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The Aspects of Strain Fields' Measurement Performed on Small Surfaces Using Digital Image Correlation Method

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Abstract. The contribution deals with the aspects of strain fields' investigation of small surfaces using low-speed correlation system Q-400 Dantec Dynamics. It includes comparison of the results obtained by the determination of strain fields of the specimen with a small hole loaded by tension loading by different adjustment of facets' size, by realization of 2-D like 3-D measurement as well as by cameras calibration performed with calibration targets of different sizes.

Introduction

Digital image correlation is a modern non-contact method serving for determination of displacement and strain fields. Digital image correlation systems can be divided into two fundamental groups – low-speed correlation systems and high-speed ones. While the high-speed systems reach the sampling frequency of several frames per second and are mainly used in dynamics applications [1, 2, 3, 4], the low-speed systems are used for strain fields' investigation due to their high spatial resolution, which allows use them by analysis of small and big surfaces as well [5, 6, 7]. Writing this contribution we would like to point out some aspects and potential mistakes, which can appear by strain fields' investigation of surfaces of small dimensions.

Principle of Digital Image Correlation

Principle of digital image correlation is based on a comparison (called correlation) of digital images obtained during the process of investigated object loading. The images are compared along small picture elements, called facets, which size is defined by the user. Typical facet size is from 10x10 to 30 x 30 pixels, whereby using smaller facets the results are influenced by increasing systematical error [8].

To ensure the comparison of identical image parts it is necessary to create a random black and white pattern on the object surface, when each of the facets becomes unique with specific content of black and white color.

The correlation can be carried out between images obtained from one camera or several cameras. By the use of single-camera system the measurement is 2-D and thus it is needful to ensure the parallelism between camera's image plane and object surface (Fig. 1a). In the case if minimally two cameras are used, this condition does not exist and the output of the experiment is in the form of 3-D displacements (Fig. 1b).

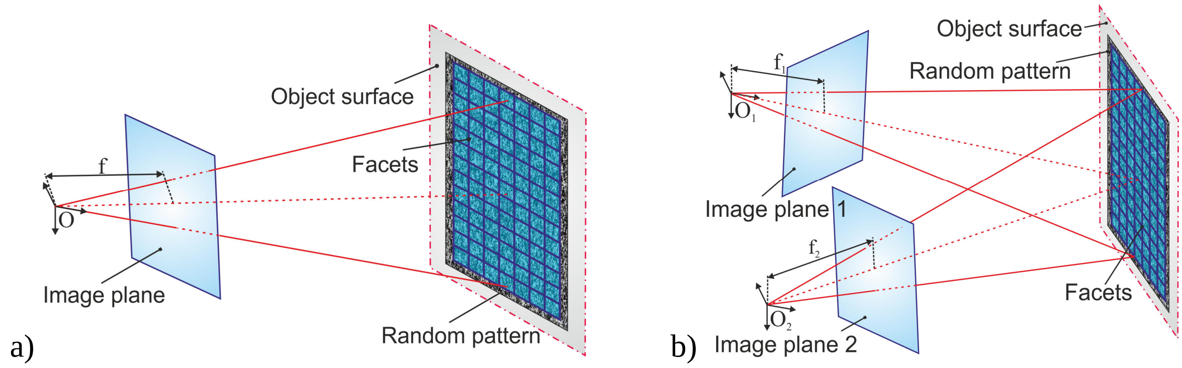

Fig. 1. Basic principle of: a) 2-D digital image correlation, b) 3-D digital image correlation.

Influence of some Factors on the Results of Deformation Analysis

For the investigation of strain fields a low-speed (max. 2fps) correlation system Q-400 was used. For its high spatial resolution (5 MPx) it is possible to use it by the analysis of small objects during their static loading. The analysis was performed on a specimen (Fig. 2) with stress concentrator (hole with diameter of 2.5 mm) loaded by a tension loading.

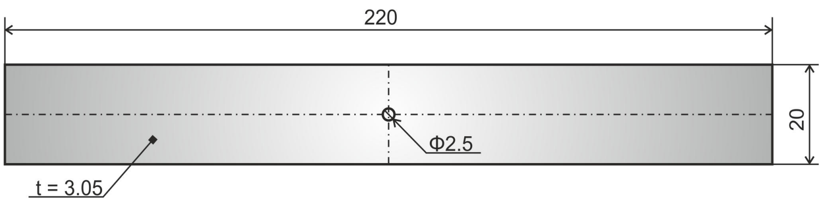

Fig. 2. Dimensions of the investigated specimen.

