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Experimental Stress Analysis

Accuracy Testing of the DIC Optical Measuring Method the ARAMIS System by GOM

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Abstract: Digital Image Correlation is a relatively new optical method, which allows for specifying displacements on speckle pattern body surfaces and using them to determine strain and stress. It does not matter whether the body material is elastic or elastic-plastic. The paper mentions basic hardware and software principles of this method and the first results of analyses that will deal with the accuracy of displacement and strain determination. They are comparative analyses of displacements and strain that are acquired through experiment and calculation (FEM). The use of complete and properly formatted references is particularly important.

Keywords: Digital Image Correlation, Displacements, Strain, Accuracy of measurement, Comparative analyses, Experiment, Calculation

1. Introduction – problem situation

ARAMIS is a non-contact optical 3D deformation measuring system which allows for specifying displacements on the surface of loaded bodies using the relations (and the appropriate programme systems) corresponding to the principle of this measuring method. The displacements can be used to determine strain using geometrical equations. If we know the constitutive characteristics for the body material (the module of elasticity in elongation and the coefficient of lateral contraction), we can determine stress using the constitutive relations between stress and strain. For determining all the entities mentioned, there exist programme systems which are the intellectual property of the GOM company. These programme systems are a black box for users. The result is that the accuracy of displacement measurements and the accuracy of strain and stress determined by calculation can only be assumed from the information provided by GOM if the company releases it.

These facts caused a non-standard situation where a customer does not know with what accuracy displacements, stress and strain are determined. It is a problem, the solution of which requires the following: “To carry out comparative analyses of the displacement, stress and strain values, measured with the DIC (ARAMIS) method and calculated using the FEM numerical method with a test sample, which should be a tension loaded flat band with a central opening; the aim is to check the accuracy of the entities obtained by DIC, whereas the FEM results will be considered as standard”.

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2. The principle of the DIC method

DIC (Digital Image Correlation) is a method for a full-area contactless experimental determination of deformation displacements from which linear deformation on free body surfaces is determined ranging from the „unloaded state of the body“ to breaking the cohesion of its materials (cracks, fracture) [1]. “Digital” means that digital image scanning is used; “correlation” means that the statistical method of correlation analysis (e.g. Pearson Correlation Coefficient) is used for evaluation of values of displacements on body surfaces. Important characteristics of the DIC method are:

- The basic assumption of using DIC is a contrast pattern of the body surface. That corresponds to: surface with coherence grain (Fig. 1a) and surface with incoherent application of contrast paint called speckle pattern (Fig. 1b)
- The speckle pattern body surface is scanned with a digital camera with a particular resolution level (number of pixels CCD). The digital image of the scanned body surface is therefore covered with a particular number of pixels (Fig. 2).
- One camera is enough to determine deformation on flat speckle pattern surfaces. Two cameras are necessary for curved surfaces (Fig. 3).
- For the needs of DIC, hierarchically superior units, so called *facets*, are formed. They are composed of a higher number of pixels (usually from 10 x 10 pixels to 40 x 40 pixels). To ensure the required accuracy of the measurement of displacements on a body surface, the individual facets should overlap. They usually overlap by 2 pixels (Fig. 4).

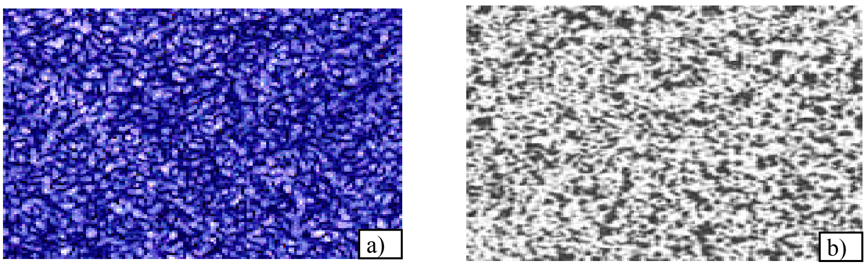

Fig. 1. Body surfaces with contrast patterns a) coherence grain, b) sprayed on speckled surface

