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Davide Bigoni, Giovanni Noselli

Institutions: University of Trento

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LOCALIZED STRESS PERCOLATION THROUGH DRY MASONRY WALLS. PART I - EXPERIMENTS

DAVIDE BIGONI and **GIOVANNI NOSELLI**

Dipartimento di Ingegneria Meccanica e Strutturale, Università di Trento,
Via Mesiano 77 – 38050 Povo, Trento, Italia[1]

Transmission photoelasticity on scale models is shown to disclose the stress distribution within dry masonry walls. This distribution is found to be complicated by unilateral joints between elements, where 'randomness constrained within a geometrical scheme' of contact points occurs, so that stress percolation results highly localized, evidencing 'unloading islands' in a 'stress stream'. These findings are theoretically explained in Part II of this paper from both micromechanical and continuous modelling perspectives.

Key words: Photoelasticity, masonry, granular materials, localized stress paths

1. Introduction

How does the stress flow round a rose window in a masonry façade of a church? How does the stress rearrange when a new hole is punched in a masonry? What is the complexity of a stress state in the vicinity of a relieving arch of several voussoirs embedded in a masonry? Although masonry is an ancient and extremely successful[2] composite material, these questions still remain for many aspects open. This is due to the fact that, even for simple geometries and far from failure loadings, masonry structures exhibit a mechanical response affected by extreme stiffness contrast between constituents, randomness of contact points between bricks where unilaterality and Coulomb friction dominate. These effects are known to be important in granular materials, which represent typical disordered media. In contrast, masonry is a *regular distribution of elements possessing uniform geometry*[3], so that the contact point distribution is 'orderly random', in the sense that it is randomly distributed within a constraining regular scheme.

The interplay between extreme stiffness contrast and randomness on the one hand and

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[1] *E-mail*: bigoni@ing.unitn.it, giovanni.noselli@ing.unitn.it; *Website*: http://www.ing.unitn.it/~bigoni/

[2] Nacre (mother-of-pearl) is a natural material with unchallenged mechanical properties (Gao et al. 2003) and very similar to masonry (Bertoldi et al., 2008).

[3] The texture is fundamental to determine the 'global' mechanical behaviour of a masonry structure. To highlight this concept with a simple example, we remark that the construction without centering of the Brunelleschi's dome in the Florence Cathedral and the achievement of a minimal safety factor against collapse in this structure would have both been simply impossible without the recourse to a highly sophisticated –and effective– brick disposition (Mainstone, 1970).

regularity of the fabric on the other, yields stress distributions within masonry walls that may present localized stress paths, evidencing stress concentrations and stress relieves (for instance, the so-called ‘arching effect’). Surprisingly, transmission photoelasticity –successfully employed for granular materials[4]– has never been applied to the analysis of the stress state in a masonry wall, so that the only experimental setting resembling a stone block construction (rather than a granular assemblage or a masonry) has been investigated by Da Silva and Rajchenbach (2000).

We consider for the first time in the present article the so-called ‘stretcher-bond fabric’ (in the masonry nomenclature), reproduced without mortar[5] and with different spacing between the vertical joints, where transmission of a vertical compressive force (applied on a small area) is analyzed. Results reveal that the contact points are practically always located at the brick corners, but with a random distribution so that a highly localized, tree-like stress percolation results, showing ‘unloading islands’ separated by ‘stress streams’. The ‘streams’ are shown to broaden when load is increased, as a result of the fact that contact ‘points’ between bricks evolve into contact ‘areas’.[6] Moreover, different stress percolations occur in ‘nominally identical’ masonries, due to the different contact distributions.

Two alternatives are proposed (in part II of this article) to *fully explain* experiments, namely, (i.) the micromechanical model –where the masonry is treated as an elastic structure with unilateral ‘orderly random’ contacts, to generate a form of random cascade of vertical forces, where ‘random coalescence’ may occur in addition to the usual rule of random branching– and (ii.) the continuum model –where the masonry behaves as a strongly orthotropic material close to the elliptic border and reveals stress localization following concepts proposed by Bigoni and Capuani (2002; 2005).

