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DEVELOPMENT OF DIGITAL IMAGE CORRELATION TOOL TO DETERMINE DISPLACEMENTS AND STRAINS IN MECHANICAL TESTING

Ellon Bernardes de Assis

Francisco Evangelista Junior

ellonber@hotmail.com

fejr@unb.br

Universidade de Brasília

Postgraduate program in Structural Engineering and Construction (PECC), Prédio SG 12, primeiro andar, Campus Darcy Ribeiro, Universidade de Brasília, 70910-900, Brasília, Distrito Federal, Brasil.

Abstract. *This paper intends to implement a computational tool using DIC (Digital Image Correlation) for determining in-plane displacement and strain of objects subjected to mechanical testing. DIC is a robust technique for measuring full field of displacements and strain from comparison between object images on undeformed and deformed state. The first step of the routine is dividing the image in small subsets that have their displacement estimated by a first order function. The Zero Normalized Sum of Squared Differences is used as correlation criteria for comparison of the subsets. The Newton-Raphson algorithm is used to minimize the correlation criteria and determine the unknown displacement parameters of each subset. The calculation order of the subsets is guided by the correlation coefficient as proposed by the Reliabity Guided DIC algorithm. This allows the calculation of objects with irregular borders. Finally, the Savitsky-Golay algorithm is used for smoothing of the strain field. The implemented routine is tested using images artificially deformed with digital image editors and real mechanical test images. The results of the implemented routine are compared to the artificial predetermined displacements and to results from other open source DIC.*

Keywords: *Digital image correlation, Displacement/deformation measurement, Full field measurement, Non-contact measurement, Reliability guided DIC*

1 INTRODUCTION

In face of the limitations of traditional measuring instruments such as LVDTs (Linear Variable Differential Transformer) and strain gauges, new measuring techniques have been developed such as the Digital Image Correlation (DIC). Their main characteristics are the absence of contact between instruments and specimen and the possibility to measure the full field solution of displacement and strain (Bruck et al., 1989); (Sutton et al., 2009); (Pan et al., 2009). These characteristics allow extracting more data from a test at low experimental cost. DIC technique, which deployment has started in the 1980s, has been improved greatly in the past years achieving less computational cost and improved accuracy (Pan et al., 2009). Its concept is based on comparing consecutive images of the same object, which can be displaced and deformed. The estimation of displacement and strain is done by grey-level intensity comparison over the specimen surface in different instants of loading.

In this work it is studied only 2D DIC, which is used for in-plane measures. In order to use DIC successfully is fundamental to do a previous study to determine the appropriate experimental apparatus as well as doing appropriate image processing (Sutton et al., 2009). Concerning to experimental apparatus the main aspects are contrast in the specimen surface, camera and lighting. Contrast in the specimen surface is usually guaranteed by speckling it with small random paint dots (Reu,2015). It is also important to use DIC algorithms that are adequate for each experimental situation. It is need to be conscious that the image processing algorithm influences the way of conducting experimental tests. In other words, it is necessary to use a DIC routine capable of processing accurately the desired displacement and strain according to the particularities of the test.

2 DIC ALGORITHM

The objective of image processing algorithm is to calculate the full field solution of displacements and strain in the specimen surface using undeformed and deformed specimen images. This is achieved by a numeric comparison of grey-level intensities between different images. In this context, some steps are necessary. First, it is necessary to divide the image in small subsets of pixels that are assumed to move and deform together because of continuity hypothesis. Then a mapping function is applied to grey-level intensity to describe the displacement and strain of each image subset in different moments. The next step is choosing correlation criteria to compare numerically the similarity of subsets in different moments. After that, correlation criteria is minimized to calculate the optimal displacement and strain values. The steps described above are valid for only one subset, in order to calculate the full field of displacements and strain it must be solved for all subsets in the image surface. Care is taken in the calculation order since it affects the results and convergence characteristics of the algorithm according to Pan et al. (2009). Finally, the strain field is calculated based on the displacement field using a smoothing filter because of the numerical noise presence in the data calculated by the minimization process.

