FINITE ELEMENT ANALYSES OF THE HOLE-DRILLING METHOD FOR RESIDUAL STRESS EVALUATION

ENRICO REFFO

INTRODUCTION

Residual stresses are stresses that persist in a structural component even when no loads are applied on it. They play a fundamental role in determining the resistance of several structural components. Among the available measurement techniques, the hole-drilling strain-gage method is the most widespread, because of its cost and flexibility. It is a semi-destructive experimental technique: it involves attaching a purpose designed strain-gage rosette to the specimen surface, drilling a small diameter hole (typically 1 to 2 mm) at the center of the rosette by consecutive steps and measuring the resulting relieved strains after each step. The residual stresses within the removed material are then determined from the measured strains through calculation.

Fig.1 – From the left: drilling equipment, strain-gage rosette, setup configuration.

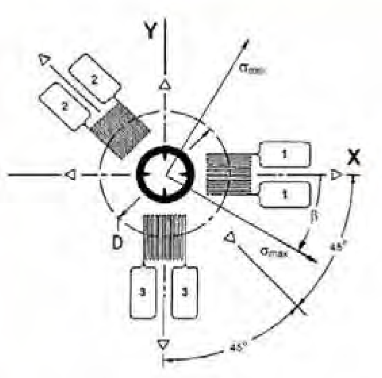
The aim of this work is to develop a FEM based method capable of emulating the response of components to the removal of material by means of the hole-drilling strain-gage method and to deeply review this measurement technique with both experimental and numerical approach.

CALIBRATION COEFFICIENTS

The hole-drilling strain-gage method is completely defined by ASTM E837-13a standard [1] and summarized in Fig.2.

THIN WORKPIECE: UNIFORM STRESS PROFILE	THICK WORKPIECE: UNIFORM STRESS PROFILE	THICK WORKPIECE: NON UNIFORM STRESS PROFILE
THROUGH HOLE 1 STEP	BLIND HOLE 10 STEPS	BLIND HOLE 20 STEPS

ε_1 ε_2 ε_3 MEASURED ON THE STRAIN GAGES ON THE WORKPIECE SURFACE AROUND THE HOLE AFTER EACH STEP



$$p = \frac{\varepsilon_3 + \varepsilon_1}{2}, \quad q = \frac{\varepsilon_3 - \varepsilon_1}{2}, \quad t = \frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{2}$$

$$\begin{bmatrix} \bar{a}_{11} & 0 & 0 & \dots & 0 \\ \bar{a}_{21} & \bar{a}_{22} & 0 & \dots & 0 \\ \bar{a}_{31} & \bar{a}_{32} & \bar{a}_{33} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \bar{a}_{j1} & \bar{a}_{j2} & \bar{a}_{j3} & \dots & \bar{a}_{jj} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ \vdots \\ P_j \end{bmatrix} = \frac{E}{1+\nu} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \vdots \\ p_j \end{bmatrix}$$

$$[\bar{\mathrm{a}}]\,\mathbf{P} = \frac{E}{1+\nu}\,\mathbf{p}, \quad [\bar{\mathrm{b}}]\,\mathbf{Q} = E\,\mathbf{q}, \quad [\bar{\mathrm{b}}]\,\mathbf{T} = E\,\mathbf{t}$$

$$(\sigma_{max})_k = P_k + \sqrt{Q_k^2 + T_k^2}, \quad (\sigma_{min})_k = P_k - \sqrt{Q_k^2 + T_k^2}, \quad \beta_k = \frac{1}{2}\arctan\left(\frac{-T_k}{-Q_k}\right)$$

Fig.2 – Stress profile calculation procedure. Formulas correspond to the non uniform stress profile case.

p,q,t (or **P,Q,T**) represent the equi-biaxial, deviatoric and pure shear strains (or stresses) arrays, computed from the measured strains ε_1, ε_2 and ε_3. Principal stress profiles come from the solution of each set of equations, which requires the second order Tikhonov regularization technique. [a] and [b] are lower triangular matrices made by calibration coefficients a_{jk} (or b_{jk}) which indicate the relieved strain in a *j*-step deep hole, due to unit equi-biaxial (or shear) stress within hole step *k*.