Although simple structural models are addressed in this article, the proposed experimental technique and mechanical constitutive description can be applied to brick or stone masonry, as well as to megalithic constructions, and easily extended to analyze: (i.) different *homogeneous* or

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[4] The idea of employing photoelasticity to investigate the stress distribution within granular materials goes back to Drescher and de Josseling de Jong (1972). A reference interesting to our purposes is Zhu *et al.* (1996), where results are referred to elliptical particles, which are more similar to a brick masonry than the circular or pentagonal disks used for instance by Geng *et al*. (2001; 2003).

[5] An attempt to simulate mortar is presented in Appendix A2.

[6] The fact that the contact between bricks is localized at random points is perfectly known in the building practice, where mortar is introduced with the main purpose of distributing loading. Although less evident, this function of mortar is important also for megalithic block constructions, where mortar facilitates masonry setting, but also prevents cracking of stone blocks (see the example reported by Clarke and Engelbach (1930) referred to the casing-blocks of the Great Pyramid at Giza). We have tried to simulate mortar layers in our experiments by adding 0.5 mm thick paper slices between bricks. The resulting stress percolation patterns still remain highly localized (see

composite masonry textures;[7] (ii.) structural masonry elements (for instance, an arch opening in a masonry); (iii.) effectiveness of restoration design (for instance, a structural rehabilitation through reinforcement with FRP).

2. Experimental

Three different photoelastic materials produced in sheets have been employed, namely, an extruded PC (Lexan®), a PSM-9 (purchased from Vishay®), and a PMMA (Plexiglas®) to manufacture 187 miniaturized 20 mm × 10 mm × 6 mm bricks (some of these have different dimensions, namely 30 mm × 10 mm × 6 mm, to complete the rectangular geometry employed in the experiments). The miniaturized bricks have been ordered into two types of stretcher-bond fabric masonries, one with nominally null and another with thick (8 mm) vertical joints.

The PMMA and PC bricks have been cut with a AKE Cutting & Better® circular saw blade HM-KS 200×2.2×30 Z80, while the PSM-9 with a Dremel® moto-scroller saw blade 16440. To enhance optical properties, all bricks have been hand polished employing sand-paper P120.

The masonries have been positioned between two glasses to prevent possible out-of-plane displacements, but a 1 mm gap has been left between the model and the glasses, to avoid diffused contact (in fact the masonry samples have in some cases 'touched' the glasses at a few points only, so that masonry/glass friction has not been involved).

Temperature near the samples, monitored with a thermocouple connected to a Xplorer GLX Pasco®, has been found to lie around 22 °C, without sensible oscillations during experiments. Loading has been prescribed by providing a vertical fixed 2 mm/min velocity of displacement (corresponding to a 'global' conventional 1% per minute velocity of deformation) to a steel tool similar to the edge of a screwdriver. The vertical displacement has been imposed using a ELE Tritest 50 machine (ELE International Ltd) on which a linear and a circular (with quarter-wave retarders for 560 nm) polariscope (equipped with a white and Sodium vapor lightbox purchased from Tiedemann & Betz) has been installed, which has been designed by us and manufactured at the University of Trento (a description of photoelasticty and related experimental techniques can be found for example in Coker and Filon, 1957 and Frocht, 1965) .

Photos have been taken with a Nikon® D200 digital camera, equipped with a AF-S micro

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Appendix A.2).

[7] With reference to the ancient Roman architecture, examples of homogeneous textures, different from those analyzed in the present article, are the so-called 'opus reticulatum', or 'opus spicatum', while 'opus mixtum' denotes an example of composite texture (Alberti, 1452).

Nikkor (105 mm 1:2.8G ED) lens and with a AF-S micro Nikkor (70-180 mm 1:4.5-5.6 D) lens for details. Vertical displacements and vertical forces have been recorded during all tests employing a PY2-F-25 vertical displacement transducer (purchased from Gefran spa), a TH-KN1D loading cell (also purchased from Gefran spa), and a Datascan 7320 data acquisition system (Measurement System Ltd).

Typical results obtained with a linear transmission polariscope on PSM-9 material are shown in Figs. 1 and 2, obtained with polarizer axes inclined at 45° with respect to the vertical, using white and Sodium vapor lamps. The figures refer to low (125 N for Fig. 1) and high (250N for Fig. 2) loading. Figs. 1 and 2 pertain to a masonry with null space forming the vertical joints (see Appendix A for further experimental results [8]).

