DIC Measurements in Engineering Applications

DIC Algorithms and Strategy, Benchmarking, and Projects
DIC Algorithms and Strategy

Digital image correlation (DIC) became indispensable when monitoring and analyzing the development of displacement or strain fields in time. The method is capable of capturing strain localization (such as plasticity or cracking) in any direction. It is not limited to a relative measurement of discrete points as conventional contact methods and appears to be more accurate than monitoring by means of extensometers or strain-gauges that often suffer from imperfect attachment to the measured surface. Moreover, the use of the DIC tools when analyzing the development of displacement or strain fields on a surface of a loaded structure or specimen can significantly reduce the cost of the experiment.

There are numerous ways how to measure deformations of a structure or specimen and conventionally used extensometers and strain-gauges at pre-determined locations are among the most frequently used. However, such approach has a few drawbacks compared to optical full field monitoring: the strain must be within a certain range and is averaged over the strain-gauge length, the measurement is accomplished at discrete locations, and the investigated surface must be smooth enough to attach the gauge. Optical measurements are capable of capturing even complex deformation until the ultimate material failure [1].

The basic theory of DIC, as a method to determine image motion and distortions [2], was established decades ago. Since then it has been extensively exploited as an efficient experimental tool to track displacement and strain fields of a surface texture or a stochastic pattern applied onto the tested specimen surface. To that goal, a subset of gray-scale pixels in the reference image (representing the initial state) is matched to a similar subset in the target image of a deformed surface.

Such an approach allows an efficient observation of localization phenomena where the conventional contact methods fail. The averaging of strains is also minimized and depends purely on the resolution of images and setting of DIC algorithms. Therefore, there is no inherent length-scale to DIC – by choosing the appropriate magnification of images and the corresponding speckle size, DIC can be used to measure displacements spanning from the meter to micron scale. Several studies that deal with evaluation of errors in the field of displacements and deformations obtained by DIC show a good accuracy of the method, e.g. [3].
DIC Principles and Requirements

The main idea of DIC is to find a correspondence between control points in a reference image and images of a deformed state. This is accomplished by tracking small subsets of the reference image, and determining their locations and distortions in the images representing the deformed state. The DIC output is provided in the form of a grid containing displacement and strain information with respect to the reference configuration.

The strains and displacements can be then either reduced or interpolated to form a continuous strain / displacement field. Detailed information about the DIC algorithms can be found in the papers by e.g. Pan et al. [3] or Lu and Cary [4].

DIC relies on a contrasting pattern applied onto the surface of the test specimen [5, 6, 7]. This pattern can be in the form of a natural texture or it can be applied artificially. The pattern quality has a dominant influence on the maximum resolution and accuracy of DIC results; the pattern must be random, isotropic, and highly contrasting.

For the purpose of image acquisition it is recommended to use a digital high-resolution camera fixed on a tripod. The camera has to be placed perpendicular to the specimen surface. The distance of the camera from the observed surface and focal length must be adjusted to mitigate the lens distortion effect [8]. Bright and constant illumination must be ensured through the image acquisition process, so that a short exposure time (e.g. 1/125) can be set.

References


Benchmarking

To the best of our knowledge there is no commercial competitor on the Czech market and even the academic research is limited mostly to the use of conventional strain and displacement measurement methods.

Based on a comprehensive research and communication with companies involved in the business we provide a brief summary of the international competitors.

Dantec Dynamics

Main area of the company activity is a development and sales of integrated measurement systems for diagnostics and research. Dantec Dynamics offers 2D and 3D DIC systems (including SW and HW). The company does not offer in situ measurement. The price of the 2D system Q-400 is 34,000 EUR (920,000 CZK) containing camera (5 Mpx, 15 fps), lens (17 mm focal length), control and analysis electronics system, software platform, camera acquisition module, correlation software module, graphical visualization software module, calibration targets, mounting rail and brackets, tripod, installation and 1-day training.

MatchID

Company was founded by three experts in the fields of image correlation, simulation and identification. MatchID offers 2D and 3D DIC software (not hardware). The company does not offer in situ measurement. The price of the 2D software MI-2D is 20,000 EUR (542,000 CZK) + optional yearly support fee 3,000 EUR (81,000 CZK). The price of the 3D software MI-Stereo is 50,000 EUR (1,356,000 CZK) + optional yearly support fee 7,500 EUR (203,000 CZK). 3-days in-company training costs 4,000 EUR (108,000 CZK).

Instron

Founded in 1946 and focuses on the material testing industry. Instron offers 2D DIC system only. Moreover, Instron DIC Replay software has to be coupled with Instron’s extensometer AVE 2, which collects data for later evaluation by the DIC Replay. The system costs 48,000 EUR (1,300,000 CZK).
Correlated Solutions

Founded in 1998 to commercialize Digital Image Correlation technology. Correlated Solutions offer 2D and 3D DIC systems (including SW and HW). It also offers an in situ measurement, however, the company comes from the USA, which makes the service unavailable for the Czech and even European market. The price of the 3D turn-key system VIC-3D, including training, is 60,000 EUR (1,627,000 CZK).

LaVision

Founded in 1989 as a spin-off from Max Planck Institute and Laser Laboratory in Goettingen, Germany. LaVision offers 2D and 3D DIC systems StrainMaster (including SW and HW). The company does not offer in situ measurement. The price of the StrainMaster 2D system, including 15 – 20 Mpx camera, is 55,000 EUR (1,492,000 CZK).

GOM

Company is an industrial manufacturer that develops and produces optical measurement solutions and technologies for a coordinate measurement and deformation analysis. GOM offers 2D and 3D DIC systems Aramis (including SW and HW). The company does not offer in situ measurement. The price of their products was not provided.

