Laser speckle measurements and numerical simulations of the deformation of masonry loaded in compression

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Abstract

This study focuses on the comparison of the results of a laser speckle technique, ESPI, and numerical simulations with DIANA when used for research into the role of brick–mortar interaction on the deformation of masonry loaded in compression. When a masonry structure is loaded, the interaction of brick and mortar is considered of paramount importance with respect to the mechanical behaviour of masonry. As a consequence of the brick laying process and positioning of the unit, masonry has weak spots at the mortar-unit interface. The clay–brick–mortar interaction was measured in detail with ESPI, a specially designed laser speckle test equipment. It was shown that most of the deformation occurred in the brick–mortar interface. DIANA was used for some numerical simulations of the brick–mortar interaction. Simulated specimen dimensions were as in the experiments. An interface layer of 1 mm thickness was modelled between mortar and top unit to simulate the contact layer. Fissures were modelled as 15 mm deep openings. Similarities between ESPI and DIANA are seen in the way the results i.e. node displacements are presented. Both DIANA and ESPI produce a similar tabular output with node coordinates and their displacements. This output can be used in spread sheet programs for further analyses. As DIANA and ESPI give comparable results, the advantage of DIANA – i.e. the calculation of stresses – can be utilized. Results of the study can be used for more detailed modelling of masonry.

Keywords: experimental methods, composites, optical method, numerical simulation, brick mortar interface, compressive loading.

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1 Introduction

Masonry structures are made in layers of bricks and mortar. The ways these components affect masonry deformational behaviour and strength have been studied over the years (e.g. Hendry [1]). One of the key factors concerns the brick–mortar interaction under compression and the resulting deformation of bricks and mortar separately [2]. For reliable estimation of the capacity of a structure, analytical and numerical simulations can be performed, for which input data obtained from detailed experiments are required. Data, like the modulus of elasticity and Poisson's ratio, are obtained by measuring the change in length of a part of the specimen by means of an LVDT, a Demec gauge or a strain gauge, Figure 1.

All these instruments measure the change in distance between two points. To observe the deformation in more detail of a mortar joint, measuring at a (large) number of points and preferably over a shorter distance is required. In addition, reliable values for lateral expansions are difficult to obtain from ordinary walls with LVDTs or Demec gauges. Therefore, a refined measurement methodology, based on the laser speckle technique (ESPI) was used. The major advantage of using a laser-speckle system like ESPI over systems like LVDTs or Demec is that the displacement of a (theoretically infinite) number of points of a certain area can be observed. In addition, DIANA was used for the numerical simulations. Both methods were used to observe the brick–mortar interaction under concentric compression, using 25 mm thick specimens.

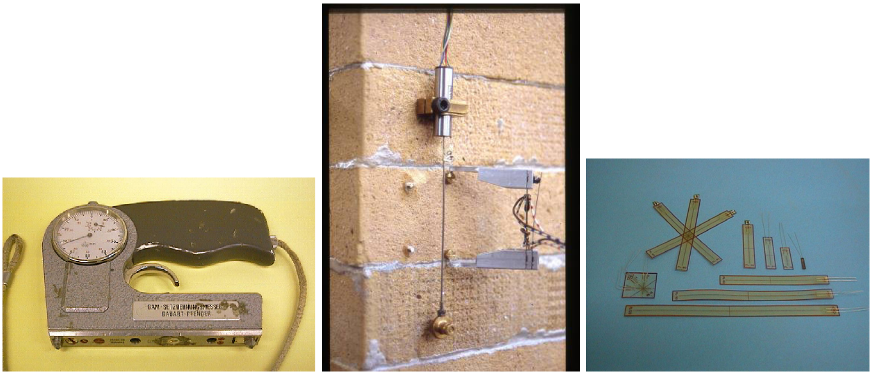
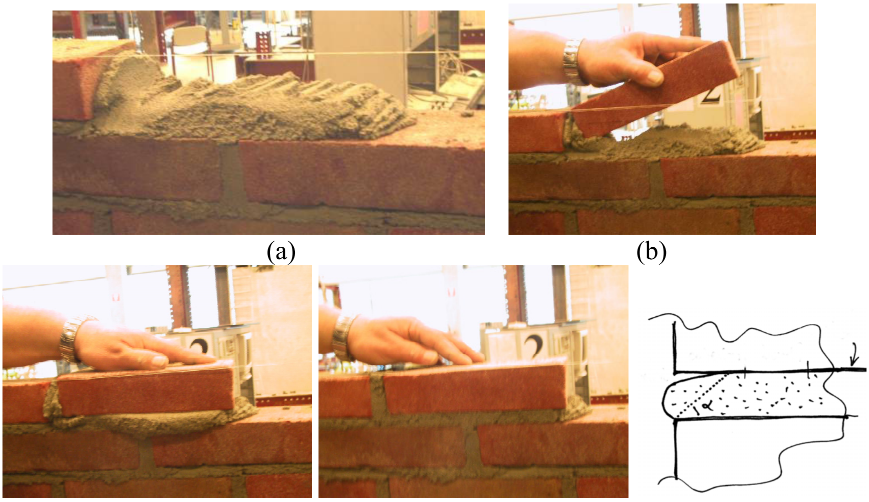