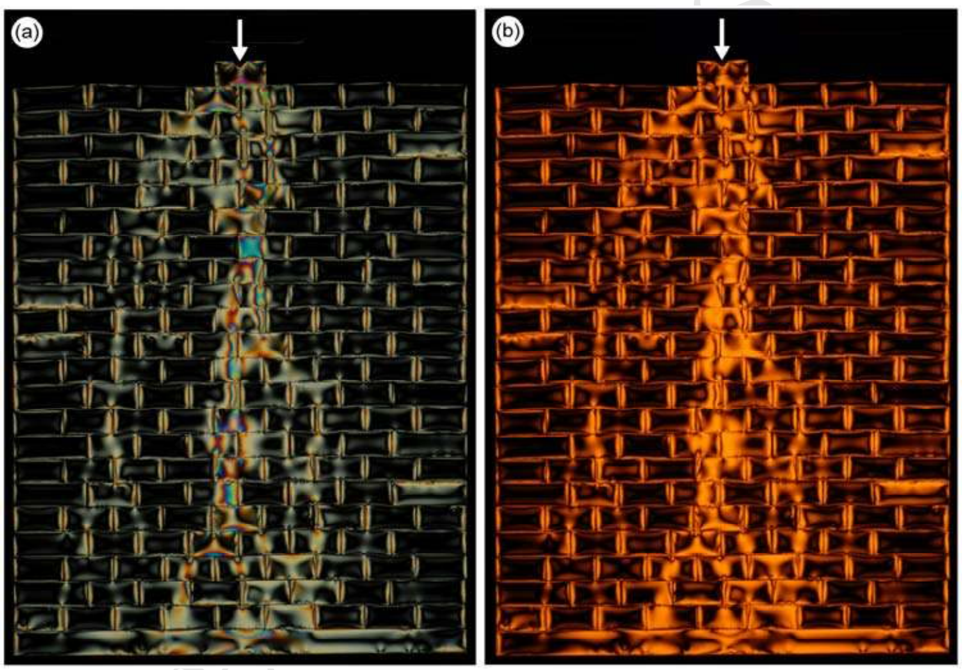

Fig. 1 – Photoelastic fringes of a model of dry masonry with thin vertical joints detected with a linear transmission polariscope (axes at 45° with respect to the vertical) at white light (a) and sodium vapor lamp (λ = 589.3 nm) (b). Low vertical applied load (125 N), denoted with a white arrow.

Thick joints are investigated in Fig. 3 obtained with a circular polariscope at low (200 N for Fig. 3a) and high (800 N for Fig. 3b) load, employing white light. The joints are 8 mm thick.

[8] A movie of an experiment and other information can be downloaded from: http://www.ing.unitn.it/dims/.