Taking into account that by investigation of such small surface in the surroundings of the hole it is necessary to configure the cameras to the specimen as closely as possible the best solution seemed to be the avoidance of robust loading systems and realization of the measurements in the laboratory conditions. The loading was thus performed with mechanical loading system working on lever mechanism with attached force transducer HBM RSCC/200kg (see Fig. 3).

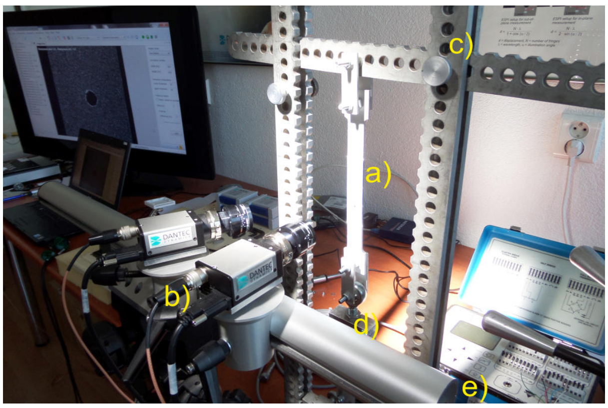

Fig. 3. Configuration of the measuring apparatus: a) specimen, b) two-cameras system Q-400, c) mechanical loading system, d) force transducer HBM RSCC/200kg, e) indicator Vishay P3.

The specimen was due to relatively small forces caused by mentioned mechanical loading system made from material PS-1 with the thickness of 3.05mm and following mechanical properties E = 2500 MPa, η = 0,38, $R_{p0,2}$ = 80 MPa, ρ = 1280 $kg.m^{-3}$ used in PhotoStress method.

For the investigation of small areas it is needed to create a random pattern with very fine structure on the specimen surface. It is not possible to achieve such pattern using the most standard form - spraying black dots on the white background. For that reason the pattern was printed on vinyl foil, which was subsequently attached to the specimen surface.

In Fig. 4 it is possible to see the image, captured by one of the correlation system cameras, expressing the size of evaluated specimen surface (ca. 6 x 6 mm^2). For the illustration this figure similarly depicts chosen facet sizes (12 px, 20 px and 30 px) used for the evaluation of the measurements.

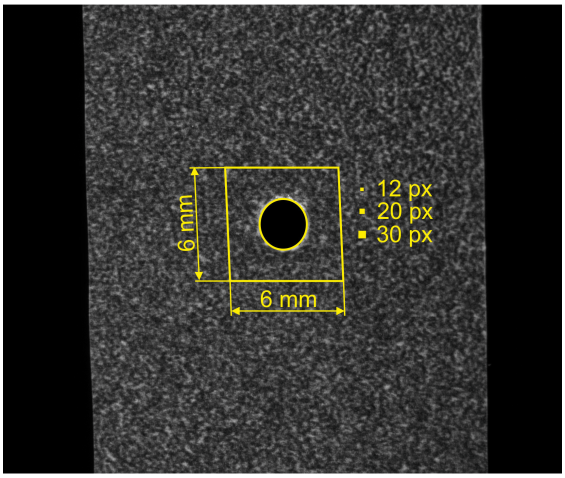

Fig. 4. Size of the evaluated specimen surface with chosen facet sizes used for evaluation.

The specimen was loaded in vertical direction by a tension force varying from 0N to maximal value 700N with constant increment of 50N, by which the snapshots were captured in manual mode. Correlation system thus besides the reference image (without loading) captured next fourteen loading states of specimen. For the identification of the tension force amount the tenzometric equipment Vishay P3 was used.

The aim of our measurements was refer to:

- the influence of facet size on the quality of obtained results,
- the differences existing by the use of 3-D or 2-D correlation systems,
- the influence of calibration targets size on the quality of obtained results.

