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THE ASPECTS OF STRESS ANALYSIS PERFORMED BY DIGITAL IMAGE CORRELATION METHOD RELATED WITH SMOOTHING AND ITS INFLUENCE ON THE RESULTS

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Abstract: The paper deals with a description of the aspects of stress analysis performed by 2D or 3D digital image correlation system. It describes the differences between the types of smoothing used in Istra4D that is a software commercially delivered with correlation systems Dantec Dynamics. The analysis was performed on flat specimen made from PSM-1 material used in photoelasticity method. By loading of the specimen in form of three-point bending, a proper dependence between the facet size set for correlation of the images and level of local regression filter (characterized by a kernel size) was found. The finding for mentioned dependence was realised by comparison of the results with the results obtained numerically in Ansys Workbench 17.0.

1 Introduction

The full-field deformation/stress analysis performed by digital image correlation method requires the use of one or more digital camera(s) with image resolution adequate to realized measurement. While the specimens of common sizes (in range from several mm2 to several m2) are mostly analysed using standard digital image correlation systems consisting CCD cameras with image resolution of several Mpx, the analysis of micro-objects are performed by specially design correlation systems similar to microscopes. Correlation system consisting in one camera (Figure 1) theoretically suffices for the analysis of plane deformation [1-3].

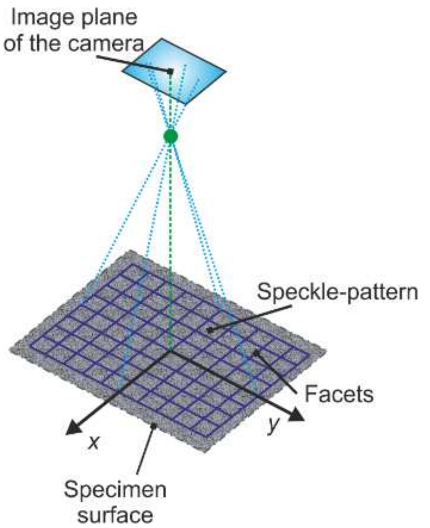

Figure 1 The scheme of single-camera (2D) correlation system

In case of spatial deformation analysis, the correlation system has to contain more cameras (Figure 2). While the concurrent between the image plane of single-camera system and the analysed specimen surface leads to the occurrence of some correlation errors, the use of more-cameras system (even in case of 2D analysis) overcomes this drawback [1-3].

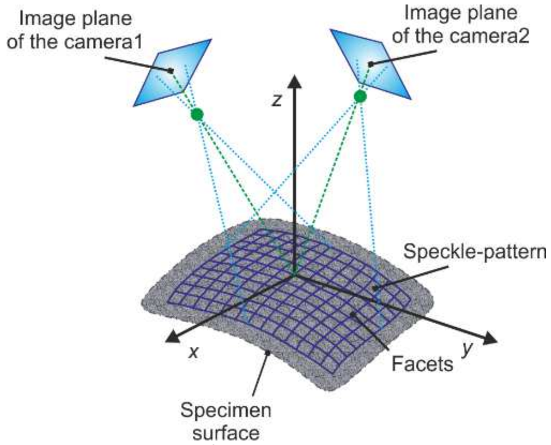

Figure 2 The scheme of two-camera (3D) correlation system

Already two-camera system can be used for analysis of the specimens with curved surface. For a purpose of high accuracy and reliability of the results, the four-camera system is able to realize both-sided deformation analysis of flat specimens and the eight-camera system (Figure 3) manages to evaluate the cylindrical shaped object along its circumference.

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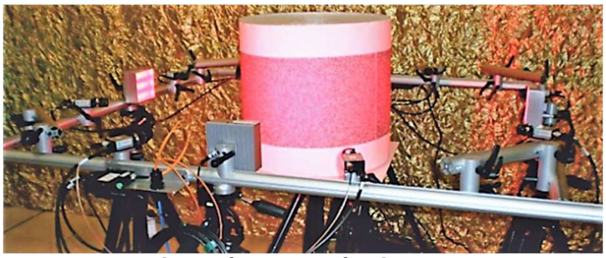

Figure 3 The configuration of eight-camera system

Digital image correlation method is based on the correlation of the digital images captured during specimen loading. It is performed along small picture elements called facets. Commonly, the facet is a group of pixels with squared shape and size from 15x15 px up to 30x30 px, however, the facet size can be adapted (increased or decreased) due to the type of the analysis. To perform proper correlation of the images, it is necessary to ensure the uniqueness of the facets, i.e. each facet has to contain unique distribution of the pixels with different level of grey value. The facets can touch or overlay themselves, but the gap between them is not possible. As the information about the displacements of the analysed object are obtained in nodal points of so-called virtual grid (the middles of the facets), the overlay of the facets (see Figure 4) belongs to the ways how to improve the image resolution, i.e. to obtain more data points and thus to copy the surface in better way.

