Full-field optical measurement for material parameter identification with inverse methods

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Abstract

The application of FE simulation in manufacturing processes and virtual prototyping increases every day. In order to allow accurate simulations, correct constitutive models are needed as input to the FE software. A modern and promising way to identify the material parameters in those constitutive models is "inverse modeling". Full-field measurement is a suitable way to get the necessary experimental data. The technique has many advantages such as large information contents, non-contacting measurement, and versatile size of observation region, among others. However, there is no standardization yet for this kind of measurements. Therefore, there are many disagreements among researchers about how to design DICT experiments and how to correctly collect the data from DICT experiments. This paper will concentrate on discussing the key points of those problems as well as presenting some work experience with the DICT.
Keywords: inverse method, FEA, full field measurement, digital image correlation.

1 Introduction

Identification of cracks and defects, and estimation of distributions of material properties from experimental data are inverse problems, which are not well recognized till the middle of 1980's. Thanks to the development of information technology by leaps and bounds, increasing efforts have been devoted to advance

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in inverse problem research, especially at beginning of 1990's [1]. The main reason is that the production cycles in industry, such as automobile and aircraft industry, become shorter since 1990's. To face this challenge, many industries take advantage of computer simulations to provide powerful insight into structural behavior of mechanical systems, manufacturing processes, and many other engineering problems, which can reduce the dependency of the manufacturers on expensive and time consuming hardware prototyping [2]. A common requirement for the success of the numerical models used in computer simulation software is the input of the correct material properties. The properties of many materials however can not be found in literature. A modern alternative to find the material properties is inverse modeling.

The principle of inverse modeling is shown in Figure 1. The input quantities are assumed to be perfectly known and are the same for the experiment as for the numerical model. The unknown parameters in the numerical model are tuned in such a way that the computed output matches the experimentally measured output, e.g. displacements or strains, as closely as possible.

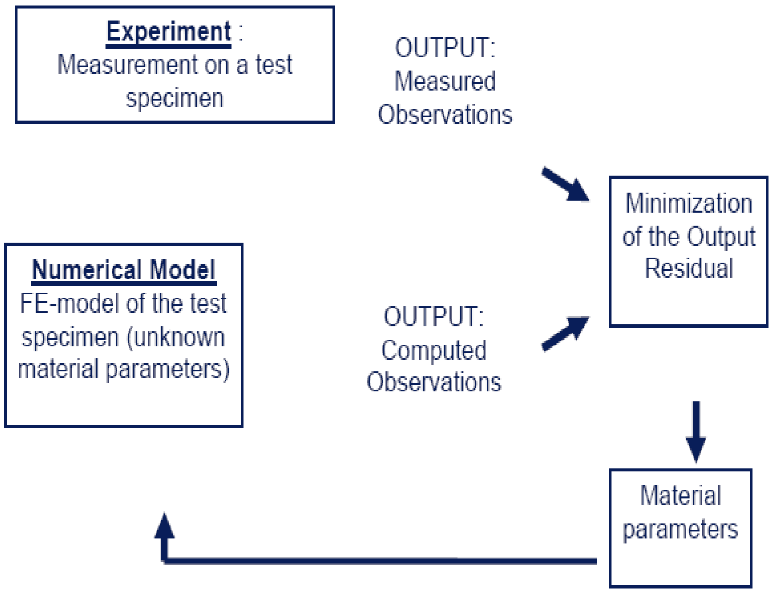

Figure 1: The principle of an inverse method for material identification.

In general, the elasto-plastic material parameters are determined by means of standard tests, such as tensile tests, bending tests and torsion tests. However, the stress and strain fields occurring during these traditional tests do not represent the complex stress and strain fields which are generated during real production processes. With those techniques, the specimen can be tested in such a way that the material circumstances are comparable with the circumstances of the material

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during the service life of the construction or during the manufacturing process, e.g. Single Point Incremental Forming process (SPIF).

The main problem of adopting more complicated tests in the past was always hindered by the fact that complex displacement fields simply could not be measured. In recent years however, an increasing number of important developments in the field of full-field displacement measuring have been presented. Moreover, modern measurement equipment, as there are Flow Induced Birefringence, Electronic Speckle Pattern Interferometry, Digital Image Correlation techniques, have become commercially available and more accessible than they used to be in the past. Furthermore, more information about material parameters can be caught from one experiment, so called "full field measurement".

