1- A SIMPLE METHOD FOR DETERMINATION OF RESIDUAL STRESSES
2- USING DOUBLE-HOLE DRILLING TECHNIQUE

3- M.O. HENDY*, M.M. EL-SAYED* AND E.E. EL-SOALY**

4- ABSTRACT

One of the most common semi-distructive methods for determination of residual stresses in plates is the drilling hole method. In this method, a strain rosette or a set of strain gauges are usually used to measure the relaxed strains induced due to drilling of a central hole. The present work introduces a new simple method for determination of residual stresses in uniaxially stressed plates using double hole technique. Optimum dimensions for hole diameter and hole spacing, associated with a specific strain-gauge length, are determined. A constant relating the residual stress and the relaxed strain in a plate is obtained. Three different plate materials are considered; steel, laminated brass and aluminum. An experimental work is done to verify the theoretical analysis. For the stated plate materials, the experimental and theoretical results are in a good agreement.

INTRODUCTION

Residual stresses play an important role in fatigue failure, brittle fracture and environmental or stress corrosion cracking of engineering structures and components. There exist many different approaches which give accurate information on surface and sub-surface residual stress distributions. These approaches include analytical, numerical and experimental methods or their combinations.

The X-ray diffraction technique is the most common of non-destructive techniques. It is based on measuring the change in crystal lattice spacing caused by residual or applied stress at the surface [1]. The X-ray technique is susceptible to errors where plastic deformations or high temperatures cause distortion of the atomic structure of the material.

5- * Graduate Student and Assoc. Prof. in Mech. Design Dept., Faculty of Eng. and Tech., Mataria, Helwan University, Cairo.

** Prof. Gen. Chief of Mech. and Elasticity Dept., Military Technical College.

The most widely used technique for measuring residual stresses is the "Blind - Hole - Drilling" method. With this method, after installing strain gauges on the part surface, a small shallow hole is drilled in the surface [2]. After hole drilling, the change in strain at the immediate vicinity of the hole is measured, and the relaxed residual stresses were computed from these data, [3-6]. As the distance from hole increases, the relieved strains decrease very rapidly. Hence, it is desirable to measure the strain as close as possible to the hole in order to obtain maximum out-put signal of the strain gauges. On the other hand, parasitic effects also increase in the immediate vicinity of the hole. These considerations necessitate a compromise in the selection of the optimum measurement radius [7,8].

In the present work, a new technique is proposed to determine the residual stresses in a finite width plate subjected to uniaxial tensile loading. The residual strains were measured using relaxation technique. Instead of using a strain rosette or a strain gauge set, one strain gauge is used to determine the value of residual strains. After installing of the strain gauge, two equal small holes are drilled at equal distances along the measuring length of the strain gauge. The average relaxed strain over gauge length between the two holes is analytically determined. In the region between the two holes, more relaxed strain is obtained and hence more accurate results are expected. Two strain gauges, one on each face of the plate, may be used to minimize the bending effect in the plate.

Optimum hole dimensions and locations associated with a specific strain gauge length are determined. The relaxed strain in a stressed plate, associated with the proposed double hole technique, is used to determine the applied stress on the plate knowing the elastic properties of the plate material; Young's modulus and Poisson's ratio. The experimental work is performed on three sets of different engineering plate materials; steel, laminated Brass and aluminium. For each set of plate material, a constant is obtained relating the measured relaxed strain and applied stress. Knowing the material constant; associated with the double hole method, unknown residual stresses in uniaxially stressed plates can be determined.

THEORETICAL APPROACH

For a thin plate subjected to uniaxial tensile stress of magnitude σ_o, Fig.1, the radial strain relieved at a point $P(R,\theta)$, due to drilling of a small central hole of radius a, is given by, [2]:

$$\varepsilon_r(r,\theta) = -\frac{\sigma_o(1+\nu)}{2E} \cdot \left[\frac{1}{r^2} - \frac{3}{r^4}\cos 2\theta + \left(\frac{4}{1+\nu}\right)\frac{1}{r^2}\cos 2\theta\right] \quad (1)$$

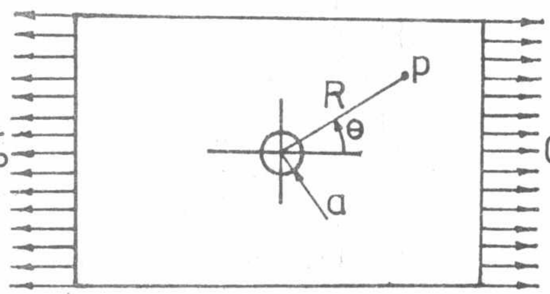


Fig.1. Uniaxially stressed plate with a small central hole.

where:

$$r = R/a$$

E and ν are the Young's modulus and Poisson's ratio of the plate material respectively.