2.1 Image dividing, mapping function and interpolation

Image division in subsets of pixels was implemented using small squared subsets that are sized according to routine input. The subset size is important for algorithm convergence and depends on image in processing. According to Reu (2014), at least two or three speckles of the speckle patterning must be inside a single subset. It is assumed that pixels inside a subset deforms together as shown in the Fig. 1 using the standard axis definition for image processing.

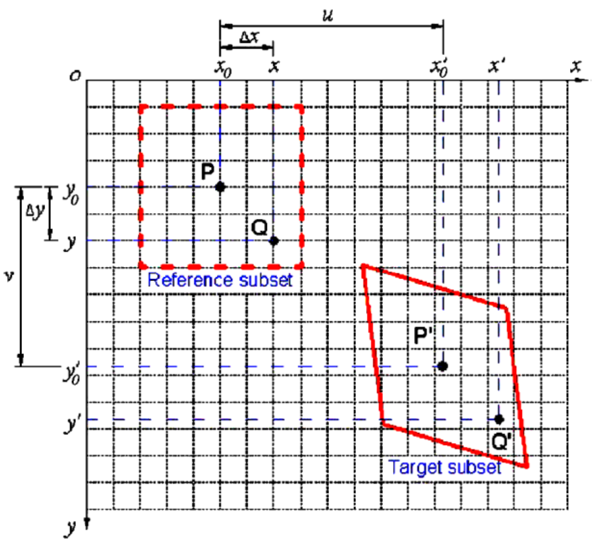


Figure 1 – Example of a subset deformation (Pan et al., 2007)

The mapping of original pixels positions **Q(**x, y**)** around the subset center **P(**x_0, y_0**)** in different moments of loading is done by a first order mapping function defined by Eq. (1) and Eq. (2). **Q'(**x', y'**)** denotes the pixel position after deformation.

$$x' = x_0 + \Delta x + u + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta y \tag{1}$$

$$y' = y_0 + \Delta y + v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y \tag{2}$$

Where u and v are the displacement components of the subset as shown in Fig. 1; $\partial u / \partial x$, $\partial u / \partial y$, $\partial v / \partial x$ and $\partial v / \partial y$ are the strain components of the subset. These six unknowns define the vector $\mathbf{p} = (u \quad u_x \quad u_y \quad v \quad v_x \quad v_y)$ that must be calculated by the algorithm.

A digital image is formed by grey-levels intensity values in discrete points known as pixels. However, the real object is continuous, so it is possible that the pixel discrete points that describe the image do not cover some points of the real object. In other words, some points of the object can be in a subpixel position. Because of this, it is crucial the interpolation of the grey-levels intensity to get subpixel information. In this work a polynomial bicubic interpolator was used.

2.2 Correlation Criteria

The calculation of vector $\mathbf{p}$ is done using a function that shows the similarity between an undeformed subset and a deformed one. In this work we use the Zero Normalized Sum of Squared Differences (ZNSSD), Eq. (3), because it allows changes in lighting between undeformed and deformed subsets. In addition, it permits easier differentiation than other correlation criteria (Sutton et al., 2009); (Pan et al., 2009).

$$C_{f,g}(\mathbf{p}) = \sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[\frac{f(x,y)-f_m}{\left\{\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[f(x,y)-f_m\right]^2\right\}^{1/2}} - \frac{g(x',y')-g_m}{\left\{\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[g(x',y')-g_m\right]^2\right\}^{1/2}}\right]^2 \tag{3}$$

Where the subset center is assumed as origin and summation is taken from *-M* pixel to *+M* pixel. In other words, subset is *2M x 2M* pixels. The functions *f* and *g* are the grey-levels intensity in the undeformed and deformed image, respectively. The f_m and g_m values are the mean grey-level value in the undeformed and deformed subset, respectively.