Figure 1: Demec, LVDT, clip-on gauge and strain gauges.

This paper discusses refined ESPI measurements and numerical simulation of the deformation of masonry specimens in the area of the mortar joint. The effects of fissures on deformational behaviour both in the loading direction as in the lateral direction are emphasized. The use of DIANA as a numerical simulation tool is compared with the use of ESPI as an experimental tool.



(a) (b)

(c) (d) (e)

Figure 2: Steps in the brick-laying process: (a) putting mortar on the wall; (b) the brick is pushed into the mortar; (c) mortar moved from the centre bulges at the edges; (d) surplus of mortar scraped off; (e) unsupported mortar at the edge of a joint.

2 Brick–mortar joint

Brick-laying is the piling of bricks on top of each other. Mortar serves as a tolerance aid, allowing for size variation of the bricks. In The Netherlands, the mason puts the quantity of mortar needed for one brick on the wall (Figure 2). The brick is first pushed into the fresh mortar and then the surplus of mortar is scraped off (Figure 2(c)). The fresh mortar in the centre of the joint is compressed to the appropriate joint thickness, and the mortar is squeezed from the centre to the edges. At the edges, the mortar is hardly compressed vertically. After scraping off, the fresh mortar at the edges is not supported. Due to gravity, the top surface will drop a little. Depending on the moisture content and the sand used, the edge material runs off under a certain slope (approximately 30 - 45°).

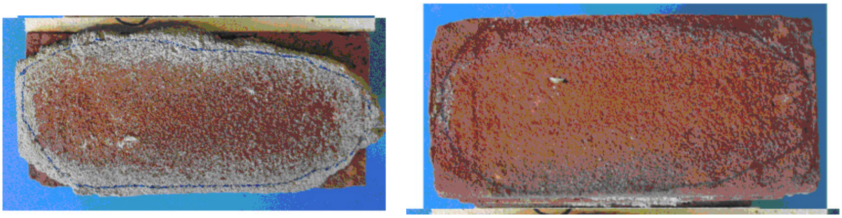


Figure 3: Fracture surfaces between brick and mortar showing bonded central area.

Traces of the brick-laying process can be observed in fracture surfaces after bond wrench bending tests, Figure 3. The central part of the mortar joint that first came in contact with the brick shows residues of the brick surface. This indicates better bonding in the centre than at the edges. The “settlement” of the mortar at the edges (Figure 2(e)) also negatively affects bonding.

2.1 Specimen dimensions and appearance

Brick–mortar interaction was studied by testing representative pieces of masonry representing a sample of a joint, in combination with the adjoining bricks. The specimens, cut from couplets as 25 mm thick slices, were loaded vertically, i.e. perpendicular to the bed joint. The specimens were approximately 100 mm wide, the original width of the brick, and 115 mm high, two bricks and one joint. The deformation of the front surface was observed with ESPI. With these specimen sizes a representative sample is obtained in which a stress distribution develops, similar to that in the real wall.

