Application of Digital Image Correlation for strain measurements of large masonry walls

A.H. Salmanpour[1] and *N. Mojsilović[1]

[1]Institute of Structural Engineering, ETH Zurich, Switzerland.

*Corresponding author: mojsilovic@ibk.baug.ethz.ch

Abstract

Full-scale testing of large unreinforced masonry walls subjected to in-plane static-cyclic loading is underway at ETH Zurich. During testing the measurements included all applied forces together with an overall and a local picture of the deformation state of the specimens. In order to achieve this, in addition to the traditional hard-wired instruments, i.e. LVDTs, a 2D Digital Image Correlation (DIC) measurement system was used. DIC is a cutting-edge, non-contact, optical measurement technique that provides full-field displacements and strains by comparing the digital images of the test object's surface obtained before and after deformation. The present paper reports on the measurement procedure and discusses the results obtained and the applicability of DIC for strain measurements when testing large masonry walls at full-scale. A set of conclusions and recommendations for the practical application are also given.

Keywords: Full-scale testing, unreinforced masonry, digital image correlation, static-cyclic loading, strain measurement.

Introduction

A research project on the deformation capacity of unreinforced masonry structures has been initiated at the Institute of Structural Engineering of ETH Zurich. The objective of the research project, which should be seen as the first step of an initiative to investigate the limits of the deformation capacity of structural masonry, is the development of the basic building blocks for the displacement-based design of masonry structures. Before our own experimental program started, a thorough survey and assessment of existing experimental and analytical research in the area of the deformation capacity of structural masonry was carried out (Salmanpour et al., 2012a,b). The experimental work is divided into two phases, i.e. the preliminary and main phases, and consists of a total of 11 cyclic-static tests on full-scale unreinforced masonry walls in order to investigate the effects of the various factors, i.e. unit type, vertical pre-compression level, aspect ratio, size effect and boundary conditions on the deformation capacity of structural masonry. A novel approach will be developed and utilized for the purpose of applying experimental evidence collected from our own tests for the development of reliable mechanical models for structural masonry. The abovementioned experimental data, i.e. full-field information on displacements, deformation and strains of the specimens has been acquired using the Digital Image Correlation (DIC) method.

From early in the 1950's until recent years, various non-contact optical methods, e.g. electronic speckle pattern interferometry, shearography, Moiré interferometry, holographic interferometry and digital image correlation have been developed to extract full-field shape, deformation and motion information. Amongst the abovementioned methods, DIC is the most widely used because of its low requirements on equipment, easy application, wide range of measurement resolution and, above all, high accuracy. In principle, DIC is optical metrology based on digital image processing and numerical computing. It directly provides full-field displacements and strains by comparing the digital images of the specimen surface obtained before and after deformation. The DIC measurement system was first developed by a group of researchers at the University of South Carolina in the 1980s when digital image processing and numerical computing were still in their infancy (Bing et al., 2009). Although DIC has been widely accepted and used in the field of experimental mechanics, its application has been limited to rather small specimens. However, in recent applications also tests on larger specimens, e.g. concrete and masonry walls, and even in-situ tests on large-scale structures, e.g. bridges and towers, have been considered (Salmanpour et al., 2013 and McCormick and Lord, 2010). Such applications have been made possible by recent developments in computational technology and the availability of high-resolution digital cameras. Recently, tests on full-scale masonry shear walls were performed at ETH Zurich applying DIC to measure full-field displacements and strains. The present paper reports on the measurement procedure and discusses the results obtained and the applicability of DIC for strain measurements when testing large masonry shear walls at full-scale.

Testing Program

In order to investigate the deformation capacity of structural masonry, a total of 11 static-cyclic tests were performed in two phases. Table 1 summarizes the details of the performed tests, where l_w, h_w and t_w are the length, the height and the thickness of the specimens, σ_0 is the pre-compression stress, and f_x is the mean compressive strength of the masonry (perpendicular to the bed joints). The first phase (preliminary phase) of the experimental program included tests P1 to P4, and the second phase (main phase) of the experiments included tests T1 to T7.