Using the expression of the relaxed strain, Eq.(1), and considering the two holes 1 and 2 shown in Fig.2, the relaxed strain at point A due to presence of holes 1 and 2 are expressed in the following relations, respectively:

$$\varepsilon_r(r,0) = -\frac{\sigma_o(1+\nu)}{2E}\left[\frac{1}{r^2}\left(\frac{5+\nu}{1+\nu}\right) - \frac{3}{r^4}\right] \tag{2}$$

$$\varepsilon_r^*(r^*,\pi) = -\frac{\sigma_o(1+\nu)}{2E}\left[\frac{1}{r^{*2}}\left(\frac{5+\nu}{1+\nu}\right) - \frac{3}{r^{*4}}\right] \tag{3}$$

Superimposing the above two expressions,the radial strain relieved at point A caused from drilling of the two holes can be written in the form:

$$\varepsilon_r+\varepsilon_r^* = -\frac{\sigma_o(1+\nu)}{2E}\left[\left(\frac{5+\nu}{1+\nu}\right)\left(\frac{1}{r^2}+\frac{1}{r^{*2}}\right)-3\left(\frac{1}{r^4}+\frac{1}{r^{*4}}\right)\right] \tag{4}$$

If the relative distance r^* is expressed in terms of the relative hole spacing d and the radius r, Eq.(4) can be reduced to:

$$\varepsilon_r+\varepsilon_r^* = -\frac{\sigma_o(1+\nu)}{2E}\left(\frac{5+\nu}{1+\nu}\right)\left[\frac{1}{r^2}+\frac{1}{(d-r)^2}\right] - 3\left[\frac{1}{r^4}+\frac{1}{(d-r)^4}\right] \tag{5}$$

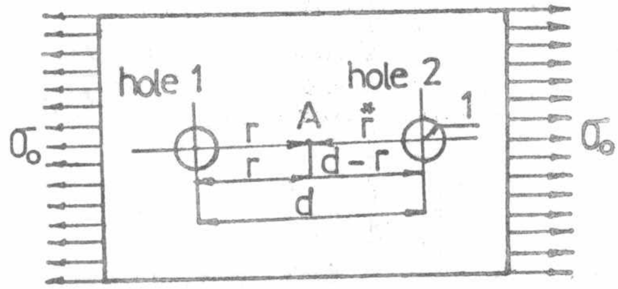


Fig.2. Double hole with relative dimensions.

Using the above expression, the average strain over a gauge length L between the two hole centers is determined as follows, see Fig.3:

$$\varepsilon_{av} = \frac{1}{L}\int_B^{D-B}(\varepsilon_r+\varepsilon_r^*)\,dR \tag{6}$$

Considering the following dimensionless relations;

$r = R/a, \quad \ell = L/a, \quad b = B/a, \quad d = D/a,$

Eqs.(4) and (6) lead to the following expression.

$$\varepsilon_{av} = -\frac{2\,\sigma_o(1+\nu)}{E\,\ell} \quad \frac{5+\nu}{1+\nu}\left[\frac{1}{d-\ell} - \frac{1}{d+\ell}\right] +$$

$$+\,4\left[\frac{1}{(d+\ell)^3} - \frac{1}{(d-\ell)^3}\right] \qquad (7)$$

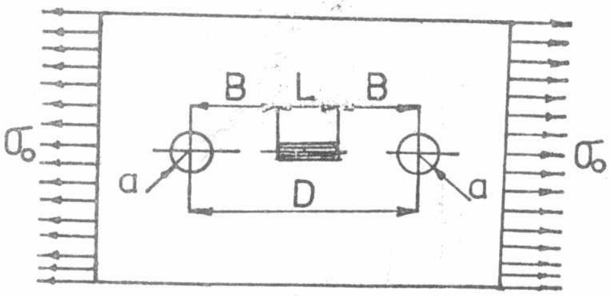


Fig.3. Strain gauge and double hole geometry.

For a given relative length ℓ , the maximum value of the relieved strain is obtained under the condition:

$$\frac{d\,\varepsilon_{av}}{d(d)} = 0 \qquad (8)$$

The condition (8) leads to the following relation between the relative spacing d and the relative length ℓ :

$$\frac{d^2+\ell^2}{(d^2-\ell^2)^2} = \frac{5+\nu}{24(1+\nu)} \qquad (9)$$

EXPERIMENTAL WORK

Three sets of standard specimens according to (ASTM 8), [9], were used in experimental work (4 steel specimens, 4 laminated brass, and 4 aluminium). The following are the specimen dimensions; Fig.4.