2.3 Minimization of correlation criteria

Calculation of unknown vector $\mathbf{p}$ is done by minimizing the ZNSSD function using Newton-Raphson method as presented by Bruck el al. (1989) and improved by Vendroux & Knauss (1998). The Eq. (4) is solved iteratively.

$$\mathbf{p} = \mathbf{p_0} - \frac{\nabla C(\mathbf{p_0})}{\nabla^2 C(\mathbf{p_0})} \tag{4}$$

Where $\mathbf{p_0}$ is the initial guess, $\mathbf{p}$ is the next iteration vector, $\nabla C(\mathbf{p_0})$ is the gradient matrix of the correlation function and $\nabla^2 C(\mathbf{p_0})$ is the matrix of second order derivatives, known as Hessian matrix.

2.4 Determining full field solution

The calculation of full field solution is achieved using the Reliability-Guided DIC (RG-DIC) proposed by Pan (2009). The Newton-Raphson initial guess for the first subset is determined using the calculated Zero Normalized Cross Correlation (ZNCC) over all the deformed image. This allows using a initial guess that corresponds to a peak of correlation. In sequence, the other subsets are calculated starting from the neighborhood of the first one. The initial guess is the vector calculated immediately before the current subset. However, the Zero Normalized Cross Correlation (ZNCC) is used to guide which neighboring subset will be the next to be calculated. Using the initial guess proposed, the algorithm calculates the values of ZNCC of the neighboring subsets, then the highest ZNCC subset is solved next. This calculation order avoids the transmission of bad guesses thrown the algorithm, it improves Newton-Raphson convergence and ability to deal with irregular boundary.

The values of strain field are directly calculated by Newton-Raphson, however these values are noisy. Because of that, it is implement the Savitzky-Golay algorithm proposed by Pan et al. (2007). The method consists in local least squares approximation of the displacement field using planes of 30 pixels by 30 pixels, such way that is easy differentiate it to get the strain field.

3 ROUTINE ASSESMENT METHODOLOGY AND RESULTS

The implemented DIC routine was assessed by two trials. These trials were done using images provided by the Society for Experimental Mechanics which encourages research in DIC through the DIC Challenge initiative (SEM, 2017). In this work was used two set of images, the first consists of prescribed displaced speckle images virtually created and the second consist in tensile test images of a plate with a hole.

The results of the implement DIC routine are compared to results of open source software Ncorr, which was proposed by Blaber et al. (2015). Ncorr is one of few free open source 2D-DIC routines.

3.1 Prescribed displacement

Assessment of subpixel measuring performance was done using the Sample 1 of the SEM-DIC Challenge database. This set of images consists in 20 images computationally generated to simulate simultaneous displacement in standard x and y axis as showed in Fig. 1. Shifting of 0.05 pixels are applied in steps to each image which results in 1 pixel of total displacement in the x axis and -1 pixel in the y axis. The images are 512x512 pixels size. Figure 2 shows the reference image.

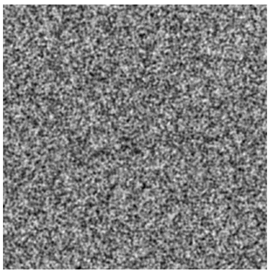
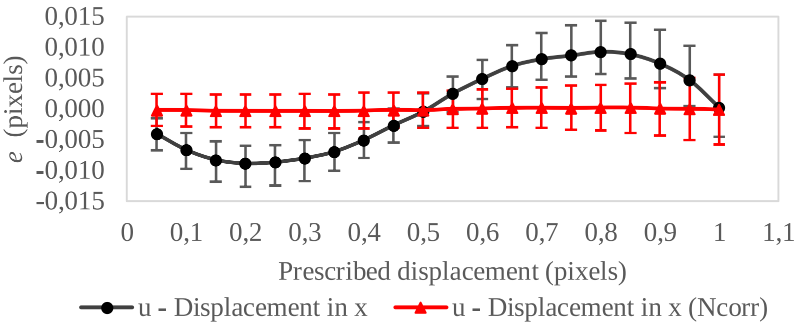