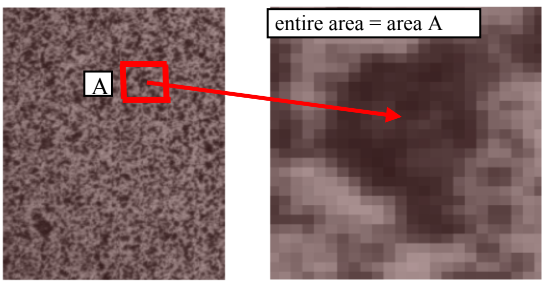

Fig. 2. Speckle pattern on the left, area A pixels on the right

Fig. 3. A system for scanning body surfaces with two digital cameras and lights

Deformation displacements of the analyzed body surface points are determined optically (the points are scanned with two digital cameras) with respect to a coordinate system attached to the body. The displacement of a body surface point is the difference between the displaced and the original positions of the point where the displaced position is the one in which the correlation function, representing the degree of grey in the neighborhood of the body surface point reaches an extreme.

Fig. 5 shows cameras 1 and 2 "seeing" the facets on the body surface in an unloaded and loaded state. 5. Some of the facets are shown as green squares in the picture. The facets showing deformation in a loaded state are marked red.

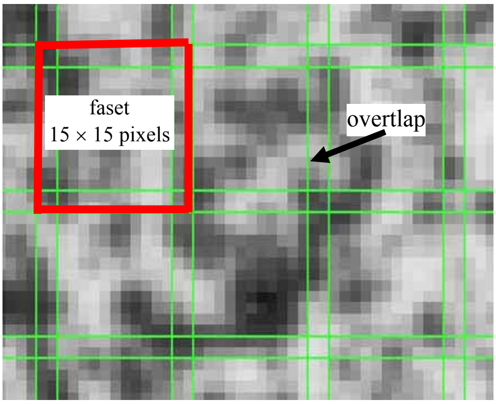

Fig. 4. Overlapping facets (green squares) (by 2 pix.)

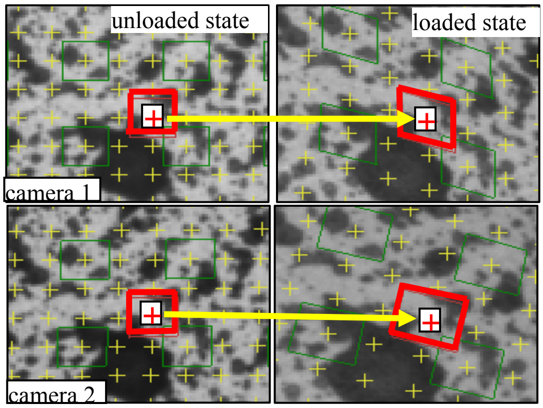

Fig. 5. Cameras „seeing“ the pixels

The ***set of facts*** on which digital image correlation is based:

① The area of the body surface with a contrast pattern is virtually covered with pixels, the size of which is related to the resolution of the digital camera and to the dimensions of the area analyzed.

② Optical properties of the individual pixels are described by a discrete function which represents the level of grey of each pixel.

③ Correlation analyses are performed on specified sets of pixels described as *facets (subsets)*. The number of pixels is the same in all surface facets.

④ A homogenous field of displacements is assumed inside each facet.

⑤ The initial deformation state of a facet before the transformation of the area is described by a discreet function *f(x, y)* and it is transformed into another discreet function *g (x', y')*.

A facet on an activated body can be shifted, revolved and deformed or it can show various combinations of the changes mentioned with respect to a reference facet on a non-activated body, Fig. 6. Let point P(x_0, y_0) be the centre of a facet. Q(x_i, y_i) describes a point of a facet. After the activation of the body, the position of both the points will change and they will have different coordinates P′(x'_0, y'_0), Q′(x'_i, y'_i). The change of the position of point Q in

