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The Possibilities in Use of ESPI Method by Investigation of Strain Fields of Specimen with Stress Concentrator

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Abstract The analysis of sheets deformation and corresponding knowledge of their elastic and plastic properties has a great meaning by their following processing. The aim of this contribution is to focus on the description of use an optical ESPI system Q-300 Dantec Dynamics by investigation of elastic deformations of sheets with stress concentrators in a form of notch. The results obtained experimentally using mentioned measuring device were verified numerically in program Ansys Workbench. The paper briefly describes the methodologies of both, experimental and numerical, types of modeling.

Keywords: *electronic speckle pattern interferometry, strain analysis, sheet, Finite Element Analysis, Ansys Workbench*

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1. Introduction

Electronic speckle pattern interferometry (ESPI) is a non-contact measuring technique serving for high-sensitive investigation of all the three components of displacements and after that for determination of strain as well as stress fields on the whole investigated object surface. The origin of this method traces to the year 1965, when Powell and Stetson introduced holographic interferometry – the method based on recording and consecutive reconstruction of hologram. The holographic image was created by the incidence of coherent light beams to the photographic plate, where they interfered with coherent beams of direct illumination emitted by the source of light. By subsequent development of the methodology and by replacement of the photographic plate by a CCD camera the reduction of time needed for the realization of experiment was achieved, because the reconstruction is performed numerically and the results of analysis are depicted on the computer display. Due to its high sensitivity and notable spatial resolution, speckle interferometry has found a scope in investigation of homogenous, but also heterogeneous materials of various kinds (e.g. metals, polymers, composites, ceramics, …), where it is used mainly for in-plane stress/strain analysis or bending.

2. Basic Principle of ESPI

ESPI is an optic method based on interference of two monochromatic beams of light. The beam, denoted as reference beam, entering to the CCD camera, interferes with the beam reflected from diffuse specimen surface (object beam) and create together a characteristic pattern, called speckle effect. There is a certain phase shift ϕ between the object beam and the reference one, which after object deformation changes to $\varphi+\Delta$. By subtraction of the beam phase shifts for loaded and unloaded object state we get a relative phase shift Δ depending on the deformation level in direction of so-called sensitivity factor $\mathbf{k}_S$ [1]. The visual result of subtraction is a fringe pattern with different light intensity of points (Figure 1).

The fringes present the areas with the same displacement, however the direction and size of deformation cannot be from this picture determine. For that reason, an algorithm of phase shift, based on investigation of particular speckle pattern points intensity, was established. The intensity of points by reference and loaded object state can be expressed [2]

$$I_{ref}(x,y)=I_{0,ref}(x,y)+\ldots+I_{\mathrm{mod},ref}(x,y)\cos(\varphi(x,y)) \quad (1)$$

$$\begin{aligned} I_{load}(x,y) &= I_{0,load}(x,y)+\ldots \\ &\ldots+I_{\mathrm{mod},load}(x,y)\cos(\varphi(x,y)+\Delta(x,y)) \end{aligned} \quad (2)$$

where $I_0(x,y)$ is the intensity of surroundings, $I_{\mathrm{mod}}(x,y)$ is the intensity of modulation, $\varphi(x,y)$ is the optical phase, stochastic for each pixel of the speckle effect and $\Delta(x,y)$ is a change of optical phase caused by the object deformation.

The algorithm of phase shift is based on determination of four images of intensity for each loaded state, by which the length of the reference beams optical path changes pursuant to premeditate determined phase value

$$I_i(x,y)=I_{0,i}(x,y)+I_{\mathrm{mod},i}(x,y)\cos(\varphi(x,y)+\phi_i) \quad (3)$$

where $\phi_i = \frac{\pi}{2}, \pi, \frac{3}{2}\pi, 2\pi$ denotes the known phase shift of the length of the reference beams optical path.