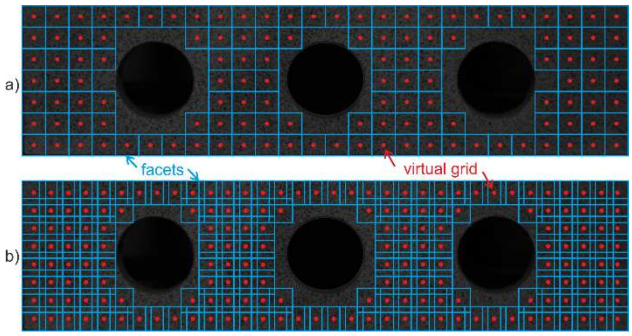

Figure 4 a) Facets without overlay, b) Facets with overlay

The manufacturer of correlation systems Dantec Dynamics recommends overlying the facets up to 1/3 of the facet size, because by such overlay the data points are still independent [4, 5]. The bigger overlay causes, that the neighboring data points lose independence. The similar situation occurs, if the smoothing filter is applied on the data. The higher level of overlying, the higher the level of smoothing as well as the number of data points used for smoothing. However, the determination of more data, or even higher image resolution does not occur. The last, simplest way for the image resolution increasing is the decreasing of facet size, however, it is limited by the quality (fineness) of the speckle-pattern created on the analysed object surface.

The results of deformation analysis performed by Dantec Dynamics correlation systems are relatively much influenced by a level of smoothing chosen by the user of software Istra4D, which is control and test software of mentioned correlation systems. The software allows filtering the data using two functions. The first one, called *Smoothing spline*, works globally on the data points and serves mainly for investigation of areas with homogeneously distributed deformation. This function fits the object surface by the bi-cubic smoothing function, whereby it uses two boundary conditions for the calculation of the spline functions. The first spline function minimizes the difference between the data point and the spline function and the second one minimizes the integral of curvature of all spline functions. In case of using this type of smoothing, two parameters are set in Istra4D – the *Grid Reduction Factor* (GRF) and the *Smoothness factor* (SF). If the GRF is increasing, the amount of measuring points is reduced and thus the obtained data are smoothed. The SF influences the condition of surface smoothing – the higher this value is, the more filtered the data are. Based on the analysis performed by manufacturer of Dantec Dynamics correlation systems, the following enclosures and recommendations for smoothing of object contour, displacements or strains using *Smoothing spline* were accepted [5]:

- SF has the biggest influence on the filtering of contour and displacements,
- by the displacement analysis oversized SF causes the higher level deviations – it smooths the whole surface and thus the noise or artefacts located in one part can affect the filtered data in another part,
- by the strain analysis oversized SF causes the devaluation of the results on the object edges,
- GRF has much lower influence on the results of displacement and strain analysis as SF.

The default levels of mentioned factors are GRF = 2.0 and SF = -1.0. The recommended range of particular factor levels for the specimen with big or small gradient of the contour, displacements and strains is given in Table 1.

Table 1 The recommended settings for GRF and SF [5]

	GRF		**SF**	
	Big gradient	**Small gradient**	**Big gradient**	**Small gradient**
Contour	2.0-2.5	≤ 3,0	-1,0-(-0,5)	≤ 0,0
Displ.	2.0	2.0	ca. -0,5	≤ 0,0
Strains	2.0	2.0	ca. -0,5	≤ 0,0

The second type of filtering used in Istra4D is *Local regression*, which fits the 2D polynomial object surface to 3rd order in the data. It is the type of smoothing optimized for keeping of local extremes and essentially determined for smoothing of non-homogenous fields (the analysis of the specimen with stress concentrators, crack initiation, etc.). Depending of the kernel size, set by the user, it is possible to define the level as well as the type of displacements and strains smoothing. While this filter is not activated, the strain is calculated from the deformation of the facet. On the other hand, the higher the kernel size, the higher the influence of deformation gradient for calculation of strains. Practically, by the set of kernel size bigger than 7x7, the strain is determined just from the deformation gradient. As can be seen in Figure 5 and Figure 6, where the typical differences obtained by the use of both smoothing filters are depicted, it is necessary to pay attention by the choice of adequate type and level of smoothing. According to the information available for authors, there is no rule, how to set the adequate kernel size by the evaluation of the experiments using local regression filter in Istra4D.