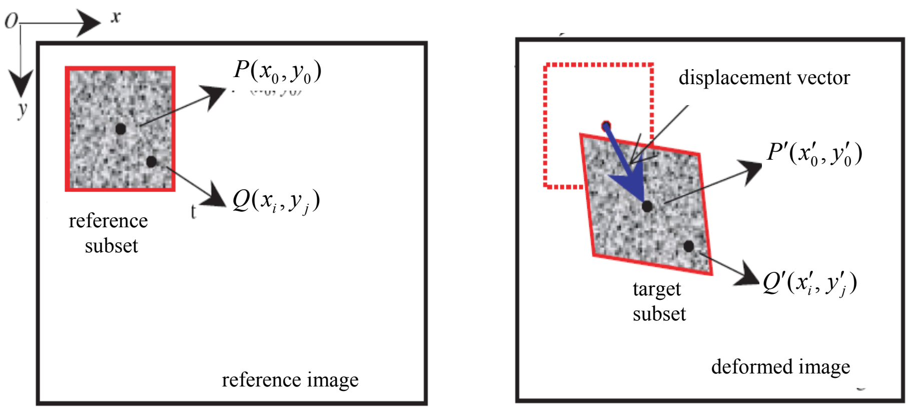

Fig. 6. Scheme of mapping

an activated facet with respect to the non-activated one is described as ***mapping***. Functions describing the change of the position of point Q are called ***shape functions*** (defining the change of the facet shape).

Let us denote the shape functions by ξ and η. Then the coordinates of point Q′ can be written as: $x'_i = x_i + \xi(x_i, y_j)$, $y'_i = y_i + \eta(x_i, y_j)$, $(i, j = -M{:}M)$.

To measure the extent of correspondence between a reference facet (non-activated, i.e. non-deformed state of the body) and a target facet (activated, i.e. deformed state of the body) ***correlation criteria*** are used. A target facet is considered to be identical with a reference facet if an extreme is reached at the corresponding correlation coefficient. The position of this extreme then determines the position of the target facet and this position can be used to determine the displacement of the facet with respect to its reference position. In the development process of digital image correlation (DIC), many correlation criteria have been published [2].

The most frequently used correlation coefficient is the ***Zero-normalized cross correlation –*** ZNCC, also C(u, v) which is „robust“, therefore little sensitive to deviations in intensity amplitudes (in the case of DIC the intensity of grey) and little sensitive to noise in comparison with other correlation criteria. It is defined by the following relation:

$$C(u,v)=\frac{\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[f(x,y)-f_m\right]\left[g(x^*,y^*)-g_m\right]}{\sqrt{\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[f(x,y)-f_m\right]^2\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[g(x^*,y^*)-g_m\right]^2}}, \tag{1}$$

$$where:\ x^* = x+u\,,\quad y^* = y+v\,,$$

$f(x, y)$ is the scale of grey value of the reference facet gravity centre (the facet intensity matrix), thus a facet in the non-activated state of the body,

$g(x^*, y^*) = g(x + u, y + v)$ is the scale of grey value of the target facet, thus a facet in the activated state of the body,

There are two levels of determining displacements on body surfaces:

❶ ***The inter-facet (pixel) level*** [3] – the C_{ZNCC} coefficient is used to specify the position (thus the displacement) of the facet geometrical centre for the state before and after the activation (load) of the body. This correlates with the facet degree of grey, which means that you try to find where the reference facet with a particular degree of grey has shifted on the body surface. If this is carried out for all the facets, all displacements of all the body surface points are determined (as facets are what models the body surface). At this level, displacements are determined with an accuracy of pixels. That is why this level is also referred to as a pixel level. The position of the correlation coefficient extreme $C(u, v)$ is considered to be the position of the target facet on the surface of an activated body Fig. 7.

❷ ***The sub-facet (sub-pixel) level*** [4] – in many practical applications, the results with the accuracy of one pixel at the inter-facet level are not sufficient and that is why a correlation level with a higher resolution level is necessary. The correlation coefficient value extreme is looked for in the corresponding facet area. Algorithms used for this are called ***sub-pixel registration algorithms*** (the term sub-pixel meaning that the accuracy of displacement determination is less than one pixel). The purpose of sub-pixel registration algorithms is to make the displacement values of a reference facet during the activation of the body more accurate in comparison with the displacement values of its gravity centre specified at the