Table 1. Test program

Phase	Test	Units	Specimen Dimensions l_wxh_wxt_w [mm]	Boundary Conditions	σ_0/f_x
Preliminary	P1	Clay	1500x1600x150	Fixed Ends	0.10
Preliminary	P2	Clay	1500x1600x150	Fixed Ends	0.15
Preliminary	P3	Calcium-Silicate	1550x1600x150	Fixed Ends	0.10
Preliminary	P4	Calcium-Silicate	1550x1600x150	Fixed Ends	0.15
Main	T1	Clay	2700x2600x150	Fixed Ends	0.10
Main	T2	Clay	2700x2600x150	Fixed Ends	0.05
Main	T3	Clay	2700x2600x150	Fixed Ends	0.15
Main	T4	Clay	900x2600x150	Fixed Ends	0.10
Main	T5	Clay	1800x2600x150	Fixed Ends	0.10
Main	T6	Clay	3600x2600x150	Fixed Ends	0.10
Main	T7	Clay	2700x2600x150	Cantilever	0.10

Figure 1 shows a picture of the test set-up. The specimens are built on 350 mm thick reinforced concrete foundations, which can be clamped to the strong floor by means of post-tensioned steel bars. The horizontal servo-hydraulic actuator reacting on the strong wall of the laboratory applies a shear force to the top of the walls through a stiff steel beam (loading beam). The loading beam is connected to the walls by a layer of mortar. The vertical load is applied by means of two servo-hydraulic actuators reacting on the reaction frame. A more detailed description of the testing procedure can be found in Salmanpour et al. (2013).

Figure 1. Test set-up with tested wall T2

DIC instrumentation and measurement procedure

During the tests, measurements included all applied forces together with an overall and a local picture of the deformation state of the specimens. In order to achieve this, in addition to the traditional hard-wired instruments, i.e. LVDTs, a two-dimensional DIC measurement system was used. DIC is a non-contact, optical measurement technique that provides full-field displacements and strains by comparing digital images of the test object's surface obtained before and after deformation. In general, the implementation of the 2D DIC method comprises the following three steps: (1) specimen preparation; (2) recording images of the specimen's surface before and after deformation; (3) processing the acquired images. This section reports and discusses issues on these three steps.

Specimen preparation

The digital image correlation technique relies on a contrasting speckle pattern on the surface of the test specimen. This pattern can be the natural texture of the surface or artificially made. The pattern quality has a dominant influence on the spatial resolution and accuracy of DIC results. In general, to achieve effective correlation, the pattern must be random, isotropic, i.e. must not exhibit a bias to one orientation, and highly contrasting, i.e. must show dark blacks and bright whites (Correlated Solutions, 2011). In addition to the above requirements, speckles should be neither too small nor too large. In DIC, a small subset of the image is tracked as the specimen moves and deforms. To perform the tracking, the subset is shifted until the pattern in the deformed image matches the pattern in the reference image as closely as possible; this match is calculated as the total difference in gray levels at each point. If the pattern is too large, we may find that certain subsets may be entirely on a black field or entirely on a white field. This does not allow us to make a good match. We can compensate for this by increasing the subset size, but at the cost of spatial resolution. Conversely, too small speckles can cause the aliasing effect resulting in images that often show a pronounced Moiré pattern in the measurement results (Correlated Solutions, 2011). As a rule, speckles should be 3-8 pixels in size to achieve effective correlation.

Applying the pattern is the most important and challenging step in the implementation of 2D DIC method. There are several techniques for applying different pattern sizes on the specimen surface, e.g. spraying paint, printing, lithography, using toner powder and stencils. For our own tests, the surface of the specimen was first coated with a white paint and then random black speckles were applied. Figure 2 shows the detail of the applied patterns on an area of 150×150 mm of the wall surface. Three different techniques were tried out for application of the speckles. In the first preliminary test (P3), the pattern was obtained by means of a marker pen, see Figure 2. A pattern of adequate density could not be obtained using this method. Although the compensation of the low-density pattern was made possible, it came at the cost of spatial resolution. Hence, for the other preliminary tests, the pattern was applied using a stencil with randomly distributed openings produced using a laser printer. The stencil was made of acrylic glass and had the dimensions 900×600 mm. The latter method appeared better and was less labor intensive. However, the material used for stencil degraded continuously during the pattern application and the stencil had to be re-printed. For the main tests, in order to increase the spatial resolution of DIC results, smaller speckles were created using a paint gun. Speckles of the right size could be achieved by adjusting the air pressure, paint flow and also paint viscosity. However, this technique was found to be prone to some too small speckles which can sometimes cause aliasing.