Then for optical phase of reference as well as loaded state can be stated [3, 4]

$$\varphi_{ref}\left(x,y\right) = \arctan\frac{I_{1,ref}\left(x,y\right)-I_{3,ref}\left(x,y\right)}{I_{4,ref}\left(x,y\right)-I_{2,ref}\left(x,y\right)}, \quad (4)$$

or

$$\left[\varphi\left(x,y\right)+\Delta\left(x,y\right)\right]_{zat'} = \arctan\frac{I_{1,zat'}\left(x,y\right)-I_{3,zat'}\left(x,y\right)}{I_{4,zat'}\left(x,y\right)-I_{2,zat'}\left(x,y\right)} \quad (5)$$

and for the relative phase shift can be applied

$$\Delta\left(x,y\right) = \left[\varphi\left(x,y\right)+\Delta\left(x,y\right)\right]_{zat'} - \varphi_{ref}\left(x,y\right). \quad (6)$$

In this way the information about the whole speckle field was acquired, by which so-called 2π phase image, digital image created by black points with 0 grey level and white points with 255 grey level, was generated. Such image still does not provide information about object deformation, but if it will be unwrapped, what is a process of the starting point determination, the removing of discontinuities from the grey scale as well as the offset definition, the continuous phase map is obtained (Figure 2).

By determination of the conversion factor it is possible from unwrapped phase map calculate the displacements. The conversion factor, known also as the sensitivity vector $\mathbf{k}_S$, expresses a difference between the observing and the illuminating vector. It is different for each object point, but considering small object deformations in regard to its distance from CCD camera, it can be assumed as constant for the whole object surface.

For expression of relative phase difference in Cartesian coordinate system can be stated [3,4]

$$\Delta = \mathbf{k}_S\left(u\mathbf{e}_x + v\mathbf{e}_y + w\mathbf{e}_z\right) = u\mathbf{k}_S\mathbf{e}_x + v\mathbf{k}_S\mathbf{e}_y + w\mathbf{k}_S\mathbf{e}_Z, \quad (7)$$

where u, v and w are the components of deformation vector and $\mathbf{e}_x$, $\mathbf{e}_y$ or $\mathbf{e}_z$ are the unit vectors in directions x, y or z.

The value of the sensitivity vector can be expressed by a relation

$$\left|\mathbf{k}_S\right| = \frac{4\pi}{\lambda}\cos\frac{\theta_{xz}}{2}, \quad (8)$$

where λ represents the wavelength of the laser light and θ_{xz} is the angle between the illuminating and the observing vector in plane xz.

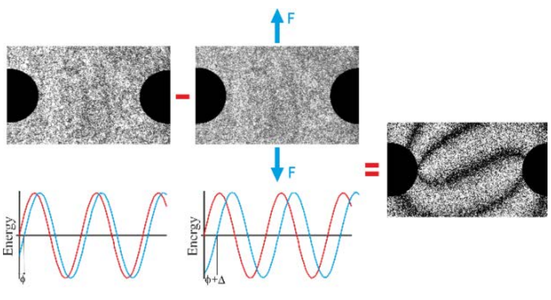

Figure 1. Speckle effect for unloaded and loaded state with the results of subtraction

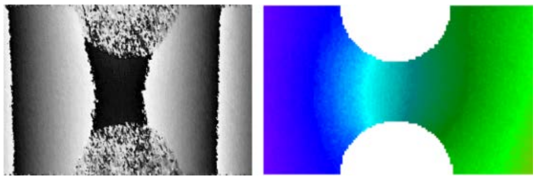

Figure 2. Typical 2π phase image (left) and corresponding phase map (right)