Influence of Facet Size on the Quality of Obtained Results

As mentioned above the quality of the obtained results can be affected by the facet size used for the evaluation of the measurement. The experiment was realized using two-cameras correlation system. Its purpose was to assess the influence of facet size and corresponding virtual grid size (in its corners displacements are calculated) on:

- approximated error radius,
- contour of the object in the surroundings of the hole and evaluated hole diameter.

The evaluation was realized using commonly used facet sizes: 12 x 12 px, 14 x 14 px, 16 x 16 px, 18 x 18 px, 20 x 20 px, 22 x 22 px, 24 x 24 px, 26 x 26 px, 28 x 28 px and 30 x 30 px.

In Fig. 5 can be seen the course of mean value of approximated error radius. The calibration of the cameras was performed with the calibration target with 9 x 9 squares of size 1.0 mm. This quantity was estimated for reference image and deformed image as well.

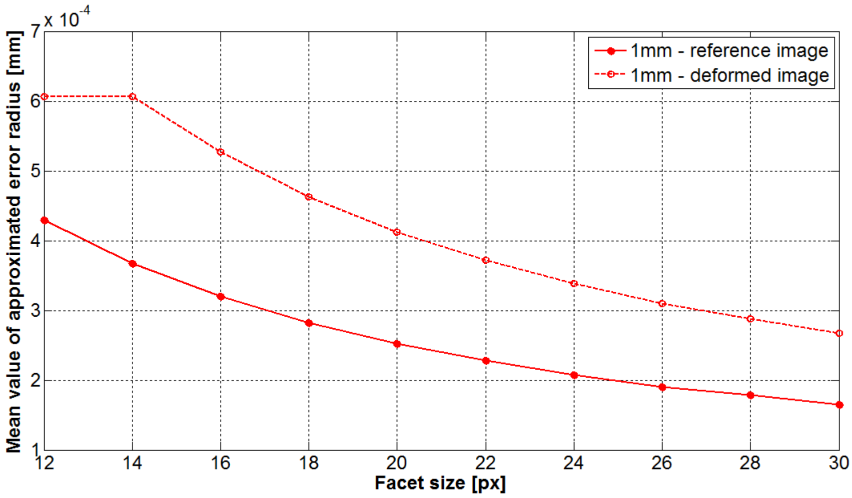

Fig. 5. Influence of the facet size on the mean value of approximated error radius.

From the course it can be concluded that the biggest error radius is estimated by the use of the smallest facet size and it decreases with the increasing facet size. The error radius is even bigger, when the specimen is deformed.

In Fig. 6 can be seen the contour of the investigated object in surroundings of the hole and the tangential strain fields ε_y (loading force 700N) obtained for variously adjusted facet size by the use of the same filtering working on adaptive spline polynomial algorithm (ACSP).

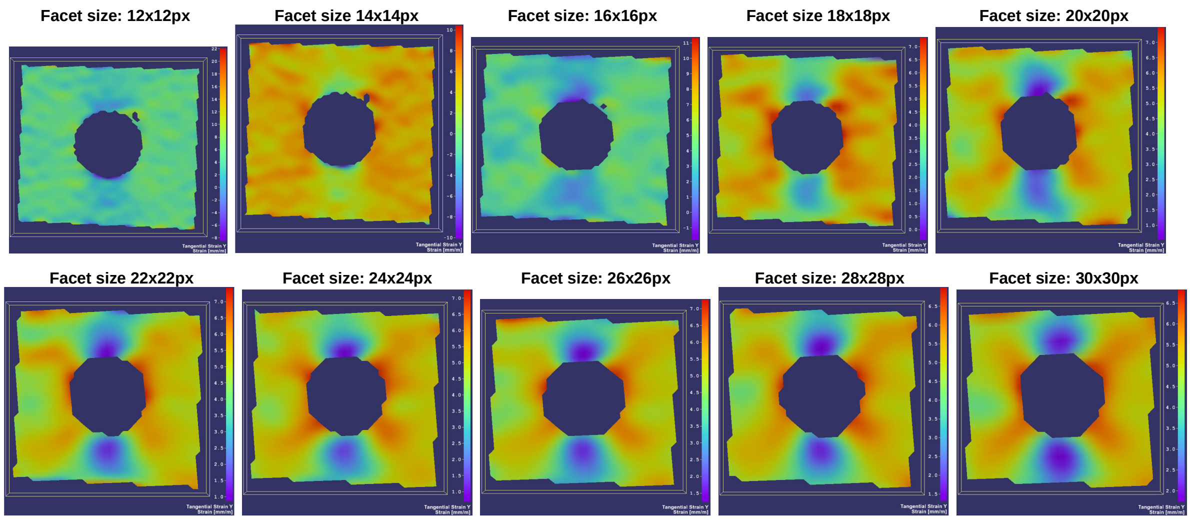

Fig. 6. Fields of tangential strain ε_y obtained for variously adjusted facet size.