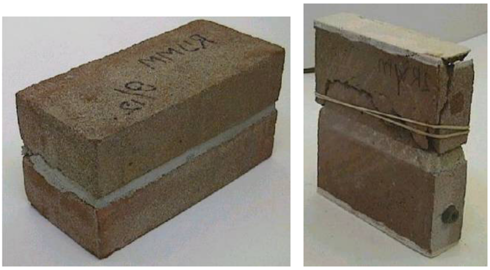
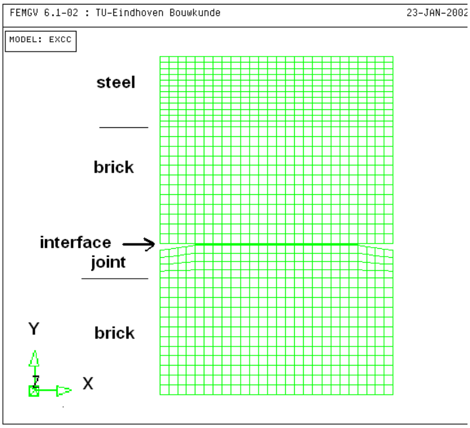


Figure 4: RW couplet and a 25 mm thick specimen after testing.



E_{steel} = 210000 N/mm^2
E_{brick} = 4000 N/mm^2
E_{mortar} = 5000 N/mm^2
$E_{interface}$ = 1000 N/mm^2
υ_{steel} = 0.30
υ_{brick} = 0.18
υ_{mortar} = 0.15
υ = Poisson’s ratio

Figure 5: Scheme of element pattern and mechanical values used.

3 Numerical simulations

The finite element program DIANA [3] was used for some explorative numerical simulations. Figure 5 shows a scheme of the model used. Specimen dimensions were as in the experiments except for the thickness for which one layer of elements of 10 mm thickness was used. An interface layer of 1 mm thickness was modelled between mortar and top unit to simulate the contact layer. The fissures were modelled as 15 mm deep openings. The specimen was loaded by assigning a 1 mm displacement to two points on top of the steel block.

Figure 6 shows contour plots of the displacements and stresses of a concentrically loaded specimen with a fissure on either side. The parts of the specimen above and below the fissure remained without stress. Peak stresses occurred at the load introduction point in the steel load block and at the crack tips.

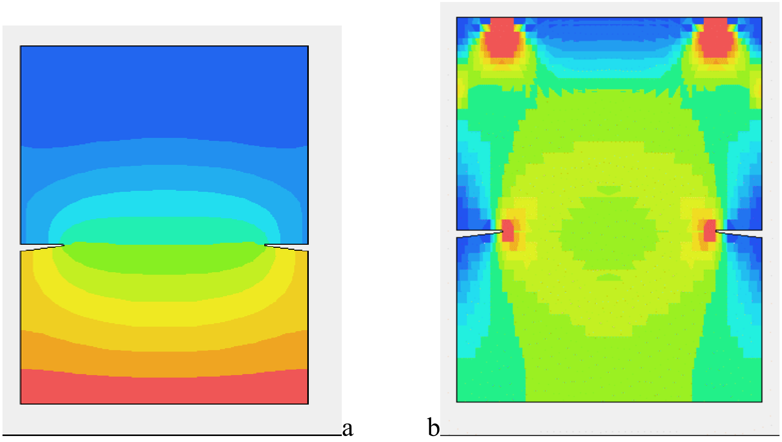


Figure 6: (a) Deformation and (b) stress contours of a concentrically loaded specimen, DIANA results.

3.1 Vertical deformation

The DIANA software provides a table with X- and Y-coordinates for each point (node of an element) and “measured values”. This table was used to draw graphs of vertical displacements against the horizontal position (X-value) of the corresponding node (Figure 7).

Specimen behaviour is symmetric about the joint. The effect of the fissure is clear. The node displacements are smaller near these openings. Nodes of the bottom brick displace more and those of the top brick less than expected for a closed joint. The close contour lines represent the softer interface layer. The node displacement lines of this softer layer with smaller elements fan out at the end, near the fissure. Symmetry around the joint can be observed.

