Photoelasticity and DIC as optical techniques for monitoring masonry specimens under mechanical loads

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Abstract. To evaluate the complex behaviour of masonry structures under mechanical loads, numerical models are developed and continuously implemented at diverse scales, whilst, from an experimental viewpoint, laboratory standard mechanical tests are usually carried out by instrumenting the specimens via traditional measuring devices. Extracted values collected in the few points where the tools were installed are assumed to represent the behaviour of the whole specimen but this may be quite optimistic or approximate. Optical monitoring techniques may help in overcoming some of these limitations by providing full-field visualization of mechanical parameters. Photoelasticity and the more recent DIC, employed to monitor masonry columns during compression tests are here presented and a lab case study is compared listing procedures, data acquisitions, advantages and limitations. It is shown that the information recorded by traditional measuring tools must be considered limited to the specific instrumented points. Instead, DIC in particular among the optical techniques, is proving both a very precise global and local picture of the masonry performance, opening new horizons towards a deeper knowledge of this complex construction material. The applicability of an innovative DIC procedure to cultural heritage constructions is also discussed.

1. Introduction and aims
The response of masonry structures under mechanical loads is very complex and not easily determinable mainly due to their heterogeneous character, long life-cycle and effects from the environment. Numerous factors such as characteristics properties of the single component materials, the arrangement of the units, the properties of the interfaces between mortar layers and brick units affect the masonry behaviour, its durability and strength [1]. Masonry being a composite material used since ancient time, largely widespread and with innumerable local variations, several researches have been carried out to evaluate the mechanical behaviour of masonry and of masonry structures, as well as to establish correct ways of analysis. From the computational viewpoint, numerical models are developed and continuously implemented at diverse scales from micro to macro-scales [2], with the aim of obtaining as realistic as possible evaluations. Here, in addition to the theoretical approach adopted, the results largely depend on the required input parameters, which may derive from estimations or from experimental determinations. On the other hand, from an experimental viewpoint approach, standard mechanical tests are available for measurements in the laboratory or, less common, on site. In these cases, instrumentation of the specimen or masonry portion is generally achieved by means of traditional measuring devices, such as linear variable displacement transducers or strain gauges, thus performing punctual and “blind” measures of strains and stresses. These instruments are quite popular due to their low-cost character, their replacement easiness and possible re-use together with the advantages of obtaining a rapid evaluation of principal strains in specific directions.
Nonetheless, drawbacks exist also by this consolidated way of operating: values are collected in few points where the tools are installed and extracted figures are assumed to represent the behaviour of the whole specimen or of large portions of it. This may be optimistic or too approximate in many cases due, for example, to the contemporarily presence of stress concentration areas and stress release areas in masonry under loading. These were documented even for masonry with simple geometries and far from failure loading [3]. Optical monitoring techniques such as photoelasticity or image correlation methods may help overcoming some of these limitations by providing full-field information of the area under test. The production or visualization of test outcome in the form of parameter maps allows qualitative and/or quantitative appreciation of distribution variations. Accurate determination of mechanical parameters may also be possible at local points or over lines and areas. These methods are suitable for almost any kind of material and element subjected to static or dynamic loads [4]; hence, they have the potential to be applied to investigate the real development and distribution of strains in masonry too. Surprisingly, optical methods, although known since decades [3], are still very scarcely employed in civil engineering; even fewer were the experimental attempts of studying the behaviour of masonry structures by optical methods. From a rapid literature search it appears that experimental monitoring of masonry tests via photoelasticity were carried out only on dry masonry models in which the units were made by photoelastic materials [3], [5]. Instead, initial but very promising investigations were carried out via 2D digital image correlation for assessing the physical or mechanical behaviour of masonry [6]-[10].

In this paper, a novel experimental work is presented. It was carried out with the purpose of obtaining an insight into the mechanical behaviour of regular brick masonry when undergoing mechanical compression tests in the lab under eccentric load configurations. Monitoring of two tests over the time was undertaken by two non-destructive optical monitoring methods – photoelasticity and digital image correlation. Testing aims, procedures, data acquisition and data post-processing phases are described for a laboratory study on brick masonry and are compared with traditional, punctual measurement tools. Their advantages and limitations are discussed. Hence, the feasibility and reliability of the two selected optical techniques in providing a deeper knowledge on the response of brick masonry specimens subjected to eccentric compression tests is evaluated. Finally, further developments and applicability of image correlation method for on-site tests on cultural heritage and historic structures are also discussed.

