Crack monitoring of masonry walls with standard and enhanced Digital Image Correlation methods

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Abstract

Many contact and optical methods have been developed and tested over the past decades for structural crack monitoring. Contact instruments provide only localized information and require direct contact with the monitored surface. In contrast, optical methods remotely offer information at a larger scale. Among optical methods, Digital Image Correlation (DIC) has been widely used to monitor surfaces by tracking points in images collected using cameras with fixed positions between each collected frame. However, the fixed setup significantly limits the applications for long-term monitoring. To overcome DIC limitations, we investigated Crack Monitoring from Motion (CMfM) which can measure the propagation of cracks over time in images captured using cameras with non-fixed positions. Here, we present the results obtained during laboratory tests on masonry walls by comparing DEMEC mechanical strain gauge measurements, standard DIC and CMfM. Specifically, we measured the crack propagation in masonry walls under compression and bending loading at different stages using the DEMEC instrument and by collecting images with fixed and non-fixed cameras. We processed images collected with the fixed camera using Py2DIC standard DIC software and images from non-fixed cameras using CMfM. Comparing the crack propagation measured with the three techniques showed a high level of agreement, i.e. a few hundredths of millimetres in terms of median, Root Mean Square Error (RMSE) and Normalized Median Absolute Deviation (NMAD) of the differences, demonstrating the potential for monitoring cracks with permanent and non-permanent camera setup.

Keywords: Crack measurement, Masonry wall testing, Digital Image Correlation, Non-fixed camera setup

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1 Introduction

Historical masonry structures dominate cultural heritage sites worldwide. Evaluating the safety of existing unreinforced masonry structures is a major concern and typically requires in-situ inspections and surveys. During inspections, monitoring cracks is crucial for the damage assessment of historical masonry structures since it provides vital information on the cause and severity of the damage. In severe cases, it is also important to continuously monitor cracks to assess the damage evolution and estimate the structure integrity (Verstrynge et al., 2018; Verstrynge and Van Gemert, 2018; Soleymani et al., 2023).

Another essential aspect of assessing historical masonry structures involves using numerical models to study their complex behaviour due to the intricate structural interactions among units and mortar joints. For built heritage and existing structures, geometry and material properties are often insufficient to properly capture the structural response of masonry systems (Verstrynge, 2010). Degradation of material and structural elements, and damage from past events significantly influence the structural resilience against future human-made and natural hazards. Therefore, an important improvement to structural models for masonry-built heritage can be achieved by efficiently integrating on-site crack patterns and material pathologies, detected and measured automatically, into these models.

For crack measurements, different contact and optical methods have been tested. Contact instruments such as strain gauges and Linear Variable Differential Transducers (LVDTs) provide accurate local measurements but require direct contact with the monitored surface. On the other hand, optical methods remotely offer information on a larger scale. Among them, the Digital Image Correlation (DIC) technique has been widely adopted to measure displacements, strains, and crack propagation on sample surfaces by tracking the positions of points in images collected using cameras with a fixed position over time (fixed between each inspection/frame) (Pan et al., 2009; Blaber et al., 2015; Ravanelli et al., 2017; Belloni et al., 2019; Verstrynge et al., 2018). DIC can provide accurate results remotely however, the permanent setup (i.e. a fixed camera mounted on a tripod) strongly limits the application of the technique for long-term monitoring, especially outside the controlled laboratory environment. Potential vibrations, wind, or ground instability could also affect the results. To overcome DIC limitations, a new methodology has been developed and tested at Sapienza University of Rome in collaboration with KTH Royal Institute of Technology (Stockholm) within the Tunnel Automatic CracK detection (TACK) project (Belloni et al., 2020). The innovative approach, called Crack Monitoring from Motion (CMfM), can measure the propagation of cracks in images captured using cameras with non-fixed positions. Therefore, it can overcome the main limitation of using a fixed camera position and open the possibility of long-term monitoring (Belloni et al., 2023; Sjölander et al., 2023). This will greatly improve the efficiency and adaptability of structural monitoring and assessment outside controlled laboratory conditions, especially for historical structures.

This work aimed to test and validate image-based techniques for crack measurements on masonry walls subjected to different loading systems in the laboratory with fixed and non-fixed setups. Specifically, we investigated the standard DIC technique and the CMfM approach through comparisons with the reference DEMEC mechanical strain gauge for measuring crack propagation over time.

