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THE TREPAN OR RING CORE METHOD, CENTRE-HOLE METHOD, SACH'S METHOD, BLIND HOLE METHODS, DEEP HOLE TECHNIQUE

E. Procter* and E. M. Beaney‡

**Procter & Chester (Measurements) Ltd., Theatre Street, Warwick CV34 4DP*
‡CEGB, Berkeley Nuclear Labs. Berkeley, Glos. GL13 9PB, UK

ABSTRACT

Mechanical methods can be used to measure practically all types of residual stresses, from near surface to depths in excess of 0.25 metre. They have been used for much longer and have thus seen more development than other methods and, as a consequence, their limitations and applications are more clearly defined. Their major disadvantage is that, by their nature, they are destructive although the amount of structural damage may be insignificant in many cases.

The essence of the techniques is that changing the geometry of a structure changes its residual stress pattern. This change in stress causes strain changes, which can be measured using strain gauges or some other deformation measuring device. In principle, if the change in geometry is known and the strain measurement is sufficiently comprehensive and accurate, then residual stresses can always be calculated. However, due to the complexity of this calculation in its general form, all the mechanical techniques rely on making well defined changes in geometry for which the relationship between measured strain and residual stress are known or can easily be obtained.

The techniques fall into two categories, namely those which measure surface or near-surface stresses, and those designed to give sub-surface or through-thickness stress.

The chapter considers the following techniques:

Sectioning for surface and sub-surface measurement, including Sach's and Blind Hole methods.

The trepan or ring-core method.

The centre-hole method.

The deep hole technique.

NOMENCLATURE

E = Young's Modulus

t = Tube wall thickness

r_2 = Initial mean radius of curvature of tube
r_1 = Final mean radius of curvature of tube
σ_t = Tangential stress
σ_a = Axial stress
σ_r = Radial stress
ν = Poisson's ratio
A_o = Original cross-section area of cylinder
A = Area machined away
θ = $\varepsilon_t + \nu\varepsilon_1$
λ = $\varepsilon_a + \nu\varepsilon_t$
ε_t = Tangential strain
ε_a = Axial strain
$_x, \sigma_y, \sigma_z$ = stress in x, y and z directions
$_{xy}$ = Shear stress in x,y plane
$_x, \sigma'_y$ = Stress on hole bottom
$_{xy}$ = Shear stress on hole bottom
$_1, \sigma_2$ = Principal stresses
= Angle from ε_{R1} to σ_1
$_{R1}, \varepsilon_{R2}, \varepsilon_{R3}$ = Relaxed strains
,N = Constants
$/K_1$ = Function in centre-hole equations
K_2/K_1 = Function in centre-hole equations
a = Axial strain
Ra = Relaxed axial strain
RT = Relaxed transverse strain
= Block loads on cylinder
ε = Strain x 10^6

INTRODUCTION

:chanical methods can be used to measure practically all types of residual :resses, from near surface to depths in excess of one quarter of a metre. ıey have been used for much longer and have thus seen more development than :her methods and, as a consequence, their limitations and methods of application 'e more clearly defined. Their major disadvantage is that, by their nature, ıey are destructive, although the amount of structural damage may be insignificant . many cases.

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The techniques fall into two categories, namely those which measure surface or near surface stress and those designed to give sub-surface or through-thickness stress. There are three commonly used techniques for the measurement of near surface stress namely:

(1) Trepan or ring-core

(2) Centre-hole drilling

(3) Sectioning

The sectioning method consists of measuring a surface strain whilst the residual stress is completely relaxed by removing the piece of material on which the strain is measured. The residual stress is then related to the relaxed strain by the normal material stress/strain relationships. The trepan or ring-core method can be used as either a partial or full relaxation technique. In the full relaxation case stress is calculated from the relaxed strains by the normal material stress/strain relationships. When used as a partial relaxation method an empirical relationship is used to relate stress and strain. The hole drilling method relies on the partial strain relaxation which occurs when a small blind hole is drilled in the centre of a strain gauge rosette. All of these methods are well developed and capable of giving accurate results if applied correctly.

There are four techniques for the measurement of sub-surface stresses:

(1) Sectioning

(2) Blind hole drilling

(3) Sach's method

(4) Deep hole drilling

The sectioning method consists of cutting up the structure whilst measuring the relaxed strains on suitable free surfaces. In general it requires the stress field or the geometry to be relatively simple so that the relaxed strains are easily related to residual stress. The Sach's method is a particular form of sectioning for evaluating residual stress in cylindrical components. The blind hole method relies on the complete relaxation of stress at the bottom of a hole when the hole and surrounding is trepanned out of the structure. Since the stresses are completely relaxed the normal material stress/strain relationships hold, but the effect on stress of the initial blind hole is uncertain and thus the technique has dubious accuracy. The most comprehensive of the sub-surface measurement systems is the deep hole method in which the stresses around a hole can be simply related to changes in hole dimensions occurring as the stresses are released by over-coring. In the current technique all changes in hole dimension are measured which facilitates the prediction of the complete stress pattern through the thickness of the structure with the use of one hole.

The following chapter discusses the fundamentals of each technique and, where appropriate, gives examples and references to other work. The centre-hole technique and the deep hole technique are covered in considerable detail, the former because it is the most widely used mechanical technique for surface measurement and the latter because of its uniqueness for measuring in virtually any geometry and stress field.

TREPAN OR RING-CORE METHOD

The trepan method was originally conceived as a simple full-relaxation technique for the measurement of surface residual stresses. The principle involves machining an annulus, i.e. trepanning, into the wall of the structure, which effectively isolates the surface of the island which is formed, as shown in Fig. 1, thereby causing the stresses to relax. In order to determine the stresses, the relaxed strains on the surface of the island have to be measured and conventional elastic theory used.

The modern method is probably advanced from work by Gunnert [1], who drilled a small hole to act as a guide for a fly-cutting device to machine the groove. In the current practice electric resistance strain gauge rosettes are first attached to the structure surface at the point of interest and an annulus machined around the rosette by any one of a number of methods.

Wolf and Böhm [2] and Freddi [3] used a small end mill mounted eccentrically in a cutting head to machine the circular grooves and had to disconnect the strain gauge leads during the machining operation, which is most udesirable. Morland and Haynes [4] used a hollow cylindrical cutting tool so that the strain gauge leads could be threaded through its centre and thereby remain connected during the machining operation. The problem with this method, and probably with the small end mill method, is that the machining operation introduces additional stress. Not only would this induced stress relate to tool design and machining parameters it would also depend on the material being machined.

Böhm et al. [5] have developed an air-abrasion method for use on hard and tough materials but a method well suited for use in most structural materials is Electro-Discharge (EDM) or Spark Erosion machining. EDM is a relatively simple method to apply, in that there are no rotating parts and the electrodes are made from thin-wall copper tube so the strain gauge leads can easily be threaded through their hollow centres. However, there are disadvantages. It is necessary to submerge the part being machined in a fluid, usually paraffin, and consequently the strain gauges require protection from this environment. Also, EDM creates localized temperature changes if discharge currents are not controlled, which can influence strain gauge behaviour and induce detectable stress changes.

THEORETICAL CONSIDERATIONS

At Berkeley Nuclear Laboratories, (BNL) a finite element analysis was used to examine the relaxation of strain across the surface of the trepanned island with respect to trepanned depth, in an infinitely thick plate. For the case of uniform stress field the result is shown in Fig. 2. This shows that for total strain relaxation at the surface the minimum required trepanned depth is 1.2 times the diameter of the trepanned island. Since the minimum practical diameter of island required for the strain rosette is 10 mm, the required depth must be at least 12 mm. This was considered to be much too deep for general use hence consideration was given to part-depth trepanning, i.e. using the technique as a partial relaxation method. The figure shows that significant strains are relaxed at small depths - assuming a 10 mm island the relaxation is nominally 100% at 2-3 mm depth. However. the strain relaxation across the diameter of the island is not uniform, therefore the position of the rosette relative to the centre of the island becomes important and also, the rate of strain relaxation with respect to depth is such that the machined depth is critical. An error of 0.2 mm on depth can lead to an error of 10% on stress.

Because of these factors, as well as the practical considerations, this technique was generally abandoned, at least in the UK, in favour of the centre-hole method.

The results of the BNL analysis are confirmed by the work of Freddi [3] and Böhm et al. [5]. Using uniaxially loaded test specimens, Freddi investigated strain relaxation with depth in plates of 10, 14 and 17 mm thickness. Since he was concerned with making measurements in cylinders having these specific wall

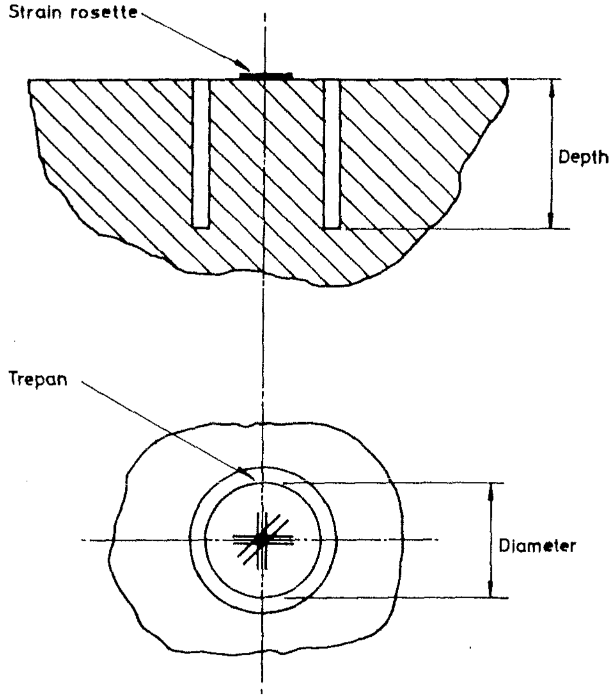


Fig. 1 Principle of trepan technique.

thicknesses the work enabled him to determine the minimum depth he needed to machine for 100% relaxation in each case. However, his machining depth had to be precise, since any over-machining resulted in an overestimate of the stress. He could, of course, have machined through the wall, to totally isolate the machined island, and consequently guaranteed total relaxation.

Böhm et al. refer to measurements in turbine and generator shafts and components which are of infinite thickness, relatively speaking. Using specially designed strain rosettes they achieved concentric machining. Preliminary work on uniformly stressed uniaxial test specimens gave values for influence coefficients which relate the related strains to stress with respect to the depth of trepan. Also, in situations where the principal stress directions were known, a second design of gauge was used to indicate the change in stress with depth. It was assumed that the stress was constant through any one depth step, which is probably not a severe limitation in their cases. The strain change due to machining one depth step was subtracted from the change which would have occurred in a uniform stress field (determined from preliminary tests) and this, in turn, related mathematically to the stress changes. They point out that there is a limit on depth, imposed by sensitivity of response of the surface to stresses at depths below the surface. Using a 14 mm diameter trepanned island they claim that stress gradients can be measured to a depth of 5 mm. For greater depths they machine out the first 5 mm deep trepan, leaving a flat-bottomed hole 25 mm diameter, then install a new gauge on the bottom of this hole and repeat the trepan procedure. They do not appear to make any corrections to account for the changes in the stress field due to the machined hole, or to consider the possible influence of stresses induced by the machining.