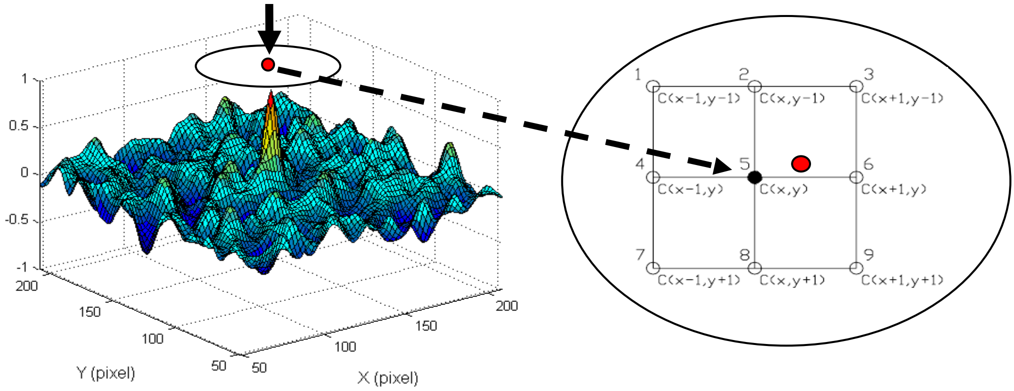

Fig. 7. Displacement determination at pixel level

inter-facet level. There are different sub-pixel algorithms: fitting method, Newton-Raphson method, gradient base method. Different sub-pixel registration algorithms result in different accuracies of determining the displacements on body surfaces. Newton-Raphson iteration method shows both the lowest values of systematic errors of displacements and the lowest values of their standard deviations.

Determining strain is a separate issue in the DIC method. The DIC method is used to obtain the fields of displacements that are not smooth in the mathematical sense. As the transformations are defined by the displacement derivatives, this is "very unpleasant". When using the DIC method, the accuracy of defining the transformation can be improved by first numerically smoothing the displacements fields (edges in the displacement areas are removed for displacement areas to be mathematically smooth) to subsequently determine the transformation field. Although there are many papers on numerical smoothing of displacement areas, there is no information in ARAMIS on the smoothing type used and, therefore, it is not possible to "identify" the accuracy of strain determination.

3. The analysis of the accuracy of displacements and strain determination

The first phase of testing the accuracy of displacement and strain determination was carried out with a test sample with the dimensions corresponding to Fig. 8. "Stress – strain" material of test sample diagram. The red dot in this picture shows a stress-strain condition for which comparative analyses have been carried out.

Testing involved comparative analyses of iso-areas and the behaviours of displacements, stress and strain obtained experimentally using the DIC method on ARAMIS and by calculation using FEM. The test sample was loaded with tension forces in the position of the load device jaws. The displacements were measured by a special scanner. The size of the facets on the sample surface was 16 x 16 pixels.

In Fig. 10 there are position dependencies of displacements x in the area of the central opening along the y-axis and in Fig. 11 strain Eps x along the y-axis.

Fig. 12 shows an example of measurement results provided by the ARAMIS software. The upper left-hand corner shows the behavior of the quantity measured (Epsilon X) along the x-axis. The lower corner shows in red the stress-strain condition for which the relevant information is provided in the picture. In the right part of the picture there are iso-areas of the quantity featured (Epsilon X here).