2 Methods

This section presents the instruments and methodologies tested for crack propagation monitoring during laboratory testing on masonry walls.

2.1 DEMEC mechanical strain gauge

The DEMEC mechanical strain gauge is a device that measures displacements at specific points on a structure using a single instrument. It is reliable and accurate but provides only local information and requires direct contact with the surface. Compared to other sensors such as electrical strain gauges and LVDTs, it is not attached to the surface for the entire duration of the monitoring and needs direct contact only during each measurement. It consists of an invar main beam with two conical locating points, one fixed and the other pivoting on a special knife edge. For measuring, the conical points are located in holes in pre-drilled stainless steel discs attached to the element being monitored (Figure 1).

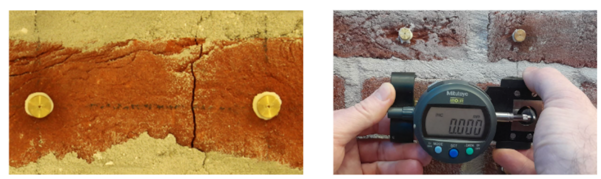


Figure 1. DEMEC measurements

If there is a relative displacement between the steel discs, the movement of the pivoting point is measured by the strain gauge attached to a base plate on the invar beam. The DEMEC provides only relative measurements, therefore the instrument is first set to zero by placing it on a reference metallic bar (usually 100 or 200 millimetres long). Then, a series of measurements are performed to monitor the deformation process. The reference measurement m_0 is the first DEMEC measurement (time t_0). Then, for each measurement m_i (time t_i, with $i = 1,...,n$) the relative ε_i strain and ΔL_i displacement are computed according to the following equations:

$$\begin{aligned} \varepsilon_i &= (m_i - m_0)C \\ \Delta L_i &= \varepsilon_i L \end{aligned}$$

where C is the strain gauge constant and L is its base length.

The device used in this work is a digital DEMEC mechanical strain gauge produced by W.H. Mayes & Son (`http://www.mayes.co.uk/`). The instrument has base length L = 100 mm and constant C = 0.792×10^{-5}.

2.2 Digital Image Correlation (DIC)

DIC is an image-based technique to compute displacement and strain fields using a set of images of a surface subjected to a loading system and a deformation process. To perform standard DIC, the images should be collected using fixed cameras at different levels of the deformation process. The technique can be performed in two (2D DIC) or three (3D or stereo DIC) dimensions. The 2D DIC uses a single fixed camera and estimates displacements and strains in a selected plane corresponding to the planar surface under investigation. Therefore, 2D DIC is appropriate only when the displacement and strain fields can be considered planar within the Area Of Interest (AOI). On the other hand, the 3D DIC is used when out-of-plane movements cannot be neglected but requires two fixed synchronized cameras to collect the images (Belloni et al., 2019).

Today different commercial and open-source DIC software are available (Belloni et al., 2018). Among them, Py2DIC is a Python open-source 2D DIC software developed at the Geodesy and Geomatics Division of Sapienza University of Rome and it is available at `https://github.com/Geod-Geom/py2DIC`. It is based on the well-known template matching method to track the movement of specific points of interest over a surface by comparing the gray intensity changes of the surface in the undeformed or reference (time t_0) and deformed states respectively (time t_i, with $i = 1, ..., n$). Specifically, at each level of the deformation, it computes displacement fields by selecting a reference area (template $w \times w$) around each pixel of interest (p) in the reference image and searching for the corresponding area inside the search window $(w+d) \times (w+b)$ in the search image using cross-correlation techniques (Figure 2). The sub-pixel resolution is reached by oversampling the reference template and the research window using a bicubic interpolation. Repeating this procedure for each pixel of the AOI, Py2DIC can also provide the full-field displacement fields (Belloni et al., 2019). Compared to DEMEC mechanical strain gauges, DIC can remotely provide information on larger areas. However, it still requires a fixed setup (i.e. a fixed camera), which can limit its application outside controlled laboratory conditions and for long periods.