In the current article, an example of full-field measurement by means of digital image correlation technique (DICT) will be presented. This technique exploits a good prospect for inverse modeling since it has some important advantages, for instance non-contacting measurement, large observation region, etc. However, there is no standardization for such kind of measurements. Therefore, there are many disputations about how to design DIC experiment and how to correctly collect the data from DIC experiment. In the following the influence of subset size, step size and strain window size on the final strain computation will be discussed in detail. Some experiences for DIC experiment will be introduced for sharing the knowledge.

2 Full field digital image correlation experiment

In general DICT is just a method to measure displacements. However, some extra calculations on the displacement field allow us to extract strain data from the displacement measurement. In this case, this technique will be applied for the measurement of the heterogeneous deformation fields during a forming process

2.1 Principle of DIC

Basically, the displacement measurement goes as follows: a **random speckle pattern** is applied on the surface of the object of interest. During the forming process, a number of pictures of the object of interest are taken with one or more CCD (Charge Coupled Device) cameras (if two cameras are used, it is possible to measure the displacements in three orthogonal directions). Each picture corresponds to a different state of deformation (usually the first picture is taken at zero loading and is called the reference image). Finally the speckle pattern allows us to correlate the different images to each other and as a result the displacement field (relative to the reference image) in the different images can be measured. As was already mentioned, some extra calculations make it possible to extract strain data from this deformation measurement. Figure 2 summarizes the above described technique.

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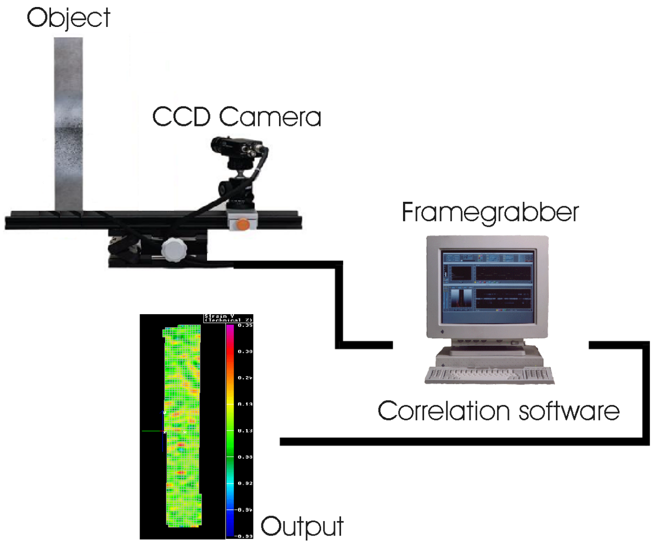

Figure 2: Diagram of digital image correlation experiment.

The CCD cameras use a small, rectangular piece of silicon, which has been segmented into arrays of individual light-sensitive cells, also known as “photo sites”. Each cell constitutes one element of the whole picture and is called a pixel. Every pixel stores a certain grey scale value varying from 0 to 255, in agreement with the intensity of the light, reflected by the surface of the tested specimen. Thus, an image can be looked at as a matrix in which every element represents the grey value of the corresponding pixel.

In order to run the correlation algorithm, the image is divided in a number of subsets. A subset represents a part of the whole image. The size of a subset can be varied by the user and the choice of a good subset size depends on the deformation. As was already mentioned, this technique uses a random speckle pattern that is simply sprayed onto the surface of the object or that is offered by the texture of the specimen’s material. The objective is to obtain an image with a varied and distinctive pattern, which enables the correlation algorithm to trace the subsets of the reference image in the deformed images [3, 4]. The concept behind the DICT-software 2D matching algorithm is that the distribution of grey values in a rectangular area (subset) in the picture taken of the specimen in the undeformed state, corresponds to the distribution of grey values of the same area in the picture taken at the deformed specimen. In this way the motion and the deformation of the subsets during the deformation of the object are determined. This will finally lead to a displacement field for the whole area of interest. Some additional calculations allow to extract strain data from this displacement field. Figure 3 shows such a subset in the undeformed (left) and deformed (right) configuration.

