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Use of Digital Image Correlation for Damage Analysis of Masonry Piers

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Abstract. In order to develop a constitutive material model and to verify its consistency when implemented in a computational code, it is necessary to understand the material and to carry out a comprehensive experimental analysis. This can be a challenging task in the case of composite materials and structures, such as masonry, when using conventional measurements. Strain gauges allow recording strains at a limited number of discrete points and do not provide sufficient amount of data, thus increasing the cost of the analysis. From that reason a full-field non-contact measurements, such as Digital Image Correlation (DIC), became very popular and valuable for analysis of structures subjected to mechanical loading and precise detection of the onset of strain localization. The presented study deals with tracking the strain localization using DIC in the case of masonry piers loaded by the combination of bending and compression. In such case the strain localizes into more compliant mortar joints while the complete collapse occurs when the masonry blocks fail to transfer tensile stress due to transversal expansion. The obtained data will be used for the validation of a finite element model to predict the behavior of masonry structures.

Introduction

Masonry has been extensively used throughout history and still finds a wide use in today's building industry. The advance during the Roman period allowed the construction of magnificent structures. Many of them still exist and attract enormous amount of tourists annually. Because of the enormous value of these structures, any repairs has to be done very carefully and after a rigorous assessment, usually provided by means of numerical and/or experimental analysis. Masonry is a material which exhibits distinct directional properties due to the mortar joints acting as weak links between the stronger bricks. A comprehensive analysis about the typical failure patters encountered in masonry is provided in [1]. The common attribute is exhausted tensile strength of mortar joints causing the onset of cracking

Measuring strains conventionally measured at pre-determined locations by means of broadly available strain-gauges has a number of disadvantages: the strain must be within a certain range, the deformation is averaged over the strain-gauge length, the measurement is limited to the strain-gauge location and the surface of the loaded element must be smooth enough to attach the strain-gauge properly. Therefore, the onset of cracking and progression of cracks cannot be efficiently tracked.

Measurement of deformations on the whole surface requires optical monitoring, such as Digital Image Correlation (DIC). The DIC method has been widely accepted and commonly used as a powerful and flexible tool for the surface deformation measurement in the field of experimental solid mechanics. It directly provides the full-field displacements and strains by comparing the digital images of the specimen surface in the un-deformed (or reference) and deformed states, respectively. In principle, DIC is based on digital image processing and numerical computing [2, 3]. The evaluating software algorithm is based on the tracking of the grey value pattern in small local neighborhood facets. The texture, if not naturally available, must be applied onto the monitored surface.

However, the method also a few limitations, e.g. a two-dimensional DIC using a single fixed camera is limited to in-plane deformation measurement of the planar object surface [4]. On the other hand, several studies deal with evaluation of errors in the field of displacements and deformations obtained by DIC and show a relatively good accuracy of the method, e.g. [5]. In our study, we used a non-commercial tool Ncorr [6], created in MATLAB environment, for the evaluation of strains.

Tested Materials

Our study was mainly focused on the behavior of lime-based mortars used for nowadays repairs of masonry load-bearing elements. The full-scale testing was performed on masonry piers composed of five layers of common clay bricks of dimensions 290×140×65 mm. The mortar was composed of lime and Portland cement in the ratio of 7 : 3, and common river sand of grain size 0-2 mm. The binder to aggregate mass ratio equal to 1 : 3 was chosen to obtain suitable mechanical properties. The thickness of horizontal joints was selected as 15 mm in order to pronounce the effect of joints on the overall behavior of the tested piers, and for the vertical butt joints the thickness of 10 mm was selected to follow the modular size of the bricks, yielding the pier dimensions equal to 290×290×415 mm (Fig. 2).

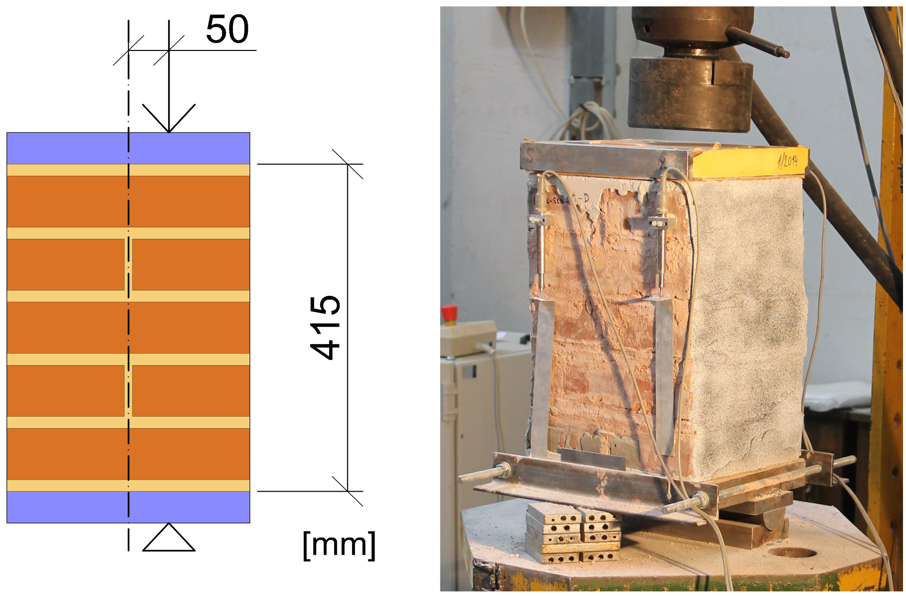

Fig. 1: Geometry of the tested specimen (left) and the testing set-up (right).