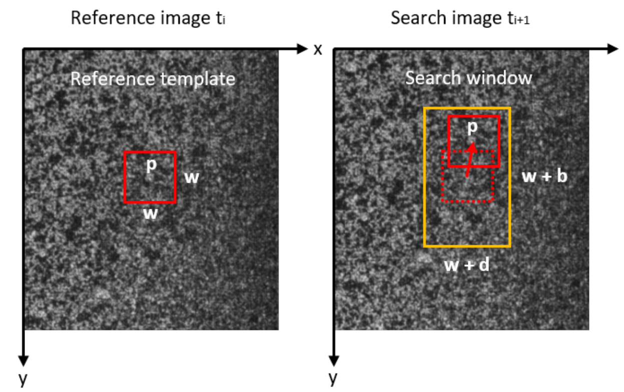


Figure 2. Template matching method for DIC

2.3 Crack Monitoring from Motion (CMfM)

CMfM is an open-source enhanced DIC-based approach developed through a collaboration between the Geodesy and Geomatics Division of Sapienza University of Rome, the Geoinformatics Division of KTH Royal Institute of Technology and the Concrete Structures Division of KTH Royal Institute of Technology. The open-source algorithm is available at `https://github.com/Geod-Geom/CMfM` and it provides crack propagation using a series of images collected using cameras with non-fixed positions over time (i.e. removed and replaced between each acquisition). CMfM is based on the Scale-Invariant Feature Transform (SIFT) and template matching algorithms. First, SIFT matches features between a reference image and each subsequent deformed image to estimate the homography between each pair. Second, points of interest along the crack are selected in the reference image and projected onto the deformed images using each homography to remove the effect of the camera movement. Finally, the displacements of the projected points are computed with template matching and reprojected onto the reference image to determine the crack aperture over time. Additional details can be found in Belloni et al. (2023). The algorithm, which has already been investigated to measure cracks during laboratory tests on concrete beams, is applied here to monitor the propagation of cracks in masonry walls.

3 Laboratory test

3.1 Masonry wall preparation

Using solid-facing bricks and hybrid lime-cement mortar, several masonry walls were built for testing at the Reyntjens Laboratory of KU Leuven. We adopted bricks of 185 mm x 55 mm x 90 mm (width x height x depth) and 15 mm mortar layers between the bricks with the following composition: 10 kg riversand 0/2 (dry), 1.5 kg hydrated lime Supercalco 90, 0.8 kg cement CEM I 52.5 N and 1.8 liter water. We prepared two walls: the first one of 500 x 700 x 90 mm³ (width x height x depth) and the second one of 1600 x 600 x 90 mm³ (width x height x depth). Then, DEMEC steel discs were glued at a distance of 100 mm to cover the walls with a measurement grid. Due to the difficulties of predicting the location of the crack over the surface, we glued 25 steel discs over the central part of one side of the first wall and we created a regular grid of points for monitoring the cracks using the DEMEC instrument during compression testing (Figure 3).

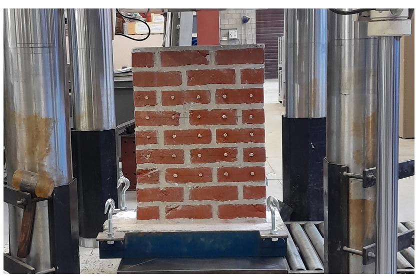


Figure 3. Masonry wall n. 1

Similarly, for the second wall that was subjected to three-point bending, we glued 60 steel discs to the central part (Figure 4).

Figure 4. Masonry wall n. 2

3.2 Compression test

We tested the first masonry wall using a compressive test with loading and unloading steps. A hydraulic test bench, type Dartec, with a maximum loading capacity of 5000 kN was used. During testing, we adopted a displacement-control protocol system (speed of 0.6 mm/min) that enables a more stable deformation increase and hence is more suitable for monitoring crack growth. We incremented the displacement at each stage to a certain value and kept it constant during data collection. Figure 5 shows the applied displacement scheme registered by the Dartec press.

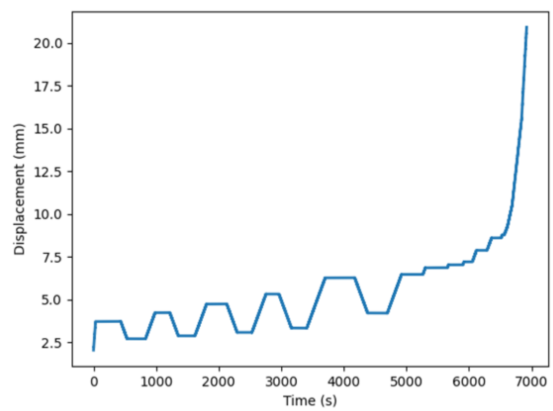


Figure 5. Displacement plot registered by the Dartec testing machine

During testing, for each of the 13 stages, we collected images using a fixed Canon EOS 2000D (distance from the wall d = 1200 mm, focal length f= 55 mm, pixel size on the object p = 0.079 mm) and a fixed MatchID stereo DIC system. We collected one image with each camera and measured all DEMEC pairs of points using the DEMEC instrument during each load step. The setup of the laboratory test is shown in Figure 6. In this work, we focused only on the data collected with the DEMEC and the fixed Canon camera. Figure 7 shows one image collected with the fixed Canon camera and the AOI selected in this study to investigate 2D DIC.

