Proposal of Strain Field Calculation Procedure in 2D Digital Image Correlation

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Abstract: The calculation of strains in digital image correlation is traditionally based on the method of affinity deformation of image elements (facets). Amount of strain of each facet is determined based on analysis of their local curvatures. To obtain relevant results, deformation gradients should be included in the solution. It requires the use of smoothing filters. Filtering level largely affects the resulting fields of deformation. The article describes the procedure of the calculation of strains that is based on the algorithms used in the finite element method and properly combined with result smoothing process. The aim of the article is to assess the efficiency and accuracy of the presented procedure.

Keywords: digital image correlation, strain calculation, smoothing.

1 Introduction

Digital image correlation method is a contactless method that uses precise cameras for the measurement of surface displacements and strains. In the case of 2D DIC, when only one camera is used to measurement, deformations are analyzed in the plane parallel to image plane of CMOS sensor (Fig. 1). 3D correlation systems use minimally two cameras arranged stereoscopically. The basic principle of digital image correlation consists in the correlation of images captured during loading. The correlation runs by small unique image elements, called facets. The uniqueness of the facets is achieved by creating a high contrast random speckle pattern on the surface of the object being analyzed. Information on the displacements is then obtained by correlation of corresponding facets in the state before and after loading of the object [1].

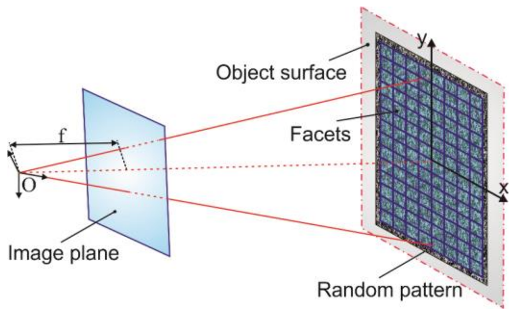


Fig. 1 Principle of 2D digital image correlation.

Displacement of any point of one facet can be described on the basis of shape functions of the first order which take into account affinity deformation [1]:

$$\xi_1(x_i, y_j) = u + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta y\,, \qquad \eta_1(x_i, y_j) = v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y\,,$$

where Δx a Δy represent distance of point (x_i, y_j) to the center of the given facet. If the displacement vectors of all points are known, it is possible to calculate strain of each facet. This calculation is based on analysis of the local curvature of facets. It practically means that strain of any facet is independent on other facets. To obtain relevant strain fields, deformation gradients have to be included in the solution. It requires the use of smoothing filters [2, 3]. As Fig.2 shows, filtering level largely affects the resulting strain fields. Therefore, a correct adjustment of filter is very important. However, a determination of a correct value is difficult. This is why the new procedure based on a combination of FEM algorithm and special smoothing filter was proposed.

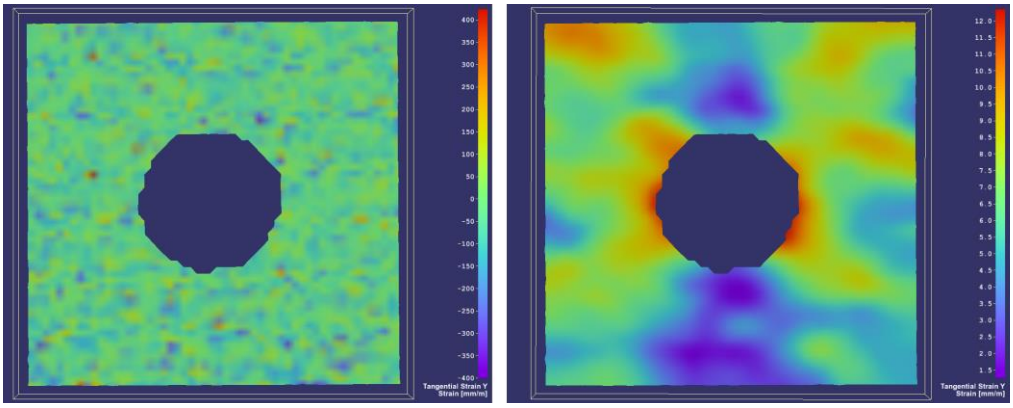


Fig. 2 The strain field before and after the smoothing of results.