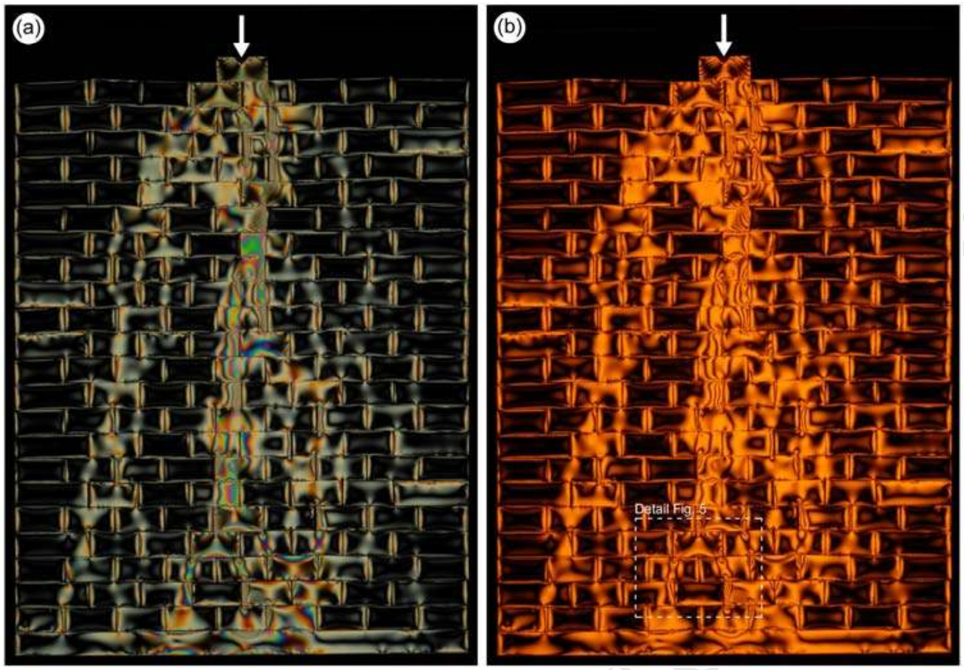

Fig. 2 – Photoelastic fringes of a model of dry masonry with thin vertical joints detected with a linear transmission polariscope (axes at 45° with respect to the vertical) at white light (a) and sodium vapor lamp (l = 589.3 nm) (b). High vertical applied load (250 N), denoted with a white arrow.

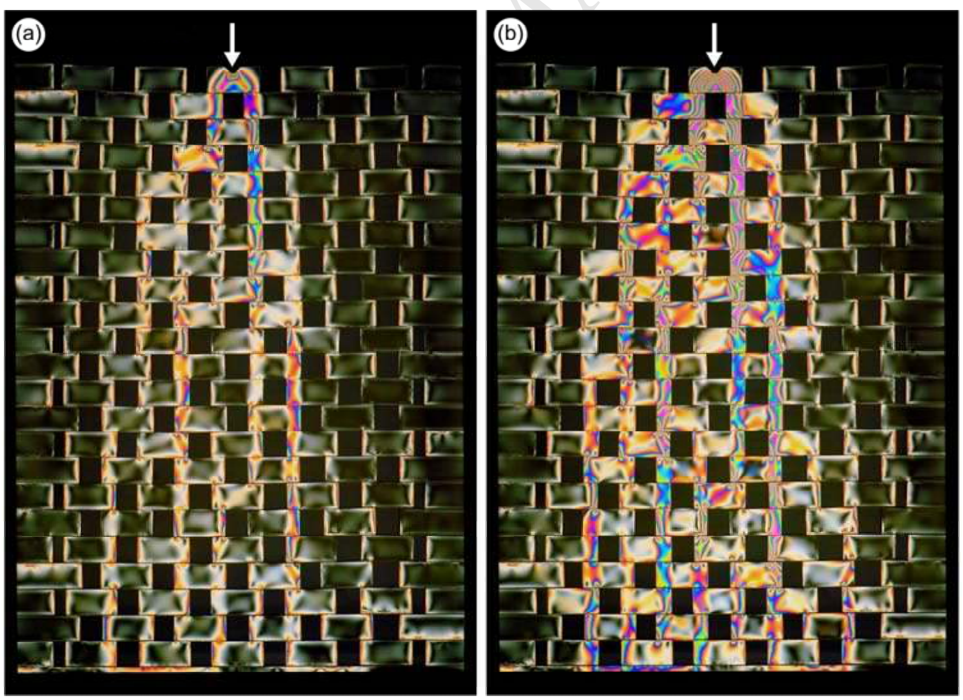

Fig. 3 – Photoelastic fringes of a model of dry masonry with thick vertical joints detected with a circular transmission polariscope at white light (the white arrow denotes the applied load). (a) low vertical load (200 N); (b) high vertical load (400 N).

Details (referred to a masonry different from those reported in Figs. 1 and 2) are reported in Fig. 4, together with the load displacement curve recorded at the top of the sample. These have been taken at red monochromatic light, employing the linear polariscope with a monochromator filter (wavelength 680 nm) and the analyzer inclined at 45°. The details reported in Fig. 4 allow investigation of contact areas and forces. Note that the nonlinearity of the load-displacement curve agrees with the fact that contact areas increase during loading, consistently with results from contact mechanics (Johnson, 1985). In particular, Hertz's theory prescribes that the total load compressing two elastic spheres is proportional to the mutual approach of the centres elevated to the power 3/2, the law which has been plotted in Fig. 3e with a proportionality coefficient taken to fit our data.

