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Hybrid method suitable for measurement of residual stresses by hole-drilling technique

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Abstract. This contribution is focused on determination of residual stresses by new hybrid methods of mechanics. There is described the evaluation of residual stresses by hole drilling method based on newly proposed approach. Numerical simulation of gradually removing material and application of suitable load on inner area of the hole are the main principle of this technique. From experimental data can be derived values and directions of principal residual stresses by iterative computing and inverse algorithm. The results are compared with results from hole drilling method evaluated by standard ASTM E837.

Introduction

Residual stresses are present in all technical materials and their effects can be harmful or helpful. Compressive stresses are considered as helpful. Compressive stresses can be created by surface peening or another technique, which are used for parts subjected to cyclic loading. Influence of tensile stresses are always negative. Tensile stresses can cause growth of cracks and decrease of fatigue limit. This is the reason, why investigation of residual stresses take place in engineering practice.

Although there is progress in numerical simulation of residual stresses, the experimental measurements are still important for validation of results from computer modelling. Numerical methods can be successfully used by evaluation of measured results. There are arising new hybrid methods of mechanics.

The contribution explains basics of the newly proposed approach for evaluation of measurement by hole-drilling method, which is based on the inverse approach considering appropriate boundary conditions in the FE simulation of hole-drilling. The results of the hybrid approach are compared with results given evaluation of measurement by standard ASTM E837 [1].

Experiment – measurement of residual stresses

Investigation of residual stresses was carried out on the thermal affected specimen by hole drilling method and measured by the strain gauge (Fig. 1). Three tensometric apparatus P-3500 from Vishay company and apparatus RS-200 were used for measurement. There were used tensometric rosettes of type A with denotations EA-06-062RE-120. Circular opening with diameter 1.8 mm was gradually drilled with 0.05 mm increment in each step [2]. Released deformations were measured by tensometric rosette up to 0.3 mm depth. Measured values of strains on the strain gauges of tensometric rosette along the depth 0.3 mm are depicted on the table 1. Strain gauges of the tensometric rosette are denoted by first three letters of alphabet and corresponds to strain indices. Strain $\boldsymbol{\varepsilon_a}$ corresponds to the L direction according to the Fig. 1. ESPI optical measurement with apparatus Q-100 from Dantec Dynamics company was used on the same specimen with hole drilling methodology. Mounting of the laser-optical sensor to the measuring jig is shown on Fig. 2 [2]. Results of this measurement were influenced by the instability of the jig and by optical noise. For analysis in this study were used only results obtained from tensometric measurement with implementation of drilling hole method.

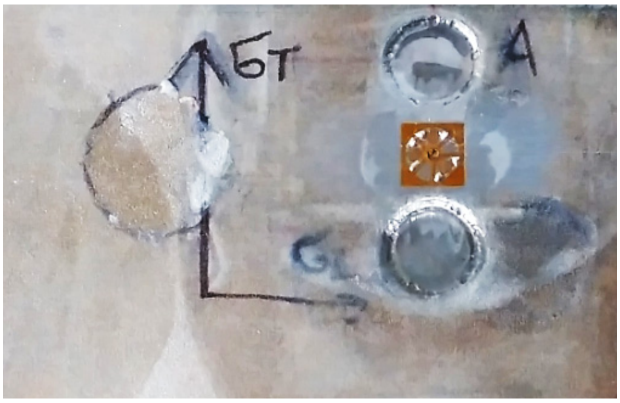

Fig. 1: Measured spot on the specimen [2].

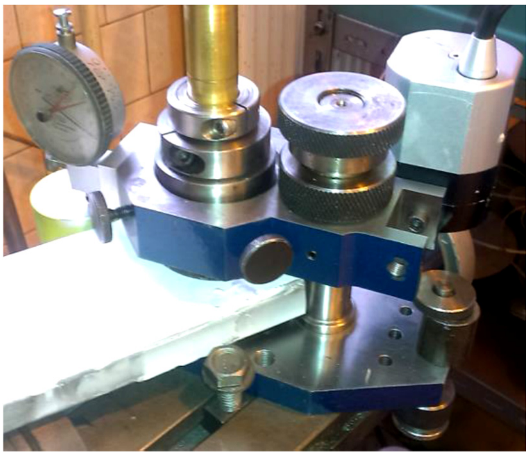

Fig. 2: Measuring jig with laser-optical sensor Q100 [2].

Table 1: Measured values of deformation on the tensometers of tensometric rosette [2].