By the use of three different directions of illumination, three independent directions of sensitivity vector, allowing the calculation of all displacement components, are acquired

$$\begin{pmatrix}\Delta_1(x,y)\\ \Delta_2(x,y)\\ \Delta_3(x,y)\end{pmatrix} = \begin{pmatrix}u(x,y)\\ v(x,y)\\ z(x,y)\end{pmatrix}\cdot\begin{pmatrix}\vec{k}_{S1}^T(x,y)\\ \vec{k}_{S2}^T(x,y)\\ \vec{k}_{S3}^T(x,y)\end{pmatrix} \quad (9)$$

and then

$$\begin{pmatrix}u(x,y)\\ v(x,y)\\ w(x,y)\end{pmatrix} = \begin{pmatrix}\Delta_1(x,y)\\ \Delta_2(x,y)\\ \Delta_3(x,y)\end{pmatrix}\cdot\begin{pmatrix}\vec{k}_{S1}^T(x,y)\\ \vec{k}_{S2}^T(x,y)\\ \vec{k}_{S3}^T(x,y)\end{pmatrix}^{-1}. \quad (10)$$

The optical system Q-300 with laser diode of 780 nm wavelength is able to illuminate the investigated object in three different directions:

- in-plane – the active illuminating arms are the left one and the right one,
- in-plane – the active illuminating arms are the upper one and the bottom one,
- out-of-plane – the left and right illuminating arms are active and the object is illuminated also by direct reference beam

In such a way it is possible to get information about displacements in directions x, y and z. For determination of normal and tangential strains the following relations are used [1]

$$\begin{pmatrix}\frac{du}{dx} & \frac{dv}{dx}\\ \frac{du}{dy} & \frac{dv}{dy}\end{pmatrix} = \begin{pmatrix}\varepsilon_x & \gamma_{yx}\\ \gamma_{xy} & \varepsilon_y\end{pmatrix}. \quad (11)$$

Typical strain fields acquired by the optical ESPI system Q-300 Dantec Dynamics are depicted in Figure 3.

3. Experimental Analysis of Deformations of the Specimen Loaded by Tension

For evaluation of deformation in arbitrary point of rolled steel sheet the optical system Q-300 Dantec Dynamics, working on the principle of electronic speckle pattern interferometry, was used. The measured specimen, which shape and dimensions are depicted in Figure 4, was prepared by a modification of Dog-bone shape, used for performing of uniaxial tensile tests.

To ensure an optically rough surface, the specimen was spraying by white difuse color. The specimen was loaded by tension force along its longer side via universal testing machine Zwick Z020 with maximal loading force of 20 kN in such a way to ensure in the area of notches only elastic deformation.

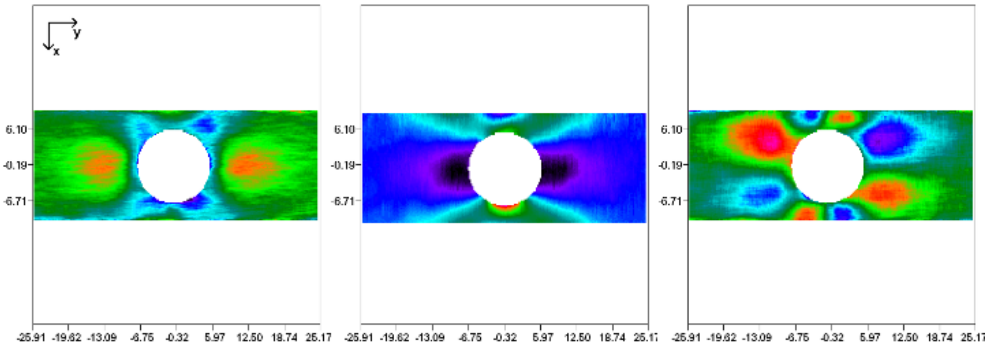

Figure 3. Illustrative strain fields obtained from Q-300 Dantec Dynamics

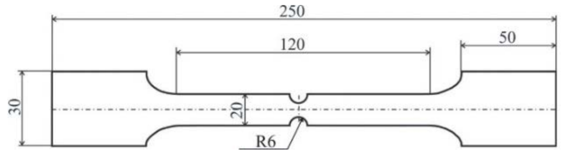

Figure 4. Shape and dimensions of the specimen

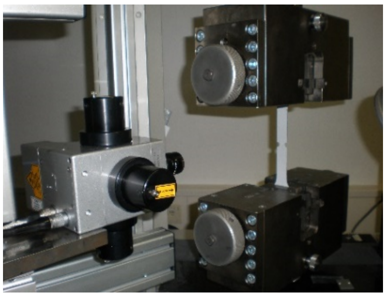

Figure 5. The measuring chain used for experimental investigation of strains

For right full-field strain investigation of specimen mentioned above using ESPI system were in control software Zwick Roell setup the following parameters:

Table 1. Setup for testing machine Zwick Z020

Travers movement	Waiting time before movement	Waiting time after movement	Maximal force
0.01 mm / step	3 s	4 s	1700 N

As by the acquisition of particular loaded steps, the relative movement between the specimen and the sensor cannot occur, the movement of travers could not be continuous. For that reason a „step movement“ (0.01 mm/step) was set, whereby to ensure stabilization of speckle image before each travers movement the sensor wait for three seconds. The acquisition of the speckle image was then realized four seconds after travers movement and this process was repeated until the maximal force (1700 N) was reached.

The distance between CCD camera and the specimen was 292 mm. By the use of configuration with 25 mm objective containing lenses of 50 mm focal length, located in four short illuminating arms, the field of view of ca. 60x50 mm was captured.

As the principal part of specimen deformation is in direction of loading, in the following parts of paper, only the strains in y direction (see coordinate system in Figure 6) will be discussed. Figure 6 – Figure 9 depict the fields of strain ε_y in four loading states caused by forces 450 N, 850 N, 1250 N and 1700 N (corresponding to the 10th, 20th, 30th and the last 40th loading step).

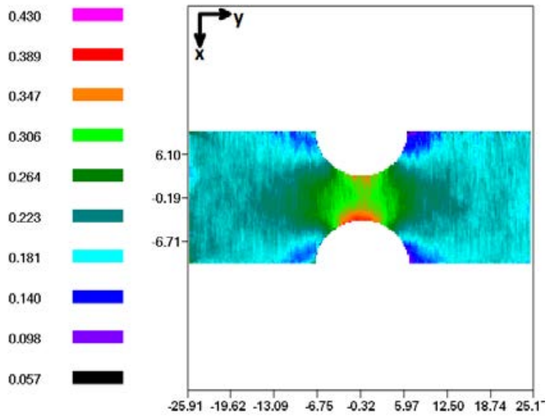

Figure 6. ε_y [mm/m] strain field acquired by loading force of 450 N

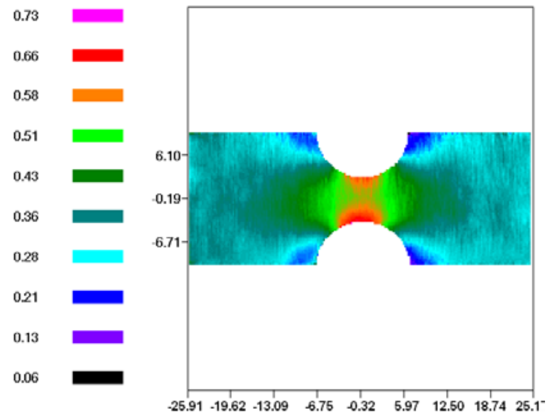

Figure 7. ε_y [mm/m] strain field acquired by loading force of 850 N

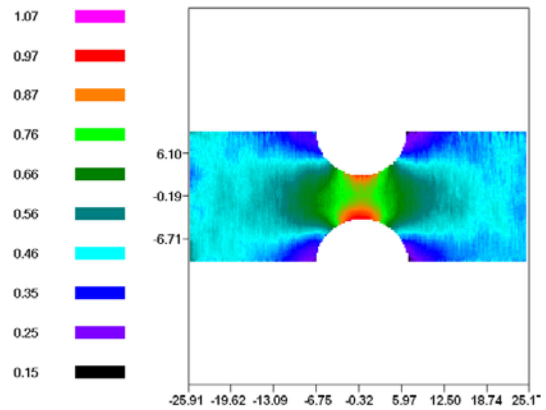

Figure 8. ε_y [mm/m] strain field acquired by loading force of 1250 N

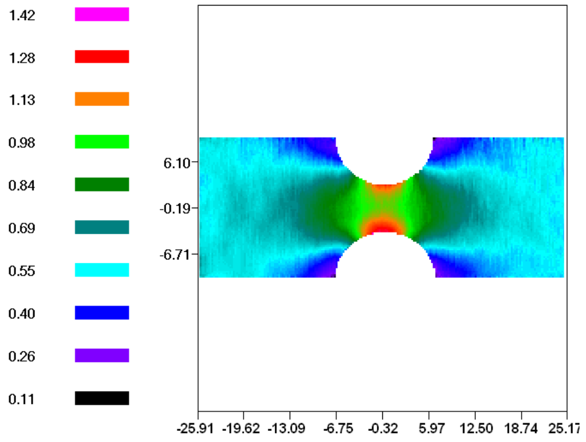