2 Proposed procedure

The proposed procedure for the determination of deformation fields in DIC method has three basic steps: 1) the calculation of strain on elements, 2) determination of averaged nodal strain values, 3) smoothing of results. To calculation of deformation parameters, procedure uses the shape functions of planar triangular finite elements with three nodes [4]:

$$N_i(x, y) = a_i + b_i x + c_i y\,,$$

where a_i, b_i, c_i are the coefficients of bilinear polynomials. Components of strains can be calculated as

$$\boldsymbol{\varepsilon} = \mathbf{B}\mathbf{d}$$

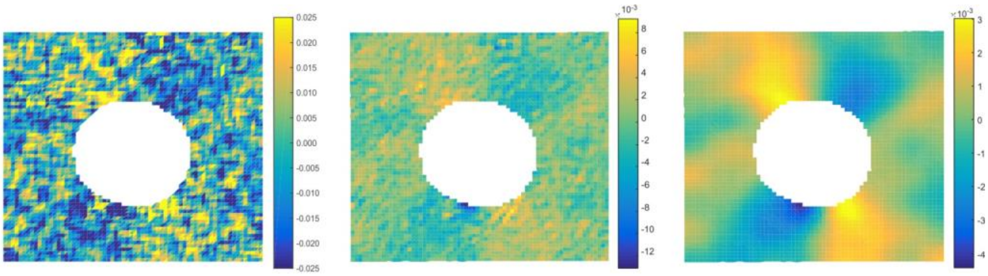
where $\mathbf{d}$ is a vector of nodal displacements of the given element, $\mathbf{B}$ is a matrix of partial derivatives of the shape functions

$$\mathbf{B} = [\mathbf{B}_1\ \ \mathbf{B}_2\ \ \mathbf{B}_3], \quad \mathbf{B}_i = \begin{bmatrix} b_i & 0 \\ 0 & c_i \\ c_i & b_i \end{bmatrix}, \ \acute{i} = 1,2,3.$$

Note that nodal displacements are determined by correlation software. After the conversion of element values (Fig. 3a) to the nodal values (Fig. 3b), results are smoothed (Fig. 3c). The procedure uses smoothing filter that replaces value in the node i by mean value of nodal values of its surrounding. This surrounding area is defined by a square whose width can be varied depending on the settings of correlation parameters (especially facet size). Smoothing algorithm can be described as

$$\widetilde{\mathbf{E}} = \boldsymbol{\Sigma}\,\mathbf{E}\,\boldsymbol{\Sigma}^T\,,$$

where $\mathbf{E}$ and $\widetilde{\mathbf{E}}$ are matrices of nodal strain values before and after the smoothing, $\boldsymbol{\Sigma}$ is sparse band matrix whose band width is equal to twice the square width.



a) b) c)

Fig. 3 Shear strain fields around the hole: a) strains on elements, b) averaged nodal strains, c) smoothed nodal values.

3 Calibration process

Calibration process was performed to determine a relation between a degree of smoothing and a facet size. The object of a calibration measurement was the flat planar sample of 30 mm wide made of aluminium sheet of a thickness of 2 mm. The sample was loaded statically in a tension machine in the longitudinal direction (Fig. 4a). Strain in this direction is therefore dominant. In an ideal case, the strain values are the same at all points. Due to spatial and correlation errors, this is not simple to achieve in reality, therefore average value $\bar{\varepsilon}_{yy}$ of a smoothed strain field (Fig. 4b) was considered in a calibration. Reference value ε_{ref} was calculated on the basis of maximal tension force $F_{\max}$ in the last loading step:

$$\varepsilon_{ref} = \frac{F_{\max}}{EA} = \frac{3600\,\mathrm{N}}{69 \cdot 10^{3}\,\mathrm{MPa} \cdot 60\,\mathrm{mm}^{2}} = 8.696 \cdot 10^{-4}\,,$$

where E is Young's modulus and A is the cross-sectional area of the sample.