2. Basic principles of the employed optical methods

2.1. Photoelastic method.

Photoelasticity is a non-destructive optical technique for the analysis of strain and stress distributions in elastic bodies. It is based upon a unique property -double refraction or birefringence- of some transparent materials such as some plastics, crystals and polymers. This is proportional to the strain and stress states of the element, artificially transferred in photoelasticity. It has been proved that, a loaded photoelastic specimen in combination with optical elements and a source of illumination, exhibits fringe patterns related to the principal stress differences in a plane normal to the light propagation direction. This technique has been mainly used for two dimensional plane problems, although, thanks to recent developments, tri-dimensional analyses are now possible too [11], [12], [13]. The photo-elastic coating method is an extension of photoelasticity that allows studying also inelastic bodies. It has been used for a variety of applications ranging from automotive, to aircraft and aerospace, to biomechanical and composite materials [13]. It is based on the direct bonding by adhesive of a thin layer of a photoelastic material (commercially available in flat-sheet or liquid form) on the surface of the element to be tested. The photoelastic effect is studied via a reflection polariscope, which illuminates the monitored surface via a polarized light. It is assumed that the strains in the structure under load and in the superficial coating will be the same. The strains in the coating layer produce proportional optical effects visible as isochromatic fringes, which are series of successive and contiguous different-coloured bands, each one representing a birefringence degree,
thus, corresponding to a specific strain level. Moreover, with a reflex polariscope, by rotating the planes of polarization of the incident light, isoclines lines may also be isolated. These connect the points where the directions of principal strains are parallel to a given direction. Hence, with this optic method it is possible to distinguish between highly stressed areas from low stressed areas i.e. where structural material is not efficiently used thus carrying out quantitative analyses [12], [13].

2.2. Digital image correlation technique.

Digital image correlation (DIC) is a quite recent non-destructive, optic, contactless method which exploits the principles of photogrammetry, digital image processing and stereo-images correlation to determine high definition displacement and strain maps of an object subjected to external forces [4]. Generated in the early ‘80s as a 2D method to measure the in-plane displacement field of an object while under load, more recently the DIC concept was extended to stereo-vision systems. Hence, a 3D version of the method was developed. This is based on the simultaneous acquisition of pairs of images, by means of two CCD cameras placed in front of the investigated surface in a stereoscopic configuration (Figure 1 left) thus allowing measuring also the out-of-plane motion [4], [14]. During data acquisition, pairs of images are collected at diverse deformation states of the investigated element. Then, each couple of images with deformed geometry of the element under tests is compared to the pair of reference images recorded in the specimen’s undisturbed configuration. A stereo imaging equation is applied followed by a correlation algorithm performing a pixel-by-pixel comparison of images. That is the same grey level of each pixel is tracked at diverse time instants of the test (Figure 1 right). Thanks to a DIC calibration procedure to be performed prior to the test start, the parameters characterizing the specific adopted optical measurement configuration are registered (in terms of distortion of the lenses, relative distance of the cameras, orientation of the cameras with respect to the object surface, ...) [4]. These values are used to calculate the reference axis system and establishing the ideal working plane. Thus, at the end of the data analysis, the 3D coordinates \((x, y, z)\) of each point \(P\) of the images are accurately determined. From these values, the 3D displacement vector \([u(P), v(P), w(P)]\) and corresponding deformations fields \([\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}]\) during the whole test duration are calculated. DIC results are usually plotted as coloured maps of each geometrical or mechanical parameter superimposed to the digital photos [15] nevertheless parameter values can be extracted along segments in addition to single points or areas.