It should be noted that strains and stresses in this section are obtained for a vertical displacement of 1 mm at the top edge, resulting in an averaged reaction stress of 29.8 N/mm^2 and an E-value of the specimen of E_{spec} = 3400 N/mm^2. This E-value was smaller than the E_{brick} of 4000 N/mm^2, due to the softer interface layer and the fissures in the model. The largest tensile stress, which occurred 15 mm from the edge was 0.8 N/mm^2. The applied load, in the simulation, was approximately three times the strength of this type of masonry.

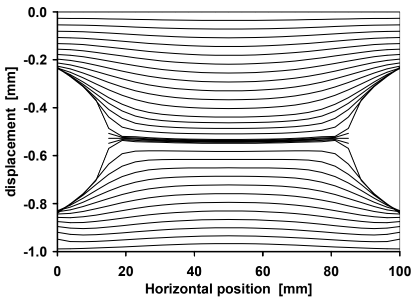


Figure 7: Vertical node displacements of a concentrically loaded specimen DIANA results.

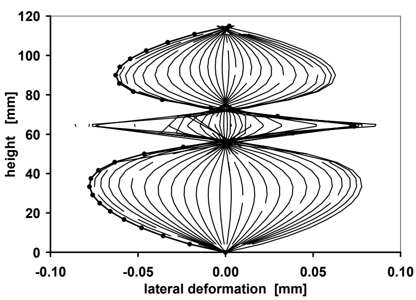


Figure 8: Horizontal node displacements of a concentrically loaded specimen DIANA results. The bricks deform in a barrel ( ) shape.

3.2 Horizontal deformation

In Figure 8 the horizontal displacement of each node was plotted versus the vertical position of the node. The image is almost symmetric around a vertical and a horizontal axis. Deviations are caused by the boundary conditions. The bottom nodes were confined both in vertical and horizontal direction. The top edge was loaded via a steel block, which results are omitted. The bricks expand laterally, the mortar is in compression. The barrel bulging shape of deformation contours in the bricks is the result of the boundary conditions and of the fissures modelled at brick mortar transition (Y = 65 mm).

Lateral stresses, plotted in Figure 9, show that the specimen is in compression in the centre, and that tensile stresses occur, in an area at 15 mm from the vertical edges of the specimen. The stress distribution is ‘rounded’, in contrast with the usually assumed ‘blocked’ stress distribution in the analytical model from Haller [4]. The highest lateral stress (37.5 N/mm^2) occurred in the soft interface layer.

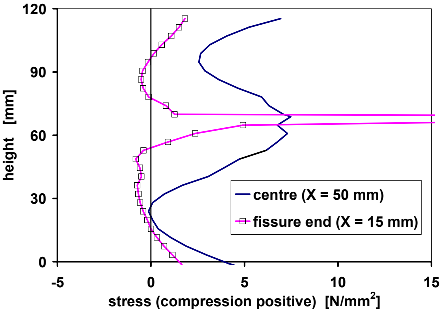


Figure 9: Horizontal stresses of a concentrically loaded specimen, in the centre and at 15 mm from the edge, DIANA results.

4 The ESPI equipment

ESPI is an abbreviation for Electronic Speckle Pattern Interferometry [5]. It is a non-contact, 3-D, displacement measurement system based on optical interference techniques that allows for the observation of deformation of surfaces. The ESPI instrument is presented in Figure 10. This section gives a short description of the employment of the ESPI system. More details are given in [2].

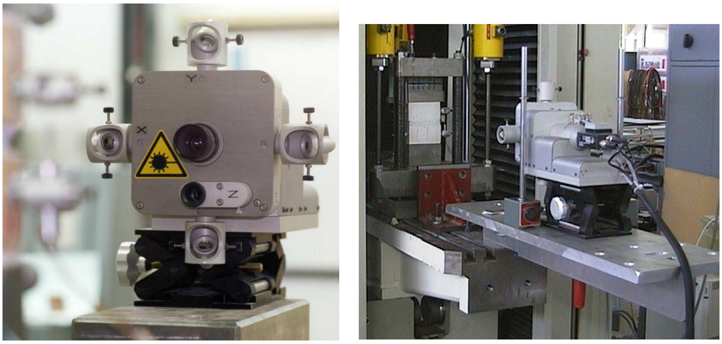


Figure 10: Front and side view of the ESPI apparatus.