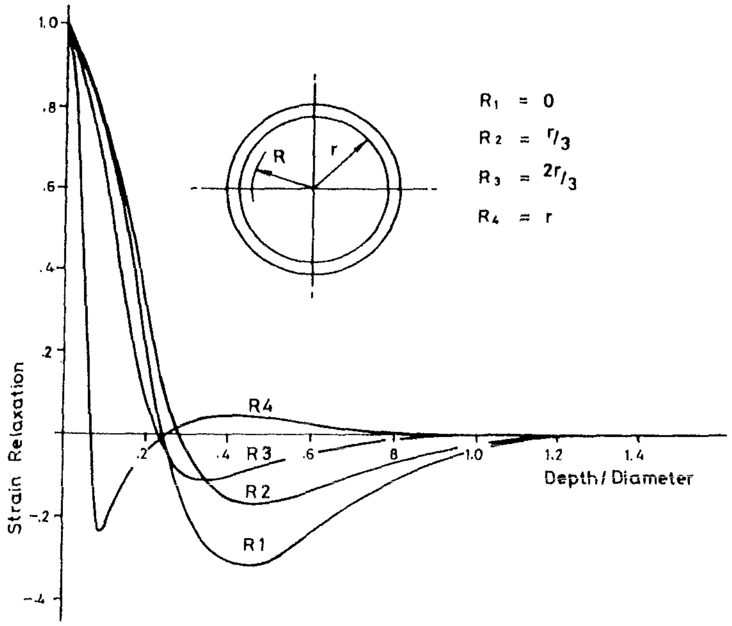


Fig. 2 Radial strains on trepanned island.

HOLE DRILLING

istory

The first recorded attempts to measure residual stresses by hole drilling were eported by Mathar in 1933 [6]. Mathar considered that if a hole was drilled hrough a flat plate then the hole would take up a shape related to the existing tress field and there would be an associated strain relief in the surrounding aterial. Thus, the measurement of this strain relief would allow the calculation f the original stressed state. He drilled 12 mm diameter holes and measured train relaxations outwards from the edge of the hole using a 157 mm gauge ength extensometer, i.e. a distance estimated to be beyond the influence of he drilled hole. This work was limited to uniaxial tensile and compressive tress fields. In 1936, Mesmer [7] developed the formula for biaxial stresses f known direction and in 1956, Campus [8] generalized the equations for biaxial tresses of unknown direction. All three workers assumed uniform plane stress istribution through the full plate thickness.

he next significant step in hole drilling was reported by Soete and Vancrombrugge n 1950 [9]. Still limiting the technique to through holes in plates they used lectrical resistance strain gauges to measure the strain relaxations local to he drilled hole. The holes were 6 mm diameter and three strain gauges of 8 mm auge length were positioned on a pitch circle approximately 10.5 mm radius in irection 0°, 90° and 135°, i.e. a 45° rosette arrangement. Boiten and Ten ate (1952) [10] introduced further improvements to the theoretical solution by aking the width and cross-sensitivity of the strain gauges into account.

e first reference to "blind" hole drilling is given in a paper by Kelsey in 56 [11]. Kelsey was attempting to measure stress change with depth, which will be discussed in greater detail later. Although his drilling and measuring techniques were similar to those used by Soete and Vancrombrugge, he introduced an empirical approach to obtain solutions in the blind hole application.

The first major advance towards standardization of the technique and, at the same time, minimize damage to the components tested was reported by Rendler and Vigness in 1966 [12].

By combining the blind hole approach with modern strain gauge technology they realized the potential for reducing hole size and producing purpose made residual stress rosettes. Their work was based on 1.6 mm and 3.2 mm diameter holes leading to the subsequent introduction of the Micro Measurements 062RE and 125RE series gauges.

In the early 1970s the Authors became interested in residual stress measurement. After gaining some experience of the Rendler and Vigness method they considered that it was not possible to maintain the required close tolerance on hole diameters for repeatedly accurate measurements and therefore actual drilled hole size should be taken into account. They also realized that previous workers had not considered the introduction of additional stresses caused by the drilling method. As a result, they carried out a full evaluation of the technique using the 062RE series gauges and published their first work in 1974.

The paper, by Beaney and Procter [13], shows:

i. Further development of the equations to a more suitable form for calibration and application.

ii. The use of mechanical cutters for hole drilling (drills, end mills and milling cutters) as used by all workers to date, introduced additional stresses and consequently had significant influence on the end result.

iii. If the drilling induced stresses could be eliminated the accuracy of the technique, using a 1.6 mm diameter hole would be between 5% and 10%, depending on the biaxial stress ratio.

Following a reference to Air-abrasive machining in a paper by Bush and Kromer [14] the Authors carried out machining trials using this technique. The resulting development of a specially designed rotating jet device was reported by Beaney in 1976 [15].

Air-abrasive machining was shown to be stress-free in all normally used structural materials. This was particularly important for use on austenitic and high alloy steels, which had been impossible to investigate by the previously used mechanical drilling methods. Of additional importance, because the drilling method was stress-free, hole diameters could be increased within a given rosette, leading to increased relaxation of the available strains and consequent improvement on accuracies. Beaney recommended that for the 062RE gauge, the hole size should be increased to 2 mm.

Increasing the hole size, obviously led to concern about drilling depth. In terms of damage to the structure the hole depth is the important parameter. However, it was shown at the time, and has since been proved for other gauge geometries, that the drilled depth required for maximum relaxation of the major strain is dependent only on rosette geometry, i.e. in a given rosette the optimum hole depth is independent of hole diameter.

Since 1976, the CEGB designed Air-abrasive drilling equipment has been widely used in many countries. In the USA, although many workers use Air-abrasive machining, they have tended to use stationary jets. It can only be presumed that these workers are content to accept the loss in accuracy which results from non-circular, tapered and varied hole shapes which have been shown to be produced by stationary jet methods.

As an alternative to Air-abrasive drilling, Flaman [16], in Canada, has developed the use of ultra-high speed drilling. Using small air-turbine powered machines, normally made for use in the dental industry, off-load drill speeds of the order of 350,000 rpm can be achieved. In many of the common structural steels this has been shown to be stress-free and drills a truly flat bottomed hole (which is not quite achieved by air-abrasion) and consequently is advantageous when investigating stress gradients within one hole depth. However, for those materials which are most difficult to machine, e.g. high manganese steels, air-abrasion remains the only successful process.

Since the developments of the early 1970s an increasing number of workers have become involved in residual stress measurement and many papers are available discussing applications of the technique. It is not the purpose of this presentation to discuss applications but a number include aspects of application, often extending its use to non-uniform stress distributions. Birley et al. [17] and Owens [18] measured stress gradient with depth using Air-abrasive drilling, which is effectively an up-date of the work by Kelsey [11] and Bathgate [19]. Procter and Mitchell [20] considered the application of the standard technique to measure stress with depth in a large structure. Sandifer and Bowie [21] considered the effects of a hole drilled off-centre relative to the rosette and showed how corrections can be applied. Bynum [22] and Schajer [23] offered experimental and theoretical evaluations of the technique, effectively confirming the Authors' work. Procter and Beaney [24] re-emphasized the importance of hole diameter and depth in the quest for maximum accuracy. Additionally, although little information is to be found in the open literature, aspects of surface preparation received considerable attention and, accordingly, is discussed in a subsequent section.

More strain rosettes have been introduced. The Micro-Measurements range of residual stress rosettes were extended to include the 031RE series. These have the same relative geometry as the 062RE and 125RE series and consequently existing calibration parameters apply. They were introduced as a result of a demand to measure residual stresses more local to the structure surface but by the standard application methods. Also they can be used on smaller and thinner components than their larger counterparts. TML in Japan introduced a rosette to compete directly with the 062RE series. The dimensional differences are so small that existing calibration data is generally applicable. Hottinger Baldwin Messtechnik in Germany introduced a special rosette with an integral centering device for use with a special drilling jig employed 1.6 mm diameter milling cutters.

All the rosettes discussed so far and available prior to 1983 have the same basic format as that first introduced by Rendler and vigness in 1966. Work within the CEGB, by the Authors and Darbyshire [25] indicated that a change from the 0°-90°-135° format might prove beneficial. Darbyshire highlighted problems, found by many other workers, in investigating streses at the fusion boundaries of butt welds. Because of the severe in-plane stress gradients holes could not be drilled at the fusion boundaries unless one gauge sensor was on the opposite side of the fusion line to the other two and this introduced anomalies in predicting, in particular, peak stress positions. Also, residual stresses at the toes of fillet welds or other small radii could not be measured at the required position. The obvious solution was to re-design the residual stress rosette to have all three sensors within one 90° quadrant.

To date, two manufacturers have introduced satisfactory, single quadrant rosettes. Micro-Measurements have introduced the 062UM series which has the same gauge length and pitch circle as the older 062RE. Unfortunately, in order to fit the three sensors into the single quadrant the sensor width had to be reduced and this means that all the previously established calibration data is no longer applicable. The Authors took the view that any re-design should take advantage of the stress free drilling processes now available in order to increase output sensitivity which, in turn, would lead to potentially improved accuracies. This has been achieved with two gauges manufactured by BLH Electronics in the USA. Both are designed for use with stress-free hole drilling processes, either air-abrasion or ultra-high speed. The 03S gauge is designed for a nominal 1.6 mm hole and the 04S is proportionally increased in size for a 2 mm diameter hole. When compared with the originally intended 1.6 mm diameter hole in the 062RE rosettes the sensitivity of these gauges is increased by a factor of two, which is clearly a worthwhile gain.

The following sections describe the principle of the technique, the development and calibration carried out at Berkeley Nuclear Laboratories, and discusses other important aspects such as measurement of stress gradient with depth, surface preparation and effect of non-elastic behaviour at the hole edge.

The Technique in Principle

Suppose an infinite plane sheet of elastic isotropic material is subjected to a state of uniform stress. If a hole is drilled through the sheet the radial stress at the edge of the hole will reduce to zero and, provided the stress field remains elastic, the re-distribution of stress away from the hole will be unique, as shown in Fig. 3. If a strain gauge is attached to the stressed sheet, this will detect a change in strain associated with the change in stress, as shown by the cross-hatching in the figure, and this strain is related to the total stress change occurring at the edge of the hole.
In practice, the components of interest are usually thick compared with hole diameter, hence blind holes are used. Also, stresses are biaxial hence three-element rosettes are required. Prior to Beaney and Procter [13] the equations for a 45° rosette were:

$$\sigma_1 = \frac{\varepsilon_{R1}(M + N \sin 2\alpha) - \varepsilon_{R2}(M - N \cos 2\alpha)}{2MN(\sin 2\alpha + \cos 2\alpha)} \tag{1}$$

$$\sigma_2 = \frac{\varepsilon_{R2}(M + N \cos 2\alpha) - \varepsilon_{R1}(M - N \sin 2\alpha)}{2MN(\sin 2\alpha + \cos 2\alpha)} \tag{2}$$

$$\alpha = 1/2 \tan^{-1} \frac{\varepsilon_{R1} - 2\,\varepsilon_{R2} + \varepsilon_{R3}}{\varepsilon_{R1} - \varepsilon_{R2}} \tag{3}$$

Further development of these equations, as pointed out by Beaney and Procter [13] gives:

$$\begin{matrix}\sigma_1\\ \sigma_2\end{matrix} = \frac{-E}{2K_1}\left\{\frac{\varepsilon_{R1} + \varepsilon_{R3}}{1 - K_2^{\nu}/K_1} \pm \frac{1}{1 + \nu K_2/K_1}\sqrt{(\varepsilon_{R1}-\varepsilon_{R3})^2 + [2\varepsilon_{R2}-(\varepsilon_{R1}+\varepsilon_{R3})]^2}\right\} \tag{4}$$

which has a distinct advantage over (1) and (2) in that the functions $(1/K_1)$ and $(\nu K_2/K_1)$ can be determined independently of each other. In the uniaxial case:

$1/K_1 = \varepsilon_a/\varepsilon_{Ra}$, i.e. $1/K_1$ is a sensitivity factor dependent only on hole diameter, and $\nu K_2/K_1 = \varepsilon_{RT}/\varepsilon_{Ra}$.