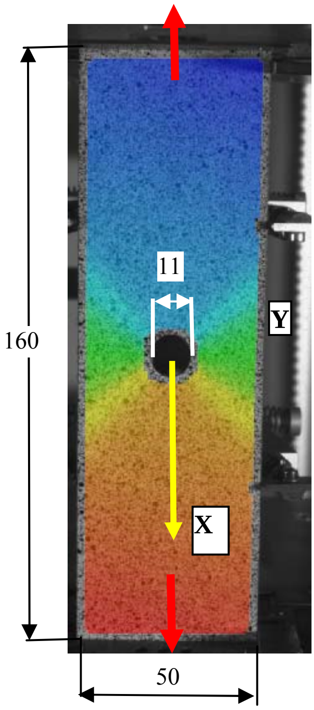

Fig. 8. Test sample

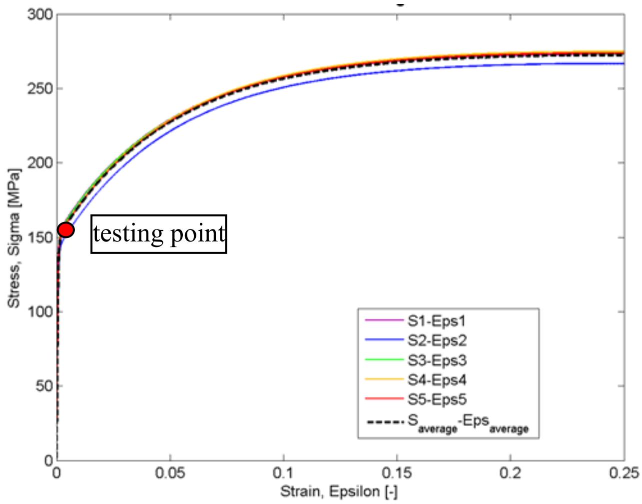

Fig. 9. “stress – strain” material of target diagram

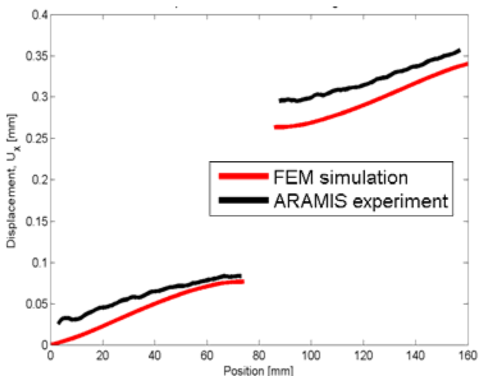

Fig. 10. Dependency of displacemets *x* along the *y-axis* at the opening

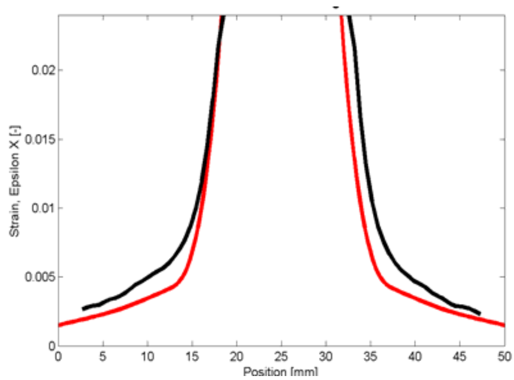

Fig. 11. Dependency of strain *Eps x* along the *y-axis* at the opening

Fig. 13 shows the values of relative errors of displacement determination along the x axis. They are calculated from this relation:

$$\delta_{ux} = \frac{u_{xE} - u_{xV}}{u_{xV}},$$

where u_{xE} is a displacement determined by the DIC experimental method, u_{xV} is a displacement determined by a FEM calculation.

Considering the low values of the displacements measured (they correspond to nominal normal stress in the direction of the test sample load of about 150 MP), the values of the relative displacement errors are acceptable.