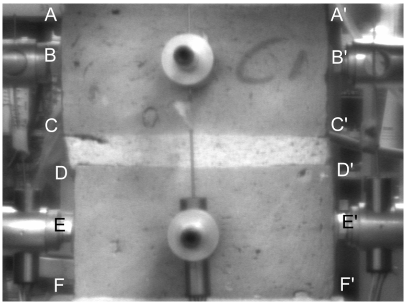


Figure 11: Specimen seen through the digital camera lens.

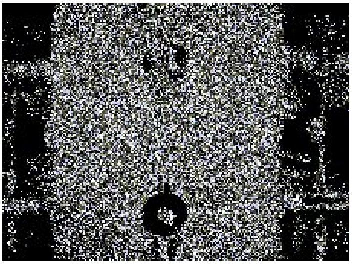


Figure 12: Speckle pattern image.

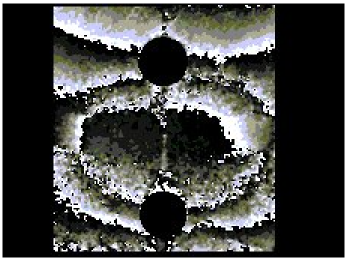


Figure 13: Fringe pattern, made by subtracting two speckle patterns. Masked circles due to the attachment of an LVDT.

The ESPI system is employed in the following steps.

- Take a photograph of the specimen.
- Establish a relationship between the real dimensions of the specimen and the number of pixels in the photograph.
- Illuminate the specimen from two sides with a split laser beam.
- Capture the reflected light with a charge-coupled device (CCD camera).
- Store the speckle pattern, Figure 12, in a computer. Speckle patterns include the reflection information of points of the measured object. During a test, speckle patterns are taken at various load levels. Speckle patterns were taken at a stress of approximately one third of the estimated strength of the specimen (load L1) and at a stress approximately 1 N/mm^2 higher (load L2).
- Subtract speckle pattern images taken at e.g. load L2 and load L1 to form interference fringes, Figure 13. The number of fringes is a measure of the displacements of points on the illuminated area.
- Determine displacements and plot them, Figure 14. By changing the polarity of the laser, displacements in X (horizontal) and Y (vertical) direction were obtained. A resolution of 10 nm was possible.
- If desired, calculate 'strains' from the measured displacements taking into account the load increment at which deformations were obtained.

5 ESPI-results

As an example, the vertical ESPI-displacements of a JW specimen are plotted versus their X position in Figure 14. In this case the deformation differences between brick and mortar are relatively small. The effect of fissures at the edges is visible, indicated by the lines with a larger spacing. At mid height of Figure 14 the lines represent the displacements of points in the joint. Their distance is largest at the edges, from X between 0 and 20 mm and from X between 80 and 100 mm. The lines at the bottom and the top of the figure indicate the brick deformation, which is contrary to the joint.

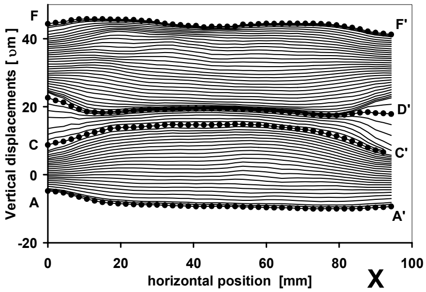


Figure 14: Vertical displacements of points, plotted versus their horizontal position (X). Displacements of brick contours are indicated.

The lines AA’ in Figure 14 are almost straight, lines CC’ and DD’ have a kink. The letters refer to the position of the observed points on the specimen (Figure 11). The distance between the displacement lines is a measure of the strain that occurred. In the centre, the strain is roughly the same for mortar and brick. The prominence of the ‘joint’ varied, depending on the brick mortar combination used.

