

Evaluating discrete deformations in masonry using natural feature based DIC

Nandini Priya Thatikonda , Daniele Baraldi , and Antonella Cecchi 

IUAV University of Venice, Santa Croce 191, Venice 30135 - Italy.

E-mail: npthatikonda@iuav.it, Orcid ID: 0000-0001-7503-7340

Abstract.

The research presents a methodology for two-dimensional Digital Image Correlation (2D-DIC) based on discretely tracking the natural surface features of masonry to characterize its mechanical response. By eliminating any surface treatment, the marker and speckle free DIC provides a non-invasive, realistic and accurate assessment of inherently feature-rich and heterogeneous media such as masonry. An experimental campaign was conducted on masonry panels, simulating historical material typologies with stiff blocks and weak mortar joints, subjected to in-plane loading conditions. The ability of the DIC methodology to capture discrete deformations and discontinuities failures, including opening of mortar joints, splitting in brick units and crack propagation, was explored. The emphasis of the research remained on the data processing stage, with elaborate visualization of the deformation patterns, leading to focused analysis and accurate insights on masonry specimen behavior in the case of in-plane loads. Further, while utilizing the natural features, key parameters influencing correlation quality and measurement reliability were identified, establishing guidelines for optimizing data acquisition and processing in heterogeneous materials.

1. Introduction

Masonry remains one of the most widely employed construction systems in both historic, modern and contemporary architecture. Its continued use is attributed to the availability of local materials, durability, and relatively simple construction techniques. Despite its apparent simplicity, masonry exhibits a complex mechanical response that arises from its heterogeneous composition, of masonry units and mortar joints. The interaction between these constituents governs the development of localized deformation mechanisms, development and propagation of cracks, and eventually failure, making the accurate characterization of masonry behaviour a longstanding topic of research [1; 2].

To understand and predict the structural response of masonry, numerous experimental and numerical approaches have been developed. Experiments on masonry range from the testing masonry cores to small scale assemblages, wallettes, and full-scale structures, to provide essential insights into its response under different loading conditions and the complex deformation and failure mechanisms presented [3; 4]. On the other hand, continuum-based numerical models are commonly adopted to evaluate the global behaviour of walls, vaults, and complete structures [5; 6], where as at smaller scales, detailed modelling strategies represent the heterogeneous



nature of masonry, accounting for the mechanical contribution of individual units, mortar joints, and their interactions [7; 8]. The increasing sophistication of these models has generated a corresponding demand for versatile and high-quality experimental data capable of capturing not only global responses but also localized deformation mechanisms necessary for their calibration and validation.

Keeping up with the trend and technological advancements, experimental data captured has also evolved from conventional contact and point-based measurements, such as transducers or extensometers towards full-field non-contact optical methods. Among these, Digital Image Correlation (DIC) has become an established tool for the investigation of masonry behaviour due to its non-contact nature and its ability to capture displacement fields [9; 10]. Several masonry studies have successfully employed DIC which have proven to be particularly valuable with the heterogeneous aspect of masonry, where deformation patterns are often highly localized and difficult to capture using traditional tools [11; 12].

While DIC is widely applied to masonry experimentation, a large area of research focuses on determining strain fields from displacements [13; 14]. Such representation could be appropriate when the analysing material exhibits either a continuous or distributed surface strain [15]. However, masonry exhibits an intrinsically discontinuous behaviour, particularly due to the weak mortar joints, which subjected to loading conditions initiate joint opening, sliding, or crack formation, primarily concentrating the damage at mortar joints, while the brick units themselves tend to behave approximately as rigid bodies. Consequently, the mechanical response of masonry may be more effectively interpreted through the relative motion of the blocks, through capturing their translations and rotations of individual blocks [8; 16; 17].

The current research addresses the inherent nature of masonry deformations, focusing on capturing the discrete response presented in masonry testing, through the application of the DIC technique. Shifting from the conventional DIC approaches, the proposed methodology introduces two key adaptations. First, it takes advantage of the natural surface features of masonry to track deformation, eliminating the need for surface preparation, either through artificial markers or speckle patterns. Second, rather than performing a full-field tracking across the entire specimen surface, the methodology selectively tracks a limited number of representative feature points, allowing the characterization of the discrete movement of masonry units.