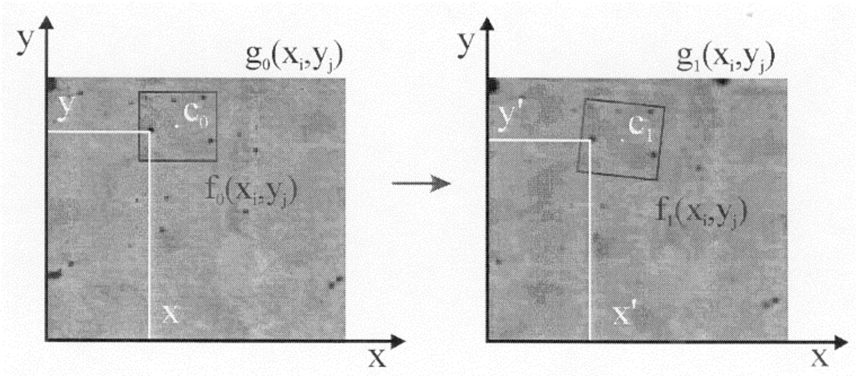

Figure 3: A subset in the undeformed (left) and deformed (right) configuration.

Measurements in three dimensional space require a measuring arrangement with two cameras, which should be placed with an angle of approx. 20° between them. A 3D measuring arrangement has to be calibrated prior to a measurement in order to be able to determine the image-forming qualities of the cameras and the lens distortions. With the aid of the determined image-forming qualities the subsequent calculations can be carried out.

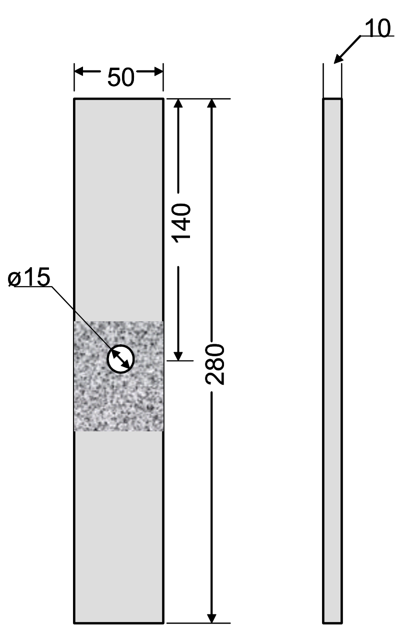

Figure 4: The geometry of the specimen and the generated speckle pattern zone.

2.2 Description of DIC experiment set-up

A tension test on an aluminium beam with a circular hole in the center is selected to study the identification of metallic plastic parameters, for instance, the anisotropic elasto-plastic law based on Hill48 yield locus with kinematic hardening. The geometry of the specimen is shown in Figure 4. The aluminium specimen was loaded in tension up to 80 kN. A speckle pattern was applied to measure the displacement field in the shaded zone by means of two CCD cameras. The images are regularly taken throughout the tension test. The software offered by **Limess Company** was used to calculate the strains in the shaded regions (see Figure 4).

3 Post processing of DIC results

During the post processing of the DIC experiment, the area-of-interest (AOI) should be selected. Following that, subset size (pixel) and step size (pixel) are chosen for calculating the displacement field. The strain window size is chosen for the strain calculation by Vic 3D software. One image, taken when force applied on the specimen reached a value of 40kN, is selected to study the influence of **S**ubset, **S**tep and **S**train window size on the strain value.

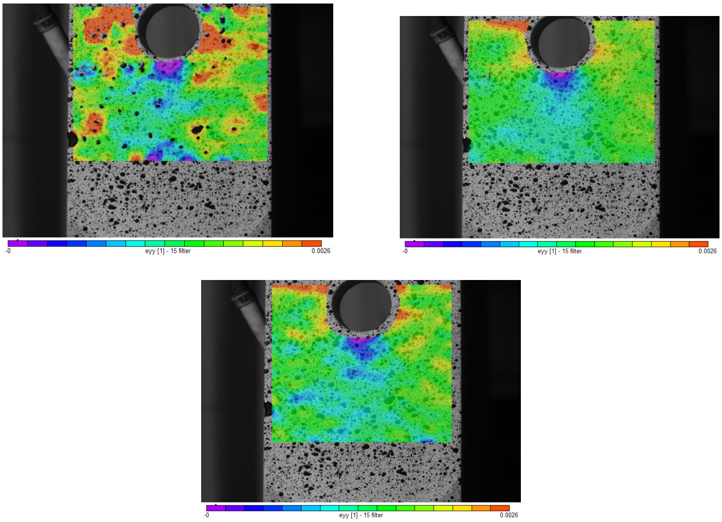

Figure 5: Upper left picture, the contour of strain y calculated with subset 11 pixels; upper right picture, the contour of strain y calculated with subset 17 pixels; lower picture, the contour of strain y calculated with subset 23 pixels.