As can be seen the quality of obtained results depends on the facet size as well as desirably chosen ACSP filter. Using this filter filtering is performed on the contour and displacements particularly, whereby for filtering strain fields it is needed to filter both, contour and displacements simultaneously, otherwise the strain fields will be calculated just from the facet deformation. Using filters the strains are computed not only from facet deformation, but also from deformation gradient, whereby increasing filtering increases the influence of deformation gradient on the quality of obtained results. Practically only the deformation gradient is used for the computation of strains using ACSP filter 7 x 7 and higher. Higher filter makes the results more smoothed and should decrease the standard deviation of the obtained results however it also decreases the spatial resolution of the image.

Following table represents the change of the diameter of the reconstructed hole by different facet sizes used for evaluation.

Table 1. Influence of the facet size on the number of evaluated facets and corresponding diameter of the reconstructed hole.

Facet size [px]	Virtual grid [px]	Number of facets [-]	Diameter of the hole [mm]
12x12	9x9	4667	2.63
14x14	10x10	3093	2.68
16x16	12x12	2578	2.71
18x18	14x14	1873	2.73
20x20	15x15	1417	2.75
22x22	17x17	1243	2.85
24x24	18x18	1099	2.90
26x26	20x20	878	2.91
28x28	21x21	721	2.92
30x30	23x23	649	2.95

Compromise between facet size used for evaluation and diameter of the reconstructed hole as well as looking for desirable level of filtering for different facet sizes become very important steps by the investigation of small objects strain fields.

The Use of 2-D Correlation System and its Influence on the Obtained Results

Mentioned measurement can be performed also with single-camera system, however it demands on precisely configuration of camera image plane parallel to the specimen surface. It is necessary to ensure this requirement during the whole loading process, because as can be seen from our measurements, also very small aberrance can lead to high mistakes in strains calculation.

Tangential strain ε_y obtained using 3-D correlation system by loading force of 700 N, depicted in Fig. 7, corresponds approximately to the results obtained for the same solved problem in SolidWorks. On the evaluated contour three points were chosen, which served as virtual gages and thus strains in these places could be compared.

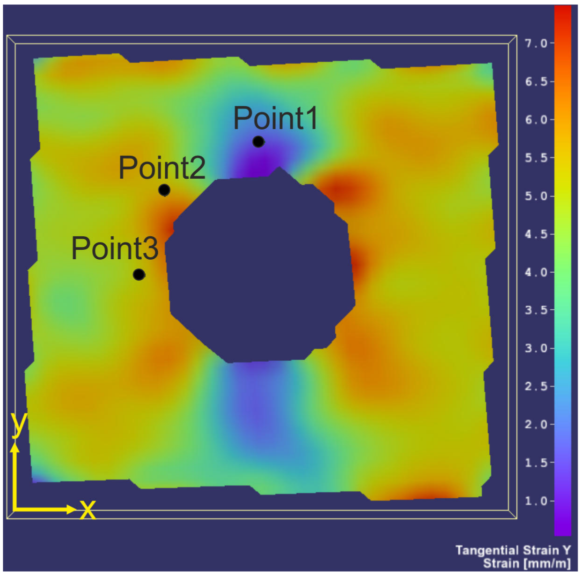

Fig. 7. Tangential strain ε_y obtained by 3-D correlation system.

Using the same correlation parameters three measurements with single-camera correlation system were done. The fields of tangential strain ε_y obtained by loading force of 700 N are depicted in Fig. 8.