The paper is organized in four brief sections followed by the conclusions. Section 2 presents the experimental campaign, in which three masonry panels were tested under uniaxial loading in different configurations, ie., boundary conditions to induce distinct deformation and failure mechanisms. Section 3a introduces the proposed natural-feature-based DIC methodology, describing how the conventional DIC workflow is adapted to our methodology in Section 3b. The application of this methodology to the three test cases is then presented in Section 4, followed by a discussion on the limitations encountered within this study.

2. Experimental Campaign

The experiments that this study considers are borrowed from an experimental campaign previously conducted on one-leaf masonry panels constructed with fired-clay brick units connected by comparatively weaker mortar joints [18; 19]. The masonry panels, measuring approximately $1.03 \text{ m} \times 1.03 \text{ m} \times 0.25 \text{ m}$, were constructed using bricks, of dimensions $0.25 \text{ m} \times 0.12 \text{ m} \times 0.055 \text{ m}$ arranged in a header-running bond pattern. Three loading configurations were adopted, see figure 1, the first two aimed at compression of the panels with load applied orthogonal and parallel to bed joints, and the third aimed at simulating shear. The first configuration consisted of uniaxial compression applied perpendicular to the bed joints, producing vertical cracking and tensile splitting near the specimen edges, as shown

in figure 1a. The second configuration involves the rotating the masonry panel by 90° , and compression applied parallel to the bed joints, promoting bed-joint opening and the detachment of masonry courses, see figure 1b. The third configuration subjected this rotated masonry panel to non-conventional setup test for shear loading over the right edge by means of a steel beam, to simulate a failure predominantly along the diagonal, see figure 1c.

The masonry panel constituent materials adopted are representative of historical masonry typologies, where the header bond layout ensures sufficient out of plane stability at the adopted panel scale and even with the rotated loading configurations considered. The increased number of units also provides a finer representation of the material heterogeneity within the periodic masonry texture, that proves to be advantageous for investigating localized deformation mechanisms and to accurately simulate panel behaviour by means of discrete models [8; 16]. A complete report on the mechanical characterization of the constituent materials adopted and the experimental campaign conducted have been presented in previous studies [18; 19].

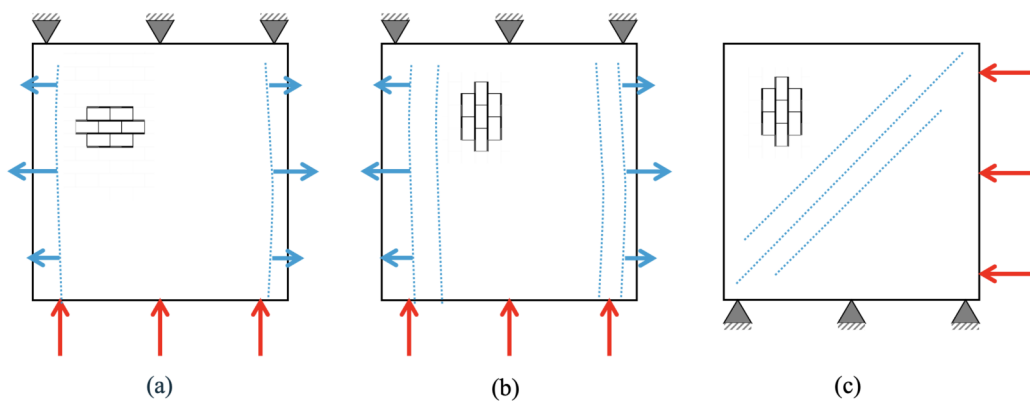


Figure 1. (a) Masonry panel in compression, (b) Rotated masonry panel in compression (c) Rotated masonry panel in shear applied along the specimen vertical edge

While the outcomes of the tests were primarily recorded with the aid of conventional LVDTs and a load cell to monitor the global displacement and load response of the masonry panels, a sequence of images was also captured for DIC- based analysis. A DSLR camera with a resolution of 6000×4000 pixels was positioned in front of the specimen to capture the entire field of view. No surface preparation was adopted and the only requirements were consistent lighting conditions, with the aid of flood lighting and a fixed frame of reference throughout the test. Images of the test specimens were acquired at fixed time interval, every 10 seconds and taking the first image, corresponding to the undeformed configuration, as the reference, the displacement were computed.