Not only does this simplify the procedure, it also leads to a readily quantifiable technique and is, therefore, worth adopting.

EVALUATION OF TECHNIQUE

Test Technique

Ideally it is required that a rosette is attached to a test specimen of sufficient width to ensure that edge effects will not influence the behaviour local to the hole when this is made, then the specimen loaded to a known stress, the hole formed and the relaxed strains measured. In this ideal case the output of any one gauge of the rosette would be of the form shown in Fig. 4.

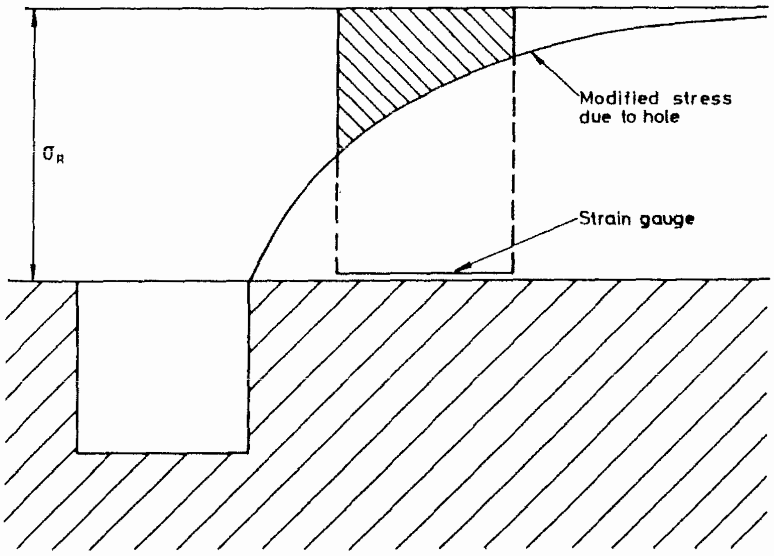


Fig. 3 Principle of centre-hole technique.

There are two possible errors in this approach:

i) The test piece cannot be guaranteed stress-free before loading.

ii) Forming the hole may induce machining stresses.

Thus, the strain change which occurs as a result of drilling the hole will also include these effects. However, the reduction in strain as a result of unloading will have the same slope as that in the ideal case, i.e. it will be parallel to line B in the figure, so the difference in slopes of the loading and unloading lines provides the information required. Alternatively, it may be more convenient to load and unload the specimen before drilling to establish line A, remove the specimen from the machine to drill the hole then re-position and re-load to establish line B.

By drilling the hole in incremental stages and repeating the above procedure at each stage, it is possible to construct curves as shown in Fig. 5. These then provide almost all the data required to allow complete evaluation of the technique and calibration of gauge types.

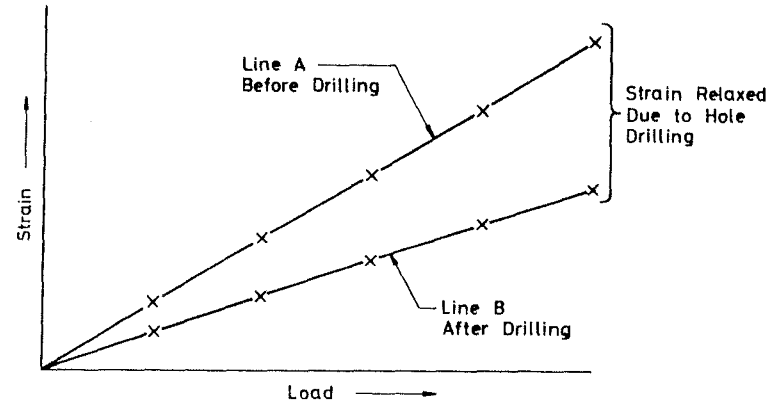


Fig. 4 Strain output on uniaxial test.

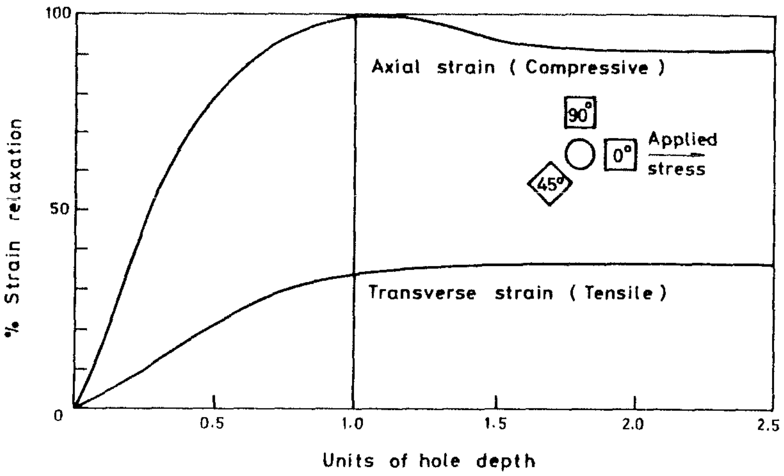


Fig. 5 Strain relaxation in uniaxial stress field.

Test Results

Complete calibration data has been obtained for two types of strain rosette. The first calibrations relate to the 062RE gauges. By maintaining the hole/gauge dimensional relationships the data can be applied to the 031 RE and 125 RE gauges. Secondly, calibrations were carried out on the 03S gauges and this data is similarly applicable in the 04S size.

Figure 6 shows families of curves of $1/K_1$ against non-dimensional hole depth for appropriate ranges of hole diameters, for the two gauge types. Two points are apparent:

i) For each hole diameter, the minimum value of $1/K_1$ coincides with the depth

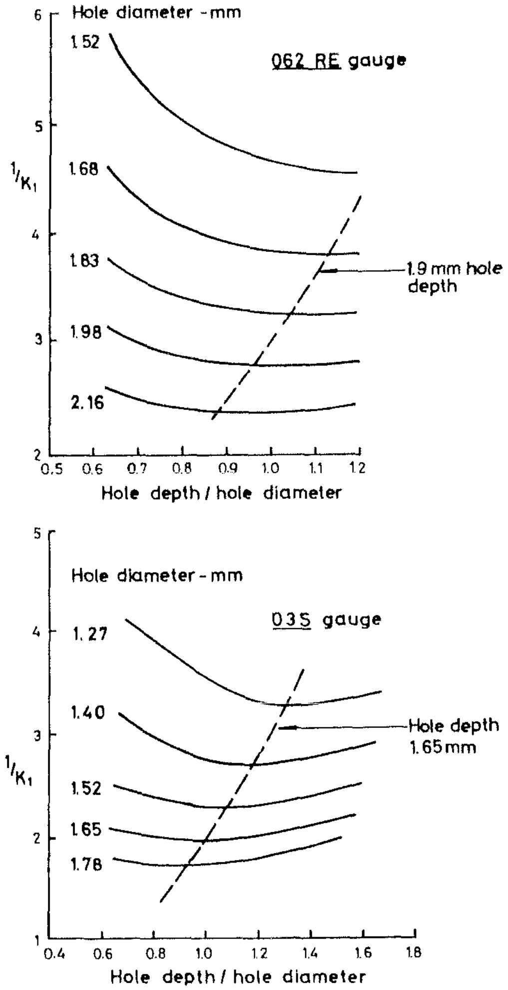


Fig. 6 Variation of $1/K_1$ with hole depth.

of maximum stress relief in Fig. 5. By connecting these minimum value points, as shown by the broken lines, it is clear that the required drill depth for maximum strain relaxation is constant for a given rosette geometry.

ii) Increasing hole size decreases $1/K_1$, i.e. increases sensitivity. Therefore, provided the drilling method is stress-free, the hole diameter should be as large as possible. Obviously, this should not be so large as to risk damage to the gauge sensors or to impair strain transfer capabilities. For the 062 RE series 2.0 mm diameter hole is ideal, and 1.6 mm diameter for the 03S series.

Comparing the two sets of curves in Fig. 6 shows these advantages. For the 062 RE gauges, increasing hole diameter from 1.6 mm to 2.0 mm decreases $1/K_1$ from

4.4 to 2.8. Using the 03S gauge $1/K_1$ is further reduced, to approximately 2.0, whilst retaining the 1.6 mm hole.

Having fixed the nominal hole diameters, the function $\nu K_2/K_1$ can be investigated within the appropriate diameter ranges. Results for the two gauge designs are plotted in Fig. 7 against the same non-dimensional depth scale. These show linear behaviour and negligible influence from hole diameter. At the appropriate depths, the mean values are 0.3 and 0.33 respectively with a scatter band of ± 8%.

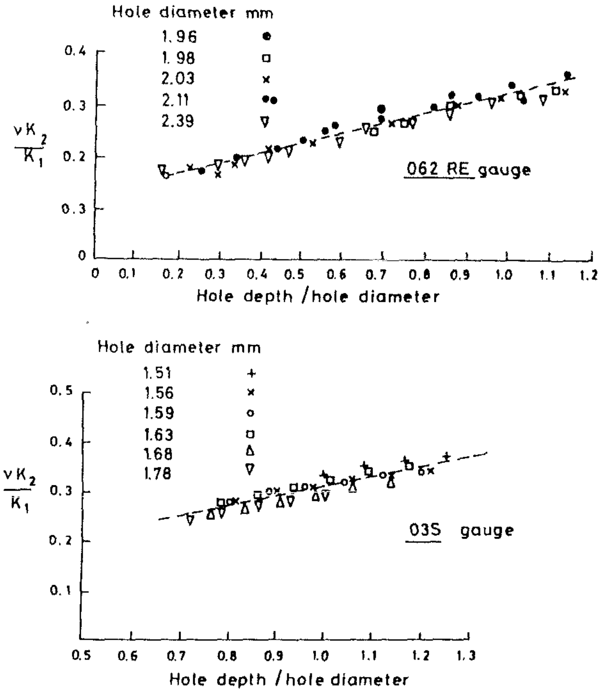


Fig. 7 Variation of $\nu K_2/K_1$ with hole depth.

Figure 8 shows the effect on stress for an error of 1% in $\nu K_2/K_1$. In the worst case, i.e. a 1:1 stress field, the resulting error is less than half that in function. It has been confirmed that Poisson's ratio ν has negligible effect on the function. Measurements made in rigid plastics having $\nu = 0.4$ and cast irons having $\nu = 0.24$ give values for $\nu K_2/K_1$ within the 8% scatter band. This is further confirmed by the theoretical analysis carried out by Schajer (23). Therefore, $\nu K_2/K_1$ can be given a fixed value relating only to gauge type, which simplifies the measurement routine, i.e. the hole is drilled and the strain changes noted, hole diameter is measured and the appropriate value for $1/K_1$ selected from a table of values. This information is sufficient to calculate the stress values.

