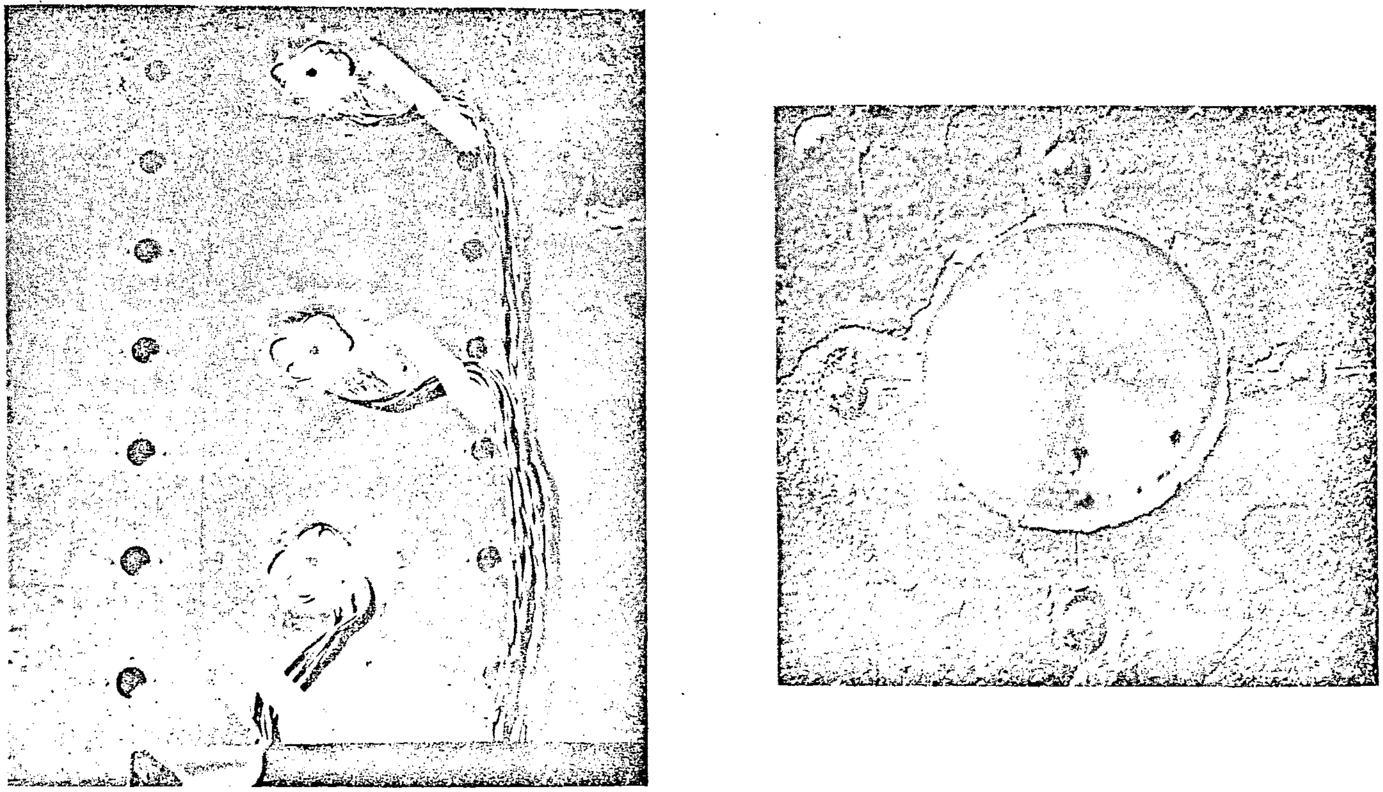


FIG. 9—*Hole drilling layout and close-up of drilled hole for residual stress measurement with Mathar's method*