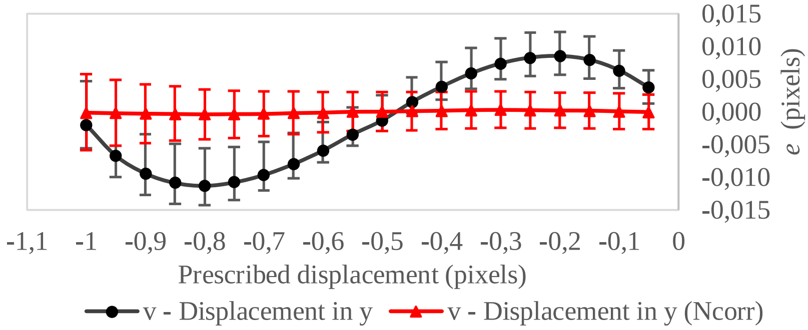
Figure 2 – Reference image for Sample 1

The set of images was processed using the implemented DIC routine using a subset correlation size of 21x21 pixels. The subsets were calculated over the entire image using 5 pixels of spacing between subsets centers in both coordinates directions. Ncorr calculation was performed using equivalent parameters. Ncorr uses circular subsets, then 10 pixels radius subsets were used. The spacing between subset was maintained.

Graphs of Fig. 3 express the error *e* of processing results for x and y displacements. The error is calculated as the mean difference between the prescribed displacement and the calculated displacement for each of the subsets. Graphs shows dots as the mean error and vertical lines as the range between 5% quantile and the 95% quantile for each prescribed displacement. All results were achieved with Zero Normalized Cross Correlation Coefficient greater than 0.95.



a) x



b) y

Figure 3 – Error, *e*, in displacement calculation by proposed algorithm and Ncorr in direction a) x and b) y

The analysis of the graphs shows that Ncorr software has great accuracy and approximately equal performance for all prescribed displacements. On the other hand, the proposed routine had similar result to Ncorr only for 0.5 pixel e 1 pixel of prescribed displacement. It can be noted that the error of intermediary values tends to push this values towards 0.5 pixel and 1 pixel. A hypothesis of this behavior is that the bicubic polynomial interpolation used can not achieve better approximation of subpixel displacement. In opposition, Ncorr uses a biquintic B-spline interpolation (Blaber et al., 2015). This agree with Schreier et al. (2000) that showed that biquintic splines results in lower systematic errors than cubic polynomial interpolation.

Despite the worse accuracy results compared to Ncorr, the error of the proposed routine is quite small. It is assumed maximum error of 0.015 pixels on the trial conditions. This value can be used for initial planning of experimental apparatus once it is a key factor for choosing speckle size and image resolution. However, this value is only an initial estimation. It should be considered that accuracy of DIC routines depends on several factors such as image contrast, subset correlation size and intensity of deformation.

3.2 Plate with circular hole

Assessment of routine performance in measuring complex displacement and strain field was done using Sample 12 images of the SEM-DIC Challenge (SEM, 2017). This set is composed of 11 images, size of 400 pixels by 1040 pixels, of real tensile test on plate with hole. The plate surface is speckled to provide good DIC matching between images. This set of images is not provided with the experimental measured values of displacement and strain. Then, this trial was performed analyzing only the difference between results of proposed algorithm and Ncorr defined by the *e'* variable. It was used squared 21x21 pixels subsets and 5 pixels of spacing between subset centers. Displacement in intermediary pixels was calculated using linear interpolation. Figure 4 and Fig. 5 shows results of proposed algorithm for displacement and strain field evaluated at last loading step, which corresponds Image 11 of Sample 12.