Finally, Fig. 9 shows curves of the sensitivity factor, $1/K_1$, plotted against hole depth. By fitting equations to these curves, reference tables of values of $1/K_1$ are produced for the range of hole sizes of interest. Additionally, for interest, $1/K_1$ values obtained from the through hole solution by Boiten and Ten Cate [10] are shown for the 062 RE gauges and finite element data is shown for the 03S gauges. The first confirms the mode of strain relaxation in blind

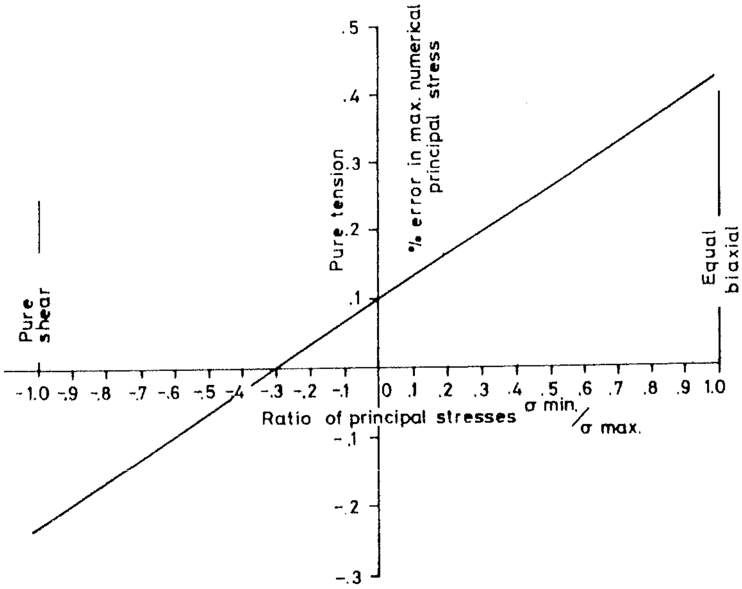


Fig. 8 Error in max. numerical principle stress for a 1% error in $\nu K_2/K_1$

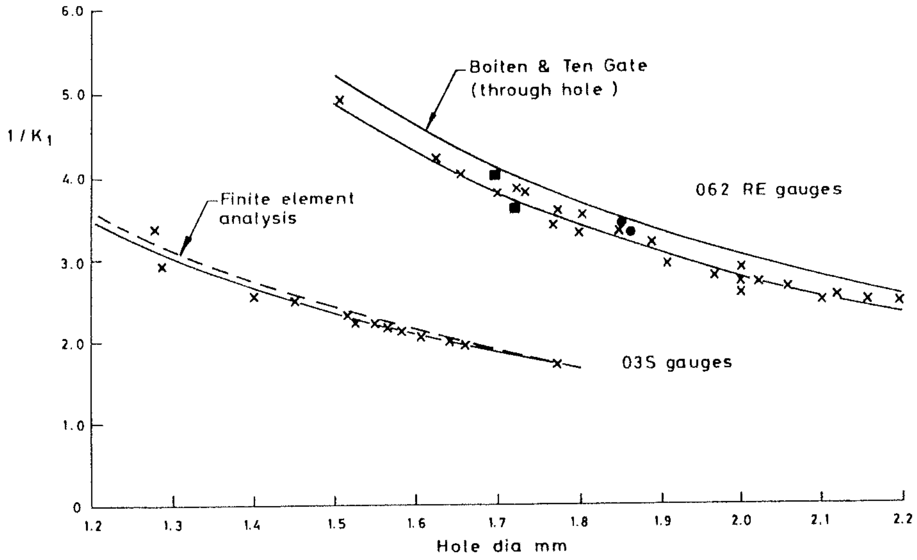


Fig. 9 Variation of $1/K_1$ with hole diameter.

holes as shown in Fig. 5 i.e. when sufficient depth is achieved in a blind hole the solution equates with that of the through hole. Further, the difference between the normal depth blind hole solution and the through hole is about 8%. The second confirms the agreement which can be achieved between finite element and empirically obtained calibration data.

Accuracy of the Technique

The evaluations and calibrations discussed so far, relate to totally elastic and uniform stress fields in homogeneous materials. Probable accuracies, can be inferred in two ways.

Assuming totally stress-free drilling, reference to equation (4) indicates possible sources of error. Any error in selection of the value of $1/K_1$ will have a direct effect on stress, and since the function is dependent on hole diameter the error will relate to the accuracy of measurement of this diameter. With the CEGB equipment the measurement will be within ± 0.025 mm and the associated error will vary between 1.5% and 3% depending on the strain rosette/hole size combination. There will also be an error if the hole is not aligned concentrically in the rosette. Clearly, this depends on the degree of misalignment and its direction with respect to the stress field and the elements of the strain rosette. The work of Sandifer and Bowie [21] supports the Beaney and Procter [13] view that in the worst case it will be similar to that resulting from hole diameter measurements, i.e. it will vary between 1.5% and 3%. The same values will also, obviously, apply to hole circularity if, say, stationary nozzles are used for air-abrasive machining. The error due to $\nu K_2/K_1$ has already been discussed and will vary between 1% and 3.5% according to the biaxial stress ratio. There then remains the accuracy of strain measurement. Since this is a straightforward application, of short duration, the accuracies should be defined by gauge factor tolerances plus the accuracy and resolutions of the strain recording instrument. In the worst case these should not exceed an overall error of, say, 2%.

By simple addition, for the CEGB equipment the worst case error for an 062 RE rosette and 1.6 mm diameter hole should not exceed ± 9%. By using a 2 mm diameter hole this improves to ± 7.5%, which is further reduced by using the 03S rosette/1.6 mm diameter hole combination.

A more direct way of estimating probable accuracy and confirming the above values is to consider the empirical data in Fig. 9. In this figure, the individual values of $1/K_1$ were calculated from equation (4). For the given fixed value of $\nu K_2/K_1$ the measured strains and the applied stress were substituted in the equation, and $1/K_1$ calculated. Therefore, the scatter of the plotted points about the fitted line is a true indication of measurement accuracy. For the 062 RE gauge all the points are within ± 6%, covering a range of stress fields. For the 03S gauge, in uniaxial stress fields, the points are within ± 3%

Additional Considerations

Plastic Deformation. As stated in the previous section, the predicted, and proven errors relate to uniform elastic stress fields. However, it is well known that machining the hole introduces a discontinuity in the structure, and therefore plastic deformation will occur locally at some fraction of yield stress dependent on the stress concentration factor. Stress concentrations local to circular holes are well understood, their maximum values are 4, 3 and 2 in pure shear, uniaxial (1:0) and equi-biaxial (1:1) stress fields respectively. Therefore plastic deformation will commence at the edge of the hole at $\frac{1}{4}$, $\frac{1}{3}$ and $\frac{1}{2}$ yield stress respectively and, presumably, affect the results obtained.

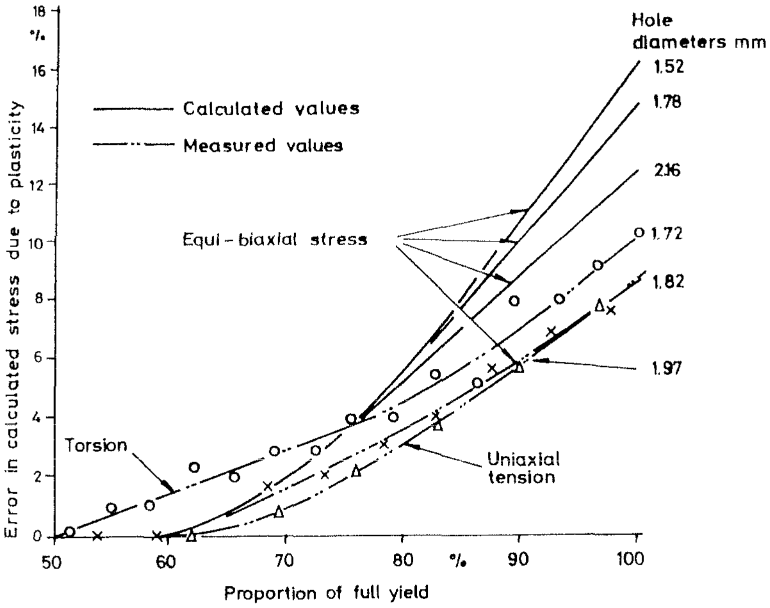


Fig. 10 Effect of plasticity around hole.

Figure 10 shows the results of investigations to determine their effects. The three stress fields have been considered. In the 1:1 case finite-element analysis was used to find the effect of hole diameter. This assumes elastic/ perfectly plastic materials behaviour, which accounts for the resulting errors being higher than those obtained by measurement in real materials.

To summarize the results: plasticity local to the machined hole leads to additional errors as stresses increase above 60% yield stress (50% in pure shear). The errors rise to about 9% at full yield. The errors will always lead to an overestimate of stress levels and consequently corrections can be made to measured values.

Stress Gradients. Stress gradients fall into two categories; those which occur along the surface of measurement and those which occur within the depth of measurement. The concern that the user should have in such cases is governed by the application and degree of gradient expected. In general structural work, stress gradients are not of major concern. However, there are exceptions and in some cases it is desired to make detailed studies.

Probably the most severe in-plane gradient likely to be encountered is that associated with weld/parent metal interfaces. Darbyshire [25] has made many measurements in these situations. He confirms that in cases where the stress reduces each side of its peak, the technique measures the average stress across the dimension equal to the hole diameter. However, in cases where the stress drops instantaneously at a boundary, the orientation of the rosette elements dictate whether the measurement relates better to the upper or lower stress value. As discussed earlier in the chapter the introduction of rosettes having all these gauge sensors in one 90° quadrant has largely alleviated the type of problem.

In-depth gradients are generally caused by some deliberate operation. Those induced by machining (including grinding) and shot-peening appear to be of greatest concern. If these are to be measured the technique requires some degree of modification.

First, it is necessary to measure the relaxed strains at chosen increments of depth, then calculate stresses at each increment, which can be attempted in more than one way. Kelsey [11] plotted measured strain changes against hole depth and compared these with a similar plot obtained from a uniform stress field. From the difference in slopes of the two curves he estimated the difference in stresses from that in the uniform case. Alternatively, values for the functions in equation (4) can be determined, empirically or theoretically, for specific increments of depth and calculations made accordingly. Unfortunately, both methods contain the same limitations. Both assume that the strain relaxed due to drilling through one increment of depth is related totally to the stress in that increment. Except for the first increment, this is clearly not the case. Succeeding increments will have been partially relaxed by preceding operations. Also, the relaxed strains are so small with respect to stress, that strain measurement resolution has a significant effect on the result.

In recent years a number of workers have combined finite element analysis with incremental drilling. (Schajer, [23], Manning and Flaman [26] and Owens [18]). Even so, the analysis can only deal accurately with specified stress fields. To date, there is no unique solution for the general case and the low sensitivity of incremental drilling cannot be avoided.

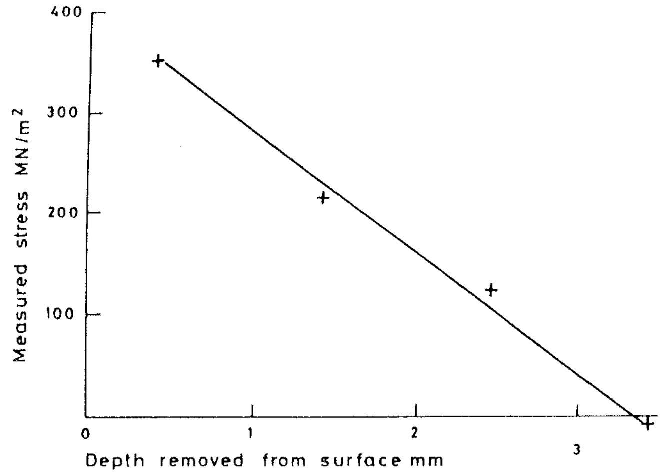
In the Authors' experience on structural work, the application of "incremental hole-drilling" has not generally been found necessary. Firstly, from the results of Kelsey [11] and Bathgate [19] it can be shown that in a linear stress gradient changing from σ_{max} at the surface to zero at full hole depth, which is severe, the technique predicts 0.8 σ_{max}, i.e. it effectively gives the stress at 20% of hole depth. Knowing this often means that a single measurement is all that is necessary. However, if more detail of the gradient is required, standard measurements coupled with layer-removal can be used. Two examples of this are given in Fig. 11.