3. Natural feature based DIC

The natural texture of masonry, with its inherent variations in colour, coarseness and geometry of bricks and mortar joints provides sufficient contrast to enable reliable feature identification and tracking for the DIC analysis. Recent studies have demonstrated that the natural appearance of masonry can serve as an effectively discrete pattern, allowing accurate displacement and strain measurements without the application of paint or other surface treatments, particularly within the context of monitoring and experimentation of masonry structures [20; 21]. This approach

preserves the original surface characteristics of the specimen while simplifying the experimental procedure and avoiding any potential influence of surface coatings on the material behaviour.

3.1. DIC and feature tracking

To evaluate the applicability of the proposed methodology, a randomized grid of correlation points was selected across the masonry panel without other prior considerations. This preliminary test aimed at evaluating the applicability and reliability of the natural surface features for tracking deformations through DIC. An open source correlation algorithm was adopted [22; 23], and was able to successfully track most of the selected points through the test, as seen in figure 2b,c,d,e, demonstrating that the inherent texture of the masonry surface is adequate for marker-free feature tracking and image correlation.

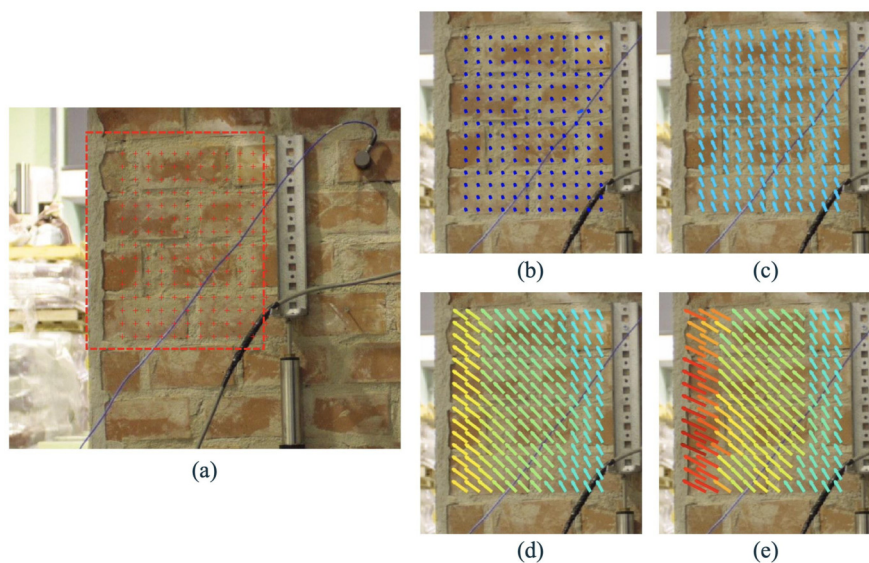


Figure 2. Evaluation of a sample uniform grid selected (a), at times (b) $t = 100$ seconds (c) $t = 300$ seconds (d) $t = 460$ seconds and (e) $t = 640$ seconds

Limitations to tracking were primarily associated with external disturbances, such as moving cables within the field of view, or with physical changes to the specimen surface. These included mortar detachment, and material loss (parts of specimen falling away), which altered or even removed the tracked features.

3.2. Rigid body displacements

The mechanical response of masonry is difficult to be investigated due to its heterogeneity. The overall deformation of the masonry assembly can be effectively interpreted as the relative motion of discrete rigid blocks connected through deformable interfaces [8]. To evaluate the mechanical response by adapting the DIC to a rigid-body description of masonry kinematics, the motion of individual units is characterized by tracking a limited number points on its surface. This approach provides a direct description of the displacement of each masonry unit and the relative movement developed across mortar joints, allowing discontinuities such as joint opening, sliding, and crack propagation to be identified.