In order to obtain the mechanical properties of individual components, a set of destructive and non-destructive tests was conducted on more than six specimens representing each material, i.e. mortar, brick and the interface. The testing of both, the piers and individual components, was scheduled to three months after their production. The analysis results, summarized in Tab. 1, will be used in future for validation a numerical model.

Table 1: Material properties of individual components.

material	Young's modulus [GPa]	compressive strength [MPa]	bending strength [MPa]
brick	11.14 ($\pm$8 %)	49.46 ($\pm$9 %)	5.24 ($\pm$8 %)
mortar	7.13 ($\pm$7 %)	14.31 ($\pm$8 %)	0.95 ($\pm$9 %)

Experimental Set-Up

On one side of the pier a white coating was applied (common white wall paint) followed by the black dots-pattern in a relatively high density to contrast with the white background. Loading of the pier was performed by the displacement-controlled hydraulic actuator in the rate of 1 mm/min via steel loading frame with the 50 mm eccentricity. Rotation-free connection of the tested pier and hydraulic ram was achieved using a special setup. The maximum load capacity of the load-cell, 1 MN, was not exceeded during the testing.

The high resolution DSLR camera, was placed with its optical axis normal to the specimen surface, taking pictures of the planar specimen surface at predetermined time-interval of 5 s. For the most accurate results the specimen surface must be flat and remain in the same plane parallel to the camera sensor target throughout the entire experiment. The out-of-plane motion of the specimen would lead to a change in the magnification of the recorded images, yielding additional in-plane displacements.

Analysis Results

The DIC method provided very detailed information about the development of in-plane deformation field, impossible to obtain using conventional techniques, clearly demonstrating the strain localization and development of cracks.

The eccentric loading of the pier introduced a constant bending moment resulting in tension on the less loaded side. From that reason the relatively weak interface between bricks and mortar failed and joints started to open when the loading force equal to 250 kN was reached, see Fig. 2. The cracking of the entire column perpendicular to the horizontal joints followed and localized into a major crack. Such failure did not reduce the column stiffness in the initial stage, but after a while the crack visibly opened and the pier lost its structural integrity and consequently also its load-bearing capacity.

The results of our analysis confirm that mortar joints act as the planes of weakness where the strain localizes. After their failure a severe cracking affecting the entire column develops. Therefore the tensile strength of mortar and bond strength at the interface between mortar and surrounding bricks have the major influence on the load-bearing capacity of piers. Based on our findings, the main attention should be paid to a development of strong mortars complying with the requirements established by the authorities for cultural heritage, and on the construction technology ensuring a proper bond between the mortar and surrounding masonry blocks.

Conclusion

The full-field displacement monitoring using DIC allows bridging the gap between calculations using finite element codes and experimental analysis. The approach enables to effectively observe the strain localization and crack initiation on the masonry surface without need for conventional point measurements accomplished by means of strain-gauges or extensometers. The

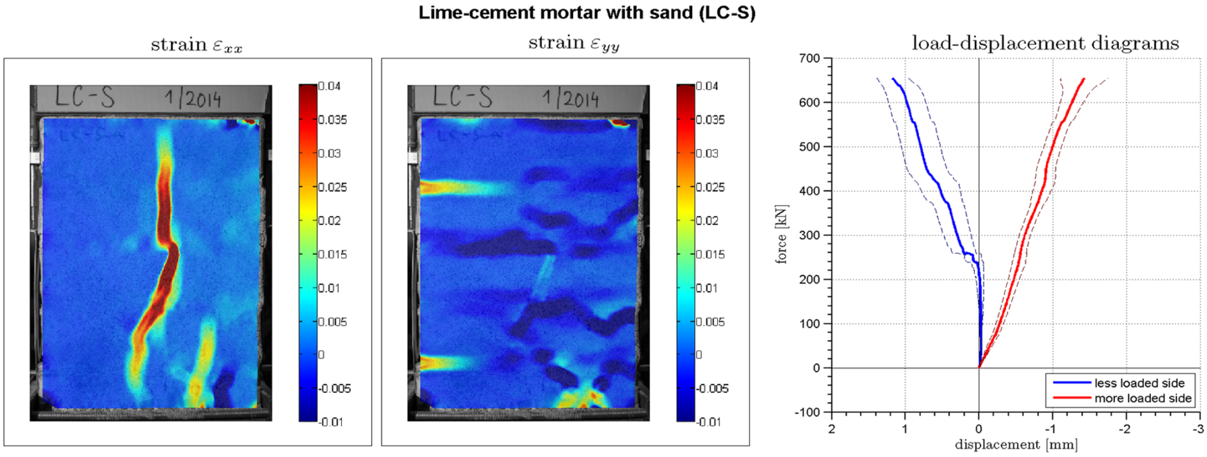

Fig. 2: Strain evolution during loading of masonry piers (left and middle) and load-displacement diagrams (right).

results clearly demonstrate that the deformation field in masonry structures is strongly inhomogeneous and localizes even at very low strain levels into mortar joints that act as the planes of weakness. After the mortar failure, the cracking affecting the bricks takes place, leading to a complete failure of the load-bearing element.

The outcome of this study will be used for a development of a material constitutive model implemented in a computer code to efficiently and accurately predict load-bearing capacity of masonry structures.

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