Figure 11a shows the stresses resulting from a heavy milling operation using a worn cutting tool [20]. The first measurement was made at the machined surface (after final preparation for gauge attachment). Then material was removed to about half the depth of the machined hole and the second measurement made at an adjacent position. Further material was removed in two stages to allow the third and fourth measurements to be made in the same positions as the first and second, respectively. Corrections could have been made for the influence of stressed material removed, but this was not done in this case. It is clear that for all practical purposes the stress gradient is linear and consequently the first result is the stress at 20% hole depth, i.e. at 0.4 mm below the surface.

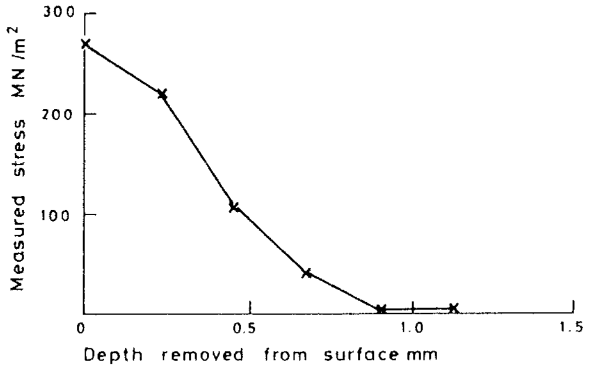
Figure 11b shows stress resulting from a surface grinding operation, such as would be used to dress welds or rough castings. The same technique was used as in the previous case, except relatively small layers were removed between each measurement.

From these two examples, and many others can be cited, it is clear that the complexities of incremental analysis only need to be attempted in special circumstances.

Surface Preparation. Where centre-hole measurements are to be made it is, obviously, necessary to prepare the surface for strain gauge bonding. As inferred by the previous discussion, machining operations, particularly grinding, can induce significant stresses which would be measured by the technique.



(a) Heavy Milling Induced Stresses



(b) Grinding Induced Stresses

Fig. 11 Measurement of in-depth stress gradients.

Surface preparation, therefore, must be undertaken with considerable care. this is particularly so if layer removal techniques are being used.

For general preparation, the use of small emery-disc polishers have been found adequate in most cases. For removing significant amounts of material, high speed tungsten - carbide burrs, provided they are used with care, are satisfactory in the easy to machine materials but tend to induce stresses in strain-hardening materials. Hand-filing has been found to be generally satisfactory but this is often slow and difficult.

As a result of working on high manganese steels, which are particularly difficult to machine, the Authors, in conjunction with NEI-Parsons in England, have developed a portable Electro-Chemical Machining (ECM) device. Using a sodium nitrate electrolyte and a DC potential of 12-15 volts, areas required for gauging can be machined at the rate of 1 mm depth in 3 or 4 minutes. This is now regarded as a general purpose tool.

SECTIONING

Full Relaxation

Sectioning is the original method of measuring residual stress. As long ago as the last century Kalakoutsky [27] used it to measure longitudinal stress in bars and throughout this century it has seen significant development. Kalakoutsky used a full relaxation technique in that, by cutting the bars into thin sections, he assumed that their stresses were completely relaxed and could thus relate the original residual stress to the relaxed strains using only the material elastic properties.

To obtain surface stress this technique is straightforward in principle, as all that is required is to measure relaxed strains, using either strain gauges or extensometors, as the piece of material on which the stress measurement is required is cut from the structure. In practice this has two drawbacks, firstly it is time consuming and, secondly, great care must be taken to ensure that no stress is introduced by the cutting processes as these will cause measurement errors. This technqiue can, however, be used on structures with complex geometries and by using suitable strain measuring rosettes can be used in any stress field. Procter and Mitchell [20] give an example of its use in a situation where the standard centre-hole technique could not be used due to inaccessibility.

Full relaxation by sectioning is limited to very simple geometries and stress fields when applied to the measurement of sub-surface stress. The reason for this is that the total strain relaxed by cutting the material from the structure cannot usually be measured directly or inferred. Clearly the circumstances in which measurements can be taken on sub-surface material is very limited. However, one application is given by Tebedge [28] who measured elongations and curvatures on slices of a welded section, as they were cut out as shown in Fig. 12. By making the assumptions that the stresses were only longitudinal and constant along the length of the specimen he built up the complete through thickness stress pattern.

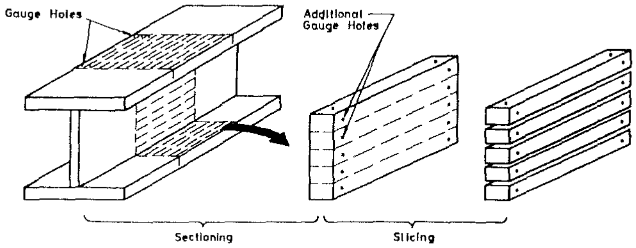


Fig. 12 Sectioning of welded joist by Tebedge.

Use is also made of full relaxation in the measurement of hoop stress in cylinders. By either making diametral measurements or surface strain measurements whilst the cylinder is cut axially and, assuming a linear through thickness stress gradient, hoop stress in the cylinder may be predicted. This is a particularly quick and easy method to apply. An example of its use is given by Crampton [29] who used it to make measurements on brass tubing.

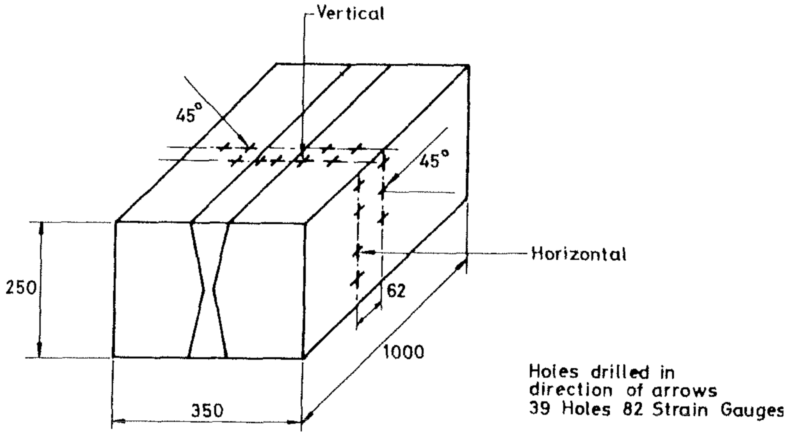


Fig. 13 Hole drilling/sectioning by Ferrill et al.

He calculated the internal circumferential stress from the measured radii using:

$$\sigma_t = \frac{Et}{2}\left(\frac{r_1 - r_2}{r_1 r_2}\right)$$

For long lengths of tube E would be better replaced by $E/(1-\nu^2)$.

Ferrill [30] investigated residual stresses in thick butt-welded specimens by drilling many 6 mm diameter holes in four directions, as shown in Fig. 13. He mounted a number of strain gauges axially in each hole and then cut the specimen into individual pieces so that the axial strains along each hole were relaxed and measured. By making various assumptions about uniformity and symmetry of the stresses he used combinations of the measured strains to calculate the stresses which had been relaxed. The major disadvantage, in addition to the assumptions about stress symmetry and uniformity, is the enormous amount of work required for drilling, cutting and strain gauging.

Blind Hole Method

More general sub-surface stress can be measured using an extension of full relaxation by sectioning, namely, the blind hole method. Leeman [31] described a technique for measuring stress in rock called the "Doorstopper" method whereby a flat bottomed hole is first drilled, the base of the hole strain gauged and then overcored, as shown in Fig. 14, to completely relax the stresses. The technique is firmly established in the mining industry and there is no reason why this same technique should not be applied in metal structures. Stoker [32] completed some calibration work in heavy steel beams under uniaxial tension but has not reported any practical applications.

The technique is not quite a full relaxation method since some of the stresses are relaxed when the initial blind hole is drilled, before strain measurements can be made. Thus the normal elastic material equations which relate stress and strain have to be modified. Working in rock, Leeman [31] suggests that if the hole is drilled along one principal stress axis and if the gauged area is

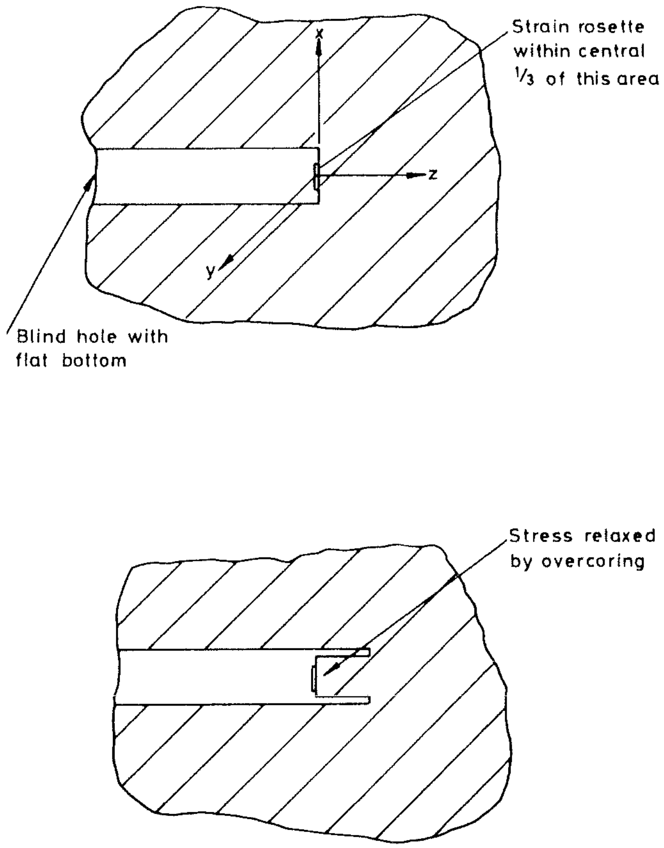


Fig. 14 Measurement of sub-surface stress by overcoring.

less than one third of the hole bottom area then, by first using the normal elastic stress strain relationships to calculate stress on the bottom of the hole, the true residual stresses can be calculated using the experimentally obtained equations:

$$\sigma'_x = 1.25\ \sigma_x - 0.75\ (0.645 + \nu)\ \sigma_z$$

$$\sigma'_x = 1.25\ \sigma_y - 0.75\ (0.645 + \nu)\ \sigma_z$$

$$\tau_{xy}' = 1.25\ \tau_{xy}$$

These same relationships should hold in metallic structures although this has not been verified. By drilling three holes it is possible to resolve principal residual stresses. The three holes must lie in one of the principal stress planes, and it must be assumed that the stresses are uniform in the volume of material under investigation.

This technique has not been fully developed and has two problem areas, firstly the strain gauge attachment and secondly the overcoring. By pre-wiring and casting the gauges in epoxy resin it should be possible to attach gauges on the hole bottom. Spark erosion or ECM appear the most promising methods for overcoring but clearly, with either method great care must be taken to protect the strain gauge installation from fluid penetration and the effect of temperature.