The motion of an individual masonry unit is determined by tracking two or more natural surface features located on the exposed face of the brick. Figure 3a illustrates this. At the initial

configuration (at time $t = 0$), two feature points A and B define the position and orientation of the unit. During loading, these points are tracked through the sequence of images, reaching new positions A' and B' . Assuming that the masonry unit behaves as a rigid body, the distance between the tracked points remains constant ($l_0 = l_t$), such that the motion of the block is completely described by three independent kinematic quantities: the horizontal translation, the vertical translation, and the in-plane rotation. Figures 3b,c,d demonstrate the applicability of this for the three experimental configurations considered in this study.

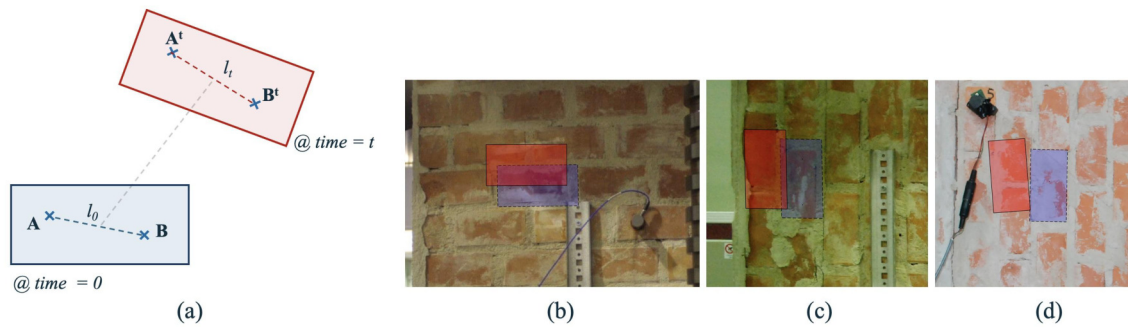


Figure 3. (a) Tracking the motion of the block at time t , with respect to the translation of the points A to A^t and B to B^t , demonstrated in the three experiments (b), (c) and (d) with blue showing the reference and red showing the tracked deformed location of the blocks



Figure 4. (a) Masonry panel under compression (b) Grid superimposed over the existing masonry texture (c) Grid as a guide to define the rigid blocks

Having established the motion of an individual masonry unit, the methodology is extended to the complete panel. A grid is superimposed on the acquired images following the existing masonry texture, as shown in figure 4a,b, and cells corresponding to a single brick units are derived, in figure 4c. The grid further provides a geometric framework for organizing the tracked features and associating them with individual masonry units. To implement the proposed methodology, two feature points within the boundary of each visible masonry unit were chosen and tracked, allowing the motion of the corresponding block to be reconstructed with respect to the captured image in the sequence and consequently with every load increment. Each unit

is therefore represented by its rigid-body motion, while the masonry panel is interpreted as an assemblage of interacting blocks. This discrete representation enables the visualization of the kinematic response of the entire specimen, highlighting the translations and rotations of individual units and providing the visual description of the deformation mechanisms developed during loading.

4. Application and Outcomes

The rigid-body based methodology described in Section 3b was applied to the complete panel for each of the three experimental configurations, allowing the discrete kinematic response of the masonry assemblies to be visualized. Using the grid and the base masonry texture as a guide, the rigid blocks were defined. To trace the motion of each rigid block, two feature points were selected arbitrarily within its defined boundary. This reduced parametrization, tracking only two points per block rather than a full-field correlation, allows for a considerably faster assessment.

The correlation process is further simplified, when the selected point proves unsuitable, for instance, due to inconstancy in the presence of natural features, the tracking point can be easily identified and replaced with an alternative within the same block boundary, without requiring the correlation to be repeated across the entire specimen surface. However, at the current stage, such errors and inconsistencies in tracking were identified manually, as an automated procedure for their detection has not yet been implemented.

In the first configuration, the panel was loaded in compression with the bed joints oriented perpendicular to the applied force, see figures 1a and 5a. The tracked units exhibited a combination of vertical and horizontal displacements. The loading plate compresses the specimen contributing to the vertical movement seen initially, figure 5b, and eventually to horizontal displacement as tensile forces take effect. The masonry blocks along the left and right edges of the panel are seen to move outward as vertical splitting cracks developed, allowing stepped joint openings to be identified directly from the displacement pattern, see figure 5c.