3. Experimental work

3.1. Description of the masonry specimens and mechanical tests

Two brick columns were studied, each made of 6 clay bricks and interposed hydraulic lime mortar joint. The columns had nominal dimensions of 250 x 120 x 380 mm$^3$ (length x width x height) while the units – new fired-clay bricks - had dimensions of 250 x 120 x 55 mm$^3$ (length x width x height);
the mortar joints were nominally 1 cm thick. The main mechanical and physical properties of the masonry component materials were determined via standard tests at the time of building the specimens (Table 1) with the purpose of estimating the strength of the specific masonry under construction. After appropriate curing period of the specimens to allow for the strength development in the mortar, the columns were prepared and instrumented for the mechanical tests. In order to simulate a realistic stress-strain configuration as it may be found in existing masonry structures, an eccentric load compression test was preferred to a standard configuration with uniform distribution of vertical in-plane load [17], [18] commonly representing the laboratory set-up for assessment of masonry mechanical properties. For these tests, the testing machine was equipped with a metal rig including the double cylindrical hinges for exerting the eccentric load [19], [20].

The load was applied with sufficient eccentricity (80 mm) from the middle vertical axis of the specimen, for it to fall outside the middle third of the central core of inertia of the specimen section (e/D>1/6 where e=eccentricity and D=base length of the specimen). See Figure 5 left.

Firstly, the specimens were instrumented via traditional or established displacements measurement tools: linear variable differential transducers (LVDTs) on the front and rear faces of the specimens in addition to TML displacement transducers on the lateral faces. Three LVDTs HBM WA series with 0-10mm range and ±1% accuracy were installed on the front side of each column, with vertical alignment to monitor the specimen’s global vertical displacements; additionally, on the specimen monitored by DIC, a fourth LVDT was installed at mid-section of the rear face of the column (Figure 2). Six TML UB-5 displacement transducers (also called “omega”, due to their shape) were installed on the lateral faces across the 2nd, 3rd and 4th mortar joints (numbering from the base), to monitor their opening/closing movements (Figure 2). These are able to record displacements up to 5 mm with a sensitivity of 1000 microepsilon/mm. This mortar joint monitoring in masonry via omegas is an innovative use of these tools, as they are more commonly applied for monitoring crack opening displacement in metal or in concrete element bending tests. All these devices, as well as the testing machine, were linked to the acquisition system through two 8-channel units. Load and displacement values were registered throughout the test and stored in a PC equipped with dedicated Labview software for both real time visualization and data post-processing. The installation of the supports for anchoring the transducers was quite a time consuming step because it requires precision in positioning and gluing on the irregular masonry surface. The presence of superficial roughness, dust and also the cables’ weight may force to repeat this preparatory operation in case of support detachment. Due to these difficulties and in order to overcome the limitations connected with the punctual character of the obtainable values, it was planned to monitor the tests also by innovative non-contact, full-field methods. The two selected methodologies – photoelasticity and digital image correlation – are described in the following text sections.

The two mechanical tests were performed at the LISG laboratory of Bologna University via a Metrocom 600 kN universal testing machine in displacement control mode. According to [21] the expected collapse stress level of masonry to be reached during the compression test was estimated from the characteristic mechanical properties of the single masonry materials to be approximately 15 MPa. The load application velocity was set to about 0.5 mm/min. Each test consisted in loading/unloading cycles at progressively increasing load levels up to the fragile collapse of the brick columns.

| Material  | Bulk density [kg/dm³] | Porosity [Vol.-%] | Compressive strength f [N/mm²] | Bending strength /[N/mm²] | E [GPa] |
|-----------|-----------------------|-------------------|-------------------------------|--------------------------|--------|
| Brick     | 1.79                  | 23.2              | 80                            | 7                        | 16     |
| NHL mortar| 2.06                  | 20.6              | 3.2                           | 1.2                      | 4.8    |
3.2. Experimental monitoring via photoelasticity

In this experiment, optical monitoring was carried out via photoelastic coating method. According to the photoelastic testing facilities present in the laboratory, the aim was to obtain at least a non-destructive qualitative visualization of the actual stress/strain distribution in the masonry specimen while subjected to eccentric vertical loading.