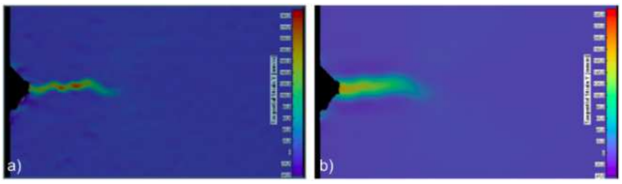

Figure 5 Smoothing of strain field with local concentrator using: a) local regression, b) smoothing spline [5]

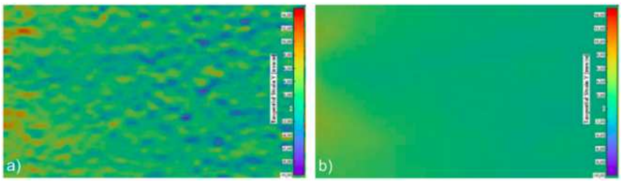

Figure 6 Smoothing of homogeneous strain field using: a) local regression, b) smoothing spline [5]

2 Experimental assessment of proper level of local regression

From mentioned reasons an analysis was performed with aim to find a dependence between the facet size and corresponding kernel size in such way, that the results of the analysis reached towards the expected results as small difference as possible. Although the authors' workplace disposes of several full-field experimental techniques (digital image correlation, electronic speckle-pattern interferometry as well as photoelasticity) it is not easy to find such method, which can serve for effective comparison of the results of strain/stress analysis on bigger surface. Although the results from experimental modelling are often used for verification of the numerical models, in some cases this process can be inversed.

The size and the shape of the analysed specimen (Figure 7) as well as the boundary conditions of the analysis were chosen with a purpose to:

- use the image resolution of low-speed CCD cameras of the correlation system Q-400 Dantec Dynamics as effectively as possible,
- have possibility to create proper speckle-pattern on the object surface, for which it will be possible to perform correlation of the images with sufficient range of chosen facet sizes,
- reach sufficient level of deformation in the surrounding of the stress concentrators even in laboratory conditions.

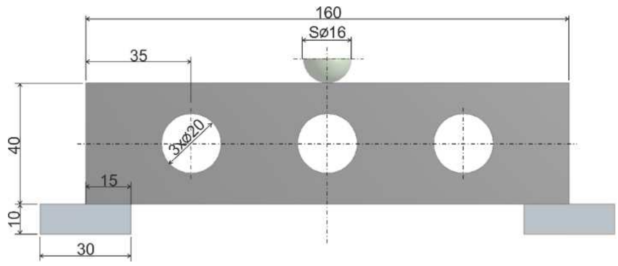

Figure 7 Shape and dimensions of the analysed specimen

The specimen was made from PSM-1 material with thickness of 10 mm, used in photoelasticity method. It was put into the loading frame, allowing the realisation of three-point bending test and loaded in such way that the displacement of the sphere-shaped spike reached 1.5 mm in the last loading step. For a purpose to minimize the potential of errors, the analysis was repeated three-times using single-camera and two-camera correlation system.

The reference images captured by both mentioned correlation systems with marked evaluation mask can be seen in Figure 8. The pixel density for 2D analysis was ca. 14.5 px/mm and for 3D analysis ca. 14.64 px/mm.