Figure 6. Experimental setup of the compression test

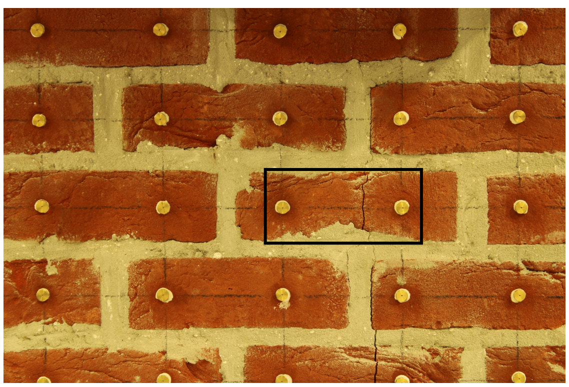


Figure 7. Image collected with the fixed Canon camera

3.3 Three-point bending test

Before testing the second wall, we removed its support at the central bottom and installed two laser sensors (precision of 0.02 mm) to monitor the wall deflection under self-weight. Then, we used a Zwick-Roell HB250 servo-hydraulic testing machine with a maximum capacity of 250 kN. Similarly to the first test, we used a displacement-control protocol system (speed of 0.6 mm/min) to perform the three-point bending test on the wall. Using this protocol system we incremented the displacement to a certain value and maintained it constant to collect the data. This way, we collected data for five steps before the wall failure. Figure 8 shows the displacement plot registered by the Zwick-Roell machine during testing and the 5 steps of constant displacement.

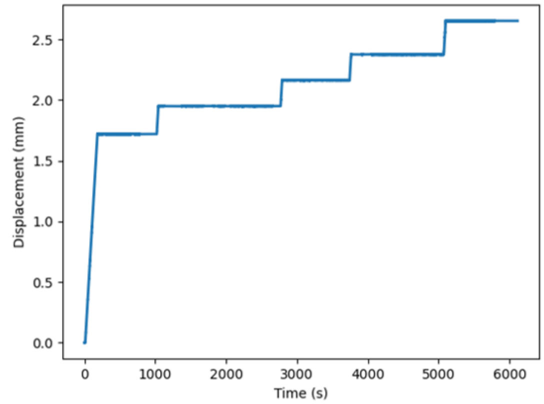


Figure 8. Displacement plot registered by the Zwick-Roell HB250 testing machine

For monitoring crack propagation we placed a fixed Canon EOS 5D Mark III camera (distance from the wall d = 1450 mm, focal length f= 50 mm, pixel size on the object p = 0.18 mm) to capture the entire wall surface and a fixed Canon EOS 2000D camera (distance from the wall d = 900 mm, focal length f= 55 mm, pixel size on the object p = 0.05 mm) to monitor the bottom central part of the wall. On the same side, we captured images from slightly different positions using an iPhone 12 Mini (pixel size on the object in the reference image p = 0.07 mm). We used the Canon EOS 5D Mark III camera to collect data for the entire test; we collected images with the Canon EOS 2000D camera and the iPhone after the appearance of the crack (i.e. after step 2). Also, for each loading step, we measured the deformation of the walls with the DEMEC instrument for each pair of conical points attached to the walls. Figure 9 presents the setup of the laboratory experiment.

Figure 9. Experimental setup of the three-point bending test

Figure 10 shows examples of images collected with the fixed Canon cameras.

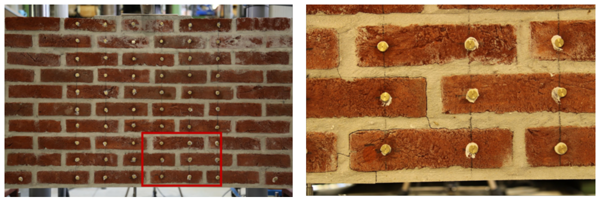


Figure 10. Images collected with the fixed EOS 5D Mark III (left) and EOS 2000D camera (right)

Figure 11 shows the iPhone images collected at two different steps of crack propagation.