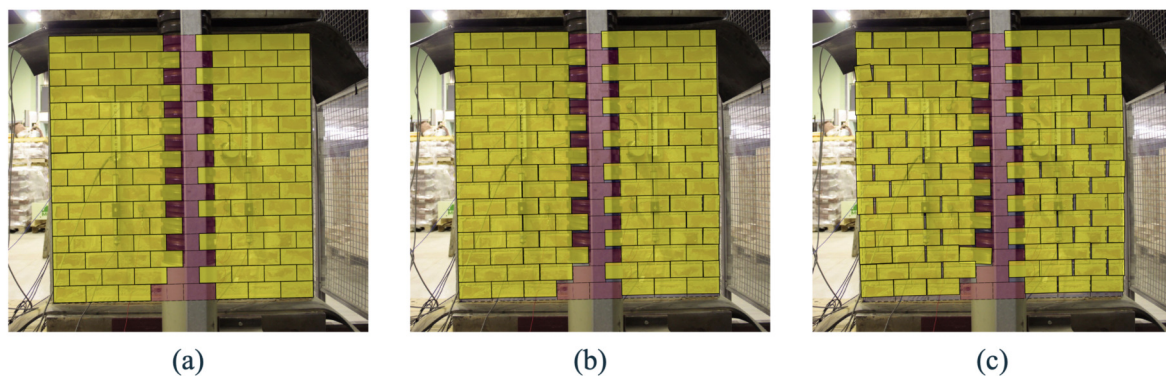


Figure 5. Masonry panel in compression, with deformations captured at (a) $t = 0$ seconds (b) $t = 250$ seconds (c) $t = 540$ seconds

In the second configuration, the panel was rotated by 90° and loaded in compression with the bed joints oriented parallel to the applied force, figures 1b, 6a. The prominent mechanism observed here was the horizontal movement of the blocks, with entire courses detaching along the bed joints. This horizontal displacement component highlighted the tensile detachment of

blocks along the left and right edges of the panel, consistent with a bed-joint opening mechanism, figures 6b,c.

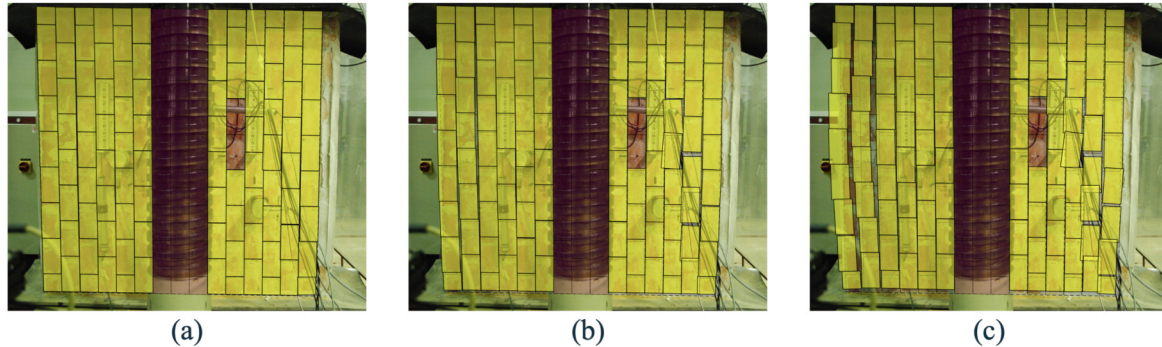


Figure 6. Rotated masonry panel in compression, with deformations captured at (a) $t = 0$ seconds (b) $t = 600$ seconds (c) $t = 1100$ seconds

In the third configuration, the rotated panel was subjected to shear loading applied along its right edge, with the bed joints again oriented perpendicular to the load direction, figures 1c,7a. The resulting deformation showed a failure mechanism concentrated along the diagonal of the panel, consistent with the expected shear response 7c. It is important to note that the specimen underwent an initial rigid-body rotation of the entire panel before internal deformations within the masonry began to develop, see figure 7b. A conventional DIC approach, which computes displacements relative to the original undeformed configuration, and would conflate this global rigid motion with the internal deformation of the specimen, leading to a potentially misleading representation and interpretation of the damage presented. The rigid block-based methodology adopted here, by contrast, allows the global rigid-body motion of the panel to be isolated, so that the relative displacements and rotations of individual units, and further the internal deformation presented in masonry can be evaluated independently of the overall panel motion. This also accounts for relative rotations of individual units, that would otherwise not be readily distinguishable through a conventional continuous strain field.