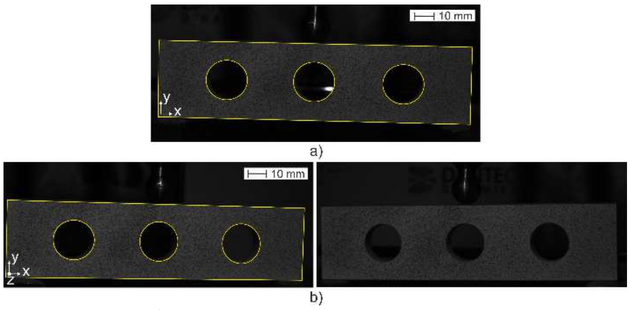

Figure 8 Reference images captured by: a) single-camera system, b) two-camera system

Numerical model consists in four bodies – the analysed specimen made from PSM-1 material with Young's modulus $E = 2.5\text{GPa}$ and Poisson ratio $\mu = 0.38$, two supports and the hemispheric spike made from stainless steel ($E = 200\text{GPa}$ and $\mu = 0.3$). The supports were located in such way that they supported the specimen on the areas of size 15x10 mm2 (see Figure 7). The loading was realized by the movement of the spike in the direction of vertical specimen axis of symmetry. The contact of two rigid bodies with friction coefficient 0.4 (the value used for friction between steel and polycarbonate) were defined between corresponding parts of the model. The mesh of finite elements, created on particular parts of the numerical model, together with defined boundary conditions can be seen in Figure 9.

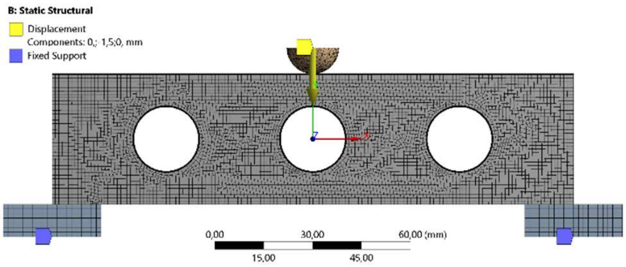

Figure 9 The finite element mesh with the boundary conditions defined at the numerical model

Figure 10 shows the distribution of equivalent von Mises stress on the analysed specimen surface. The best way, how to compare the results from both analyses would be to export nodal data from FEA and to couple them with corresponding experimental nodal data from the middles of the facets. Although, Istra4D allows to export data in hierarchical HDF5 file format, it is complicated to couple the mentioned data properly, because neither the amounts, nor the locations of nodal points have to correspond. For that reason, the authors decided to compare the values of equivalent stress on two corresponding areas with sizes 90x6 mm2 (see Figure 11), which the highest levels of stresses were determined on.

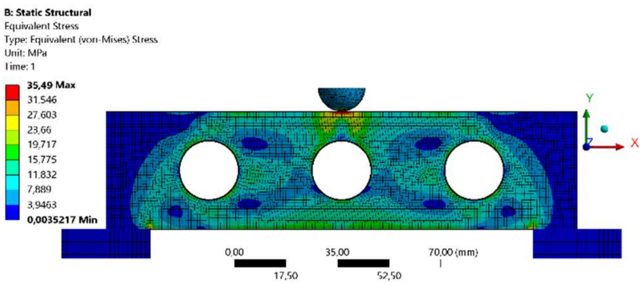

Figure 10 Equivalent von Mises stress field obtained on the analysed specimen surface

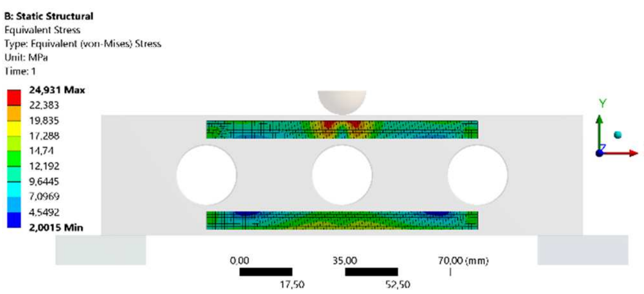

Figure 11 Two areas defined for comparison of equivalent von Mises stress determined by DIC and FEA

The height of the areas lower than 10 mm (by which the areas could touch the bottom or the upper edge of the specimen) was chosen with a purpose that digital image correlation allows to obtain data just in the middles of the facets. This fact leads to the loss of the data on the edges – the distance of first data point from the edge is minimally one half of the facet size.

