ANALYTICAL STUDY OF STRAIN'S RANDOM ERROR ON RESIDUAL STRESSES CALCULATED BY HOLE DRILLING METHOD

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1. Introduction

The hole-drilling method is an effective and popular semi-destructive technique for residual stress (RS) measurement. It consists in drilling a very small hole into the specimen; consequently, RS relaxes in the hole and stresses in the surrounding region change causing strains also to change; a strain gage rosette, specifically designed and standardized measures these strains. Using special stress-strain relationships, the RS field is calculated from the measured strains. Stress calculations are extremely sensitive to errors in the measured strain: small strain measurement errors can cause significant variations in calculated stresses, particularly for stresses far from the surface [1]. This error sensitivity occurs because the strains are measured at the specimen surface, but the desired RS are inside the specimen. This paper presents an analysis of the influence of the strain measurement error on the computed stresses. Particular emphasis is placed on influence of both the number of total steps and the type of step increment. Both the Integral and Power series stress calculation methods are investigated, and their different responses to measurement errors are described.

2. Methodology

The Power series assumes that the unknown stress distribution is expandable into a power series: $\sigma(h) = b_0 + b_1 h + b_2 h^2 + \ ...$
Finite element calculations are used to compute series of coefficients $\bar{a}^0(h)$, $\bar{a}^1(h)$, $\bar{a}^2(h)$ and $\bar{b}^0(h)$, $\bar{b}^1(h)$, $\bar{b}^2(h)$, corresponding to the strain responses when hole drilling into stress fields with power series variations with depth h, i.e., $\sigma^0(h) = 1$, $\sigma^1(h) = h$, $\sigma^2(h) = h^2$, etc. These strain responses are then used as basis functions in a least-squares analysis of the measured strain relaxations. Only the function $\bar{a}^0(h)$, $\bar{b}^0(h)$, and $\bar{a}^1(h)$, $\bar{b}^1(h)$ are given because the hole drilling method is not well adapted to giving accurate values for more than the first two power series terms for stresses. For the same reason, the maximum depth below the surface is limited to 0.5 r_m where r_m is the radius of the gage circle. An advantage of the Power series method is that it is relatively robust numerically because the least-squares procedure used tends to smooth out the effects of random errors in the experimental strain data. This averaging effect is particularly effective when strain measurements are made at many hole depth increments. A limitation of the method is that it is suitable only for smoothly varying stress fields.

In the Integral method, the surface strain relief measured after completing hole depth step j depends on the RS that existed in the material originally contained in all the hole depth steps $1 \leq k \leq j$:

$$\varepsilon_j = \frac{(1+\nu)}{E}\sum_{k=1}^{j} \bar{a}_{jk}\left(\frac{\sigma_x+\sigma_y}{2}\right)_k + \frac{1}{E}\sum_{k=1}^{j} \bar{b}_{jk}\left(\frac{\sigma_x-\sigma_y}{2}\right)_k cos2\theta + \frac{1}{E}\sum_{k=1}^{j} \bar{b}_{jk}(\tau_{xy})_k sin2\theta$$

where θ is the angle of strain gage from the x-axis. The calibration constants $\underline{a}_{jk}$ and $\underline{b}_{jk}$ indicate the relieved strains in a hole j steps deep, due to unit stresses within hole step k. Numerical values of the calibration constants have been determined by finite element calculations for standard rosette patterns. Using the Integral method, stress calculations are effective when few hole depth steps are used. For large number of drilling steps, the calibration matrices $\underline{a}$ and $\underline{b}$ become numerically ill-conditioned: small errors in experimental measurements can cause much larger errors in calculated residual stresses. To reduce this effect, ASTM E837-08 and the H-Drill software adopt the Tikhonov regularization.

3. Experimental Plan

Several works dealing with the non uniform residual stress measurement by the hole drilling method [1] have emphasized its high sensitivity to errors in the measured data. In particular, the experimental practice shows that the major errors in the computed stresses are due to the strain measurement error, since the other errors are generally minor. For this reason, the present study concentrates on the strain measurement error, which is the dominant error source. In particular we have considered a set of linear deformation (ε_{1L}, ε_{2L}, ε_{3L}), the same set both with random strain error included between ±3με ($\varepsilon_{1L\pm3}$, $\varepsilon_{2L\pm3}$, $\varepsilon_{3L\pm3}$) and with random strain error included between ±15με ($\varepsilon_{1L\pm15}$, $\varepsilon_{2L\pm15}$, $\varepsilon_{3L\pm15}$). The problem of optimizing the step distribution was considered by Schajer [2] and Stefanescu [3]. In order to provide indications for the optimal step selection we have considered both constant calculation step (20, 10, 4 in a total depth of 1 mm) and incremental calculation step (12, 10, 8, 6, 4 in a total depth of 1 mm).

The errors on the calculated stresses are obtained from the equations: $E_{\pm3} = \frac{\sigma-\sigma_{\pm3}}{\sigma} * 100$ $E_{\pm15} = \frac{\sigma-\sigma_{\pm15}}{\sigma} * 100$

where σ is the stresses calculated considering the linear deformation, $\sigma_{\pm3}$ and $\sigma_{\pm15}$ are the stresses calculated considering the linear deformation with random strain error included between ±3με and ±15με respectively.

4. Experimental Results

Figure 1 shows the maximum errors for minimum residual stress calculated by means Integral method and Power series method of Restan [4] and H-Drill software [5].

Experimental data show that error on Integral Restan are higher than on Integral H-Drill, both in case of constant and incremental step. This result should be correlated to the Tikhonov regularization that is implemented by H-Drill software and not by Restan software. Moreover, it seems that when strain measurements are made at many hole depth increments, errors of Power series H-Drill are smaller than errors of Integral H-Drill; when few hole depth steps are used, errors of Power series H-Drill are larger than errors of Integral H-Drill. Using Restan software it seems that errors of Integral method are always larger than errors of Power series method. Finally it seems that there isn't difference between constant and incremental calculation step.

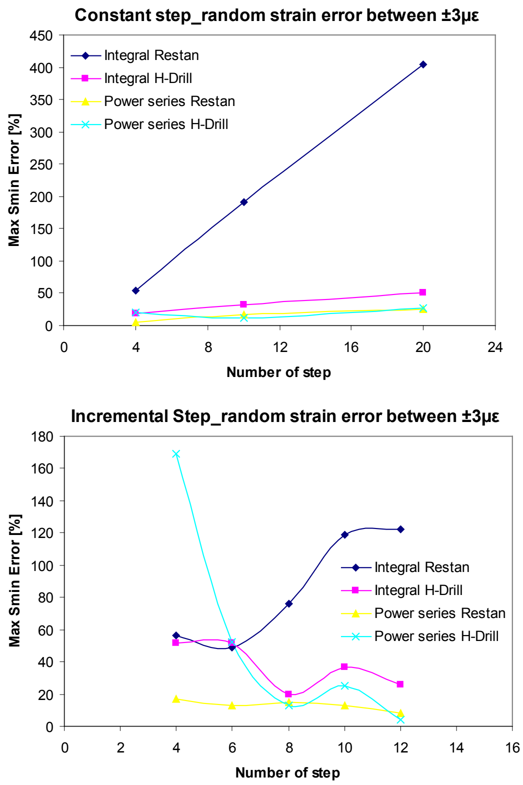

Fig. 1: Error curves

References

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