LIMESS Messtechnik und Software

Founded in 1998 as a spin-off of the University of Karlsruhe and since then develops camera-based measurement systems. LIMESS offers 2D and 3D DIC systems Q-400 (including SW and HW). The company does not offer in situ measurement. The price of their products was not provided.

Photo-Sonics International

Since the founding 70 years ago, the company focuses on the photo-optical instrumentation field and the motion picture industry. Photo-Sonics International offers only 2D DIC software TEMA DIC (not hardware). The company does not offer in situ measurement. The price of their products was not provided.
## Comparison of the Companies Dealing with DIC

<table>
<thead>
<tr>
<th>Company</th>
<th>2D SW / price</th>
<th>3D SW / price</th>
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Note: all the prices were converted using the exchange rate 1 EUR = 27.12 CZK and rounded.
Projects

Our team has a rich experience with the practical use of DIC, including some challenging tasks. To name a few: identification of crack patterns on masonry piers, monitoring of smeared cracking in composites with dispersed fiber reinforcement at low strain levels, or quantification of a slip at the interface of lamellas in glued-laminated beams.

To interpret the calculated data properly, it was necessary to develop reusable in-house software.

Investigation of Masonry Failure Mechanism

The traditional design of masonry structures, based on rules-of-thumb, has been replaced by the numerical approach to address their complex failure mechanisms. However, the simulations must be verified through an extensive experimental analysis to show the capabilities and limitations of the mathematical model.

In the case of masonry columns (Fig. 1), tested in the Experimental Center at the Faculty of Civil Engineering, Czech Technical University in Prague, the verification process was accomplished by comparing the numerical predictions with the experimentally obtained data on masonry piers containing commonly used repair mortars of rather distinct properties (Fig. 2). DIC allowed to compare the predicted and observed failure modes, and to evaluate the force-displacement diagrams with a high accuracy compared to extensometers that suffered from improper attachment and insufficient measuring range.

The optical full-field monitoring was accomplished using high-definition Canon 70D camera taking pictures at 5-seconds time intervals, set equally for all tested piers, to yield on average 210 images documenting the deformation of a single pier until its complete failure. The light sensitivity ISO parameter was manually set to 100, since a powerful artificial lighting was available. The perfect illumination allowed a short exposure time (1/125 sec) and the low aperture number set to f/8, which was kept constant for all images in the series. In order to minimize the effect of lens distortion, the distance between the camera and the observed surface was approximately 1 m, and the focal length (zoom) was set to 55 mm. The resulting DIC real scale resolution 0.202 mm/pixel was computationally feasible while preserving the required precision.
Fig. 1: Tested masonry pier subjected to the combination of compression and bending, introduced via eccentric loading and supporting.

Fig. 2: Cracking patterns on eccentrically loaded masonry piers; DIC results (left) and predictions by finite element analysis (right).
Monitoring of Multiple Cracking Development at Low Strain Levels

Conventional contact strain measurement methods, even if carried out properly, cannot be used for monitoring of the development of smeared cracks on the surface of fiber-reinforced composites because of their unpredictable location, direction and development. Therefore DIC was addressed when investigating such cracking at very low strain levels in high-performance concrete (HPC) specimens subjected to four-point bending or loaded predominantly in shear.

The DIC results confirmed the theoretical outcomes and clearly revealed the multiple cracking and strain-hardening behavior of the properly designed HPC composites. Fig. 3 demonstrates that DIC algorithms are capable of capturing the strain localization at very low strain levels (< 1/1000).

The four-point bending test (Fig. 4) results were compared with those of a direct measurement using calibrated LVDT position sensors fixed to the loading frame. Based on the calculated elastic stiffness using finite element method (FEM), represented by red line in Fig. 5, it can be concluded that the DIC techniques can provide much more accurate results than LVDT sensors. The contact sensors very often overestimate the measured displacements because of the additional compliance of the loading frame or slip in the sensor attachment.

![Image](image_url)

Fig. 3: Development of smeared cracks at low strain levels on HPC specimens with dispersed reinforcement during four-point bending test.
Fig. 4: Placement of virtual extensometers (denoted by numbered marks) on the specimen surface subjected to four-point bending test.

Fig. 5: Comparison of the results provided by DIC, LVDT sensors and finite element analysis.
Strain Distribution within Cross-Sections of Glued-Laminated Beams

The purpose of the presented study was, beside conventional deflection measurements, to investigate the normal and shear strain distribution for glued-laminated timber beams subjected to four point bending in order to reveal and quantify the shear slip between neighboring lamellas. Because the tested beams were relatively long (exceeding 4.5 m, Fig. 6) the monitoring had to be accomplished using two cameras per a single beam face.

In order to capture the strain distribution along the chosen segments, an additional extension to the DIC software (Fig. 7) had to be developed for the data post-processing. Using such tool it was possible to reveal the strain distribution within any cross-section and find the relationship between the strains and properties of individual lamellas, determined consequently by means of non-destructive testing.

Fig. 6: The tested glued-laminated beams after exceeding its load-bearing capacity.

The results indicated that the slip at the interface does occur and the strain distribution does not exactly follow the theoretical assumptions based on the Bernoulli-Navier hypothesis, which assumes perfectly elastic homogeneous beam (Fig. 8). To reach such conclusions and quantify the strain-state at any loading instance and any location, using conventional measurement techniques would be impossible and even much less informative results would be obtained for significantly higher cost.
Fig. 7: Cross-section strain and displacement distribution within a glued-laminated timber beams; analyzed in-house post-processing tool.

Fig. 8: Relative normal (top) and shear (bottom) strain distribution at chosen locations; only the results on the left part of the beam are presented.