The measurements realized using single-camera and two-camera system were evaluated in sequence using different facet sizes. In case that the facets touch themselves, the facet sizes used for correlation of the images were in the range from 10x10 px up to 25x25 px. In case of their overlay, the facet sizes were chosen in range from 10x10 px up to 30x30 px. Subsequently, the various levels of smoothing were set to filter the data and to find the best equality between the results obtained numerically and experimentally. There were two criterions for best equality. If the functions expressed by eq. (1) and eq. (2)

$$\Delta_{\sigma_{\max.}} = \frac{\sum_{i=1}^{3} abs\left(\left(\frac{\max\left(\sigma_{i_{\exp}}^{Mises}\right)}{\max\left(\sigma_{i_{num}}^{Mises}\right)}-1\right)\cdot 100\right)}{3} \qquad (1)$$

$$\Delta_{\sigma_{\mathrm{str.}}} = \frac{\sum_{i=1}^{3} abs\left(\left(\frac{\mathrm{mean}\left(\sigma_{i_{\exp}}^{Mises}\right)}{\mathrm{mean}\left(\sigma_{i_{num}}^{Mises}\right)}-1\right)\cdot 100\right)}{3} \qquad (2)$$

where $i = 1,2,3$ are three performed measurements, $\max\left(\sigma_{i_{\exp}}^{Mises}\right)$ and $\mathrm{mean}\left(\sigma_{i_{\exp}}^{Mises}\right)$ are the maximal and the mean values obtained on the analyzed areas experimentally by digital image correlation system, $\max\left(\sigma_{i_{num}}^{Mises}\right)$ and $\mathrm{mean}\left(\sigma_{i_{num}}^{Mises}\right)$ are the maximal and the mean values obtained on the analysed areas experimentally by software Ansys Workbench 17.0, reached minimum the optimal kernel size was found.

The bar graphs in Figures 12-15 show the determined optimal dependence between the facet size used for correlation of the images captured by single- or two-camera system and the kernel size of the local regression used for smoothing of the data. The obtained dependences indicate that the settings of kernel size should be approximately the same for 2D as well as 3D analysis.

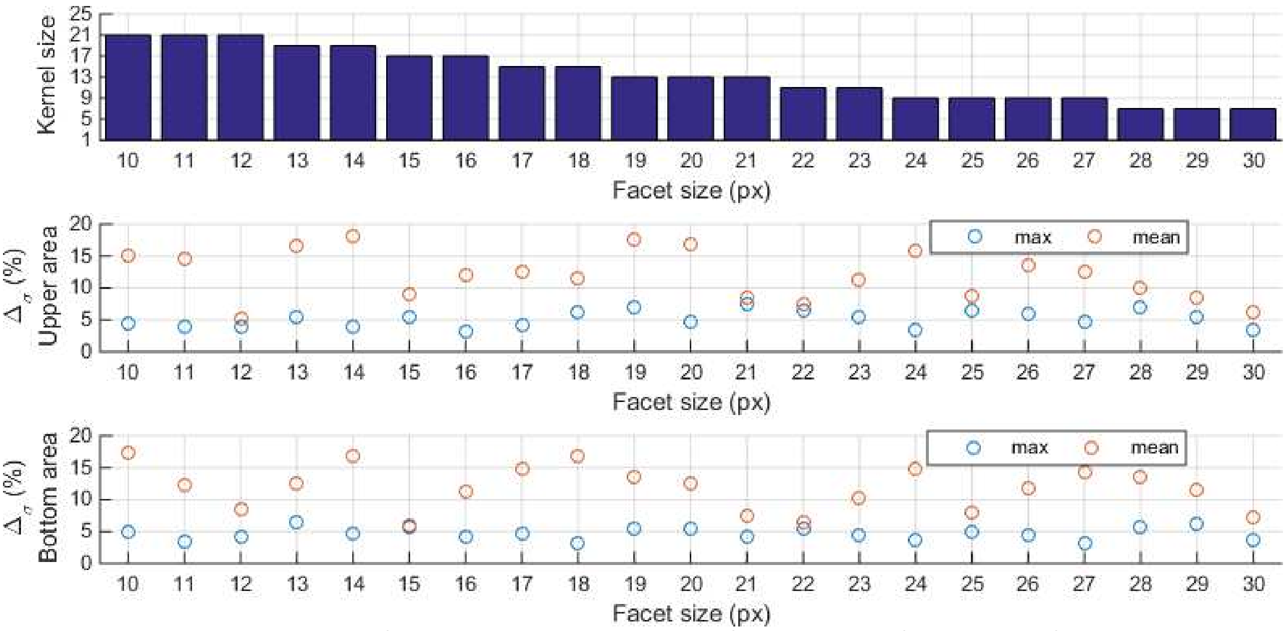

Figure 12 Dependence between the facet size and corresponding level of kernel size used for smoothing of 2D analysis without overlay of the facets (the first graph), corresponding differences in maximal and mean value of equivalent stress obtained on analysed areas (the second and the third graph)