$$\varepsilon = \frac{1+\nu}{E}\,\bar{a}\,\frac{\sigma_x + \sigma_y}{2} + \frac{1}{E}\,\bar{b}\,\frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \frac{1}{E}\,\bar{b}\,\tau_{xy}\sin 2\theta$$

ANSYS HARMONIC ELEMENTS PLANE25
FROM 3D TO 2D: MODEL BASED ON FOURIER SERIES EXPANSION

a_{jk}: CONSTANT TERMS EQUI-BIAXIAL UNIT LOAD	b_{jk}: 2nd ORDER TERMS SHEAR UNIT LOAD

530 SIMULATIONS FOR STANDARD ROSETTE PATTERNS
NEW COEFFICIENTS: RESULTS IMPROVED BY 8%

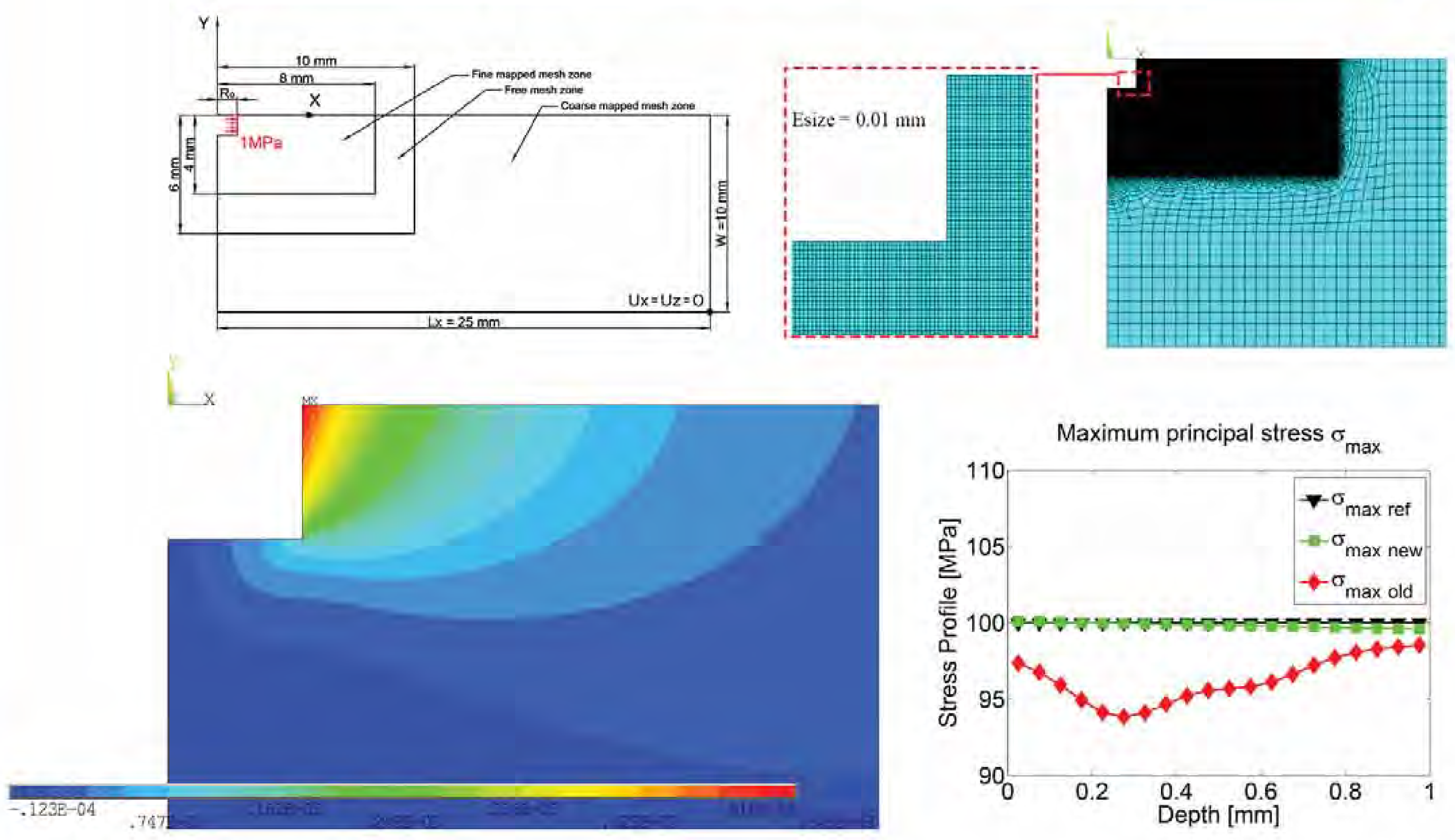


Fig.3 – From the left to right and from up to bottom: 2D model, mesh details, equi-biaxial relaxed deformation at the 20th hole step (undeformed model), comparison between maximum principal stress profiles computed with the old and the new set of calibration matrices.