$$B = \frac{\varepsilon_1 - \varepsilon_3}{2\sigma} \tag{2}$$

where ε_1 = longitudinal strain
ε_3 = transverse strain
σ = applied stress

After the calibration constants A and B are determined for the hole gauge assembly, the principal stresses in the test specimen are evaluated as:

$$\sigma_{\max} = \frac{\varepsilon_1(A + B\sin\gamma) - \varepsilon_2(A - B\cos\gamma)}{2AB(\sin\gamma + \cos\gamma)}\left(\frac{E}{\mu}\right) \tag{3}$$

$$\sigma_{\min} = \frac{\varepsilon_2(A + B\cos\gamma) - \varepsilon_1(A - B\sin\gamma)}{2AB(\sin\gamma + \cos\gamma)}\left(\frac{E}{\mu}\right) \tag{4}$$

$$\text{where } \gamma = \tan^{-1}\left[\frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3}\right]$$

ε_2 = diagonal strain

The direction of the maximum principal stress β measured counter clockwise from the transverse direction is given by

$$\beta = -\tfrac{1}{2}\gamma \tag{5}$$

The calibration constants A and B contain the material constants E and μ (Young's Modulus and Poisson's ratio), which are constant for all elastic, homogeneous and isotropic materials. Since all grades of structural steel have essentially the same values of E and μ, the variation caused by a difference in material may be ignored.

Drilling Technique

Although the drilling technique will affect the accuracy, the method will in practice be independent of machining stresses for a specific small hole diameter as long as a standardized drilling procedure is used throughout the whole operation, including the calibration test.

End mills are normally supplied with cutting edges on the end and side of the mill. The mills used in this study were so modified that they are capable of reproducing untapered holes and removing the material from the bottom of the hole only$^{(8,13)}$.

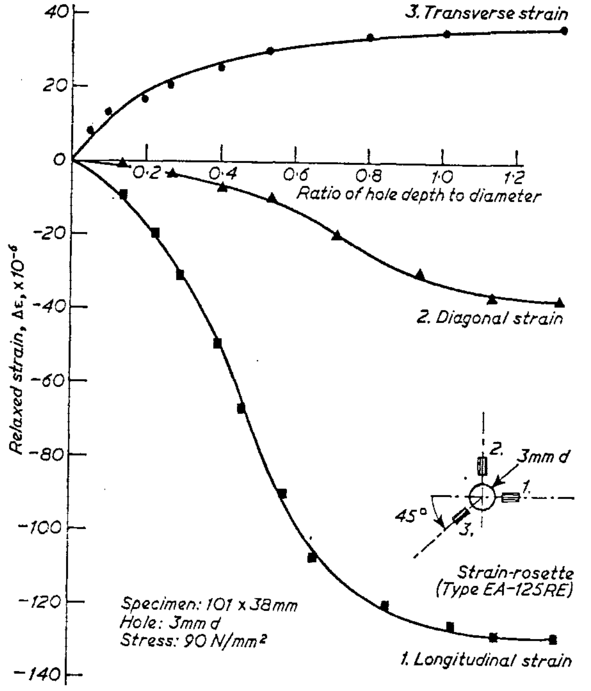


FIG. 11—*Characteristic curves of strain relaxation for Soete's method*

Test Results

Tests were first conducted on the calibration test specimen. The characteristic curves of the measured strain relaxation as a function of non-dimensional hole depth are shown in Fig. 11. It may be concluded that calibration based on a hole depth of one diameter makes use of the maximum released strain.

Using equations (1) and (2) the calibrated values of the constants A and B at the depth/diameter ratio of 1·0 are

$$A = \frac{\varepsilon_1 + \varepsilon_3}{2\sigma} = -0{\cdot}44 \times 10^{-6}\ \text{mm}^2/\text{N} \tag{1a}$$

$$B = \frac{\varepsilon_1 - \varepsilon_3}{2\sigma} = -0{\cdot}86 \times 10^{-6}\ \text{mm}^2/\text{N} \tag{2a}$$

It is noted that B is approximately equal to $2A$.