Firstly, a photoelastic coating material with coherent adhesive supporting material needed to be selected. The selection would be a compromise between the desired resulting reliability and accuracy, the sensitivity of the polariscope system to be employed, adhesive setting time and photoelastic material costs. Taking into account the expected masonry compression stress level, the inelastic behaviour of masonry and assuming a flat masonry surface, it was chosen a VishayMM PS-3C photoelastic flat-sheet material with area dimensions 10”x10” (254x254 mm²) usually employed for analysis on non-metallic materials. This is a medium-modulus, high-elongation coating sheet, just less than 1 mm thick, characterized by a K factor (strain optical coefficient) of 0.02. The sheet was glued onto the rear face of one of the two masonry columns (named 0S2) by a uniform layer of VishayMM PC-6 epoxy resin. This is a room-temperature-curing, low-modulus, high-elongation adhesive (50% elongation). It requires at least 24 hours setting at temperatures between 21 and 24°C. Although in reality the masonry specimen surface is not completely flat, especially at the edges of the bricks and at the interfaces with mortar joints, a photoelastic coating flat-sheet was preferred to a liquid coating material whose spread on the masonry surface would also have been affected by the irregularities of masonry due to the pores and superficial roughness of the bricks and mortar joints, hence it would have been difficult to mould. Several critical issues emerged in this preparatory phase given that the coating application on the rough, porous and irregular masonry surface was difficult and time-consuming. Despite the expert operator’s efforts in accurately cleaning the masonry surface to remove traces of dust and dirt before applying the resin, in filling all the open pores and thus in creating a smooth and regular adhesive surface, it remained in question if a completely uniform thickness of the resin was laid and if this layer was as plane and thin as planned. These aspects may affect the perfect adherence of the photoelastic sheet to the specimen’s surface and the response of the photoelastic material to the stress and strain transfer from the masonry.

With reference to the photoelastic material itself, pre-manufactured sheets are more economic and easier to use than liquid coatings and they guarantee uniform thickness and uniform physical, mechanical and photoelastic properties [22]. The predefined dimensions of the commercial sheets may be a limitation for specific applications. In the specific case, the sheet area was as large as the brick length but not long enough to cover the whole masonry height. Therefore, it was positioned to cover the lower masonry area with the first 4 masonry joints leaving unmonitored the top brick in the column (Figure 3 left). The whole test was monitored via a conventional reflection polariscope equipped with a high-intensity white light source (Luchsinger 030-series, 50 Hertz), together with a
medium-resolution digital video camera JVC. In order to record the whole coated area, the system was mounted on a tripod and positioned at about 90 cm distance in front of the specimen (Figure 3 centre and right).

![Figure 3. Surface preparation: pouring of the resin (top left) and application of photo-elastic sheet (bottom left); test set-up (centre) and monitoring via reflective polariscope (right).](image)

### 3.3. DIC monitoring of mechanical tests

The second optical monitoring technique considered was digital image correlation (DIC) in 3D configuration. A commercial system (VIC-3D) available at LISG laboratory is equipped with in two digital cameras (5MPx), with 23 mm Schneider lenses, a 8-channel data acquisition/synchronization unit and a laptop with dedicated software. The system is able to determine deformations with accuracy up to 50 $\mu$ε. During the test, the two cameras were fixed on the same arm and rigid tripod at a relative distance of 27 cm and at 1.45 m away from the investigated masonry surface. A white lamp with diffused light was placed between the cameras and the tested masonry surface to minimize the non-uniform brightness field caused by the scarce ambient illumination of the laboratory; moreover, a sunshade was used to protect the specimen surface from sunlight changes, which would vitiate the method performance (Figure 4 left).

![Figure 4. Six-brick column 0S4: set-up of mechanical test monitored by DIC (left); post-processing selection of analysis area (centre); positions of virtual extensometers (right).](image)

The test was carried out adopting an innovative testing procedure developed by the authors, which consists in employing the natural masonry texture as reference pattern for the DIC readings. This set-up overcomes the preparation of the investigated surface, usually a technique's mandatory requirement, performed by uniformly spraying the surface by white paint coating and overlaying a random pattern of appropriate-size black dots [15]. This simplification was developed for an intended...
further use of DIC on site, in the field of Cultural Heritage or historic structures, where coating would not be allowed [23]. After positioning the DIC equipment in front of the surface to be investigated, the exposure time, focus and aperture range of the lenses were adjusted and the calibration performed obtaining a very small error value (approx. 0.03 pixels) which indicated that the selected monitoring configuration was highly precise despite the adopted simplification. One pixel of the recorded image corresponded to 0.2 mm in reality. Continuous monitoring was first by image acquisition every 5 s whilst every 2 seconds after appearance of the 1st crack. This method is easy-to use and the very fast and simple preparatory phase, does not require high expertise operators. A disadvantage of the method is that high capacity storage memories are necessary.