Z [mm]	ε_a [μS]	ε_b [μS]	ε_c [μS]
0.1	144	103	53
0.2	362	241	121
0.3	560	364	173

Evaluation of residual stresses by finite element method

New methodology of evaluation of residual stresses is based on the numerical simulation, when the depth of drilled hole increases gradually in many steps and there are simultaneously applied appropriate tangential and normal loads on the area of the hole. The most suitable parameters of the both functions are found out from the inverse algorithm, so the values converge (in particular location) closely to the measured values.

A parametric model was created in order to perform numerical solution. The modification of the geometry, material parameters and elements size is done easily. The model was created in APDL (Ansys Parametric Design Language) script in ANSYS program.

The model has shape of cubic with edge length 8 mm. In the middle of the surface is created a hole with diameter 1.96 mm. The depth of the hole can vary, and it is possible to modify it in six steps. For numerical solution, these elastic constants were used: Young modulus $E = 2.06 \cdot 10^5$ MPa and Poisson's ratio $\nu = 0.3$.

The discretization of this model to finite elements was performed using the SOLID95 six-part spatial element.

On Fig. 3, there is depicted detail of FEM model near the hole - near the site of interest. Because of the inverse algorithm, the size of elements was adjusted in order to reduce the computation time with regards to precision (max error 5 %).
The boundary conditions are fixed support of the bottom side of the cubic and application of appropriate loading to the inner cylindrical surface of the hole (see Fig. 3). The cylindrical surface was created by deactivation of the elements. For this purpose, it is necessary to create special surface elements (Surface Effect Elements) in software ANSYS.

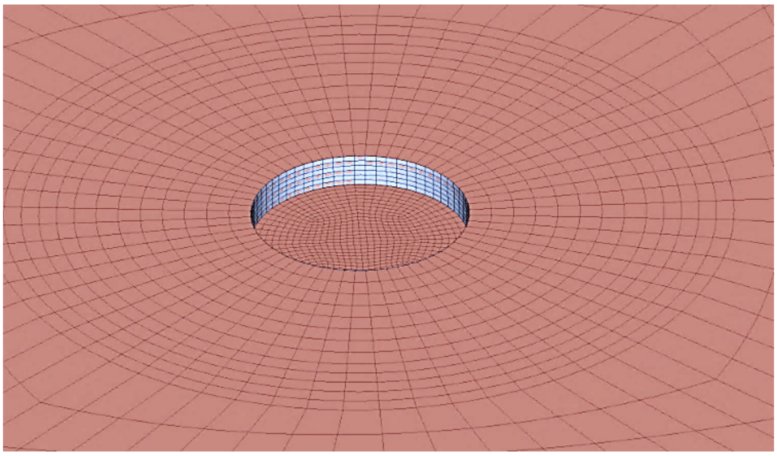
Fig. 3: Detail of FEM model near the hole.

From the strain gauge measurement performed with type of A rosette [1], deformation values were obtained at three specific points, which are located at a certain distance along the entire circumference of the hole. This is the reason, why symmetry cannot be used for this model and FEM analysis. The surface load distribution is defined by the relations that are based on the theory of elasticity for plane stress, namely the parametric equations of the circle in Mohr plane:

$$\sigma_{\rho} = P_1 + P_2 \cos\ (2\beta) + P_3, \tag{1}$$

$$\tau_{\rho} = P_2\ \sin\ (2\beta) - P_3 \cos\ (2\beta)\,. \tag{2}$$

Applied functions for examined stresses σ_{ρ}, τ_{ρ} in the plane ρ depend on the three unknow parameters P_1, P_2, P_3. Angle β is considered as a variable in a cylindrical coordinate system that is in the centre of the hole.
The aim is to find out the values of parameters P_1, P_2, P_3, so that the strain around the hole corresponds to the measured strains on the stain gauges of the tensometric rosette. Then the main stresses $\sigma_{1,2}$ and their rotation angle α can be determined from known relations:

$$\sigma_{1,2} = P_1 \pm \sqrt{{P_2}^2 + {P_3}^2}\ , \tag{3}$$

$$\alpha = \frac{1}{2}\ \arctan\ \left(\frac{P_3}{P_2}\right). \tag{4}$$

Inverse algorithm

The inverse approach serves, for example, to identify material parameters using a probabilistic algorithm, a genetic algorithm, a differential evolution method, or a neural network. However, the inverse algorithm can generally be applied to tune the computational model with the experiment.

First step is to find out the initial parameters (P_1, P_2 a P_3) and with these parameters is carried out the entrance calculation by FEM in the first layer in the depth of 0.1 mm. The calculated values of nodal deformations are compared with the measured values on strain gauges in the rosette. If the required minimum overall average deviation is not reached, new parameters are set, and the process is repeated. By repeated calculations of the inverse algorithm it is possible to achieve a good agreement between the experiment and the numerical calculation.