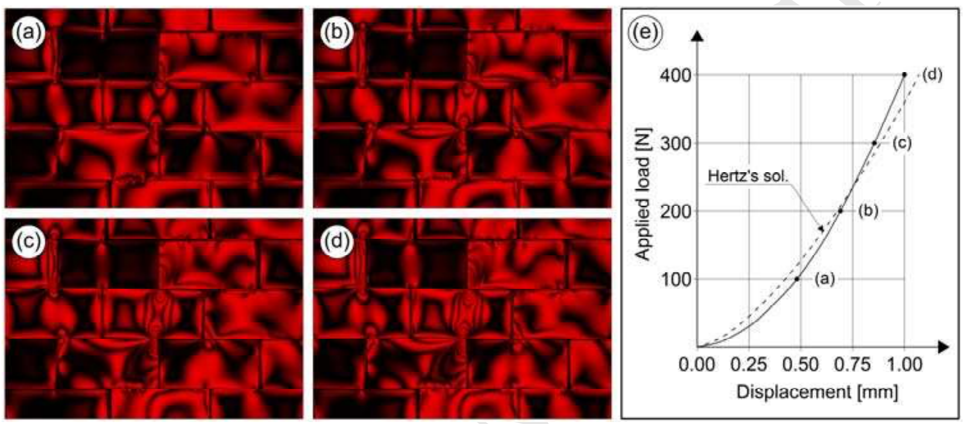

Fig. 4 – Photoelastic fringes of a model of dry masonry detected with a linear transmission polariscope at red light. (a) photo taken at 100 N of vertical load; (b) photo taken at 200 N of vertical load; (c) photo taken at 300 N of vertical load; (d) photo taken at 400 N of vertical load. Note the typical Hertzian contact fringes in the brick roughly at the centre of the photos. (e) load displacement curve, resulting nonlinear due to the broadening of contact areas between bricks, in full agreement with results referred to contact mechanics (Johnson, 1985).

An analysis of contacts between bricks with a quantification of the load transmitted between them is provided in part II of this article (see Fig. 2 in part II). A detailed investigation of a particular of Fig. 2b is reported in Fig. 5a, contrasted with a linear elastic finite element simulation of isochromatics under the plane stress assumption (reported in Fig. 5b and obtained using ABAQUS-Standard, Ver. 6.7-1, Hibbitt, Karlsson & Sorensen Inc., employing 4-nodes bilinear elements CPS4). The simulation (black contours reported on 'white' bricks) provides the difference between in-plane principal stresses, corresponding to the isochromatics. In the simulation, bricks have been separately analyzed, subjected to reciprocal contact forces taken in a way that equilibrium is satisfied. It can be noted that the experiment is nicely reproduced, so that the conclusion that the stress transmission within a masonry is dominated by contact between bricks remains fully confirmed. Note also that when the force is applied at the middle of the brick the stress state is very similar to that obtained from the elastic solution of a circular disk loaded by two opposite forces, a consideration that will be used to quantify the force percolation in the masonry in Part II of this article (see Fig. 2 of Part II).

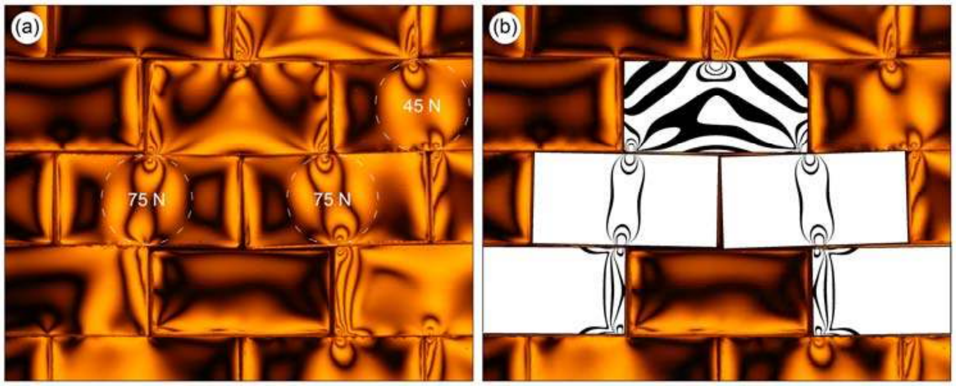

Fig. 5 – (a) Detail of Fig. 2b compared to (b) a linear elastic f.e. simulation of isochromatics in plane stress (black contours within white bricks denote calculated in-plane principal stress difference).