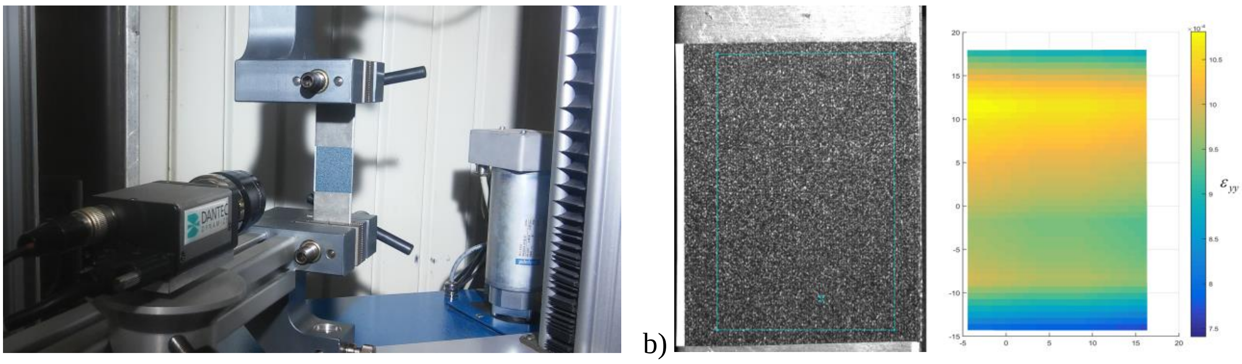
a)  b)

Fig. 4 a) Calibration measurement, b) Camera view and smoothed strain field.

System Dantec Dynamics Q-400 with one 5 Mpx sensor was used for measurement. Nodal displacements were evaluated in software Istra4D for different facet size. Correlation files were subsequently imported to Matlab for the post-processing corresponding to the procedure described above.

It is clear that average strain value was determined for different correlation files and different settings of smoothing filter, but still for the same measurement. The results were related to reference value, as can be seen in Fig. 5a, where blue squares represent average strain values for given facet size and degree of smoothing. Intersection points of approximated blue lines and reference value line define a relation between a degree of smoothing and a facet size. Trend curve that is the result of this calibration process is shown in Fig. 5b and is valid only for conditions of the performed calibration measurement. Fig. 5 shows that the degree of smoothing increases non-linearly with decreasing facet size.

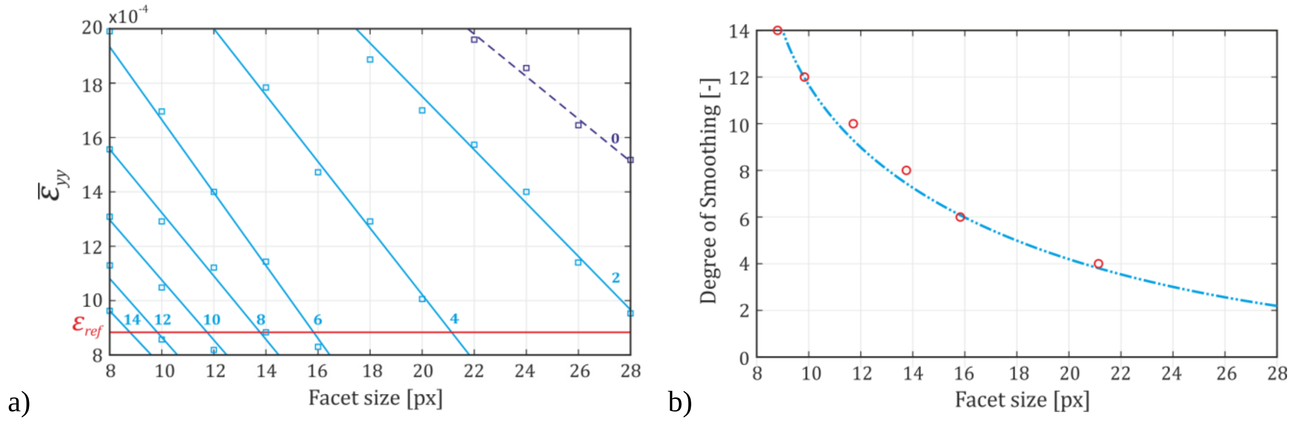


Fig. 5 a) Average strain values, b) Trend curve.