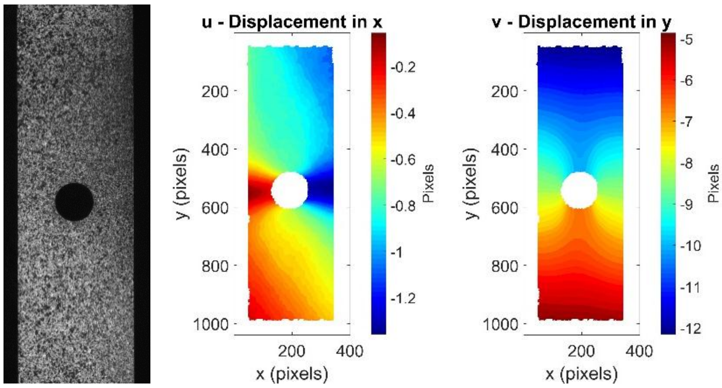


Figure 4 – Reference image and displacements results of proposed algorithm for Image 11

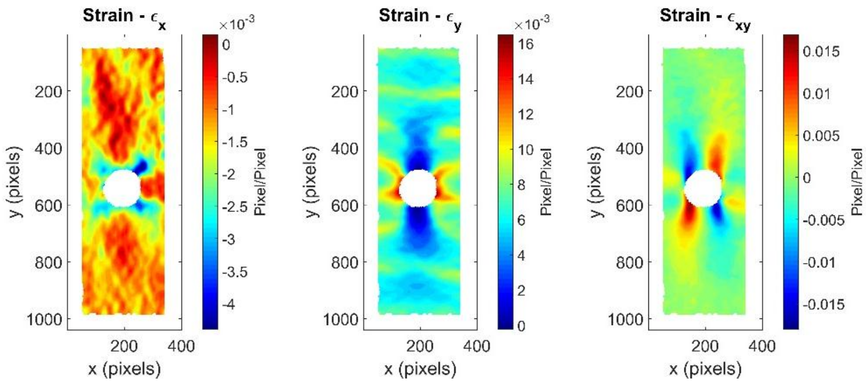
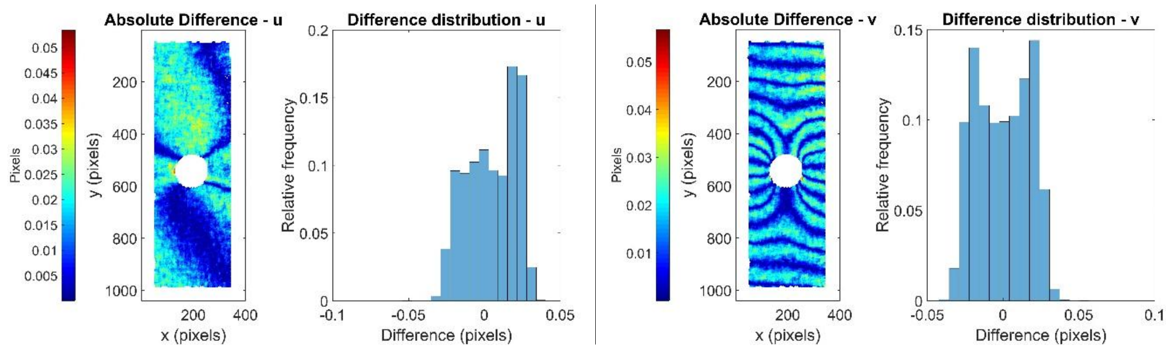