The analysis of the photos reported in Figs. 1-4 and the simulation reported in Fig. 5 reveals the following features:

i.) localized contacts at random positions (but constrained to lie near the vertices, therefore within the 'rigid' masonry geometry) between bricks;

ii.) existence of low friction at these contacts;

iii.) the stress distribution:

  a.) is *localized* and elongated in the vertical direction;

  b.) is organized as in a percolation tree;

  c.) evidences unloading zones;

iv.) due to the fact that randomness is constrained, the stress percolations do not qualitatively differ much from each other. However, our results demonstrate that 'nominally identical' masonry structures can be subjected to different stress states under the same loads. [9]

The fact that the stress percolation is highly localized explains the known difficulty in detecting the stress state of masonry structures using the so-called 'flat-jack' test.[10] Our results indicate that a sort of 'indeterminacy principle' could affect this test, since –first– the location of the stress 'streams' is not known and –second– the cut in the masonry (which is preliminary required to the introduction of the flat-jack) alters the contact points and therefore the stress distribution.

[9] Different stress percolation patterns are recorded in the same masonry, when the brick distribution is changed, see Appendix A – Additional experimental results.

[10] For a definition of the flat-jack test, see ASTM Standard: 'In-situ compressive stress within solid unit masonry estimated using flat-jack measurements' C 1196-91, 1991.

3. Interpretation of experimental results

There are two ways to successfully explain the obtained experimental results: one is the micromechanical approach, in which the masonry is modelled as a discrete structure, where bricks are randomly in contact at their vertices; another is the continuum mechanics approach, in which the material is modelled as a continuous homogeneous material, characterized by an extreme orthotropy, so that the material response is close to an instability threshold. Both approaches are deferred to part II of this article.

4. Conclusions

Scale models represent a new tool for investigating the localized and non-unique internal stress distribution induced by external loads within a dry masonry, allowing the reproduction of the *exact texture* of a masonry, crucial in the understanding of the global structural behaviour.
The experimental technique evidences the behaviour of a material on the verge of material instability, where the perturbative approach proposed by Bigoni and Capuani (2002; 2005) reveals its effectiveness, as it is shown in Part II of this paper.

Acknowledgements

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Appendix A. Additional experimental results

A.1. Dry masonry models

Experimental results, additional to those presented in Figs. 1-4, are shown in Figs. 6-8, referred to the PSM-9 material (Fig. 6), to the Lexan material (Fig. 7), and to the PMMA material (Fig. 8). The photos have been taken with a linear transmission polariscope at white light with analyzer inclined at 45°. The vertical loads have been taken equal to 400 N and 800 N for the parts (a) and (b), respectively, of Figs. 6 and 7, relative to the PSM-9 and the Lexan material. The photos in Fig. 8 , relative to the PMMA material, have been taken at a vertical load of 1000 N for part (a) and 2500 N for part (b). Details of results reported in Fig. 6 evidencing near-vertex contact points and low friction and additional to those reported in Fig. 3 are reported in Fig. 9.

The details reported in Fig. 9 allow investigation of contact areas and forces, see for example the second brick from left in the third course from the top. Here the typical Hertz (see Johnson, 1985) fringe pattern is clearly visible.