4. Experimental results and discussion

4.1. Mechanical tests: data analysis and results

During each test, load values were collected together with global and local displacements. From these data, load-displacement and stress-strain curves were plotted and the main mechanical parameters characterizing the behaviour of the masonry columns were calculated.

Being the stress distribution in the specimens’ section unknown, the compressive strength assessment was carried out following two diverse methods: 1) assuming a linear strain distribution over the section and considering a simplified perfectly brittle constitutive model; 2) by considering also the tensile contribution of masonry and employing a stress distribution for a partialized resistant cross-section (Figure 5 centre). It is known that the first hypothesis is too limiting to actually represent the masonry behaviour as it does not take into account the inelastic compressive response of masonry and it may lead to some overestimations [18], i.e. apparent increase in the compressive strength due to load eccentricity, but it was used just to perform a first discrimination.

Hence, the equations used to calculate the compressive strength values, according to the 1st and 2nd model respectively, are:

\[ f_c' = \frac{2N}{3A} \]

\[ f_{cp} = \frac{N}{A} \pm \frac{Ne}{I} y \]

where \( f_c' \) [MPa] is the maximum compressive strength in the external border of the section closest to the load application point; \( f_{cp} \) [MPa] is the compressive strength in correspondence of the load application point; \( f_t' \) [MPa] is the tensile strength; \( N \) is the maximum load, \( e \) is the load eccentricity; \( I \) is the moment of inertia of the section and \( y \) is the distance between the barycentre of the section and the load application point.

![Figure 5. Scheme of the eccentric compression test (left); linear assumed stress distribution induced by eccentric loading when \( e/D > 1/6 \) and general stress distribution under eccentric loading without neglecting the contribution of masonry tensile strength (mid-top and bottom centre); load-time history of both six-brick columns (right).](image)
The two mechanical tests lasted between 25 and 45 minutes (Figure 5 right). The maximum compressive loads were equal to 219 kN for six-brick column 0S2, monitored via photoelastic coating method, and almost 280 kN for six-brick column 0S4, monitored via DIC. The displacement values measured via LVDTs were plotted against the applied loads (Figure 6) and then used to calculate the corresponding values of stress and strain as above explained (Figure 6 right). Note that for the six-brick column 0S4 it was not possible to record the post peak behaviour because of the falling of all wired measuring instruments just after reaching the maximum load.

In Table 2 the resulting main mechanical parameters are reported for both masonry specimens and the differences between the values obtained in the two cases are highlighted.

Being the compression load applied with a certain eccentricity the LVDTs placed on the same face at the edges of the specimen, act in opposite directions: compressed under the load application point, in a tensile stress state the other (Figure 6 left). The asymmetrical behaviour (with reference to the vertical axis of the column) was further highlighted by the omegas across the mortar joints, for both columns. A closure tendency was recorded for the three mortar joints of the right side, nearest to the load application points, whilst the other three are opening (see i.e. Figure 10 right).

![Figure 6. Load-displacement curves from LVDTs positioned near the edges of the specimens for each six-brick column (left); stress-strain curves from LVDTs under the point of load application (right).](image)

|                  | Six-brick column | Nmax [kN] | $f_c' [\text{MPa}]$ | $f_{c \text{pp}}^\prime [\text{MPa}]$ | $f_c' [\text{MPa}]$ | E [GPa] |
|------------------|------------------|-----------|---------------------|---------------------------------|---------------------|--------|
| 0S2              | 219              | 27        | 16                  | 6.7                             | 8                   |
| 0S4              | 280              | 34        | 21                  | 8.6                             | 11                  |
| Difference [%]   | 27.9             | 25.6      | 29.4                | 29.9                            | 37                  |