Figure 9. ε_y [mm/m] strain field acquired by loading force of 1700 N

From the mentioned results it is clear, that the strain distribution on the specimen surface is not symmetric.

The acquired results were compared to the results obtained by numerical modelling of the investigated problem in program Ansys Workbench. As the analyzed specimen has two axis of symmetry, after its numerical model creation, two symmetry regions were set in Ansys, that led to acquiring of its quarter model (Figure 10).

By given uniaxial tension loading the mentioned procedure does not discard the quality of the acquired results. Vice versa it leads to the reduction of time needed for numerical calculation, because it increases the number of elements as well as their nodes. The material of analyzed specimen was defined as structural steel with $E = 2.10^5$ MPa a μ=0.3.

On the analyzed specimen, which was modelled as a plane one with the thickness of 1 mm, the mesh of finite elements was created, whereby the elements of type *quads* were used. The size of the elements was set to 1 mm, only in the area of notch (on two edges) the mesh was resizing to the size of 0.1 mm (see Figure 11).

The total amount of elements, used for the creation of mesh, was thus 2324 and the amount of nodes was equal to 7361. The created quarter model with defined symmetry was loaded by a force, which value corresponds to one half of the maximal loading force, thus 850 N.

The ε_y strain field, obtained numerically in the area of notch via Ansys Workbench, is depicted in Figure 12.

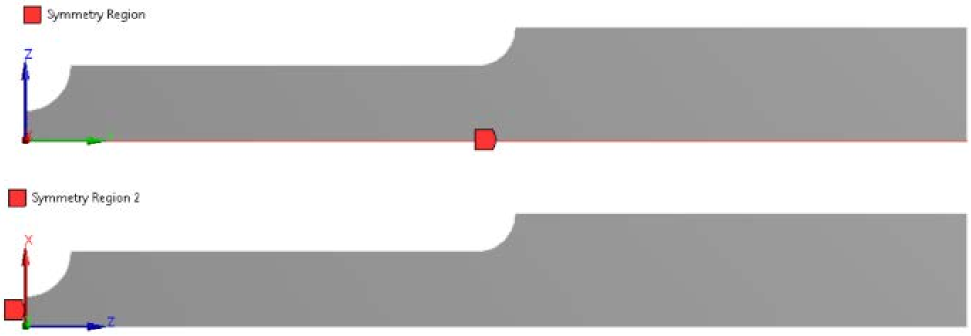

Figure 10. Defined symmetry regions in numerical model created in Ansys Workbench