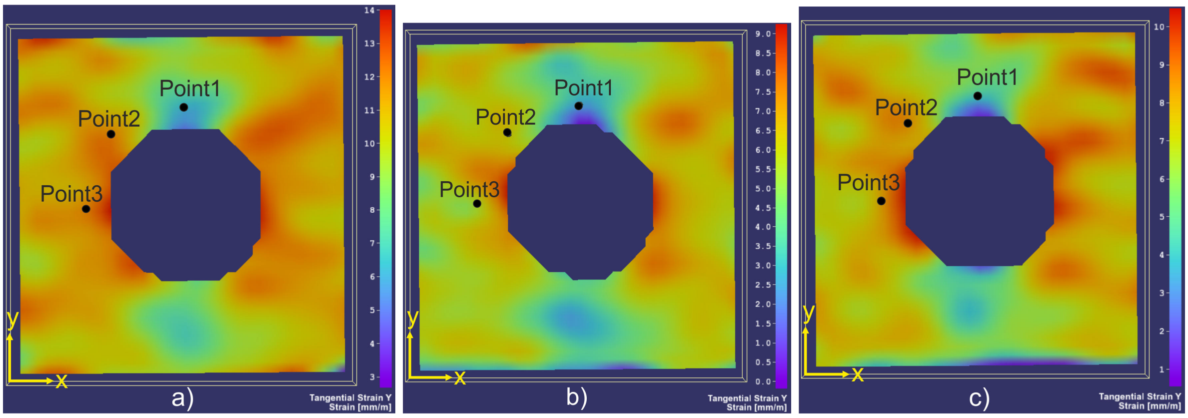

Fig. 8. Fields of tangential strain ε_y obtained by 2-D correlation system: a) 1st measurement, b) 2nd measurement, c) 3rd measurement.

As can be seen the fields of tangential strain ε_y depicted with particular scales are totally different. Likewise the fields of tangential strain ε_x as well as tangential shear strain γ_{xy} are not the same. The differences are probably caused by the fact, that our loading system was not stabile enough and during the loading the specimen was tilted toward the camera image plane. For the illustration we introduce a table with values of strains in particular points (Table 2.).

Table 2. Values of strains obtained in three chosen points by 3-D and 2-D measurement.

		Point 1	Point 2	Point3
3-D Measurement	ε_x	-0.25	-3.13	-1.38
	ε_y	1.43	5.75	5.28
	γ_{xy}	-0.33	0.93	0.17
2-D Measurement1	ε_x	6.11	3.47	4.23
	ε_y	6.10	12	12.10
	γ_{xy}	0.74	0.79	-0.47
2-D Measurement2	ε_x	1.11	-2.8	-0.91
	ε_y	2.24	6.23	5.67
	γ_{xy}	0.04	1.1	0.16
2-D Measurement3	ε_x	2.29	0.43	1.14
	ε_y	3.89	8.46	8.27
	γ_{xy}	-0.44	1.37	0.41

From the obtained results it is possible to point out, that there is not a measurement performed with single-camera system, by which the same results as with two-cameras system were achieved. For that reason, still if it is possible, we recommend to use 3-D measurement.

The Influence of Calibration Target Size on the Quality of Obtained Results

Calibration of the cameras, by which the system samples the locations of calibration target's characteristic points, is a very important part of deformation analysis using correlation systems. On the basis of obtained data the system calculates internal as well as external parameters of the cameras required for the projection of three-dimensional coordinates of object points into two-dimensional coordinates of sampled images.

The calibration should be correctly performed with the calibration target of the size corresponding approximately to the size of investigated specimen. As in our instance the investigated specimen was very small, we had just two targets, by which it was possible to calibrate the system. These calibration targets have a checkered shape with 9x9 fields of the size 1.0mm as well as 1.5mm.

Calibration residuum – a qualitative parameter for identification of properly performed calibration - expresses accuracy of the object point projection to the camera image plane. For right performed calibration this quantity should not overpass the amount of 0.5px. By the calibration of the system with calibration target with fields' size of 1.0mm the calibration residuum reached the value of 0.232 px and with the second one 0.276px, what indicates that both calibrations were done correctly.

In Fig. 9 and Fig. 10 the courses of tangential strains ε_x and ε_y obtained by performing of 3-D measurement in three points mentioned above are depicted using dashed lines. The facet size used for evaluation was set to 20x20px. For the comparison the courses obtained in SolidWorks in the same points are depicted with a solid line.