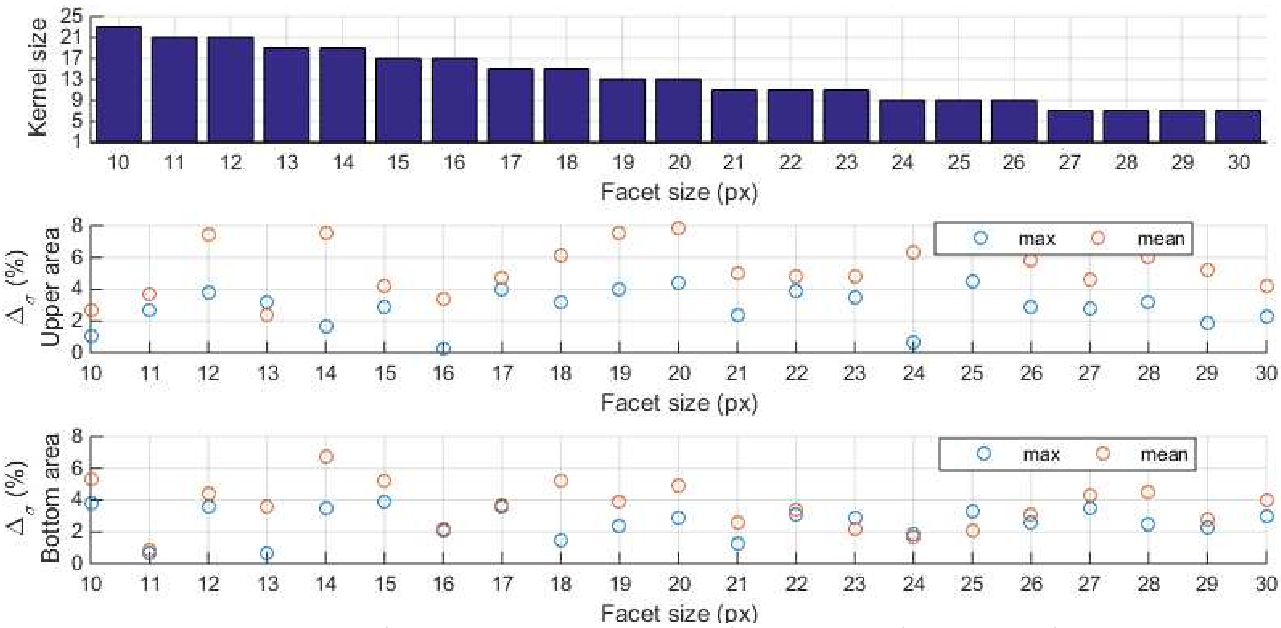

Figure 13 Dependence between the facet size and corresponding level of kernel size used for smoothing of 3D analysis without overlay of the facets (the first graph), corresponding differences in maximal and mean value of equivalent stress obtained on analysed areas (the second and the third graph)