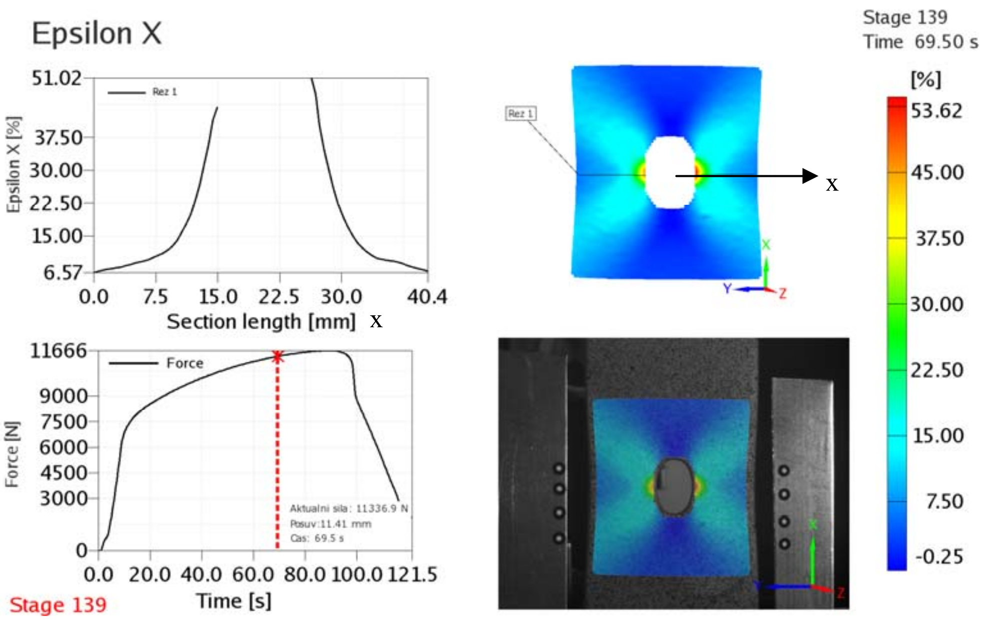

Fig. 12. An example of measurement results provided by the ARAMIS software

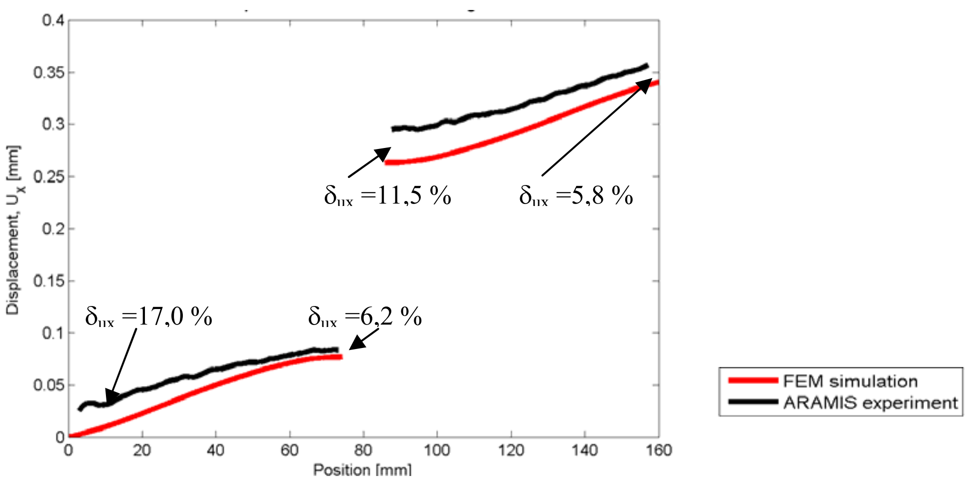

Fig. 13. Relative errors in discrete places during displacemet determination in the direction *x* along the *y-axis* at the opening

The results of the displacement and transformation measurements performed with the DIC-ARAMIS method and the results of computational modelling using FEM are in Fig. 14 to Fig. 17. They are in the form of iso-areas. There is a good correspondence between the calculation and the experiment.

4. Conclusion

The accuracy of determining displacements on the surfaces of loaded bodies using the DIC optical method is one of the basic issues of this method. The accuracy of determining strain and stress from the measured displacements is as important. It is not enough only to measure something. An engineer must know with what accuracy it has been done. This paper focuses on the beginning of DIC analyses of accuracy determination with the influence of various quantities on this accuracy.

References

[1] Digital Image Correlation. http://en.wikipedia.org/wiki/Digital_image_correlation.

[2] Pan, B., Xie, H., M., Guoa, Z., Q., Hua T.: Full-field strain measurement using a two-dimensional Savitzky-Golay digital differenziator in digital image correlation. Opt. Eng. 2007, **46** 033601

[3] Bing Pan, Kemaou Qian, Huimin Xie, Nand Asundi: Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review. Meas. Sci. Technol.**20** (2009) 062001

[4] Guizar-Sicairos, M., Thurman, S., T., Fienup, J., R.: Efficient subpixel image registration algorithms.Optics Letters, vol. 33, No. 2, January 15, 2008.