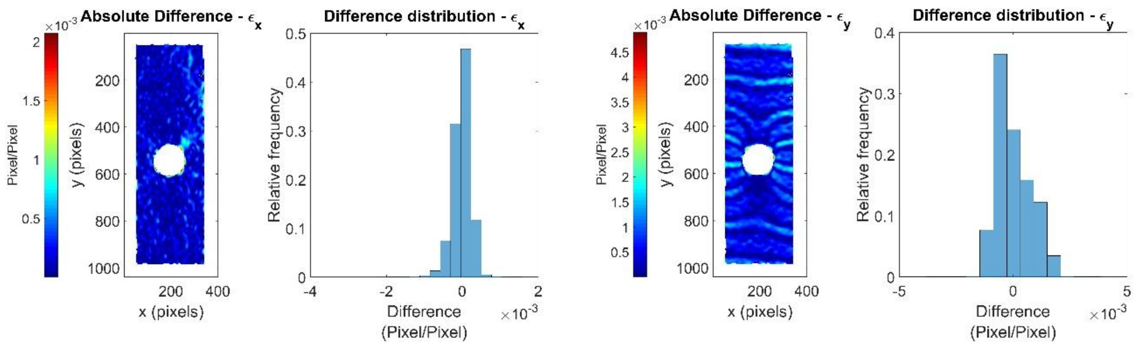
Figure 5 – Strain results of proposed algorithm for Image 11

Comparison between results of proposed algorithm and Ncorr were done by contours graphs expressing absolute difference |*e'*| between each pixel result. In addition, histograms were used to assess the distribution of difference *e'* for displacements and strain as shown in Fig. 6 and Fig. 7. The graphs analisys shows that difference is greater for displacements that are not multiples of 0.5 pixel. This result can be seen in Fig. 4 and Fig. 6 graphs for *u* displacement. In the plate area where $u \approx 0.5$ pixel, |*e'*| is around 0.005 pixels. On the other hand, in the plate area where $u \approx 0.8$ pixels, |*e'*| is around 0.02 pixels. This result is in accordance with prescribed displacement trial. Large deformation around the hole in addition to reduced number of pixels in border subsets make hole neighbourhood a critical area for image matching. As a consequence, this area presents greater differences.

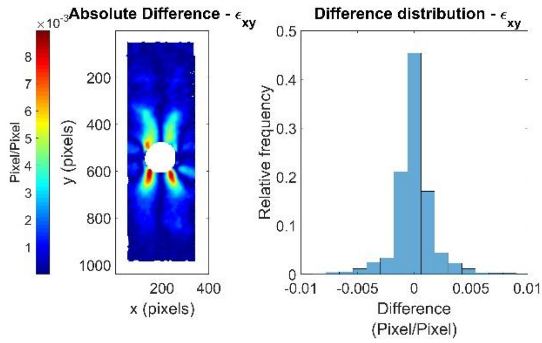


a) ***u*** **b)** ***v***

Figure 6 – Difference distribution, *e'*, and absolute difference, |*e'*|, for displacement field a) *u* and b) *v* of Image 11



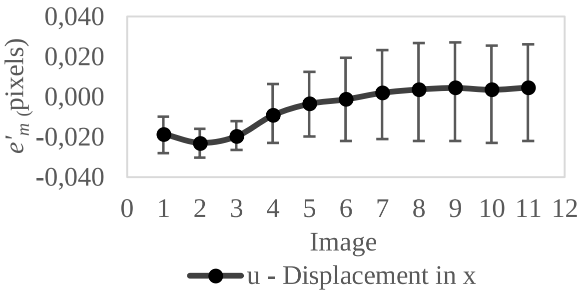
a) $\boldsymbol{\varepsilon_x}$ **b)** $\boldsymbol{\varepsilon_y}$

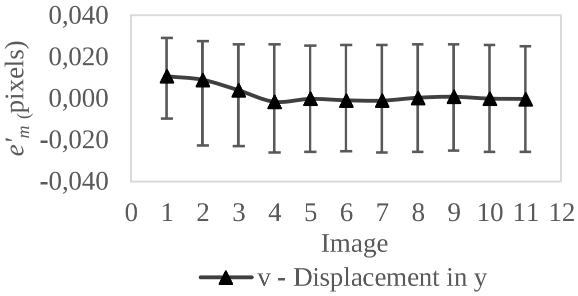


c) $\boldsymbol{\varepsilon_{xy}}$

Figure 7 – Difference distribution, *e'*, and absolute difference, |*e'*|, for strain field a) ε_x , b) ε_y and c) ε_{xy} of Image 11