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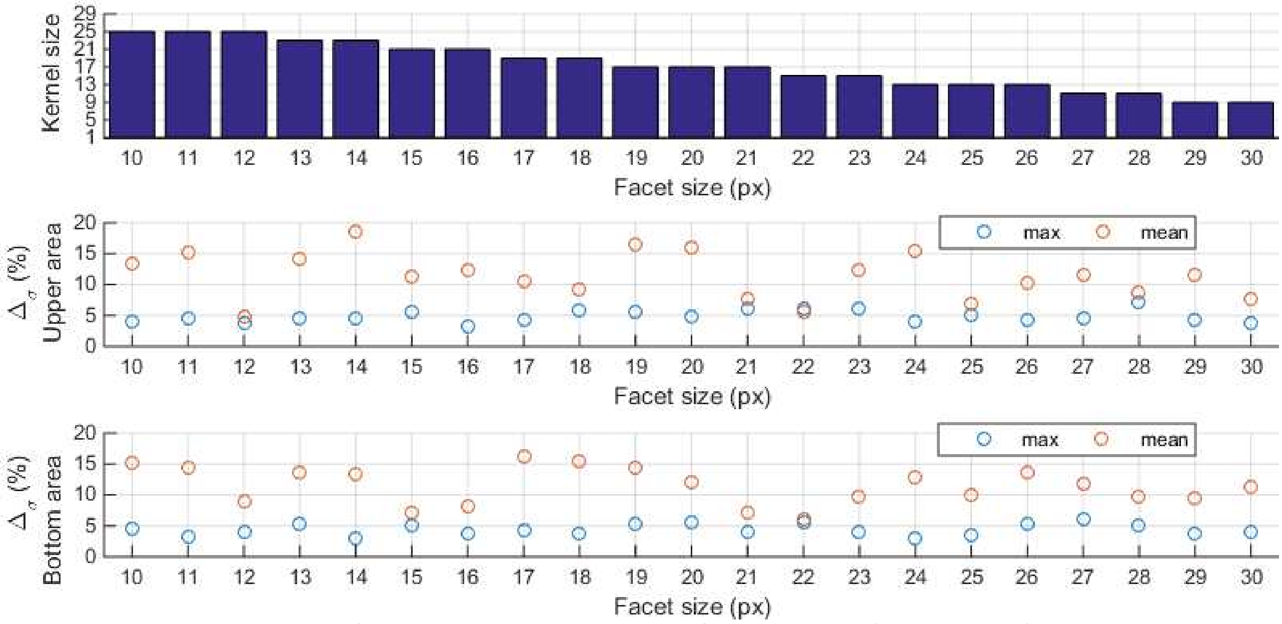

Figure 14 Dependence between the facet size and corresponding level of kernel size used for smoothing of 2D analysis with overlay of the facets (the first graph), corresponding differences in maximal and mean value of equivalent stress obtained on analysed areas (the second and the third graph)

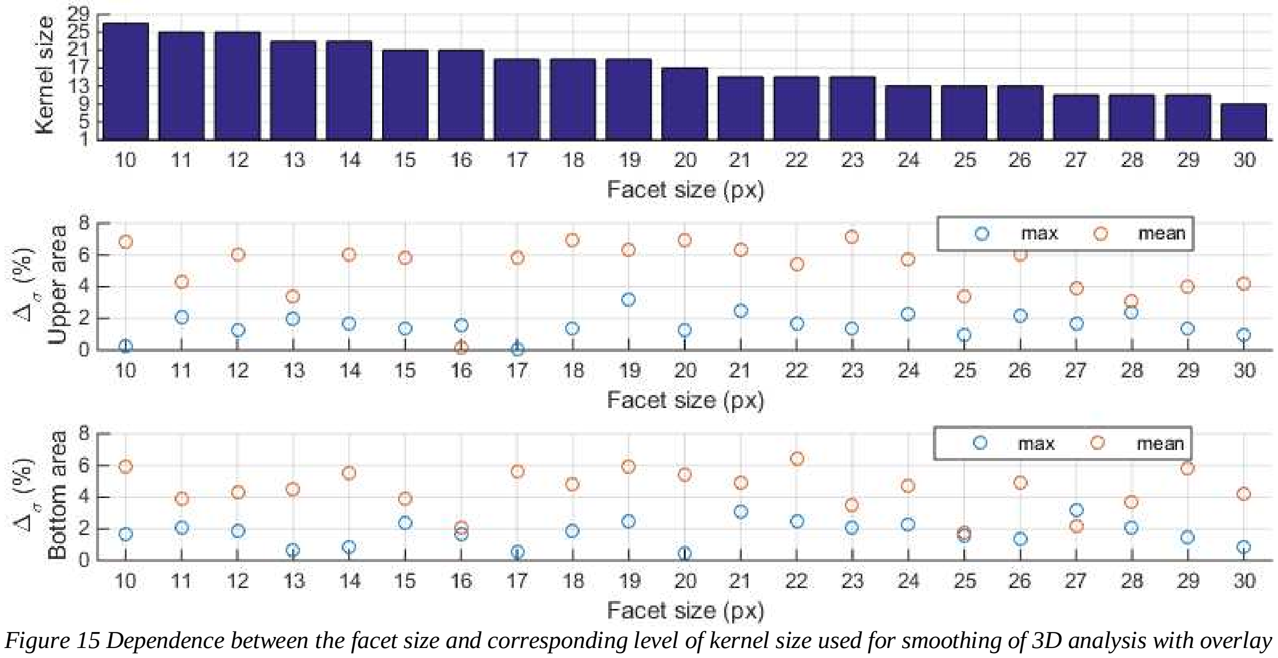

Figure 15 Dependence between the facet size and corresponding level of kernel size used for smoothing of 3D analysis with overlay of the facets (the first graph), corresponding differences in maximal and mean value of equivalent stress obtained on analysed areas (the second and the third graph)