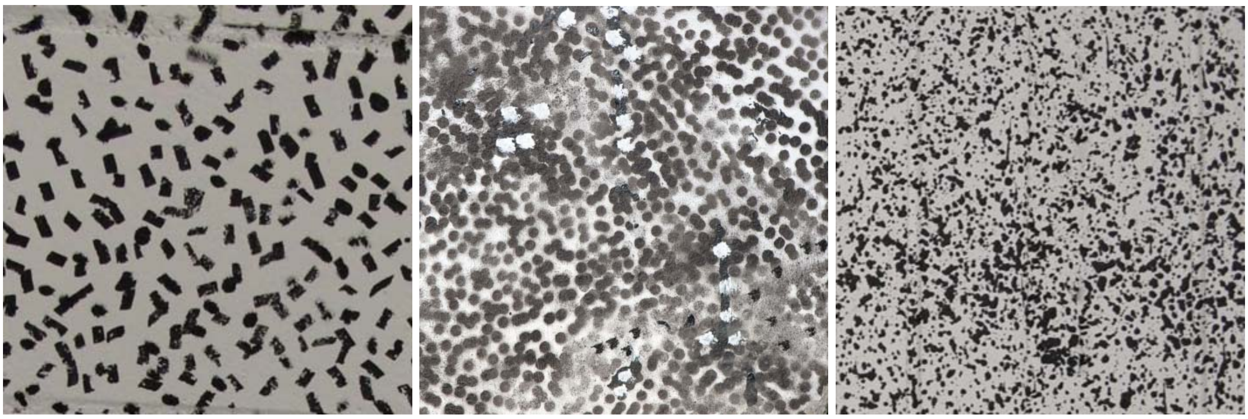

Figure 2. Random pattern applied using: marker pen (left), stencil (middle) and paint gun (right)

Recording images of the specimen's surface

Two different conventional DSLR cameras were used during the testing. For the preliminary tests (P1 to P4), a Nikon D3 camera that utilizes a full-frame size CMOS sensor of 12.1 MP was used. The camera was positioned at a distance of 5 m from the specimen and recorded the specimen surface area with a spatial resolution of 0.68 mm. For the main tests, T1 to T7, a somewhat better camera, namely the Nikon D800E, was engaged. This camera includes a 36.3 MP full-frame size CMOS sensor. While almost all digital cameras employ an optical low-pass filter over their sensors, this filter has been removed in the Nikon D800E. Removing the effect of the low-pass filter should, theoretically, result in higher resolution and sharpness but at the expense of being more prone to the Moiré patterning. The camera was located at a distance of 6 m from the specimen and recorded the specimen surface area with a spatial resolution of 0.58 mm. Since accurate 2D DIC depends on the specimen being planar and parallel to the camera sensor, special attention was given to the alignment of the cameras. A professional flash lightning set, i.e. Elinchrom Style RX 1200 (see Figure 1), was used to ensure that the specimen surface was brightly and also evenly illuminated to maintain the maximum range possible.

Before applying the load, the reference image was taken and later compared to the subsequently taken images of the deformed states of the specimen. A custom-made device interacting with the DAQ system triggered the camera at pre-specified vertical forces (while applying the pre-compression force) and horizontal displacements (while applying the cyclic displacement). On average, about 500 images per test were taken.

Processing the acquired images

The recorded digital images were first corrected to remove the lens distortion influence and then processed using licensed Vic2D commercial code to obtain full-field displacements and strains. The normalized squared differences criterion was chosen as the correlation criterion and to achieve sub-pixel accuracy, the optimized 8-tap splines were used for gray value interpolation. The size of the subsets was determined based on minimization of the confidence interval. For the description of the principles and concepts of DIC, see Bing et al. (2009) and Sutton et al. (2009). It is worth mentioning that currently, in addition to commercial codes, several free university codes are also available for the application of DIC, see Table 2.