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3.1 Different subset

The subset size controls the area of the image that is used to track the displacement between images. The subset size has to be large enough to ensure that there is a sufficiently distinctive pattern contained in the area used for correlation.

To show the influence of the subset size on the strain computation, a subset size of 11, 17 and 23 pixels was applied. The step size and the strain window size were 5 pixels and 15 respectively. It is found that some region with speckles bigger than subset lost the correlation, for instance, the upper left picture in Figure 5.

3.2 Different step

The step size controls the spacing of the points that are analyzed during correlation. If a step size of 1 pixel is chosen, a correlation analysis is performed at every pixel inside the area of interest.

To show the influence of the step size on the strain computation, a step size of 1, 5 and 11 pixels was applied. The subset size and the strain window size were 23 pixels and 15 respectively. It is found that too small step sizes result in a lot of noise on the calculated strain field. This causes some difficulties to collect strain data. To big step sizes result in too much averaging. Hence the actual strains are underestimated, especially in regions of high strain gradients, e.g. around the hole, as shown in Figure 6.

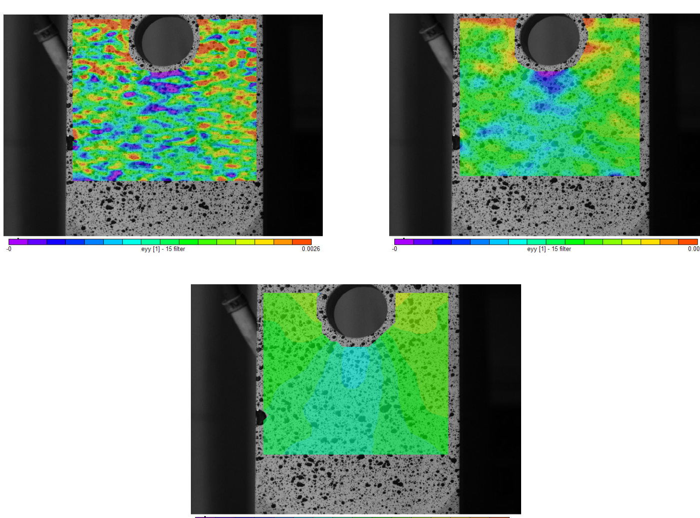

Figure 6: Upper left picture, the contour of strain y calculated with step 1 pixel; upper right picture, the contour of strain y calculated with step 5 pixels; lower picture, the contour of strain y calculated with step 11 pixels.

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3.3 Different strain window size

The strain window size can be used to adjust the size of the local neighborhood in which the derivatives of the displacement field are calculated. The value indicates the number of neighboring points instead of pixel.

To show the influence of the strain window size on the strain computation, a strain window size of 5, 15 and 25 was applied. The subset size and the step size were 23 pixels and 5 pixels respectively. It is found that too small strain window sizes result in a lot of noise on the calculated strain field (Figure 7), whereas too large strain window sizes result in too much averaging, especially in the region of high strain gradients like around the hole.

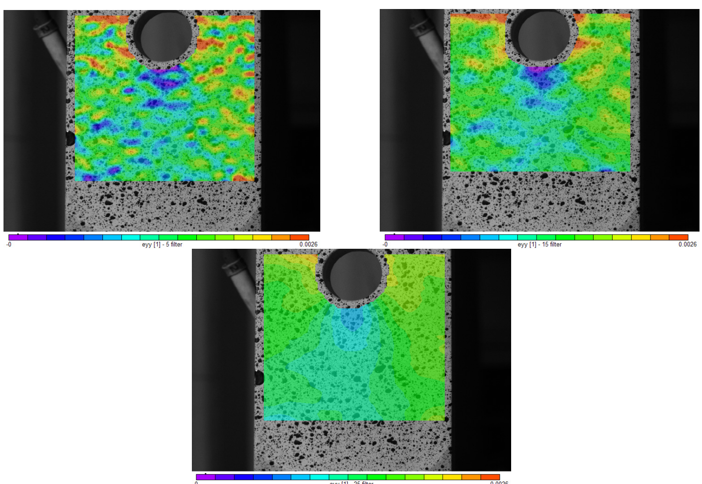

Figure 7: Upper left picture, the contour of strain y calculated with strain window size 5; upper right picture, the contour of strain y calculated with strain window size 15; lower picture, the contour of strain y calculated with and strain window size 25