FINITE ELEMENT DRILLING METHOD

In the second phase of the work a FEM based method was developed, that capable of reproducing the removal of the material from the workpiece due to drilling. Three different method were tested under 10 distinct combinations of geometry and known load conditions. The most accurate one was chosen after 1800 simulations. Based on the "Element Birth and Death" feature (also named EKILL), it consists of "freezing" groups of elements one by one in consecutive load steps.

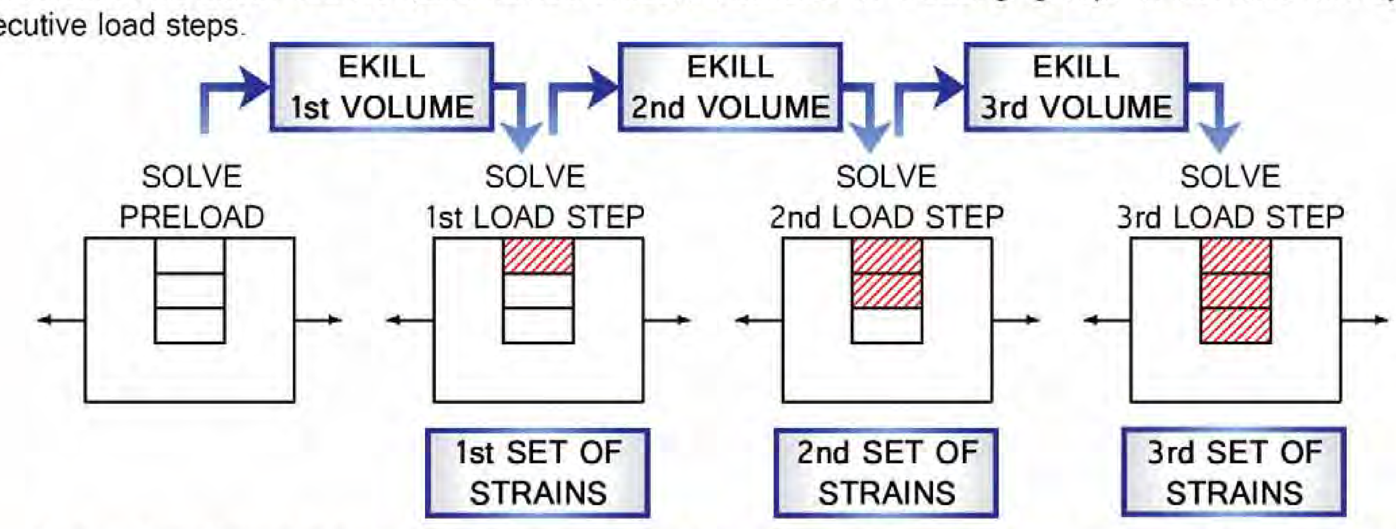


Fig.4 – Simulation of the drilling process: higlighted elements are deactivated one by one in several load steps.