The maximum compressive strength determined according to eq. 2, was of about 16MPa for column 0S2 and 21 MPa for specimen 0S4. The latter specimen is about 30% more resistant than 0S2; this difference clearly shows the inhomogeneous character of masonry structure, also when built with the same construction materials and tested in the lab, in similar conditions. Moreover, at the peak stress value, a compressive strain of 0.57% was measured for specimen 0S2, whilst only 0.40% for specimen 0S4 (Figure 6 right), hence, 0S4 appeared 30% less deformable than 0S2. The values of the secant elastic modulus E calculated from the stress-strain slopes between 0.1 and 0.4 of the maximum compressive strength ($f_{c \text{pp}}^\prime$) underlined the diverse behaviour of the two masonry columns being 0S4 stiffer than 0S2 (about 37%) (Table 2).
Additional differences were found in the failure modes of the two brick columns, although in both cases, the collapse started with the formation of a hinge located at the 4\textsuperscript{th} mortar joint, under the load application point. For six-brick column OS2, failure continued with a separation plane in correspondence of the 5\textsuperscript{th} mortar joint whilst, for specimen OS4, two separation planes occurred, involving both the 3\textsuperscript{rd} and 4\textsuperscript{th} mortar joints (Figure 7). These differences are again an index of the irregular behaviour of masonry, making it difficult to predict the reactions of masonry under loads.

![Failure mode of a) six-brick column OS2; b) OS4. Front and rear views, from left to right.](image)

Figure 7. Failure mode of a) six-brick column OS2; b) OS4. Front and rear views, from left to right.

4.2. Results of photoelastic monitoring: six-brick column OS2

Throughout the mechanical test and since the initial phases of load application, despite quite low resolution images collected with the old video camera at our disposal and a not-perfectly adherent coating photoelastic sheet, areas of strain/stress concentrations are clearly distinguishable from unloaded areas.

Since the beginning of the test to the 4\textsuperscript{th} and last loading cycle, all the strains appeared concentrated in the mortar joints and at interfaces, whilst the bricks did not present any areas of stress concentration (Figure 8 left). The different behaviour of the two masonry materials was expected due to the lower strength of the hydraulic mortar joints compared to the brick units but herein, for the first time, it was visualized on a real masonry specimen. The stresses are not uniformly distributed along the mortar joints but higher concentrations are visible towards the exterior borders of the same; they increased at increasing load levels while expanding towards the mid-section of the column. Mortar joints interact all over their lengths but the distribution of strain is not linear; hence, it appears not sufficient to measure the movements at the two extremities of the joints (as performed by the installed omega) to determine the behaviour of the entire mortar joint.

From the video collected throughout the mechanical test, it is also clear that the four monitored mortar joints – covered by photoelastic sheet- did not present the same level of strains: highest intensity in the 3\textsuperscript{rd} joint and smallest intensity in the 4\textsuperscript{th} one (again, numbering the masonry joints from the bottom of the column). This difference is very evident at the beginning of the test and tended to decrease during the load application. The difference in sign between the areas of stress concentration on the left hand side of the specimen (traction) and on the right hand side (compression) is clear during the 3\textsuperscript{rd} loading cycle (Figure 8 left). The formation of a hinge at the 4\textsuperscript{th} mortar joint, which caused the failure of the six-brick column, is clearly detectable (Figure 8 center).