4 Comparison of DIC results and FE simulation results

A FE simulation of this tensile test was performed by means of ABAQUS software, and the obtained strain contours in x and y direction are compared with those from the DIC experiment, respectively (see Figure 8 and Figure 9). Since the specimen is symmetric, only one eighth of specimen was modeled. The results of the FE simulation approach those of the DIC experiment quite well. The FE strains in x direction vary between 0.00011 and -0.00082; the strains in x direction, computed by the DIC software vary from 0.00033 to -0.00092. The FE strains in y direction vary from 0.0024 to 0.000097; the strains in y direction, computed by means of the DIC software vary between 0.0026 and 0.

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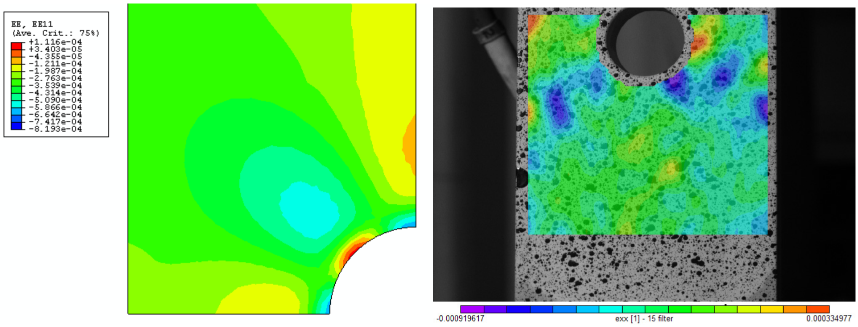

Figure 8: Left picture is the contour of strain in x direction obtained from FE simulation. The scale of strain is from 1.11e-4 to -8.19e-4; right picture is the contour of strain in x direction obtained from DIC experiment. The scale of strain is from 3.31e-4 to -9.19e-4.

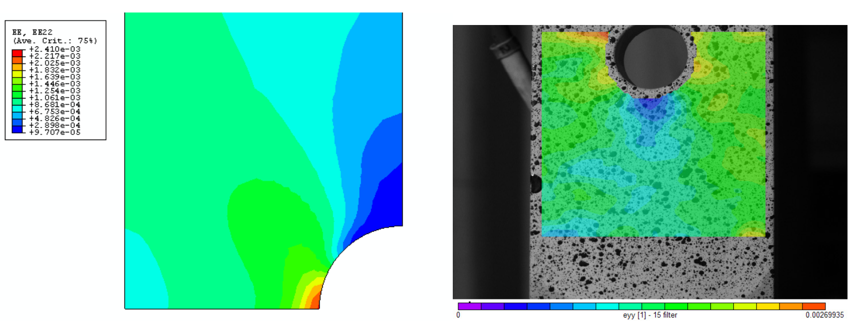

Figure 9: Up picture is the contour of strain in y direction obtained from FE simulation. The scale of strain is from 0.0024 to 9.7e-5; the picture below is the contour of strain in y direction obtained from DIC experiment. The scale of strain is from 0.0026 to 0.

5 Conclusion

In the present paper, the feasibility and reliability of data collection from full-field optical measurement is studied. It has been shown that the size of subset, step and strain window have a large influence on the accuracy of the measured displacements and calculated strains. Unsuitable subset, step size and strain window size will cause experiment data either underestimated or scattered.

In the post processing of DIC experiment, generally the larger the subsets are, the better the results are. However, large is a relative concept. It is important that the subset size is chosen in accordance with the expected deformations. It is clear

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that for steep gradients in the displacement or strain field, a large subset will smooth the real behaviour and thus yield erroneous results.

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