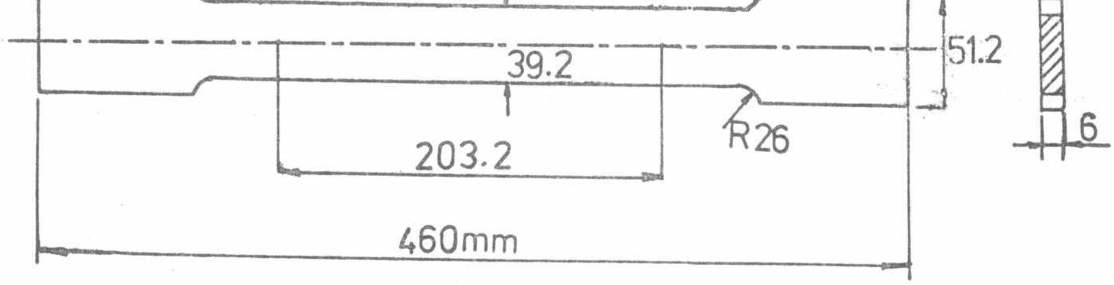


Fig.4. Standard specimen used in study.

The Mechanical properties of used specimens are given in Table 1.

Table 1. Mechanical properties of specimen Materials

Set	Material	E (GPa)	ν	σ_Y(MPa)	σ_u(MPa)	B.H.N.
I	Steel	210	0.298	338	562	120
II	L.Brass	80	0.35	256	366	30
III	Aluminium	72.5	0.33	250	130	25

The applied tensile stress must be uniform throughout the cross-sectional area of the specimen. To fulfil this requirement, preliminary tests were made on specimens 39.2x6 mm in cross-section and 460 mm. long, mounted in the flat grips in Tensile Test Machine. Two strain-gauges were mounted on the two sides of the specimen. Comparison of the obtained readings on each side of the specimen permits the detection of any change in machine specimen alignment.

The applied stress must be of magnitude sufficient to produce reasonable values of strain to be measured but at the same time it does not exceed the elastic limit of the material. To fulfil these requirements, the values of the applied stress must be smaller than one-third of the yield stress of the material .

The specifications of the strain gauges used in the experimental work are:

Type : FLA-6-11, Gauge length : L = 6 mm.

Gauge factor : K = 2-2.01, Gauge resistance : R = 120 $\pm$ 0.3 ohms.

A portable digital strain indicator equiped by a high-quality switch and balance unit were used for measuring induced strains. Tinsley Telcon switch and Balance unit Type 5794 were used in experimental application to measure the strain relaxations on the surface of the specimen.

Hole - Drilling Operation

The holes were drilled manually after the load application in the Tensile Testing Machine. To avoid the effect of heat generation and bending stresses that may result from drilling operation, the holes must be carefully drilled and small feeding rates were used. A small guide hole was used to maintain eccentricity of hole location and hole straightness through the plate thickness.