The differences in the results obtained by the correlation of the facets without as well as with overlay are not very significant. By the use of single-camera system, the higher differences from the results obtained numerically can be observed. According to the authors this phenomenon was caused by the decay of parallelism between the camera image plane and object surface during loading of the specimen. Although the authors tried to ensure the plane deformation of the specimen, in some cases it is not so easy to reach it that leads to occurring of reconstruction errors.

The advantage of the use of facets with overlay accrues from the course depicted in Figure 16, which depicts the dependence of correlated facets amount on the facet size registered in 3D analysis.

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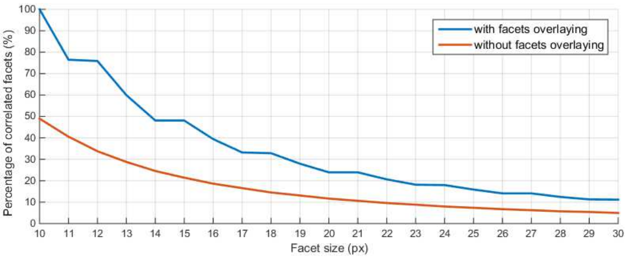

Figure 16 Dependence of percentage of correlated facets on the facet size used for evaluation with and without overlay of the facets

In this case, the 100% value corresponds to the value of correlated 22609 facets with size of 10x10 px and overlay of 33%. As can be seen the image resolution by the use of facets without overlay is approximately 2x smaller.

Figure 17 and Figure 18 depict the equivalent von Mises stress field evaluated by the smallest image resolution (the overall amount of evaluated facet with size of 30x30 px without facets overlay was 1122) as well as by the biggest image resolution (the overall amount of evaluated facet with size of 10x10 px with facets overlay was 22609).

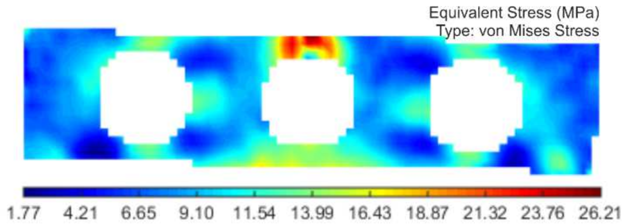

Figure 17 Equivalent von Mises stress obtained on the analysed specimen surface by the correlation with the facets size equal to 30x30 px without overlay

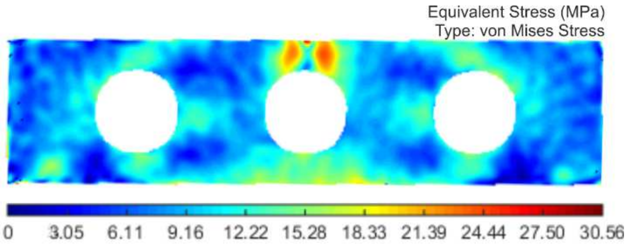

Figure 18 Equivalent von Mises stress obtained on the analysed specimen surface by the correlation with the facets size equal to 10x10 px with overlay

Although the criterions defined by eq. (1) and eq. (2) for facet size 30x30 px without overlay reached relatively favourable values, the distribution of von Mises stress field (see Fig. 17) is in the central upper part of the specimen influenced by small number of data points. Compared to mentioned fact, the von Mises stress field depicted in Fig. 18 shows good equality to the results obtained numerically. Moreover, it copies the object surface in better way and thus the maximal values of stress differ less from the maximal values of finite elements analysis.

3 Conclusions

The authors describe the aspects corresponding with the use of 2D and 3D digital image correlation system in stress analysis of flat specimen. It can be stated, that the use of two-camera system allows stress analysis with smaller risk of reconstruction errors that leads to results with higher accuracy. In the paper, the dependence between the facet size used for correlation of the images and the optimal kernel size used in local regresion filter was found. If it is possible the authors recommend to use overlayed facets, which ensure obtaining data as near to the object edges as possible. Moreover, the images has higher image resolution, that increase the quality of the obtained results.

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Review process

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