It is also interesting to note that the brick units seemed to participate to the stress distributions only after the formation of vertical cracks; in this case, the openings of cracks occurred at the 4\textsuperscript{th} loading cycle (last cycle, see Figure 5 right). These cracks were located on the 4\textsuperscript{th} and 5\textsuperscript{th} brick units (i.e. Figure 8, centre, at approx. the maximum load). The evolution of cracks was monitored during the whole test, up to the fragile collapse of the specimen (Figure 8, right). The collapse of this six-brick column occurred with the separation of the 5\textsuperscript{th} mortar joint, which, unfortunately was outside the coated area, thus, it was not possible to follow the crack formation along this joint.
From this preliminary test, it is clear that the behaviour of masonry under eccentric loading is quite complex. Measuring displacements at the extremities of the mortar joints is necessary but not sufficient to determine the development/evolution of strains along the joints’ lengths. Moreover, traditional tools are not able to collect any information regarding crack openings and developments or hinge formations. Thus, it would be desirable to have at disposal a reliable and accurate technique able to give a picture of the whole masonry surface during the entire mechanical test. Photoelasticity has all the potentialities to fulfil this aim at least from a qualitative viewpoint. Quantitative monitoring of strain distributions may also be possible, although herein it was not considered. However, its reliability and accuracy is strongly affected by the difficulties related to the surface preparation. More, the spreading of the adoption of photoelasticity in the civil engineering sector is limited by the complexity of data acquisition and elaboration phases, which require the presence of operators with a certain expertise, as well as by the high costs of the coating materials and by the large amount of waste materials.

4.3. Results of DIC monitoring: six-brick column 0S4

At the end of the mechanical test on the 0S4 specimen, DIC images were easily elaborated via dedicated software [24] by following these steps: 1) calibration recall; 2) selection of the area of interest, to be analysed (Figure 4 centre) and starting points positioning to force the data correlation and not to lose data around any out-of-plane areas (i.e. LVDTs); 3) selection of analysis parameters (such as subset size, step size and noise level, which influences the accuracy of the results); 4) data analysis; 5) rigid motion removal; 6) visualization of results and data interpretation [15]. As already said, at the end of the analysis, data in terms of coordinates, displacements and corresponding strains are available for each correlated pixel of the masonry surface throughout the whole test. However, data are lost when and where the surface is missing (i.e. due to material spalling, cracking, etc.), from that time instant onwards.

Herein, by way of example, DIC results are visualized as 3D coloured maps of strain values $\varepsilon_{yy}$ in vertical direction at increasing load levels, superimposed to the deformed images, according to a user’s defined colour legend [15], thus obtaining an immediate view of the mechanical response of the six-brick column under eccentric load (Figure 9).

These maps show that at the beginning of the test, there is a null strain state but since very low load levels, i.e. at the first loading cycle (100 kN) areas of strain concentrations become visible at some mortar joints; compressive strains in the 1st mortar joint under load application point; traction state on the 3rd and 4th mortar joints, right hand side (Figure 9left). Strain values are greater on mortar joints than on brick units being the mortar a less resistant and much more deformable material, as already seen also with photoelasticity. However, with this method, the differences are easily quantified. More, the brick units did not appear completely unloaded as some small, low-intensity areas of strain concentration are visible. Another aspect arising from these maps is that the states of strain...
concentrations are asymmetrically distributed with respect to the middle vertical axis of the specimen, as expected, being the compression load applied with an eccentricity. On the left hand side of the six-brick column, corresponding to the side of load application, there is a state of compression (violet-blue) which, at 100 kN is limited to the 1st mortar joint, whilst on the right hand side of the specimen there is a state of tension (orange-red) that at the same load level, is located on the 4th and 5th mortar joints. This asymmetric behaviour is accentuated with increasing applied load involving a greater number of mortar joints up to all, at the end of the test, with the exception of the 1st joint, which remained compressed until the end of the test all over its length. Both the states of tension and compression increased at increasing loads but of different quantities: the compression state is much greater, almost 3 times, than the tensile state. The formation of rotational hinge on the left side of the 4th mortar joint as well as of the separation planes (horizontal cracks) on the right hand side of the 3rd and 4th mortar joints are well visible with this representation. At the end of test, some parts of the surface were no longer correlated by DIC due to the falling of brick and mortar portions as well as minor detachments occurred all over the specimen surface (grey areas in Figure 9 right). Anyhow, the possibility of collecting information (although partial) also after reaching the fragile collapse of the specimen represents an added value of the technique if compared to all the other traditional, wired measurement tools, as most of them were already disconnected.

Figure 9. Six-brick column 0S4: Trend of full-field maps of principal strain, $\varepsilon_{yy}$, along the vertical direction at increasing load levels: at the maximum of the 1st and 4th loading cycles and at the end of the test (from left to right), with the same colour legend $[-0.03<\varepsilon_{yy}<0.01]$.