ZERO DEPTH ERROR

This FEM simulation of the drilling process can be used to study the effect caused by the most important error sources, such as the zero depth error. It happens whenever the cutting tool has already removed a portion of the workpiece material when it is stopped to set the zero depth reference. In the third phase of this experience a full factorial DOE was carried out, reproducing the hole-drilling method on a simple geometry by different loading condition (18 cases) and error magnitude Z_0 (10 values between 0 and 0.10mm). On the basis of 8316 simulations, the response surface in Fig.5 was obtained.

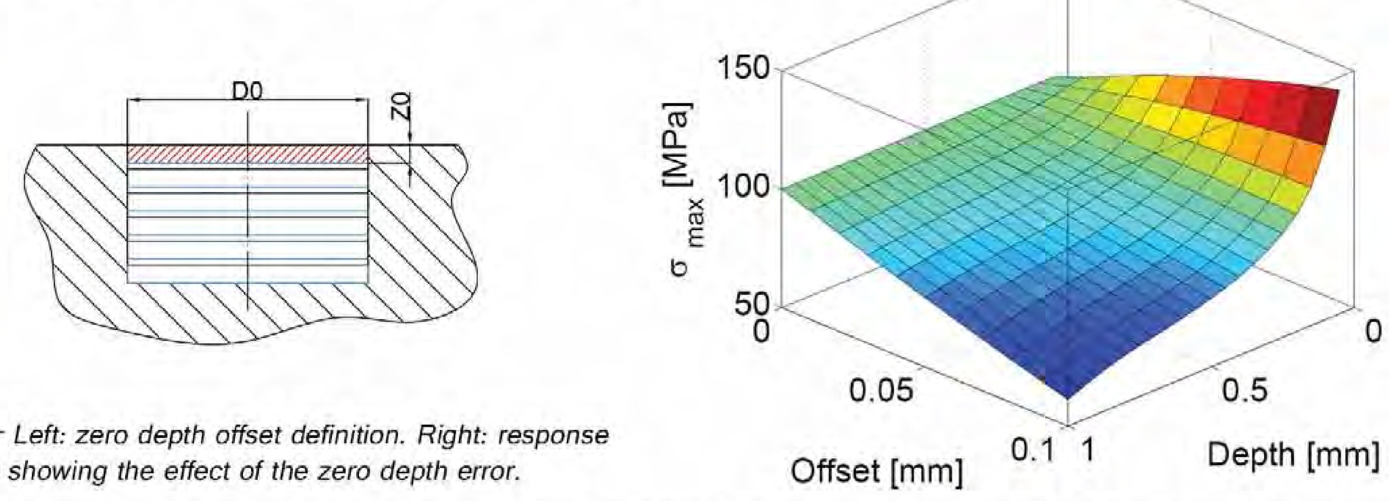


Fig.5 – Left: zero depth offset definition. Right: response surface showing the effect of the zero depth error.

It can be observed that the greater the error magnitude is, the greater the error on the calculated stress profile will be: in particular, in the worst case, with a zero depth offset Z_0 = 0.10mm, the stress profile is affected by errors ranging between -30% and +50%. This is not acceptable for practical applications, so correction equations were derived: the error on the stress profile can be reduced to around 5%. See [2] for further informations.

EXPERIMENTAL AND NUMERICAL REVIEW

In the last stage of the work, some tests were carried out in order to validate the FEM simulation of the drilling process. The hole-drilling method was applied to a cantilever beam under a known end load: strain values were measured before and after each load step to exclude the effects due to unknown residual stresses. The goal was to reproduce the known stress profile using the hole-drilling method. Results disappointed expectations, despite the inspection of the specimen excluded errors in the technique application.