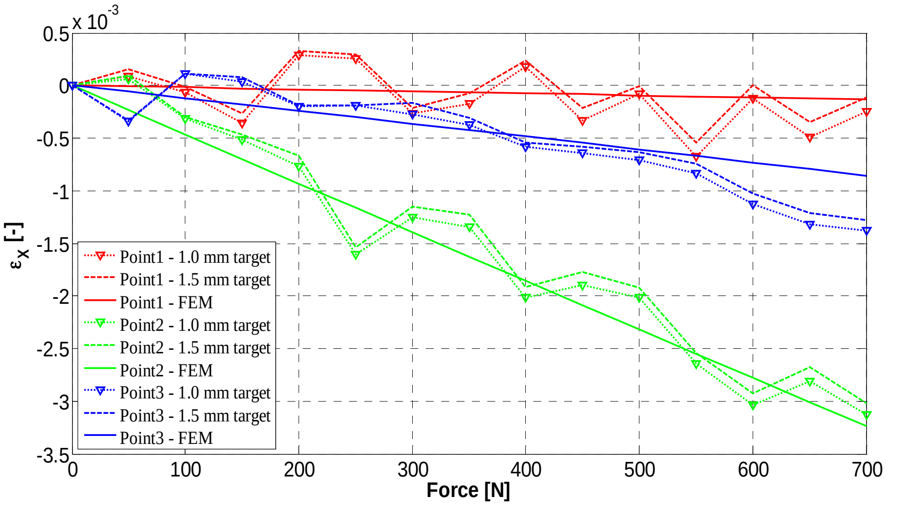

Fig. 9. Comparison of tangential strains ε_x obtained by FEM and DIC in three identic points.

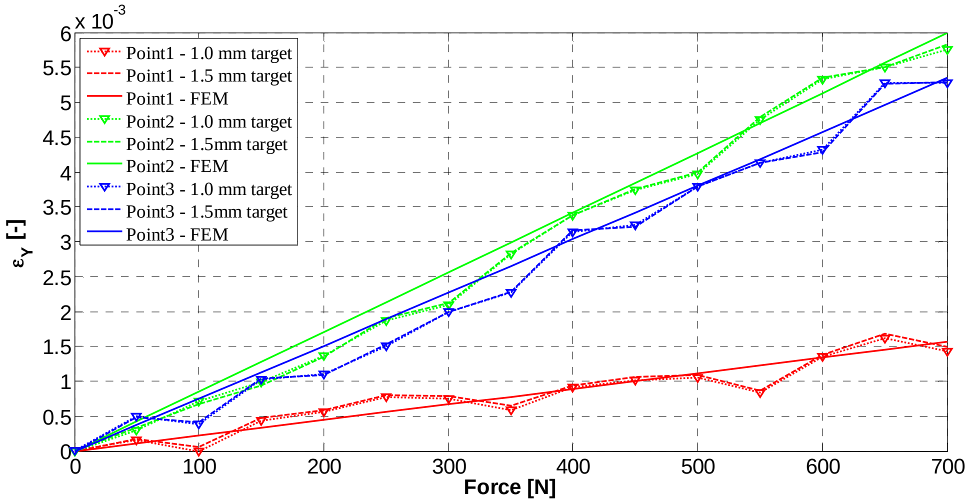

Fig. 10. Comparison of tangential strains ε_y obtained by FEM and DIC in three identic points.

From the presented results it is clear, that the cameras calibrations performed with calibration targets with fields' sizes of 1.0 mm or 1.5 mm have no significant influence on the quality of obtained results.

Conclusions

By the use of digital image correlation there is a difference between the results, if the measurement is evaluated by various adjustment of correlation parameters or performed using 2-D like 3-D correlation system. We recommend the use of 2-D measurement just to the experienced users, which will be particular in precise setting of parallelism between investigated object surface and camera's image plane during whole loading process. The incorrectly performed cameras calibration influences the quality of the results. By the use of calibration targets of similar sizes their influence should not be so relevant to devalue the obtained results.

Obtained results predicate, that it is needed to study the presented problems more precisely, especially the area of facet sizes used for evaluation, their influence on the quality of the results and corresponding setting of filtering levels. Performed measurements could become a convenient "beating board" for another investigation of presented problems.

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