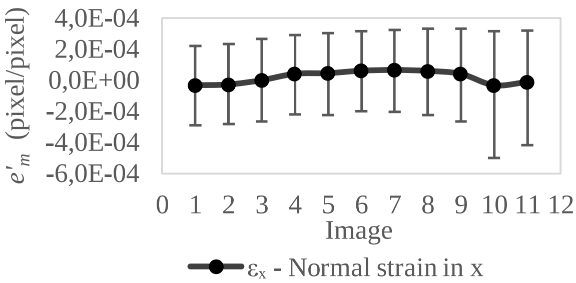
Further analysis was performed by calculating all 11 images in the sample. Figure 8 and Fig.9 shows the mean difference e'_m as dots and vertical lines as the range between 5% quantile and the 95% quantile for each image.

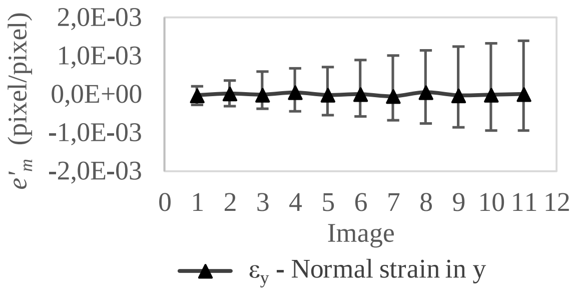




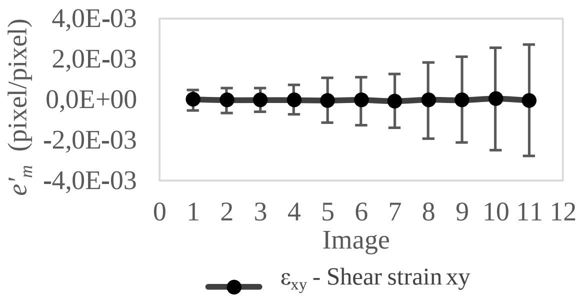
a) ***u*** **b)** ***v***

Figure 8 – Mean difference, *e'ₘ* , for displacement field a) *u* and b) *v*





a) $\boldsymbol{\varepsilon_x}$ **b)** $\boldsymbol{\varepsilon_y}$



c) $\boldsymbol{\varepsilon_{xy}}$

Figure 9 – Mean difference, e'_m , for strain field a) ε_x , b) ε_y and c) ε_{xy}

The analysis of displacement difference graphs shows that absolute mean difference is greater for initial images, which have small displacements. As loading increases, as well as displacements, the mean difference tends to zero and quantiles range keeps constant with absolute difference less than 0.03 pixels. One hypothesis for this behavior is the limitation of routine to evaluate subpixel displacements as discussed in the prescribed displacement trial.

A consequence of that inaccuracy in subpixel measurement is that results for all loading steps looks similar to Fig. 6. Because displacement field is continuous, some areas will result in less accurate values than other what makes greater difference compared to Ncorr. This is the explanation for wide amplitude in quantiles but mean difference of approximately zero.

On the other hand, strain analysis shows that as loading increases the range of quantiles increases also. However, it should be noted that errors in the displacement field results influences the accuracy of strain field as well. Although this limitation, this result is important because it shows that calculated strain accuracy depends on deformation level of object.

4 CONCLUSION

This work implemented a DIC routine for calculation of in-plane displacement and strain field. The trials results showed routine potentials and limitations. In both prescribed displacement and plate trials the routine presented less accuracy for displacements that are not multiples of 0.5 pixel. However, range of 5% and 95% quantiles shows small absolute error less than 0.015 pixels for the prescribed displacement trial. Furthermore, the analysis of plate trial shows difference compared to Ncorr less than 0.03 pixels. Results presented in this paper agree with literature about systematic error in displacement and strain measurements due to grey-level interpolation. Therefore, it is interesting to implement interpolation using splines of high order in the future to improve results.

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