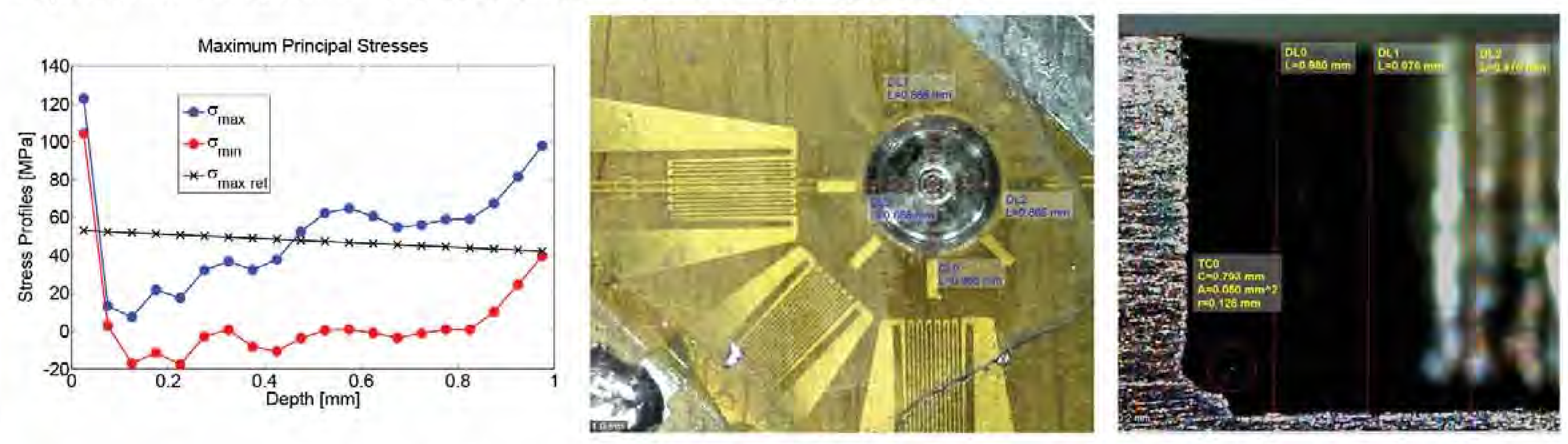
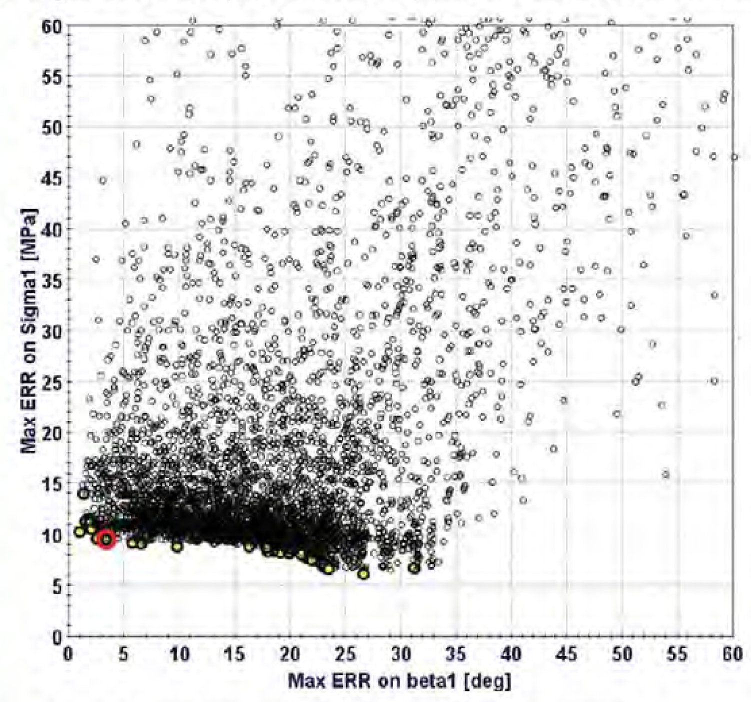


Fig.6 – Left: Experimental results. Right: inspection of the specimen after the test.