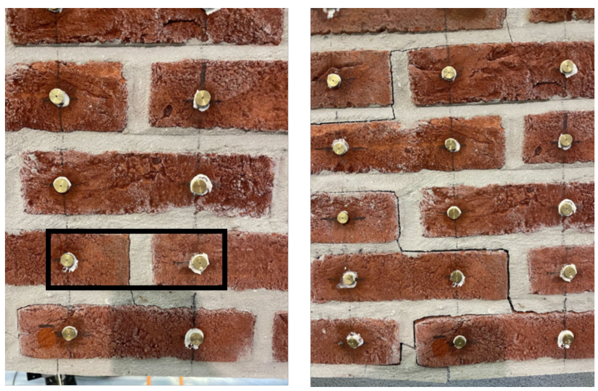


Figure 11. Images collected with the non-fixed iPhone camera

4 Results

4.1 Compression test

We processed the images collected with the fixed Canon camera using Py2DIC. Specifically, we focused on each pair of steel discs on the left and right sides of the cracks. We computed their displacement and the distance variation in the sequence of images to measure the crack propagation over time. For Py2DIC processing we used a template ($w \times w$) of 81×81 pixels, an edge ($b = d$) of 80 pixels, an oversampling factor of 20 and the Normalized Cross-Correlation (NCC) coefficient. For the pixel-to-millimetre conversion in Py2DIC, we used the distance of the steel discs measured with the DEMEC devices. For brevity's sake, in Figure 12 we present only the comparison between the DEMEC reference measurements and Py2DIC for the selected AOI.

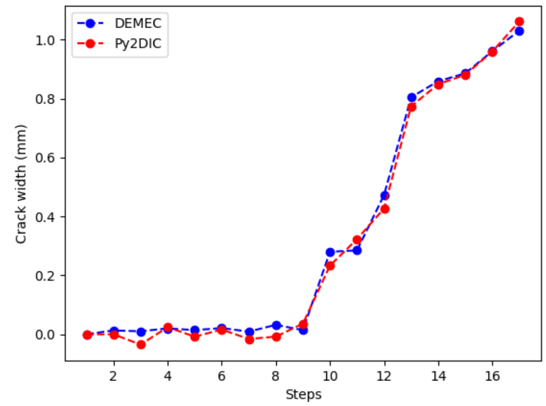


Figure 12. Comparison between DEMEC measurements and Py2DIC results

To better understand the potential of Py2DIC, we computed standard statistical metrics of the differences between Py2DIC and the DEMEC measurements: mean, median, standard deviation (Std. Dev), Root Mean Square Error (RMSE), and Normalized Median Absolute Deviation (NMAD). Table 1 shows the results of this comparison.

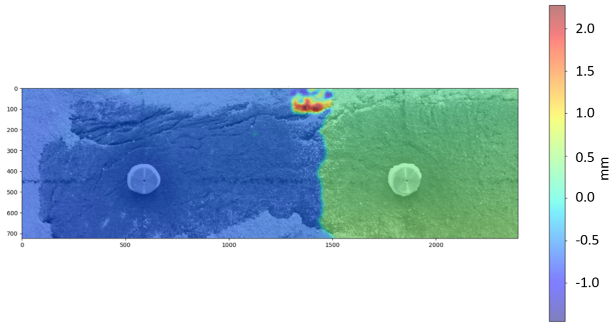
Table 1. Statistical analysis (DEMEC - Py2DIC)

Mean	**Median**	**Std. Dev**	**RMSE**	**NMAD**
(mm)	(mm)	(mm)	(mm)	(mm)
0.01	0.01	0.03	0.03	0.02

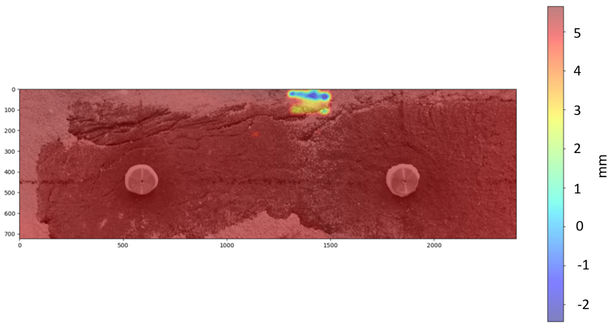
Finally, Figures 13a and 13b show the horizontal (x) and vertical (y) displacement fields computed using Py2DIC inside the AOI (time $t_0 - t_{13}$). From the horizontal displacement field, the aperture of the crack is visible, confirming an opening around 1 mm at the end of the test (t_{13}). Also, along the vertical direction, the masonry wall is subjected to a constant displacement of 5 mm due to the compression. It is worth noticing that in the upper central part of the image, the higher displacements are most likely outliers due to rapid change in the texture, which makes the template matching not applicable.