Partial Relaxation Methods

This potentially very powerful measurement technqiue can, in theory, be used to measure sub-surface stresses in structures with complex geometries. The technique consists of measuring the deformation or strains on surfaces of the structure as the body of the structure is cut or machined away. Sachs [33] was the first worker to use such a method. He took advantage of the simple relationships which relate the measured deformations due to relieved stress when an internal or external layer is removed from a cylindrical object in which it can be assumed that the stresses are both axially symmetric and constant over its axial length. His relationships are:

$$\sigma_a = \frac{E}{1-\nu^2}\left[\pm (A_o - A)\frac{d\lambda}{dA} - \lambda\right]$$

$$\sigma_t = \frac{E}{1-\nu^2}\left[\pm (A_o - A)\frac{d\theta}{dA} - \frac{(A_o + A)}{2A}\theta\right]$$

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

Where the positive sign is for boring, the negative for external material removal.

Using these equations and the systematic removal of layers a complete through thickness stress profile can be determined.

Plate-like specimens have been treated by Frick [34] in which, due to their geometric simplicity, it is again relatively easy to relate stress to relaxed strains or curvature when incremental layers are removed.

The most generalized method of measuring stress by partial relaxation is that of Stoker [32] who demonstrates that, at least in principle, any structural geometry containing any residual stress field can be evaluated. He shows, largely on mathematical models with very little experimental verification, that, using finite element analysis, stress relaxed on a cut surface can be evaluated from sufficient strain gauge measurements on free surfaces. He found however, that if the cut surface is remote from the strain gauged surface the problem is ill-conditioned and large numbers of entirely different cut surface stress distributions can give almost identical strains at the gauged surface. To overcome this problem he fixed strain gauges near the surface to be cut by attaching them to the bottom of suitably positioned flat bottomed holes.

General Comment to the Sectioning Method

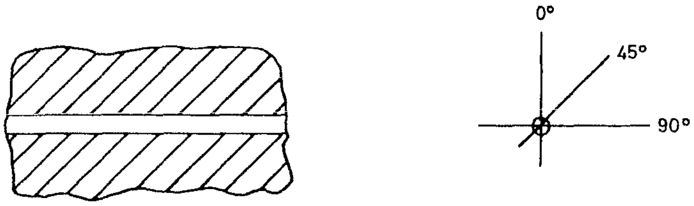
All these techniques require material removal without introducing spurious strains due to machining induced stresses. The only truly stress free methods of material removal are ECM and Chemical Etching. The former can be used to remove large volumes of material but due to the necessity of submerging the structure in salt solution it is difficult to use. Chemical Etching is very slow and can only possibly be considered for small structures. Thus, very light conventional machining, filing or gentle saw cutting are generally used, all of which may introduce errors of unknown magnitude. Because of machining difficulties and because these techniques completely destroy the structure, are very time consuming, and require great experimental expertise, they have largely given way to the now highly developed partial relaxation methods such as the centre-hole method.

DEEP HOLE METHOD

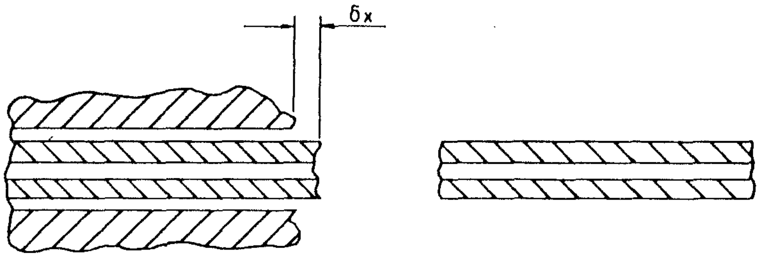
The Technique

The deep hole technique, first reported by Beaney in 1978 [35], is, to some extent, an extension of the Ferrill [30] and Leeman [31] methods, discussed before, but all the data required to obtain a full through thickness distribution of stress is obtained from one hole. This greatly reduces the work involved and need only leave holes about 20 mm diameter.

A hole is drilled through the structure and subsequently overcored. The overcoring relaxes the body stresses acting on the hole and consequently changes the hole shape. By measuring the changes in shape, diametral and axial, along the full length of the hole and with the aid of finite element analysis, a complete distribution of stress can be obtained. The principle is shown pictorially in Fig. 15.



1. Drill hole.
2. Measure diameters



3. Relax stresses & measure Axial strains
4. Re - measure diameters

Fig. 15 Principle of deep hole technique.

Analysis

Expressions were required to relate the relieved stresses on the cored-out surface to the measured bore strains. In order to determine the distribution of stress through the thickness of the structure the cylinder was analysed in blocks. Each block-length was loaded separately but the analysis accounted for any influence from adjacent blocks. Initially, however, it was necessary to account for the discontinuity effect of the drilled hole.

The analysis considered a hole in a plate uniformly loaded along one edge, as shown in Fig. 16. This resulted in values of block load (W) which were applied to single block-lengths of the overcored cylinder as shown in Fig. 17. The deformed shape of the cylinder was obtained for the application of W in three ways viz: at 0°, 90°, and at ± 45° to simulate two direct stresses and shear. In addition a direct axial stress was included in the analysis. In Fig. 18 an example is shown of the deflected shape of cylinder for one of these uni-directional loads, and the way this was averaged over block-lengths.

To account for end-effects the complete procedure was repeated, for application of the loads to adjacent blocks in turn starting at one end. End influence was found to be negligible after 5 blocks.

The result of the above analyses was a series of equations which can be expressed in matrix form. By inverting the matrix the desired equations relating the relieved stresses to the measured bore strains were produced.

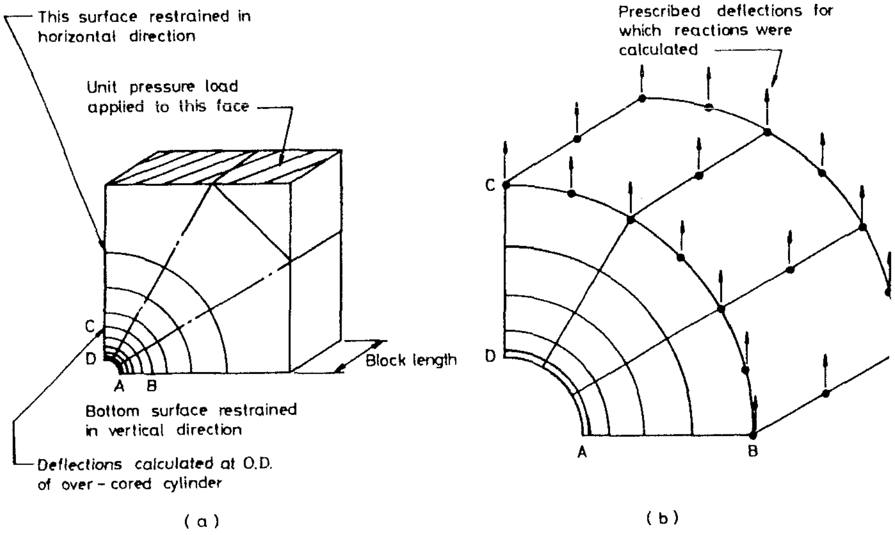


Fig. 16 Finite element analysis on plate with central hole.

Practical Considerations

From the analysis point of view, the hole and overcored cylinder diameters and block lengths are arbitrary. Thus choice of sizes relate to machining and measurement problems with respect to the quality and resolution of information. If the diameters of the hole and overcored cylinder are always of the same ratio, the analysis is valid in all cases.

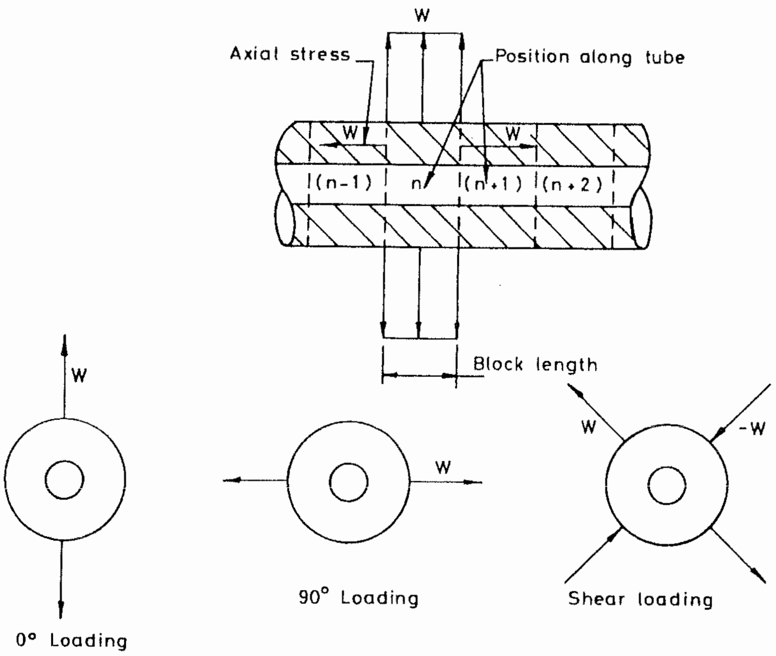


Fig. 17 Block loading on the cylinder.

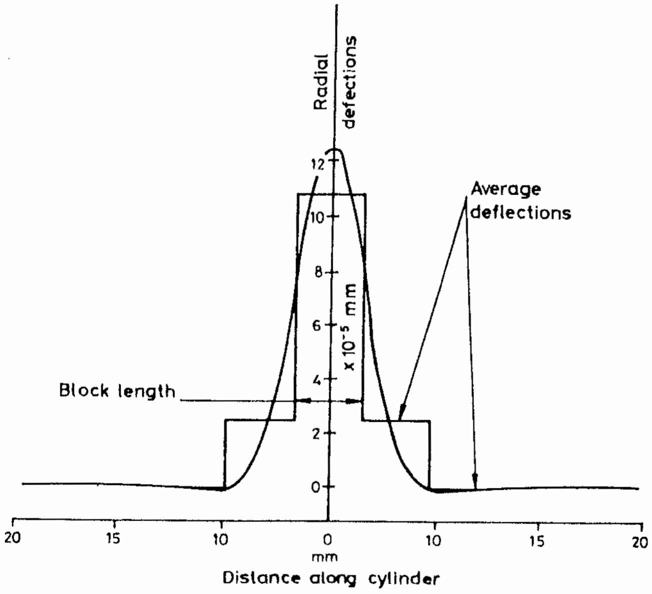


Fig. 18 Deflected shape of hole.

In welded structures in particular, where stresses are likely to be subject to considerable gradients, the method should average over the minimum area possible. In other words, the hole and overcored cylinder diameters should be as small as possible. Consideration must be given to the mechanics of hole drilling, overcoring and hole measurement. Although the presence of the drilled hole is taken into account in the analysis, any stresses induced by the drilling operation should not influence the stresses at the overcored surface. Also, it must be possible to measure the very small changes in hole diameter in order to obtain a satisfactory resolution on stress levels. Further, the overcoring technique must not be stress inducing since it is the stresses at the overcored surface which are being determined. Based largely on experience of strain measurement and mechanical machining problems it was considered that the smallest practicable cylinder size was 3.2 mm ID, 10 mm OD. A block-length of 6.35 mm was chosen as being less than one elastic die-away length for this size of cylinder and at the same time sufficient to produce detailed variations in stress on a through thickness basis.