Following the same procedure used during the calibration test, three holes for residual stress measurements were drilled on the flange of the 14H202 shape at the locations shown in Fig. 9. The resulting values are plotted as shown in Fig. 12. The results show a close agreement to those obtained to those obtained from the method of sectioning.

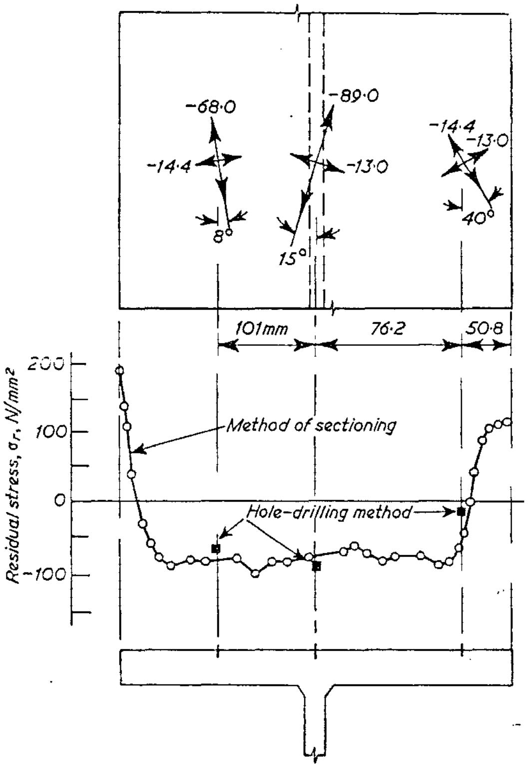


FIG. 12—*Residual stress measurement using the Soete's hole drilling method and comparison with the sectioning method*

CONCLUSIONS

This paper reports on a study which has investigated some of the different techniques of residual stress measurement. Measurements of residual stresses were performed using the method of sectioning (a destructive method), and two different hole drilling methods (both semi-destructive).

The following recommendations and conclusions may be made:

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, gauge hole locations and cutting positions and layout. Preparation of gauge 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 gauge points and the measuring device used for the test. To have meaningful results it is necessary to prepare gauge points which can stand severe test conditions. Also a dependable measuring device having a small gauge 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 semi-destructive, 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 the interpretation of test results.

ACKNOWLEDGEMENTS

The study for this paper was performed as part of the research project "Residual Stresses in Thick Welded Plates" being conducted at Fritz Engineering Laboratory, Bethlehem, Pennsylvania. This project was sponsored by the National Science Foundation, and the Column Research Council, and was under the technical guidance of the Column Research Council Task Group 1, of which John A. Gilligan is Chairman.