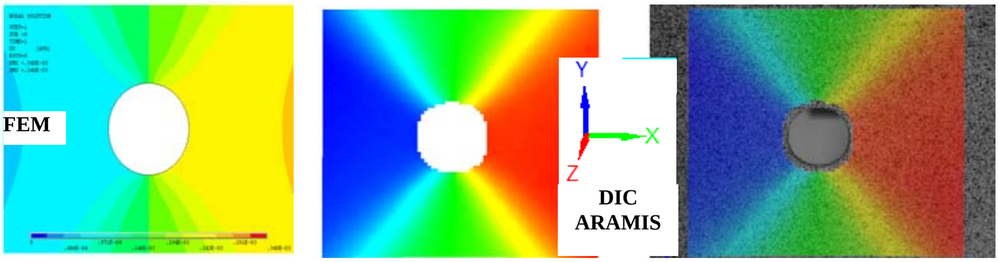

Fig. 14. Iso-areas of displacements along *x* – FEM calculation-left, DIC – ARMIS experiment-right

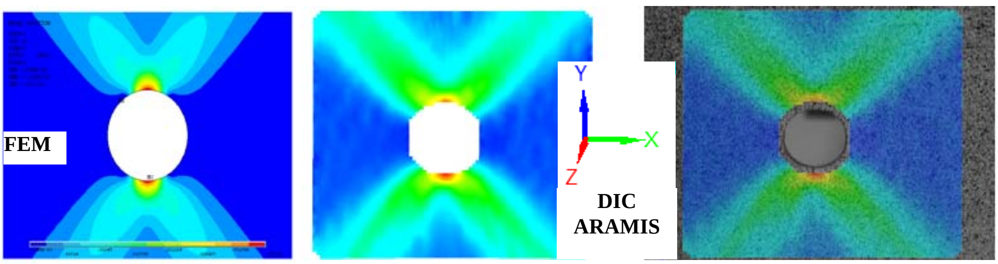

Fig. 15. Iso-areas of strains along x – FEM calculation-left, DIC – ARMIS experiment-right

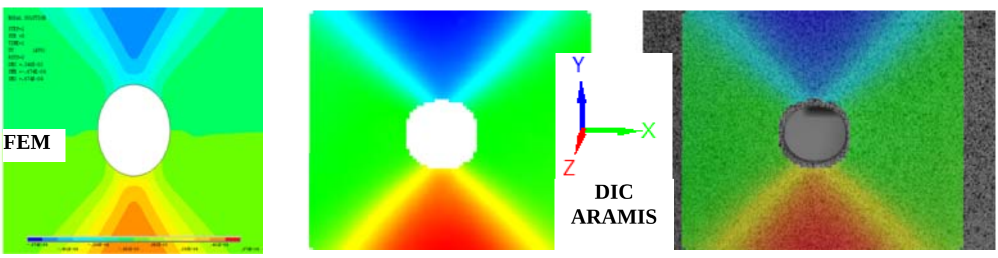

Fig. 16. Iso-areas of displacements along y – FEM calculation-left, DIC – ARMIS experiment-right

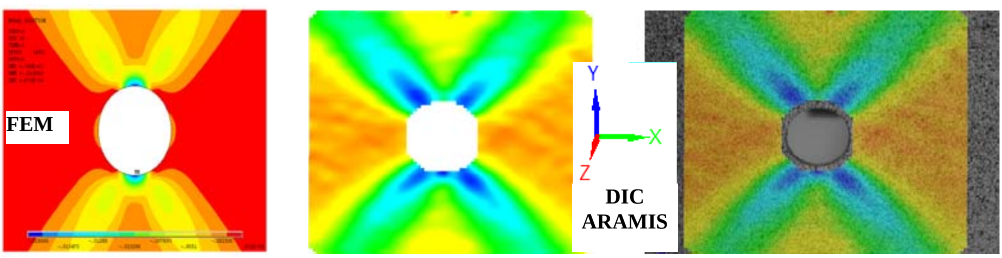

Fig. 17. Iso-areas of strains along the *y* axis – FEM calculation-left, DIC – ARMIS experiment-right