The 3.2 mm hole is made by gun-drilling which produces smooth bored straight holes. This process uses a single point drilling tool, as shown in Fig. 19. The cutting head is fixed to a hollow kidney-shaped tube which can be of almost any length and which allows cutting fluid to be pumped up the inside in order to force the swarf back along the space provided by the depressed kidney section. Depending on the material being drilled, the drill speed and feed are of the order of 3000-10,000 rpm and 0.001 to 0.003 mm per rev. The supply pressure of the cutting fluid is about 100 bar.

Because the overcoring procedure must be stress free, ECM is used. The principle is shown in Fig. 20. The tool is cylindrical, insulated on the ID and OD except for the "cutting head". The electrolyte (sodium-nitrate solution) is pumped down the inside of the tool and collected from the outside. The power requirement is of the order of 500 amps at 8-10 V DC.

Fig. 19 Gun drill.

Hole Measurement

It is assumed that the direction of the hole coincides with the third principal stress. Thus by making three diametral measurements and an axial measurement,

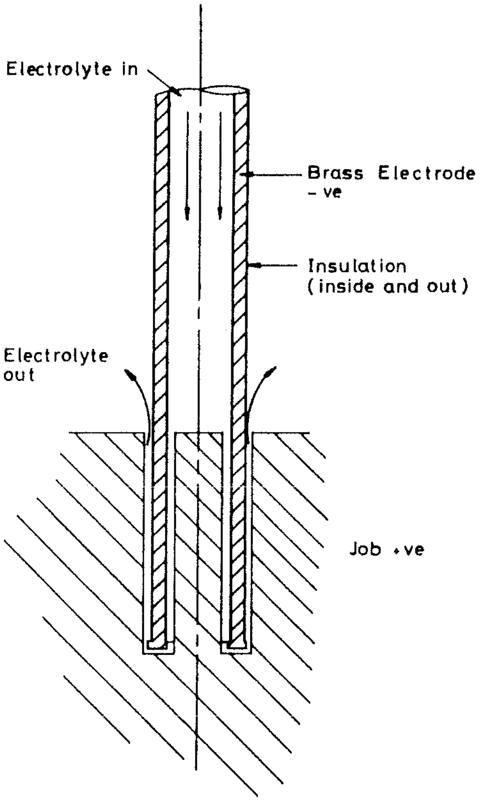


Fig. 20 Schemmatic of overcoring procedure.

the four strains are obtained which are required to calculate the three principal stress values, i.e. the maximum and minimum principal stresses and their directions normal to the hole, and the stress in the through thickness direction. For a resolution of 2 - 5 MN/m^2 in a uniaxial field, the strains are required to be determined to the order of 10-20 $\mu\varepsilon$. This means that changes on hole diameter must be measured to the order of 0.05 micron.

Diametral Measurements

To date, special measuring probes using strain gauge techniques have been made for the diametral measurements. The measuring head, shown in Fig. 21, uses two strain gauges each attached to an epoxy resin beam as the transducer. The beams are cast, with a steel pin close to their outer surface to increase sensitivity and physical response, and the strain gauges positioned at their inner surface at the casting stage. The two beams are then stuck together at their ends leaving a small gap along their "active" length. The strain-gauged assembly is mounted inside a thin-wall steel housing which has been brazed on to a length of hypodermic tubing through which the strain gauge leads pass. The housing is "belled out" at its centre to locate on the sides of the hole. Hardened steel pips are fixed to the backs of the beams to follow the hole

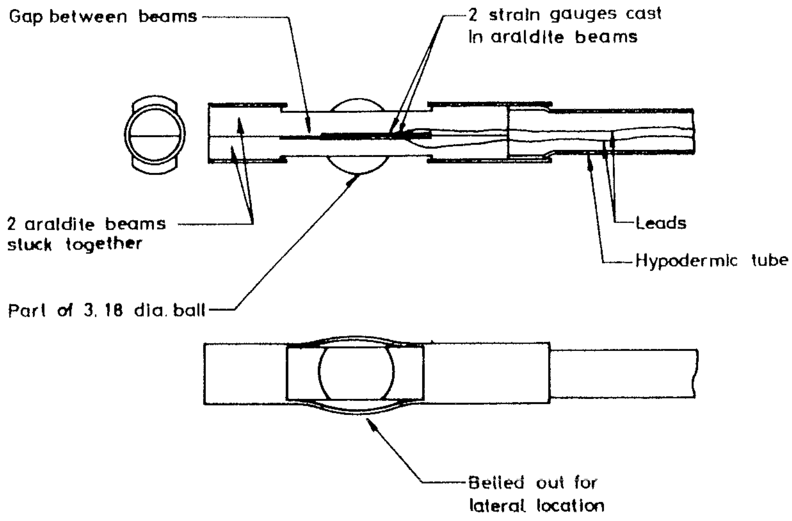


Fig. 21 Construction of measuring head.

contour. As the hole size varies the beams deflect accordingly and the strain gauge outputs are recorded on a data-logger.

Calibration of the probes has been effected by deflecting them in a bench micrometer and by drawing them through a cylinder externally loaded to a known deflection.

In use, the probe is drawn through the holes by a screwed rod mounted on a special frame and actuated by a stepper motor. The stepper motor is driven from the data-logger such that the screwed rod rotates through one revolution after each reading is recorded. Thus a reading is taken every pitch of the thread. On completion of a full length scan of the hole, the probe is driven back down the hole and the measurement repeated. After four such scans the data is averaged and inspected for consistency.

The initial sets of measurements, i.e. before coring out, are made by mounting the driver device on the structure surface. A special adaptor is used which allows the device and probe to be rotated in 45° steps. In this way, three sets of measurements are made, i.e. at 0°, 45° and 90°. After coring out, the cylinder is mounted in a secondary rig which allows the three sets of diametral measurements to be repeated.

The computer is programmed to use the averaged data from the four scans in each plane and calculate the differences in the data before and after coring out.

Because the analysis is based on a block length of 6.35 mm, the pitch of the screw thread is 2.12 mm. Thus three readings are used to obtain an average block strain.

Axial Measurements

Axial strain changes are measured and recorded during the overcoring process. Since the holes are drilled through the structure, the machining can be carried out from one side and the measurements from the other. The hole is capped at the end where machining starts and a rod inserted in the hole to transmit movement between the cap and a high accuracy capacitance displacement transducer mounted on the other surface. This transducer output is recorded with respect to depth overcored and converted to average strain per block-length.

Care is needed with the choice of material of the rod inserted in the hole and with the machining procedure to safeguard against errors resulting from thermal changes which can arise during the machining process.

Proving Trials

Verification of Theory. Three separate analyses were carried out to check the mathematics. First, an equi-biaxial stress field in the plane at right angles to the axis of the hole was considered. Bore strains were calculated using Lamés equations. These strain values were fed into the inverted matrix solution. The resultant stresses agreed to within +0/-1.8% of the values applied. Secondly, a finite element analysis of a through hole in a plate was used to obtain bore strains in a uniaxial situation. When these were fed into the matrix, varying the angle with respect to the stress field, the resulting maximum principal stresses had errors less than +2.6/-1.4%. Thirdly, a more complicated analysis was attempted. Using finite elements, a large block with external pressure loading was analysed. The analysis then considered the same block containing a 3.2 mm hole and the diametral strains on the bore of the hole calculated. The bore strains were then used in the inverted matrix to calculate stresses which should agree with those originally applied. Figure 22 shows the inverted matrix solution plotted against the applied stress values. The maximum differences between the two solutions are less than 4%, and some of this difference could arise from the course mesh used in original calculations.

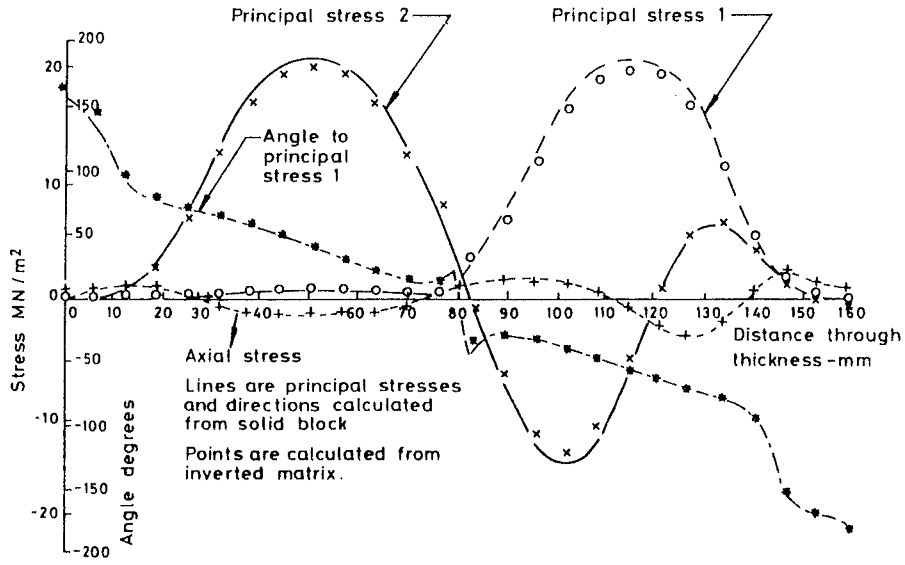


Fig. 22 Comparison of calculated stresses.

Hole Measurement Probes. In addition to the calibrations carried out in a bench micrometer, checks were made by drawing the probes through a cylinder with and without a known point load. A calculated hole deflection and probe measurements are shown in Fig. 23.

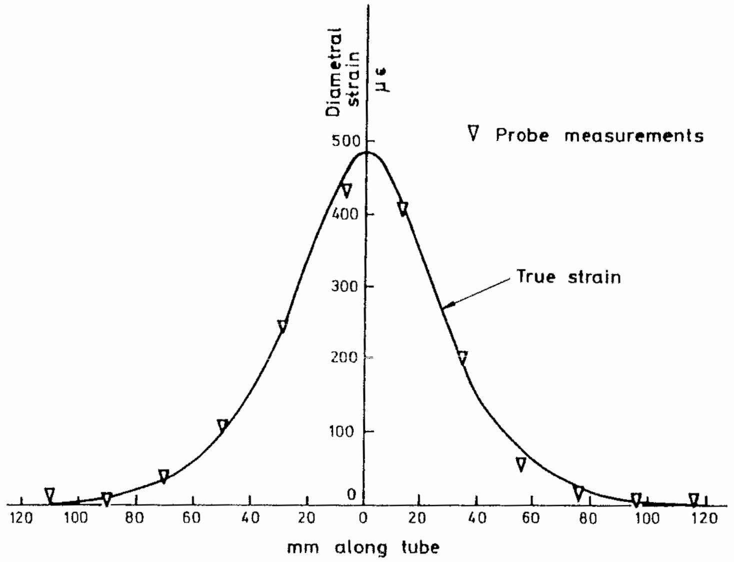


Fig. 23 Diametral strain in direction of load on the bore of a pinched tube.

Additionally, probes were drawn through an externally pressurized cylinder (Fig. 24) to which varying external pressures were applied. In all cases the measurements were within ± 8%.

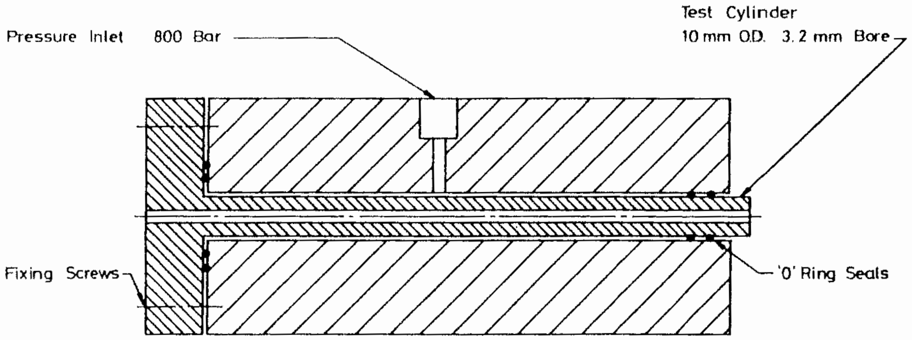


Fig. 24 Externally pressurised cylinder.