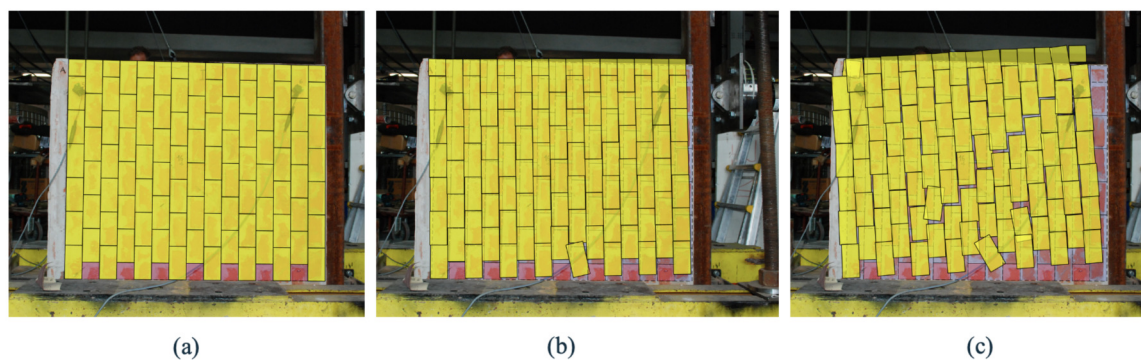


Figure 7. Rotated masonry panel subjected to shear, with deformations captured at (a) $t = 0$ seconds (b) $t = 3030$ seconds (c) $t = 4200$ seconds

A further limitation with the application of the methodology was observed related to the loss of visual access to portions of the specimen. In the first two configurations, the loading

apparatus of the compression test machine partially obstructs the field of view, preventing the central bricks of the panel from being tracked. The cable and transducers placed on the specimen surface, in the second configuration, also limit a similar access to the surface. In the third shear configuration, the brick unit detached from the panel at an early stage of loading, could no longer be tracked in the subsequent frames, resulting in a gap in the corresponding displacement data.

Despite the assumption of brick units as rigid bodies, deformations were in fact observed at the unit level, including delamination, crushing, cracking, and further material loss. As a result, the natural features used for correlation were no longer reliably identifiable in the affected regions, and tracking of the corresponding units was consequently discontinued, see lower blocks in figure 7c.

5. Conclusion

This paper presented a natural-feature-based DIC methodology for characterizing the discrete deformation response of masonry, developed to address a critical qualitative addition in the experimental characterization of heterogeneous media, such as masonry. By eliminating the need for artificial markers or speckle patterns and instead adopting the natural texture of brick and mortar surfaces, the proposed approach provides a non-invasive and realistic means of tracking masonry deformations.

The methodology was validated across panels tested in three experimental configurations, compression, rotated compression, and shear, representing distinct failure modes. In each case, the natural feature-driven DIC method reliably captured discrete block motion, illustrating aspects such as joint opening, and crack initiation. By adapting the tracking framework to a rigid-body description of masonry kinematics, the translation and rotation of individual units were isolated from the global displacements, which provided a good visualization of the associated mechanisms such as tensile splitting and bed-joint detachment, and as demonstrated in the shear test, further highlighted the advantage of a discrete, block-based interpretation over a full-field correlation. Despite these strengths, few limitations were identified. Partial obstruction of the camera's field of view by the loading apparatus, early detachment of individual units, and progressive surface damage, including crushing, and material loss, all interrupted feature tracking in localized regions, highlighting a practical constraint of the natural-feature approach. Further, the correlation process still requires a certain degree of manual post-processing, which is both an advantage, as it retains oversight over correlation quality, and a limitation, in terms of scalability.

Looking ahead, the methodology developed here provides a foundation for extending discrete DIC-based characterization from visualization toward diagnosis, by more directly linking observed deformation patterns, such as rigid block rotation or bed-joint sliding, to specific structural failure typologies. The resulting displacement and rotation data offer experimentally validated input for calibrating numerical models that account for internal block deformability and complex crack interactions.

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