Table 2. Commercial and free university DIC codes

Commercial Codes		Free University Codes	
Code	Company	Code	University
Vic2D and Vic3D	Correlated Solutions	MatchID	Catholic University College Ghent, KULeuven
StrainMaster	LaVision Inc.	Opticist	The Catholic University of America
ISTRA 4D	Dantec Dynamics	Matlab Code	Karlsruhe Institute of Technology (KIT) and Johns Hopkins University
ARAMIS	GOM Gbmh		

DIC measurement results

Using analyzed data the deformation of the specimen during static-cyclic loading can be tracked in detail. Figures 3 and 4 show the displacement and principal strain fields in specimen P4 just before the collapse of the specimen.

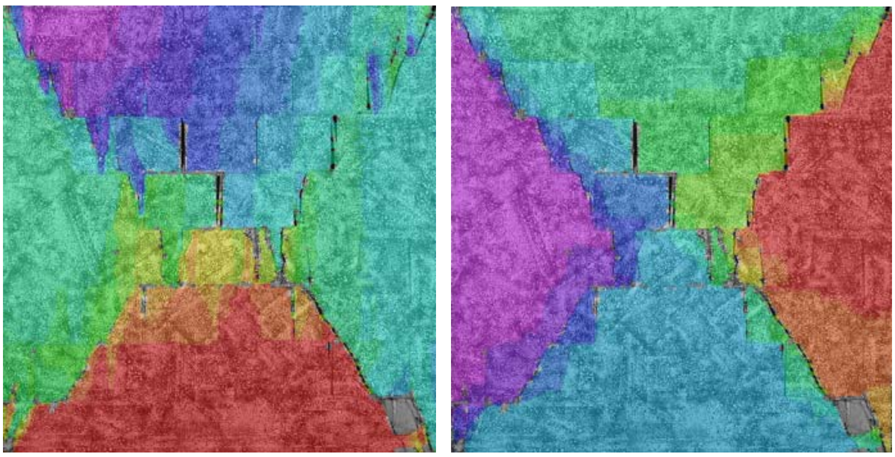

Figure 3. Vertical (left) and longitudinal (right) displacement fields in wall P4

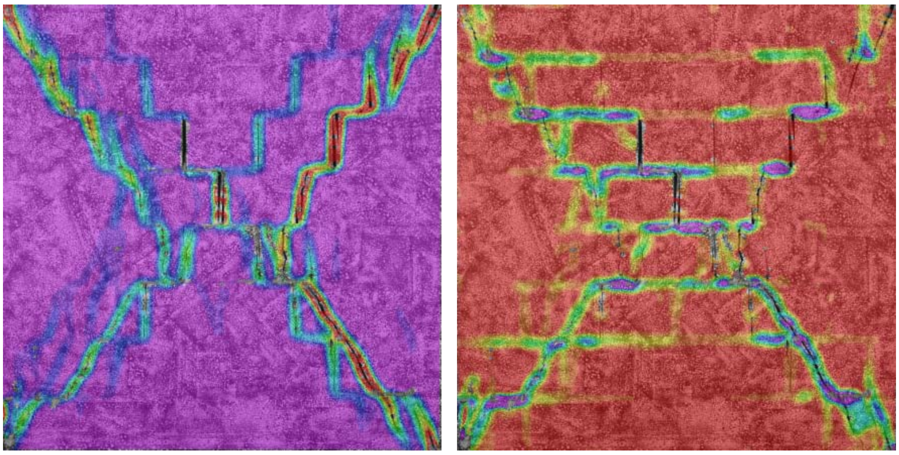

Figure 4. Major (left) and minor (right) principal strain fields in wall P4

Accuracy of DIC measurement is a controversial issue because it is very difficult, if not impossible, to exactly determine the measurement errors. The accuracy of DIC measurement is influenced by several factors. Table 3 presents a short list of error sources of 2D DIC measurement (Bing et al., 2009).