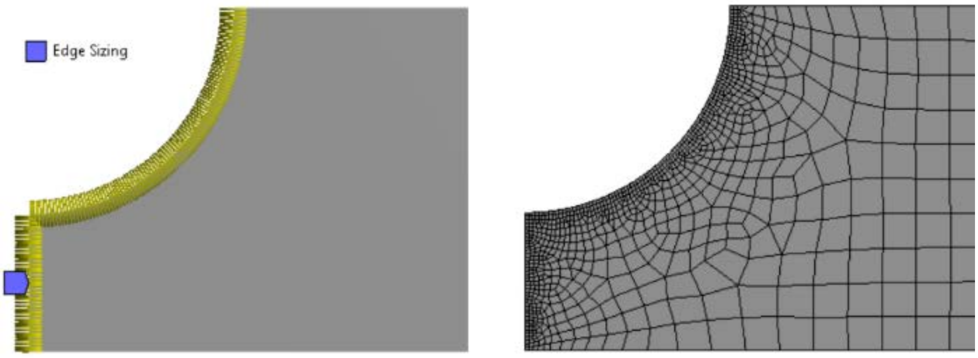

Figure 11. Resizing of the mesh in the area of notch

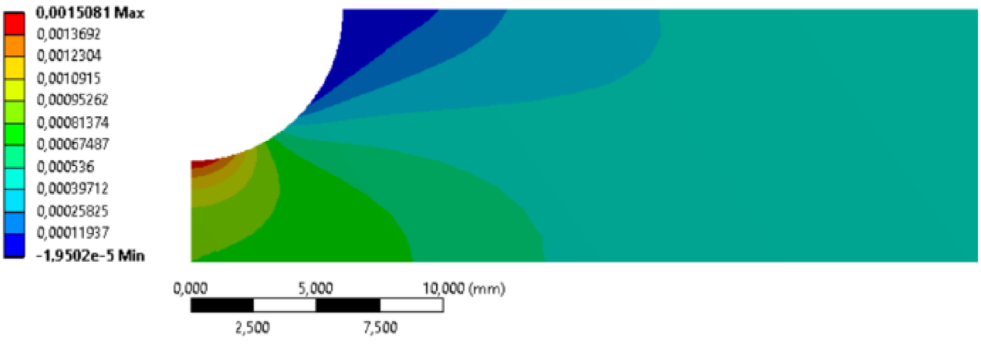

Figure 12. ε_y strain field acquired numerically by maximal loading force

From the acquired results can be stated, that the strain distribution in the interesting area of specimen has the same character as the strain field obtained experimentally using ESPI method. For the quantitative verification of acquired results, the virtual gages were used. Program ISTRA allows depicting of spatial distribution of strains along the line, circle or polygon. For that reason, a gage in a form of line passing the horizontal centerline of the specimen was chosen (see Figure 13).

The program Ansys Workbench does not allow such function. For that reason, in the numerical model several virtual gages in a form of discrete points, lying on the mentioned line, were used. Figure 14 does not depict all the virtual gages created in Ansys Workbench – to avoid their covering only one half of all gages is shown.