4.2 Three-point bending test

Again, we processed the images collected with fixed Canon cameras using Py2DIC software. For brevity's sake, here we present only the results of the Canon EOS 2000D (closed to the surface) and



(a)



(b)

Figure 13. DIC horizontal displacement field (a) and vertical displacement field (b)

the iPhone 12 Mini for the AOI presented in Figure 11. For processing Canon EOS 2000D images, we used a template of 151 pixels, an edge of 80 pixels and an oversampling factor of 20. Figure 14 and Table 2 show the comparison between the DEMEC measurements and Py2DIC results.

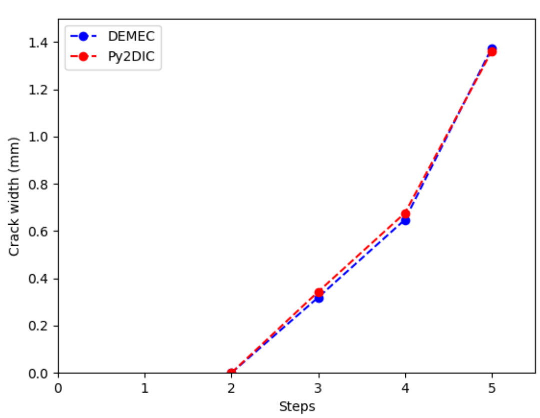


Figure 14. Comparison between DEMEC measurements and Py2DIC results

Table 2. Statistical analysis (DEMEC - Py2DIC)

Mean	Median	Std. Dev	RMSE	NMAD
(mm)	(mm)	(mm)	(mm)	(mm)
0.02	0.02	0.01	0.02	0.01

Finally, we processed the image collected with the iPhone using CMfM. Figure 15 and Table 3 show the comparison between Py2DIC applied to the images of the Canon EOS 2000D and CMfM using the non-fixed iPhone camera images.

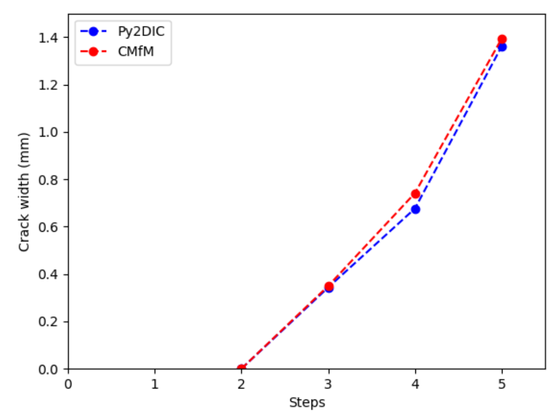


Figure 15. Comparison between Py2DIC and CMfM results

Table 3. Statistical analysis (Py2DIC - CMfM)

Mean	Median	Std. Dev	RMSE	NMAD
(mm)	(mm)	(mm)	(mm)	(mm)
0.03	0.03	0.02	0.04	0.04

The results highlight a good agreement between Py2DIC and CMfM, at the level of a few hundredths of millimetres.

5 Conclusions

In this study, we investigated crack monitoring in masonry walls through laboratory tests, comparing the performance of the DEMEC contact sensor, standard DIC implemented through the software Py2DIC and the enhanced DIC technique CMfM. During the compression test, the results validated the typical failure mode of masonry under compression, characterized by vertical splitting cracks propagating through mortar joints and bricks. Also, the DIC technique demonstrated a high degree of accuracy in remotely monitoring crack propagation compared to the standard and well-established DEMEC measurements (RMSE of 0.03 mm). In the three-point bending test, cracks predominantly formed in the central lower region of the walls, along the interface between mortar joints and bricks. Again, the results highlighted the capability of DIC to measure crack propagation with high accuracy and the feasibility of using CMfM for crack detection, showcasing the potential of a non-fixed camera setup for reliable monitoring.

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