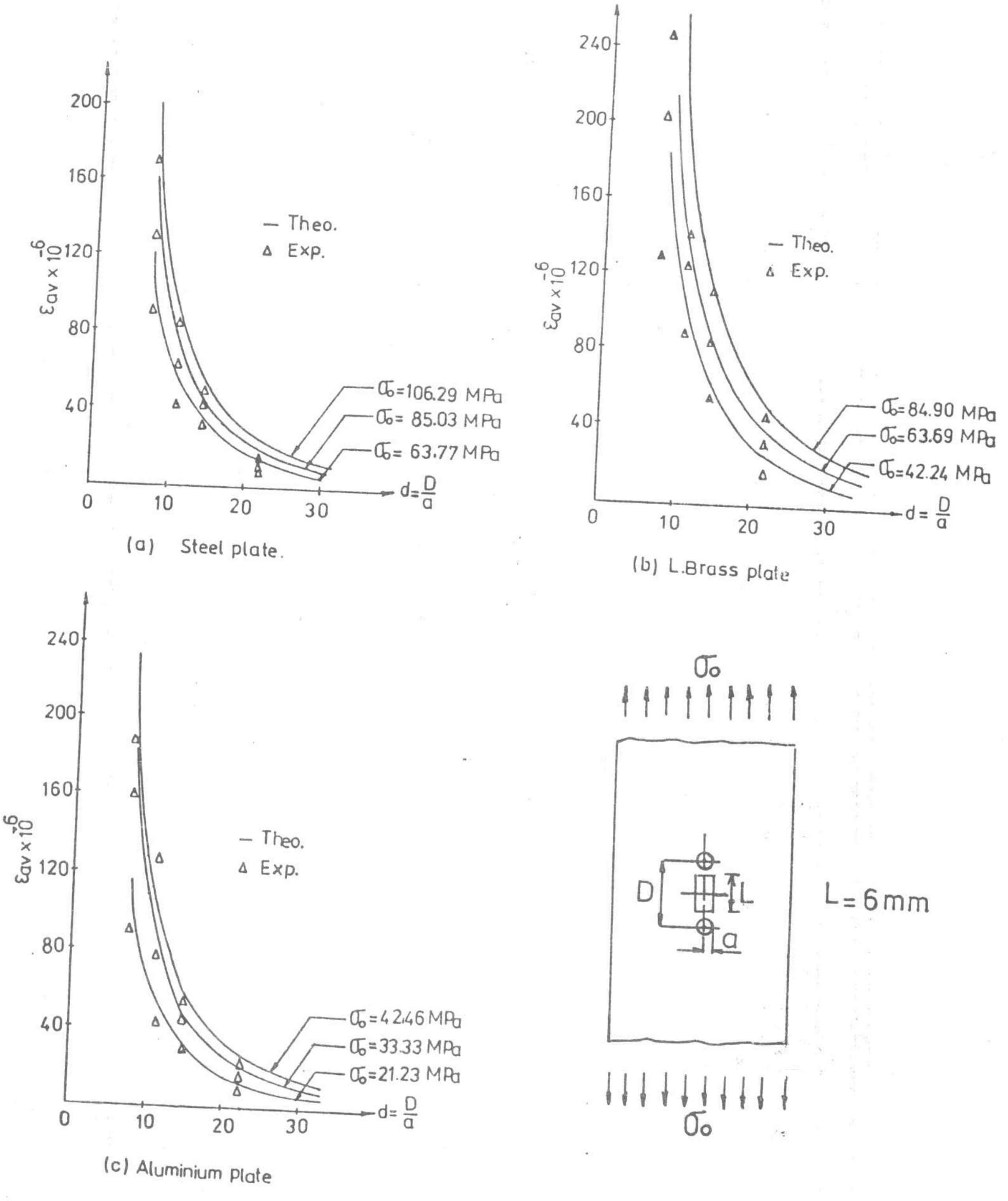


Fig.5. Variation of the average relaxed strain ε_{av} with the relative hole spacing d, for different plate materials; (a) steel, (b) laminated brass and (c) aluminium.

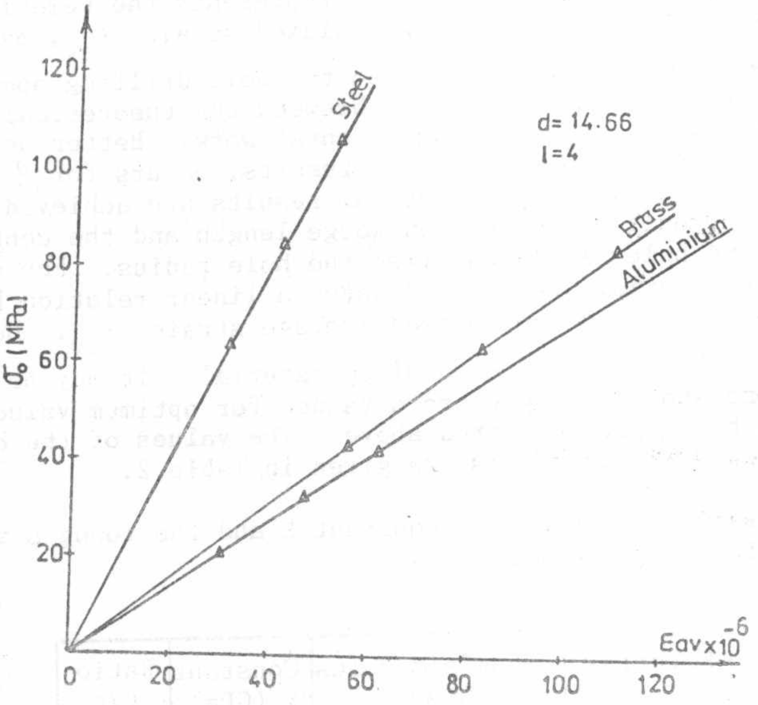
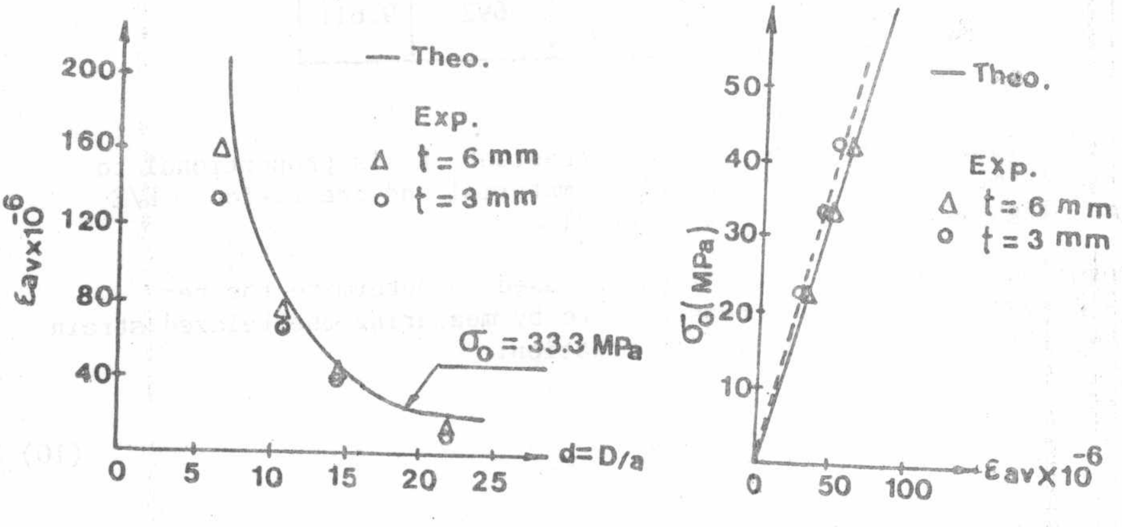