The listed load functions with the currently found parameter values remain in effect in the remaining steps. Furthermore, the second layer of elements is deactivated. New functions are introduced, and their parameters are found out in the same way. The process is repeated. All data obtained by this procedure, even with calculated and measured values, are tabulated, see Tab. 2, Tab. 3 and Tab. 4.

Table 2: Parameter values found.

Z [mm]	δ [-]	P_1 [MPa]	P_2 [MPa]	P_3 [MPa]
0.1	0.076	-1 239.9	430.7	12.4
0.2	0.104	-1 171.1	515.7	11.6
0.3	0.154	-1 088.3	482.7	10.2

Table 3: Evaluation according to the described new methodology.

Z [mm]	ε_3 [μS]	ε_2 [μS]	ε_1 [μS]	σ_1 [MPa]	σ_2 [MPa]	α [°]
0.1	98	146	45	-809.0	-1 670.8	90.8
0.2	344	220	142	-655.3	-1 686.9	90.6
0.3	559	352	247	-605.5	-1 571.1	90.6

Table 4: ASTM standard evaluation.

Z [mm]	ε_3 [μS]	ε_2 [μS]	ε_1 [μS]	σ_1 [MPa]	σ_2 [MPa]	α [°]
0.1	103	144	53	-716.4	-1 438.8	92.8
0.2	362	241	121	-742.2	-1 559.2	89.9
0.3	560	364	173	-677.8	-1 472.2	89.6

Results obtained from the numerical solution by FEM analysis and from experimental measurement are graphically depicted on Fig. 4.

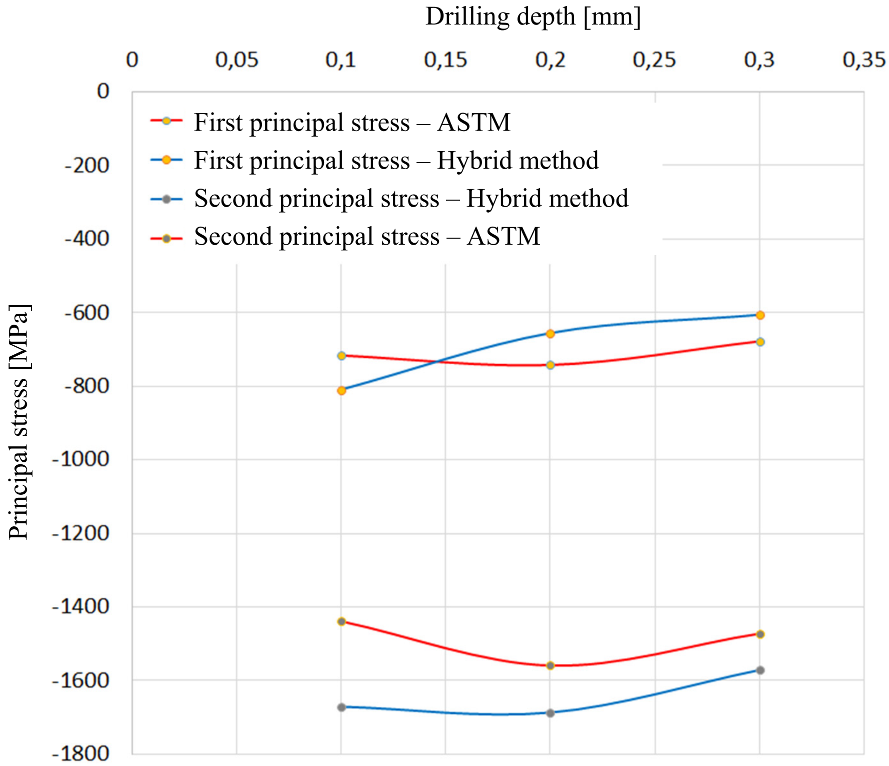

Fig. 4: Comparison of evaluated data.

To show what strains cause the applied functions around the hole, the results of the analysis are presented in the last step of the solution. Specifically, these are the contours of the first and second principal strains (Fig. 5 and Fig. 6).