Therefore a deep review of the hole-drilling method was done. A reverse engineering analysis using modeFRONTIER combined with Matlab was carried out to establish which set of relieved strains minimized the deviations both in the maximum principal stress and in its orientation from nominal values. The Pareto frontier showed that, from the practical point of view, there couldn't be any combination of relieved strains that could lead to a given stress profile. The optimal combination of relieved strains was chosen for further verifications.



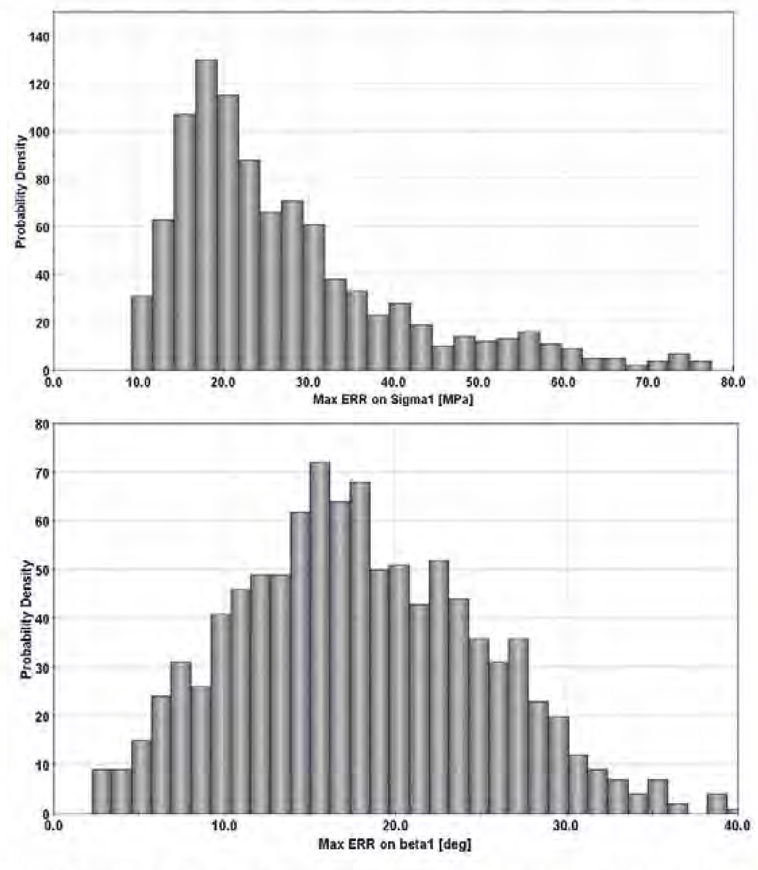


Fig.7 – Left: Pareto frontier (the red circle indicates the optimal result). Right: Probability density histograms mapping the maximum error on the maximum principal stress and its orientation.

Finally, a DOE based on statistical sampling according to the Monte Carlo criterion was set up: it was supposed that each measured strain could vary in a range of ±3με around the optimal value. 1000 virtual scenarios were simulated under these hypothesis in modeFRONTIER: histograms showed that the most probable errors on the maximum principal stress and its orientation are almost 20MPa and 18 degrees respectively. Despite that, particular strains sets can lead to errors of almost 70MPa (140% of the maximum stress value): it means that a small input error (±3με) can produce a huge output error. So the hole drilling method cannot be considered a reliable way to establish the magnitude of residual stresses in a workpiece: its results should be used only for preliminary quality assessments.

REFERENCES & CONTACTS

[1] ASTM E837-13a, "Standard test method for determining residual stresses by the hole-drilling strain-gage method", ASTM International, West Conshohocken, PA, 2013.
[2] Reffo, E., 2015, "Finite element analyses of drilling process for residual stress evaluation by the hole-drilling strain-gage method", Master's Degree Thesis in Mechanical Engineering, University of Padua, Padua, Italy.

CONTACTS: enrico.reffo.2@gmail.com, mauro.ricotta@unipd.it