Fig.6. Relation between the applied stress σ_o and the average relaxed strain ε_{av}, for steel, L.brass and aluminium plates, at optimum hole spacing and hole diameter.



(a) ε_{av} against D/a ratio (b) σ_o against ε_{av}.

Fig.7. Effect of plate thickness on measured relaxed strain for aluminium plates.

RESULTS AND DISCUSSION

Tests were carried out on three sets of standard specimens from steel, laminated brass and aluminium. Fig.5 represents the relation between the applied stress σ_o and the average relaxed strain ε_{av}, over a specified strain gauge length L, induced due to the hole drilling operation. Results in Fig.5 indicate a good agreement between the theoretical analysis, deduced from Eq.(7), and the experimental work. Better accordance, between experimental and theoretical results, occurs for $\ell = 4$ and d = 14.66. That is means that optimum results are achieved when the hole diameter is one-half of the strain gauge length and the central distance between the two holes is 14.66 times the hole radius. For each of considered plate materials, Fig.6 indicates a linear relation between the applied stress σ_o and the relaxed average strain ε_{av}. Hence, a constant can be determined for each plate material. It may be indicated that relations shown in Fig.6 are obtained for optimum values of hole diameter and hole spacing stated above. The values of the constant K for considered plate materials are given in Table 2.

Table 2. Comparison between the constant K and the Young's modulus E for different plate materials.

Material	Young's modulus E (GPa)	Constant K (GPa)	Ratio K/E
Steel	210	2050	9.762
L.Brass	80	752	9.400
Aluminium	72	692	9.611

Results in Table 2 indicate that the constant K is proportional to the Young's modulus E for each plate material and the ratio K/E differs slightly with the plate material.

The obtained constant K can be easily used to determine the residual stress σ_{res} in a stressed plate by measuring the relaxed strain ε_{av} and the use of the following relation:

$$\sigma_{res} = K \ \varepsilon_{av}. \qquad (10)$$

To study the effect of plate thickness on the measured relaxed strain, aluminium plates with different thicknesses were checked. Fig.7 shows that the effect of plate thickness on the measured relaxed strain and hence the constant K are not significant.

CONCLUSION

A proposed simple method for determination of residual stresses in uniaxially stressed plates has been introduced, using double hole technique. Optimum values of hole diameter and hole spacing, associated with a certain gauge - length, are determined to get maximum strain relaxation. Instead of using expensive strain rosettes or strain gauge sets, one strain gauge is sufficient to measure the relaxed strain and hence the residual stress in a uniaxially stressed plate. For each of the three examined plate materials; steel, laminated brass and aluminium a constant is obtained relating the residual stress and the measured relaxed strain induced after drilling of the two holes. The obtained constant K is proportional to the Young's modulus E and the ratio K/E differs slightly with the plate material; K/E = 9.762 for steel plate and 9.611 for aluminium plate.

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