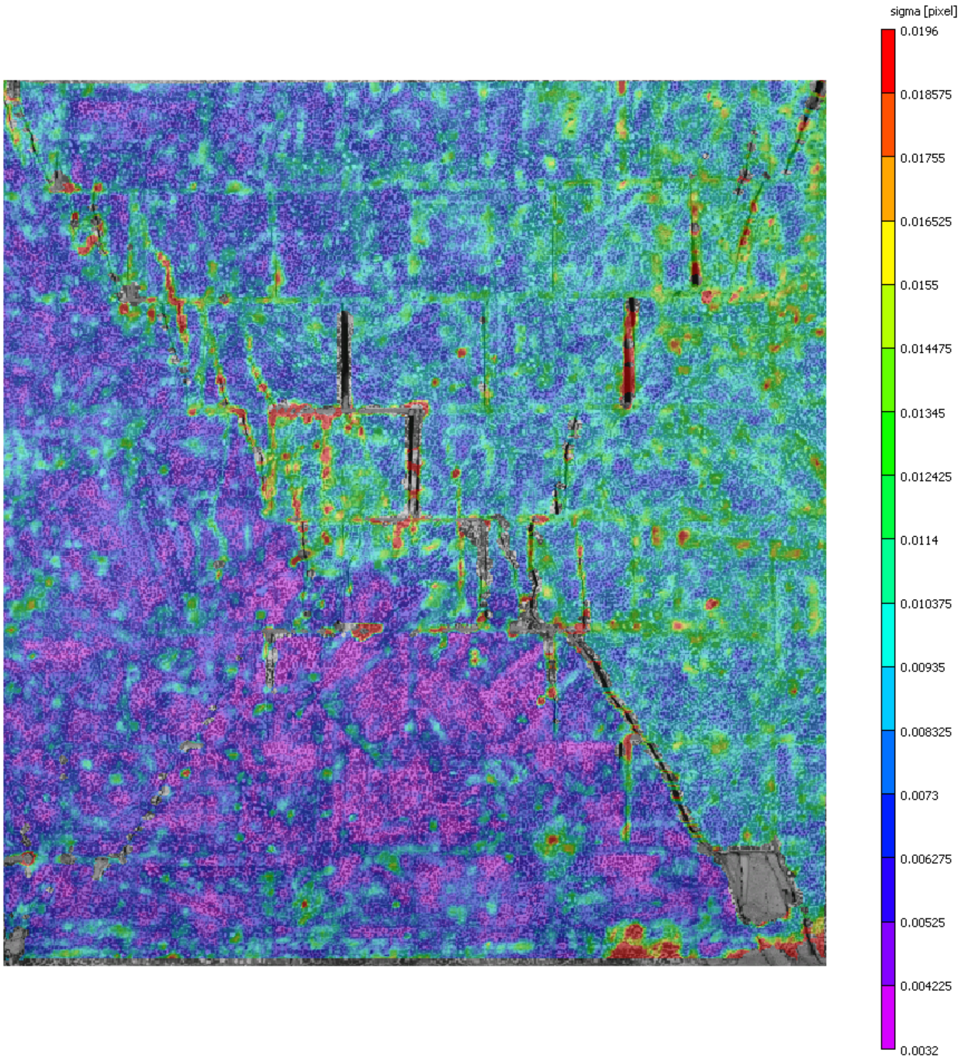

Figure 5. Confidence interval, in pixels, in wall P4

Table 3. Error sources of 2D DIC (Bing et al., 2009)

Errors related to specimen, loading and imaging	Speckle pattern Non-parallelism between sensor and the object surface Out-of-plane displacement Imaging distortion Noise during image acquisition and digitization
Errors related to the correlation algorithm	Subset size Correlation function Sub-pixel algorithm Shape function Interpolation scheme

However, as shown by several studies, a displacement accuracy of 0.01 pixel can be achieved with typical setups. Hence, the displacement accuracies of 0.0068 and 0.0058 mm are expected in the preliminary and main tests. Figure 5 shows the confidence interval (in pixels) for specimen P4 just before the collapse of the specimen. The confidence interval is calculated using the covariance matrix of the correlation equation. Although it does not reflect bias, e.g. aliasing, it is an accurate noise estimate and can be used to estimate the accuracy of the measurements. A statistical analysis of the confidence interval values for specimen P4 showed that the spatial mean value of the confidence interval was 0.0082 pixel (just before the collapse of the specimen), which somehow confirms the expected displacement accuracy of 0.01 pixel.

Conclusions

A successful implementation of the 2D DIC measurement technique using conventional DSLR cameras for cyclic-static tests on full-scale large masonry shear walls was reported. The obtained results proved that 2D DIC may be considered to be an effective technique to measure full-field displacements and strains with high level of accuracy and spatial resolution even in the case of large specimens and complicated deformation fields. Furthermore, using low-cost conventional DSLR cameras (compared to special industrial cameras) make this technique affordable in most of structural engineering laboratories.

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