5.1 Lateral displacements

ESPI was used to measure the horizontal deformation of the specimens in the same way as already discussed regarding vertical deformations. Figure 15 shows an example of the horizontal displacements.

The data were handled in the same manner as the vertical deformations. Now, the horizontal displacements of the grid points were plotted versus the Y-values of these points and the results of points with the same X values were connected with straight lines.

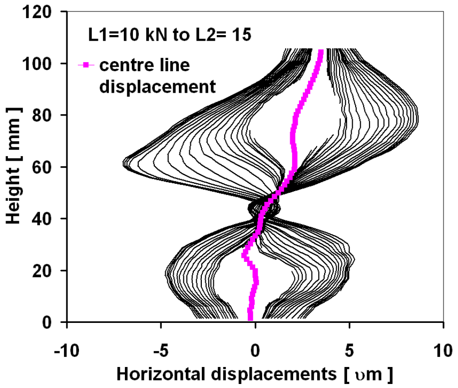


Figure 15: Lateral displacements show a barrel ( ) shape in the bricks.

The displacement lines in Figure 15 indicate that this specimen rotated during the test and kinked at joint height. Still, the similarity with DIANA results in Figure 8 is clear.

6 Discussion

By using the ESPI-technique more information was obtained from the brick–mortar interaction than with traditional LVDT-measurements. In addition, the ESPI-measurements were obtained in a similar format as the FE simulation results, allowing for easy comparison. Both methods result in displacements of a number of points at the surface. Variation of material properties may blur the experimental result while in numerical simulations the properties are uniform.

The advantage of a finite element program like DIANA is that besides strains, stresses can be calculated and the good correlation between strains both from simulation and experiments allowed the use of DIANA to establish stresses.

Both the numerical simulation and the ESPI measurements confirmed that stresses concentrate in the middle of the joint as a result of the fissures at the edges. The B-shaped deformation over height (Figure 16) observed in the experiments is almost identical to the numerical one.

Strain distribution is affected by friction between the specimen and the load platens. Equilibrium over a vertical section, with stresses given in Figure 17, is only possible by means of friction forces at the specimen's edges.

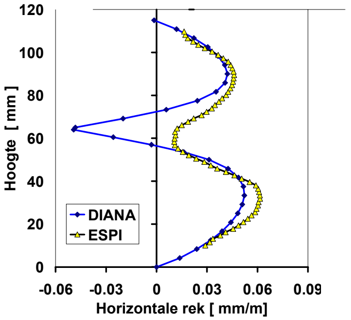


Figure 16: Horizontal strain versus height ESPI and DIANA result.

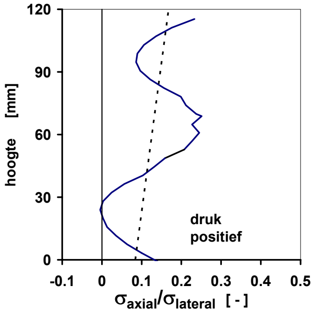


Figure 17: Stresses versus height (DIANA).

Less friction will reduce the lateral stresses, indicated by the dotted line in Figure 17. If the lateral stress distribution does not change, mortar is in compression, bricks are in tension.

The strain distribution showed the effect of fissures in the brick mortar interface.

The load was transferred via the central 60 to 70 mm in the 100 mm wide specimen.

7 Conclusion

- Brick and mortar expand laterally to axial compressive loading.
- Deformations from measurements and simulations correspond and therefore the stress distribution found with numerical simulation was considered reliable.
- Fissures at the edges of the joint affected lateral deformation.
- Results of DIANA and ESPI can be treated in a similar manner: a table with X- and Y-coordinates and "measured" values is available.
- The advantage of DIANA is that stresses can be calculated.
- A disadvantage is that (for practical reasons) properties are uniform over the volume considered, in ESPI the real material is tested.
- ESPI and DIANA proved to be a complementary couple.

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