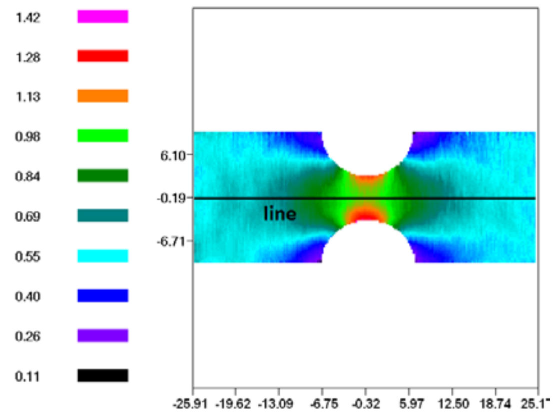

Figure 13. Virtual gage in a form of line used in ISTRA

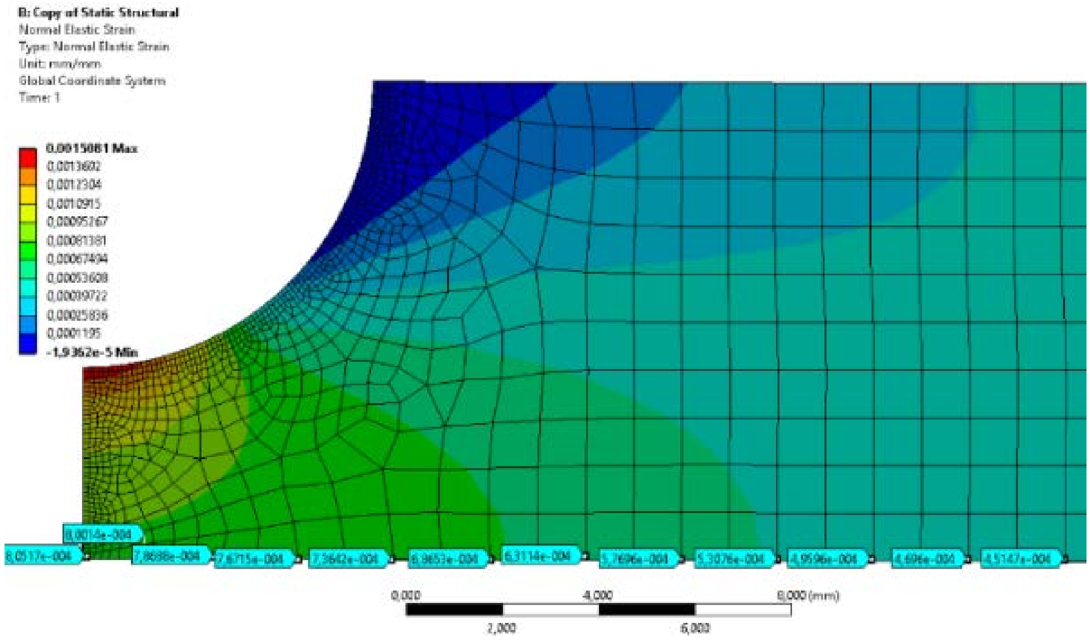

Figure 14. A half of overall amount of virtual gages used in Ansys Workbench

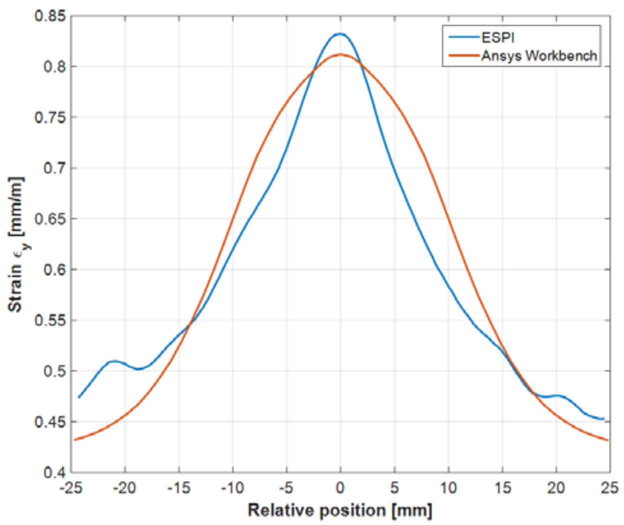

Figure 15. Course of ε_y along virtual gages obtained in ISTRA and Ansys

The comparison of ε_y courses obtained experimentally by ESPI and numerically by Ansys Workbench in mentioned virtual gages by maximal loading of specimen is depicted in Figure 15.

4. Summary

The paper describes the possibilities of using electronic speckle pattern interferometry by full-field strain analysis of investigated object loaded by tension loading. ESPI system Q-300 Dantec Dynamics is designed for evaluation of static loading with high sensitivity. Its big advantage is, that it is simply portable and non-contact. The performance of the experiment is relatively quick, as ESPI method besides the creation of optically rough surface does not demand of any other preprocessing phases of experiment.

From a comparison of the results obtained experimentally and numerically it was determined, that the strains ε_y in chosen analyzed locations differ maximally in ca. 10%. This difference can be caused e.g. by non-ideal boundary conditions – the specimen probably was not clamped directly along its longitudinal axis and the specimen was thus loaded by combined loading. It can be seen also from the strain distribution obtained by ESPI, that is non-symmetric in the area of notches. In general, it can be stated, that the obtained difference in the results is adequate to the comparison of experimental and numerical analysis.

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