REFERENCES

1) Kalakoutsky, N. "The Study of Internal Stresses in Cast Iron and Steel", London, 1888, also St. Petersburgh, 1889 (in Russian).
2) Treuting, R. G. Wishart, H. B. Lynch, J. J. and Richards, D. G. 1952. "Residual Stress Measurement", American Society for Metals, Cleveland, Ohio.
3) Alpsten, G. A. Egenspanningar och Materialhallfasthet i Kallriktade Bredflänsprofiler, *Jernkontroets Annaler*, Vol. 154, 1970, s. 255-283.
4) Alpsten, G. A. and Tall, L. "Residual Stresses in Heavy Welded Shapes", *The Welding Journal*, 49 (3), March, 1970.
5) Huber, A. W. and Beedle, L. S. 1954. "Residual Stresses and the Compressive Strength of Steel", *The Welding Journal*, 33 (12) 589-s to 614-s.
6) Huber, A. W. May, 1956. "The Influence of Residual Stress on the Instability of Columns", Ph.D. Dissertation, Lehigh University.
7) Alpsten, G. A. and Tall, L. "Residual Stress Measurements in Thick Steel Plates", Fritz Engineering Laboratory Report No. 337. 13, Feb., 1969 (in preparation).
8) Tebedge, N. Alpsten, G. and Tall, L. "Measurement of Residual Stresses—a Study of Methods", Fritz Engineering Laboratory Report No. 337. 8, February, 1970.
9) Beer, G. and Tall, L. "Automatic Plotting of Residual Stress Diagrams", Fritz Engineering Lab. Report No. 337. 26, November, 1970.
10) Mathar, J. 1934. "Determination of Initial Stress of Measuring the Deformation Around Holes", *Trans. ASME*. Vol. 56, pp. 249–254.
11) Soete, W. and Vancrombrugge, R. 1950. "An Industrial Method for the Determination of Residual Stresses", *Proceedings of the Society for Experimental Stress Analysis*. Vol. VIII, No. 1, pp. 17–28.
12) Kelsey, R. A. 1956. "Measuring Non-uniform Residual Stresses by the Hole Drilling Method", *Proceedings of the Society for Experimental Stress Analysis*. Vol. XIV, No. 1, pp. 181–194.
13) Rendler, N. J. and Vigness, I. 1966. "Hole-drilling Strain-Gage Method of Measuring Residual Stresses", *Proceedings of the Society for Experimental Stress Analysis*. Vol. XXIII, No. 2, pp. 577–586; also U.S. Naval Research Laboratory, NRL Report 6279, July, 1965.
14) Lake, B. R. Appl, F. J. and Bert, C. W. "An Investigation of the Hole Drilling Technique for Measuring Planar Residual Stresses in Rectangularly Orthotropic Materials", *Experimental Mechanics*, pp. 233–239, June 1970.
15) Kirsch, G. "Die Theorie der Elastizitaet und die Beduerfunisse der Festigkeitslehre (Theory of Elasticity and Application in Strength of Materials)", *Zeitschrift Verein Deutscher Ingenieure*, Vol. 42, No. 29, pp. 797–807, 1896.
16) Willheim, A. and Leon, Z. 1916. "Mathematik und Physik", Vol. 64, pp. 233.
17) Mesmer, G. "Fliesserscheinungen Beim Spannungsmessverfahren Nach J. Mathar", Archiv fuer das Eisenhuettenwesen, Vol. 10, No. 2, pp. 59–63, August 1936.
18) Campus, F. "Recherches, Etudes et Considerations sur les Constructions Soudees" (Research Studies and Considerations for Welded Structures), *Sciences et Lettres*; Liege (Belgium) pp. 103–109. 1946.
19) Kournossov, D. G. and Jakutorich, M. U. 1948. "The Measurement of Residual Stresses by Means of Hole Drilling", *The Engineers Digest*, Vol. 5, No. 5, pp. 251–253, July.
20) Riparbelli, C. 1950. "A Method for the Determination of Residual Stresses", *Proceedings of the Society for Experimental Stress Analysis*, Vol. VIII, No. 1, pp. 173–196.
21) Soete, W. 1949. "Measurement and Relaxation of Residual Stresses," *Sheet Metal Industries*, Vol. 26, No. 266, pp. 1269–1281, June.
22) Bolten, R. G. and Ten Cate, W. 1952. "A Routine Method for the Measurement of Residual Stresses, in Plates", *Applied Scientific Research*, Vol. 3, Section A, No. 2, pp. 317–343.
23) Soete, W. and Vancrombrugge, R. 1948. "Het Meten Van Eigenspanningen in Diepte" (Measurement of Residual Stresses in Depth), Revue de la Soudure, Lastijdshrift 4, pp. 17–28.
24) Timoshenko, S. "Theory of Elasticity", McGraw-Hill Book Company, Inc., New York, 1934.
25) Wilson, E. L. "Finite Element Analysis of Two-Dimensional Structures", Ph.D. Dissertation, University of California, Berkeley, 1963.