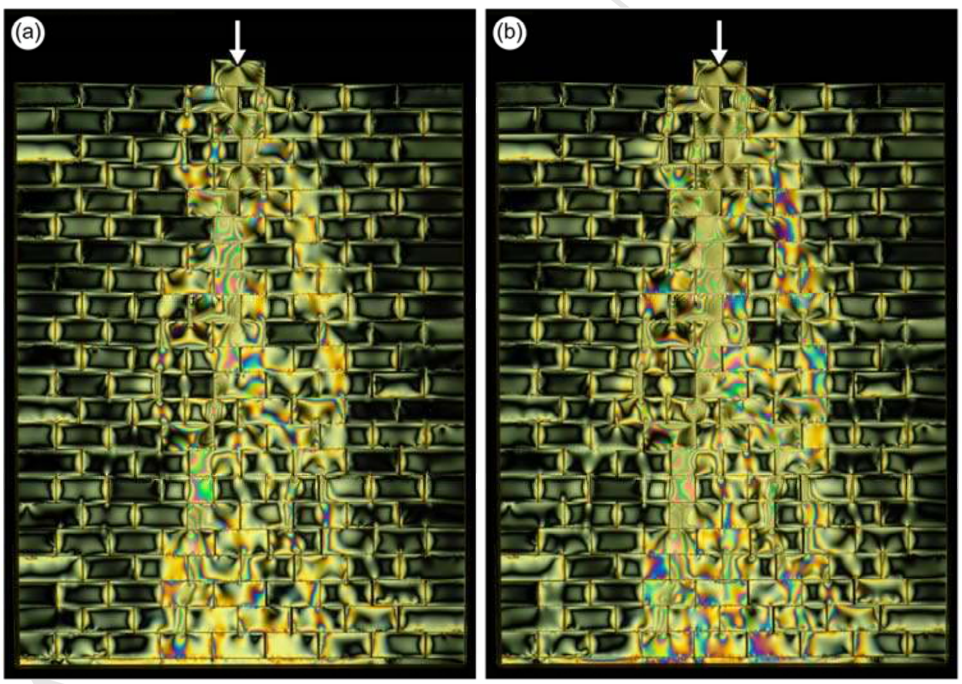

Fig. 6 – Photoelastic fringes of a model of dry masonry detected with a linear transmission polariscope at white light with analyzer inclined at 45°. Material used is PSM-9 (the white arrow denote the applied vertical load). (a) low vertical load (400 N); (b) high vertical load (800 N).

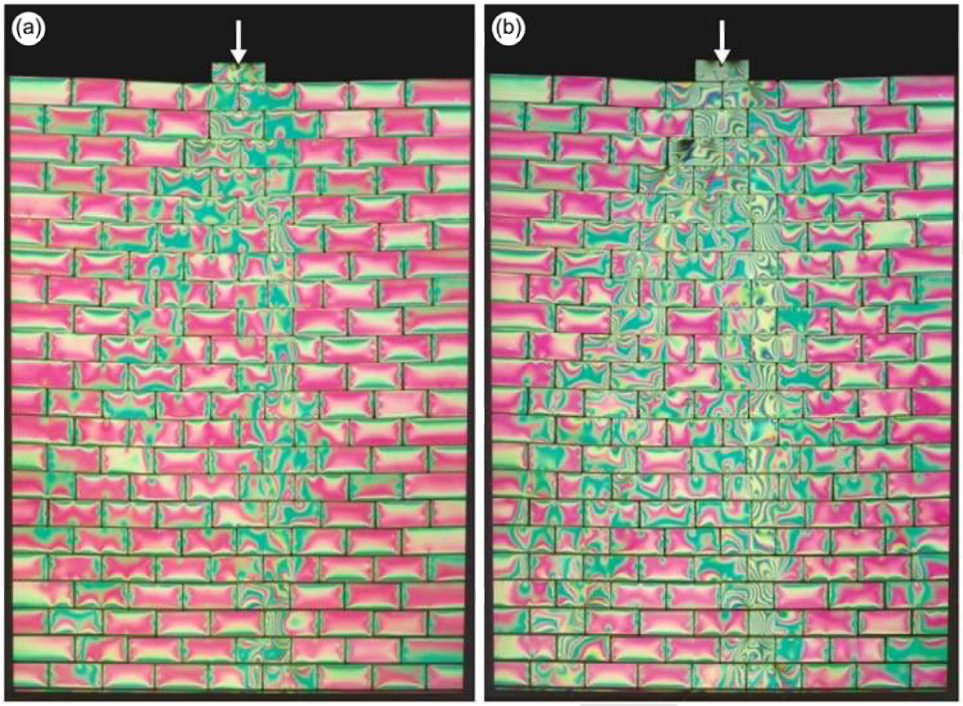

Fig. 7 – Photoelastic fringes of a model of dry masonry detected with a linear transmission polariscope at white light with analyzer inclined at 45°. Material used is Lexan® (the white arrow denote the applied vertical load). (a) low vertical load (400 N); (b) high vertical load (800 N).