Finally, to evaluate the accuracy of this optical method, a comparison was performed among data obtained by LVDTs and virtual extensometers which are a tool of the DIC software used to determine the strains between two selected points. Herein, by way of example, the stress-strain diagrams for the two LVDTs (in compression and traction) positioned on the edges of the front side of the specimen are compared with similar curves obtained by virtual tools positioned in the same positions but on the rear side of the specimen (Figure 10 left). The curves present a very similar slope, being coincident in traction. The vertical compressive strain value measured at the maximum stress is about 35% greater for the virtual extensometer whilst, the tensile strain value measured by DIC is only 2% greater than by LVDT (Table 3). The differences may be explained with the different positions of the instruments (specimen’s rear face for DIC, front face for LVTDs).

A similar comparison was carried out also considering the opening/closing movements of the mortar joints measured by wired omega vs. DIC virtual tools. Also in these cases, the slopes of the curves are very similar and differences explainable with diverse positions of the instruments.

This brief example of DIC monitoring of masonry under eccentric loads shows several advantages of this technique both compared with traditional wired tools and with photoelastic-coating method. The 3D DIC technique was easier to use (both the set-up and data analysis phase), did not necessarily
require a surface preparation, thus being completely non-destructive and allowed obtaining a complete picture of the whole monitored area by accurately performing a tri-dimensional measure of the geometry of every point of the surface during the whole test duration. Thus, gaining an insight into the mechanical response of masonry; this should help in obtaining a better understanding of the complex behaviour of this composite material. Moreover, there are no additional costs to those of the testing equipment and there are no waste materials (as, instead, in the case of photo-elastic coating). A disadvantage is given by the high computational requirements in terms of time and space, which are necessary to perform data analysis after long-duration tests. The developed testing procedure, which allows overcoming the need for surface preparation represent a great advantage, especially in view of on-site testing [23], also in case of historic masonry structure.

![Figure 10. Six-brick column 0S4: stress-strain diagram via LVDTs and virtual DIC extensometers (left); mortar joints movements measured via TML transducers and DIC (dotted lines) (right).](image)

| ε_c [µε] | ε_t [µε] | E [GPa] | Avg Closing [mm] | Avg Opening [mm] |
|----------|----------|---------|------------------|-----------------|
| LVDT/TML | 4027     | 2906    | 11               | -0.13*          | 0.43            |
| DIC      | 5432     | 2962    | 8.2              | -0.18           | 0.36            |
| Difference [%] | 34.9 | 1.9    | -25.5           | 39.9           | -16.1           |

* data from two over three TML transducers

5. Conclusions

An experimental laboratory work aimed at assessing the mechanical behaviour of masonry was carried out considering two six-brick columns subjected to eccentric compression tests. Traditional wired tools were used for measuring the displacements during the mechanical tests. The novelty of the work is represented by the additional use of two optical techniques to monitor the mechanical tests. The feasibility and reliability of these methods, still scarcely employed in civil engineering, in obtaining a full-field visualization of mechanical parameters and a better understanding of the behaviour of masonry under loads was tested.

The photo-elastic coating method proved to be suitable for the testing aims, at least for obtaining a qualitative detection of strain concentrations’ areas and cracks formation. The global and local behaviour of masonry was qualitatively assessed, obtaining additional information in comparison with the results from punctual measurement tools. Anyhow, the difficulties encountered while preparing the surface to be monitored with a layer of coating material together with the high level of expertise required for a quantitative analysis, the high costs and amount of waste materials are discouraging factors in the spreading of the technique. Moreover, this method would not be feasible for large areas or outdoors masonry because too expensive and invasive.
Instead, digital image correlation (DIC) offers easiness of use and of data elaboration that may allow fast spreading of its adoption also in the construction sector. The full-field visualization of strains herein easily obtained with DIC allows understanding qualitatively and quantitatively the global and local response of masonry under eccentric loads. The differences between masonry component materials were also measured, thus opening new horizons towards a deeper knowledge of this complex construction material. The innovative procedure presented proved to be suitable and accurate, hence opening possibilities for a future application of DIC on-site for monitoring large areas, Cultural Heritage or historic structures.

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