4 Experiment

Experimental measurement was carried out in the identical conditions as calibration process. The object of measurement was the flat sample with a 3 mm diameter hole placed in the center. Sample material and dimensions were the same as in the previous case. The sample was loaded by tension as is shown in Fig. 6. Maximal force in the last step was 3600 N.

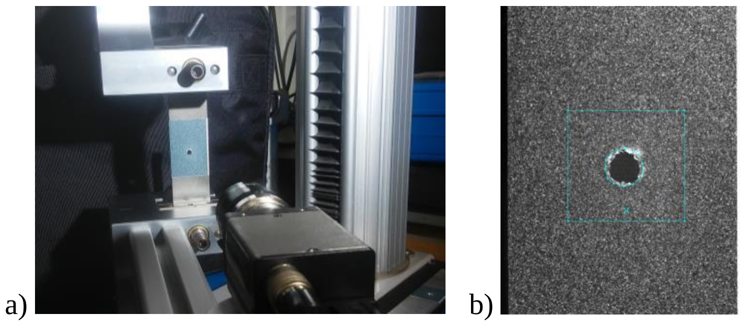


Fig. 6 a) Measurement configuration, b) Camera view and evaluated area.

The aim of experiment was to investigate deformations around the hole. Strain fields were determined using the proposed algorithm. Degree of smoothing for the given facet size was defined using the curve obtained on the basis of calibration. For an example, Fig. 7 shows the resulting fields of strain ε_{yy} for two different sizes of facets.

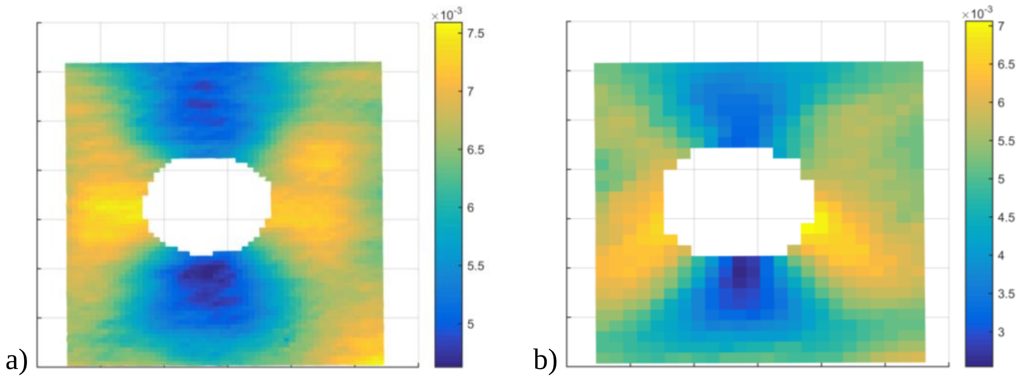


Fig. 7 Strain field ε_{yy} around the hole, a) facet size: 12px, degree of smoothing: 9, b) facet size: 28px, degree of smoothing: 2.

Fig. 7 shows that the resolution of resulting strain field primarily depends on a facet size. If the bigger facets are being used, the information about deformation is averaged over the bigger area during the image correlation process. In addition, part of the information near the geometrical boundary is definitely lost. If the smaller facets are being used, the systematical correlation errors increase due to a bigger noise. In that case, the adequate stochastic speckle pattern has to be used, i.e. every facet must contain characteristic part of a pattern with sufficient sharpness. The mentioned aspects are typical for digital image correlation method.

Conclusion

The results of experiment presented in the paper indicate that the introduced procedure is very well applicable in DIC method. The necessary part of this procedure is the calibration process to determine the correct smoothing parameter. As was shown, a degree of smoothing is primarily dependent on a facet size. The future work will be focused on verification of the procedure by using a conventional experimental method, e.g. Photostress®. With respect to a number of practical problems associated with 2D DIC method, the authors will focus their efforts on an application of proposed procedure for 3D measurement.

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