Full Analysis Trials. Despite proving the individual aspects of mathematical analysis and the measurement etc. final proof of the validity of the technique can only be demonstrated by full scale applications in known stress fields.

At the time of original development, tests were carried out in a specially cast cylindrical steel block. The block, 200 mm diameter, 150 mm long, was cast in a low alloy steel, and normalized and tempered as per production requirements. Residual stress levels were, obviously, unknown, but it was assumed that symmetry would apply. Eighteen holes were gun-drilled through the block in various directions. Twelve holes were strain gauged such that when the block was sectioned the stresses were totally relieved and calculated from the strain changes. Six holes were subjected to the deep hole analysis technique.

The results were encouraging but, arguably, did not provide categorical proof of the accuracy of the technique. The strain gauge/sectioning method indicated very low levels of residual stress, i.e. less than 20 MN/m^2, and the deep hole method gave no result in excess of this.

In subsequent trials, two rigs have been constructed. The externally pressurized cylinder as shown in Fig. 24 can be used to apply equi-biaxial compressive stress and a constant moment bending device, as shown in Fig. 25 to apply a linearly varying stress. These rigs are showing that the stresses can be predicted to within ± 10%. Probably more important, they are proving extremely useful in helping to solve various practical problems which have arisen during full scale applications.

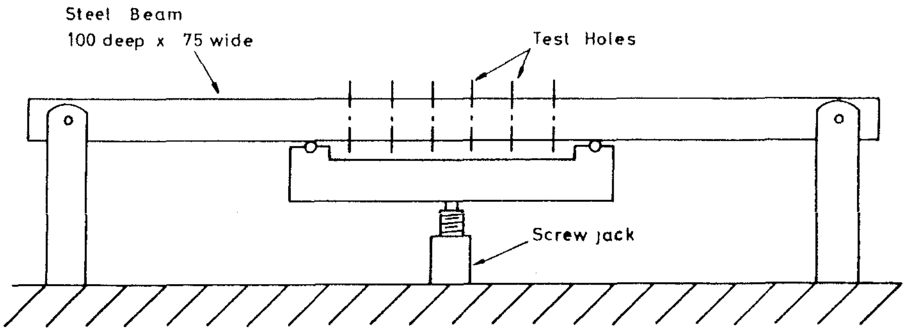


Fig. 25 Constant moment rig.

CONCLUSIONS

There is no doubt that the centre-hole technique is the most popular mechanical method for measuring surface residual stresses. This has evolved as a result of its simplicity of application, potential accuracy and the minimal damage to the structure under investigation. Additionally, the equipment required to make measurements is highly portable and, accordingly can be used in many working environments, i.e. on construction sites, power plants, factories, etc. There is a choice of centre-hole rosette strain gauges which allow a range of hole diameters and depths to suit particular requirements. Modern hole drilling methods, air-abrasion and ultra-high speed drilling, are simple to apply and offer stress-free drilling in most materials. The surface preparation required for bonding the strain rosettes is straightforward provided non-stress inducing methods are used. Considerable expertise is available, even with the most difficult to machine materials, and some guidelines have been provided in the text.

Many workers use the centre-hole technique to measure the gradient of stress with depth into the structure. Using incremental drilling techniques the gradients within one hole depth can be predicted, but the analysis relies on assumptions which are not strictly correct. The Authors have shown that the application of the technique in its standard form combined with layer-removal procedures, can produce reliable data for most structural requirements.

The trepan or ring-core method has been largely superseded by the centre-hole technique. To obtain full relaxation of strain at the surface the depth of trepan required is generally considered too damaging for structural applications, thus "part-depth" trepanning is practised. This, however, reduces the technique to one of partial relaxation and because of the greater problems of applications it is difficult to see any advantage over the centre-hole method.

Sectioning techniques will always have potential for specific applications, perhaps where the geometry restricts the use of standard methods. The theory is simple, i.e. provided a strain gauge can be attached in the required position and the material to which it is attached can be isolated from the main body, then the residual stress can be determined. Even for surface measurements, isolating the appropriate volume of material can be difficult, especially when it is remembered that stress-free machining processes should be used. If body stresses are being investigated the component has often to be modified in order to fix strain gauges in the required positions and this, of course, affects the analysis procedures. In regularly shaped geometries unique solutions can sometimes be established. The best example is probably that relating to straight cylinders in which measurements can be made on the inner or outer surface and layers remnoved from the other. The measurements can then be related to the stresses in the volume of material removed. Even this must assume uniformity of stress in the material removed and not be affected by the machining processes. Also, sensitivity requirements restrict the thickness of component which can be investigated.

Finite element analysis has clearly increased the potential of sectioning for the examination of complex geometries. The most recent development, that of deep hole drilling, has the potential of a standardized technique which can be used for the determination of complete through-thickness stress distributions in any geometry. Advanced measurement and machining technqiues are required, thus capital outlay can be considerable. However, when compared with the costs and problems of general sectioning this is not necessarily a major consideration. Further, and most important, the technique is quantifiable and has been shown to have a high accuracy potential.

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REFERENCES

1] Gunnert, R. (1955) Residual Stresses, Almquist and Wicksell, Stockholm.

2] Wolf, H. and W. Böhm (1971) The Ring-Core Method for Measuring Residual Stresses and its Use with Turbines and Generator Shafts. Archiv. Eisenhüttenwesen 42, pp. 195-200.

3] Freddi, A. (1974) Proposed Modification for the Analysis of Residual Tensions Using the Annular Groove Method. Int. Conf. on Exp. Stress Analysis, Udine Italy (Paper 38).

4] Morland, G. W. and J. M. Haynes (1972) Some Field Experience in Residual Stress Measurement. Inst. of Marine Engineers Conf. "The Recording and Interpretation of Engineering Measurements", London.

5] Böhm, W., E. Stucker and H. Wolf (1980) Principles and Application of the Ring-Core Method for Determining Residual Stresses. Messtechnische Briefe 16, Vol. 2.

[6] Mathar, J. (1934) Determination of Initial Stresses by Measuring the Deformation Around Drilled Holes. ASME Vol. 56, No. 4, pp. 249-254.

[7] Mesmer, G. A. (1936) Arc. Eisenhuttenwesen, Vol. 10, p. 59.

[8] Campus, F. (1946) Recherches, Etudes et Considerations sur les Constructions Soudees. Sciences et Lettres, Liege (Belgium), pp. 103-109.

[9] Soete, W. and R. Vancrombrugge (1950) An Industrial Method for the Determination of Residual Stresses. Proc. SESA, Vol. 8, No. 1, pp. 17-28.

[10] Boiten, R. G. and W. Ten Cate (1952) A Routine Method for the Measurement of Residual Stresses in Plates. Appl. Sci. Res. Section A Vol. 3, pp. 313-343.

[11] Kelsey, R. A. (1956) Measuring Non-Uniform Residual Stresses by the Hole Drilling Method. Proc. SESA, Vol. 14, No. 1, p. 181.

[12] Rendler, N. J. and I. Vigness (1966) Hole-Drilling Strain-Gage Method of Measuring Residual Stresses. Expl. Mechanics, Vol. 6, No. 12, pp. 577-586.

[13] Beaney, E. M. and E. Procter (1974) A Critical Evaluation of the Centre Hole Technique for the Measurement of Residual Stress, Strain, Vol. 10, No. 1.

[14] Bush, A. J. and F. J. Kromer (1972) Simplification of the Hole-Drilling Method of Residual Stress Measurement. Inst. Soc. America Trans. 112 (3) p. 249.

[15] Beaney, E. M. (1976) Accurate Measurement of Residual Stress on any Steel Using the Centre Hole Method. Strain, Vol. 12, No. 3, pp. 99-106.

[16] Flaman, M. T. (1980) Brief Investigation of Induced Drilling Stresses in the Center-Hole Method of Residual-Stress Measurement. SESA Spring Meeting, Boston.

[17] Birley, S. S., A. Owens and D. Clark (1978) The Application of Materials Testing to Experimental Stress Analysis. BSSM Conf. Bradford.

[18] Owens, A. (1983) Extension to the Blind Hole Drilling Technique for Residual Stress Determination with Airbrasive Hole Forming. Presented at "Residual Stress in Design and Fabrication", City University, London.

[19] Bathgate, R. G. (1968) Measurement of Non-Uniform Bi-Axial Residual Stresses by the Hole Drilling Method. Strain, Vol. 4, No. 2.

[20] Procter, E. and D. H. Mitchell (1983) Investigation of Machining Stresses on a Large Alternator Rotor. Proc. SESA Cleveland Ohio, pp. 345-349.

[21] Sandifier, J. P. and G. E. Bowie (1976) Modifications to the Hole-Drilling Method with Off-Centre Hole. SESA Spring Meeting, Silver Spring, USA.

[22] Bynum, J. E. (1979) Modifications to the Hole-Drilling Technique of Measuring Residual Stresses for Improved Accuracy and reproducibility. SESA Spring Meeting, San Francisco.

[23] Schajer, G. S. (1981) Application of Finite Element Calculations to Residual Stress Measurement. ASME, Vol. 103.

[24] Procter, E. and E. M. Beaney (1981) Recent Developments in Centre-Hole Technique for Residual Stress Measurement. SESA Proc. of Fall Meeting, Keystone, Colorado.

[25] Darbyshire, J. M. (1980) Some Effects of Strain Gauge Position and Orientation on Residual Stresses in Welded Joints as Measured by the Centre-Hole Technique. BSSM Int. Conf. "Product Liability and Reliability", University of Aston in Birmingham.

[26] Manning, B. W. and M. T. Flaman (1982) Finite Element Calculations of Calibration Constants for Determiantion of Residual Stress with Depth by the Hole-Drilling Method. Ontario Hydro Research Division Report 82-88-K.

[27] Kalakoutsky, N. (1888) The Study of Internal Stresses in Cast Iron and Steel.

[28] Tebedge, N., G. Alpsten and L. Tall (1973) Residual Stress Measurement by the Sectioning Method. Experimental Mechanics.

[29] Crampton, D. K. (1930) Trans. AIME 89, New York Meeting, February.

[30] Ferrill, D. A., P. B. Johl and D. R. Miller (1966) Measurement of Residual Stresses in Heavy Weldment. American Welding Research Supplement, Nov.

[31] Leeman, E. R. (1969) The Doorstopper and Triaxial Rock Stress Measuring Instrument Developed by the CSIR. Journal of the South African Institute of Mining and Metallurgy, pp. 305-339, February.

[32] Stoker, J. R. and P. J. Moir (1974) The Use of Finite Element Analysis and Strain Gauge Measurement in the Determination of Residual Stress. Int. Conf. on Exp. Stress analysis, Udine, Italy.

[33] Sachs, G. and G. Espey (1941) The Measurement of Residual Stresses in Metal. The Iron Age.

[34] Frick, R. P., G. A. Gurtman and H. D. Meriwether (19) Experimental Determination of Residual Stress in an Orthotropic Materials. Journal of Materials, Vol. 2, No. 4.

[35] Beaney, E. M. (1978) Measurement of sub-surface stress, BSSM Conference, Bradford.