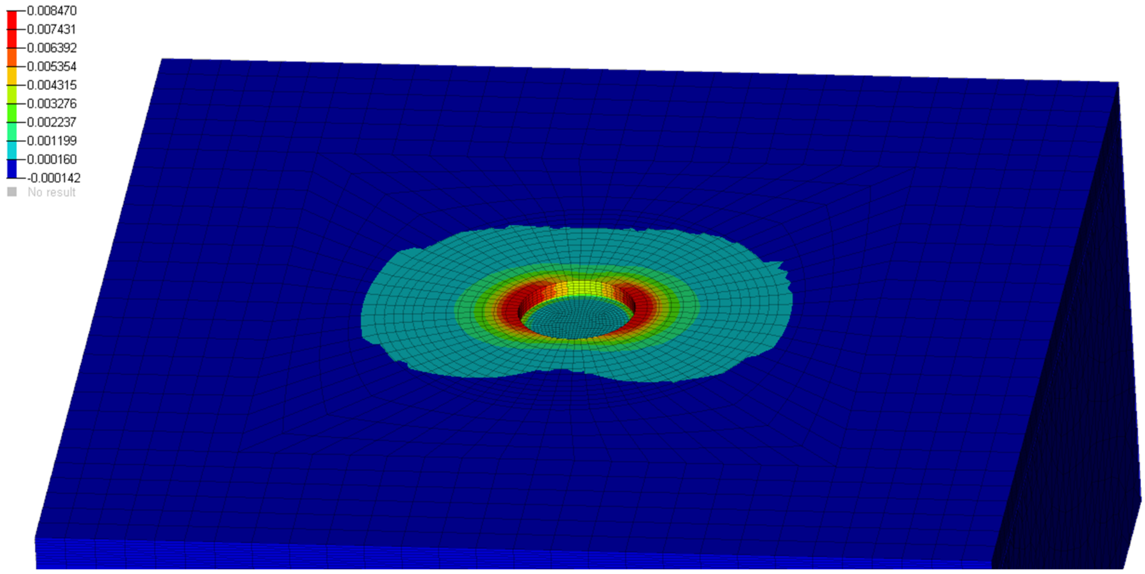

Fig. 5: The first principal strain contours.

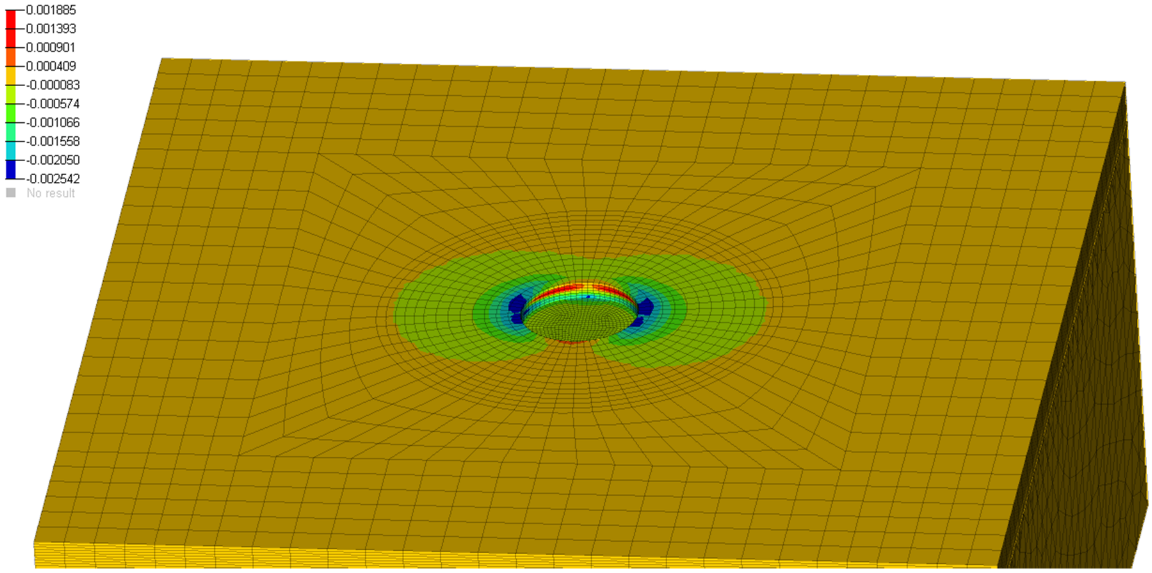

Fig. 6: The second principal strain contours.

Conclusions

Proposed methodology can determine residual stresses, which can be even unevenly distributed along the depth of the drilled hole. In addition to the value of stresses, can be also determined orientation of these stresses. From the numerical and graphical solution of residual stresses can be observed good agreement between evaluation by ASTM E837 [3] and by the proposed approach. Maximum deviation, related to the evaluation by mentioned standard, is 16.1 % and is observed in the second principal stress in the depth of 0.1 mm.

Acknowledgement

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