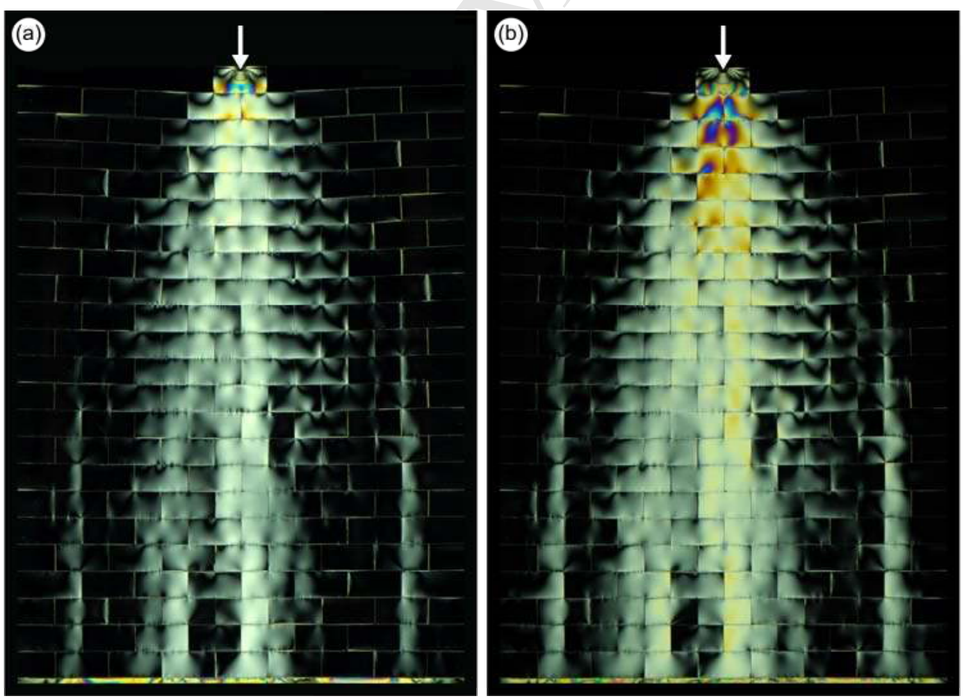

Fig. 8 – Photoelastic fringes of a model of dry masonry detected with a linear transmission polariscope at white light with analyzer inclined at 45°. Material used is PMMA (the white arrow denote the applied vertical load). (a) low vertical load (1000 N); (b) high vertical load (2500 N).

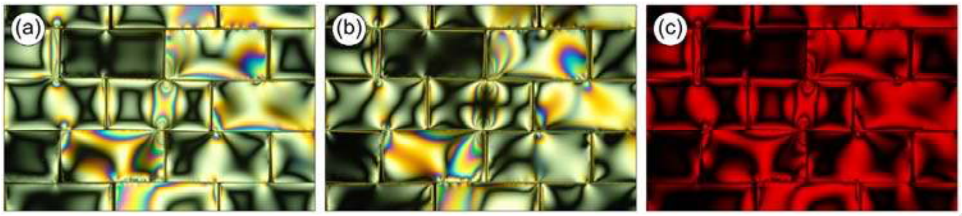

Fig. 9 – Photoelastic fringes of a model of dry masonry with thin vertical joints detected with a linear transmission polariscope at 200 N of vertical load. (a) white light with analyzer inclined at 45°; (b) white light with analyzer inclined at 9° with respect to the vertical axis; (c) red light with analyzer inclined at 45°. The isoclines are visible from which low friction and near vertex contact points can be detected.

A.2. An attempt to simulate the effects of mortar

In an attempt to simulate the effects of mortar, 0.5 mm thick paper layers have been introduced between brick courses, while the vertical joints between bricks have been kept dry. Results obtained with a circular polariscope are reported in Fig. 10, where a comparison is made with the same masonry (with exactly the same brick distribution) at the same vertical load.

It is clear from Fig. 10 that *the 'mortar' courses mitigate the stress intensity, but the stress localization results even more pronounced in the case where mortar is simulated using paper layers (Fig. 10b), than for dry masonry (Fig. 10a).*

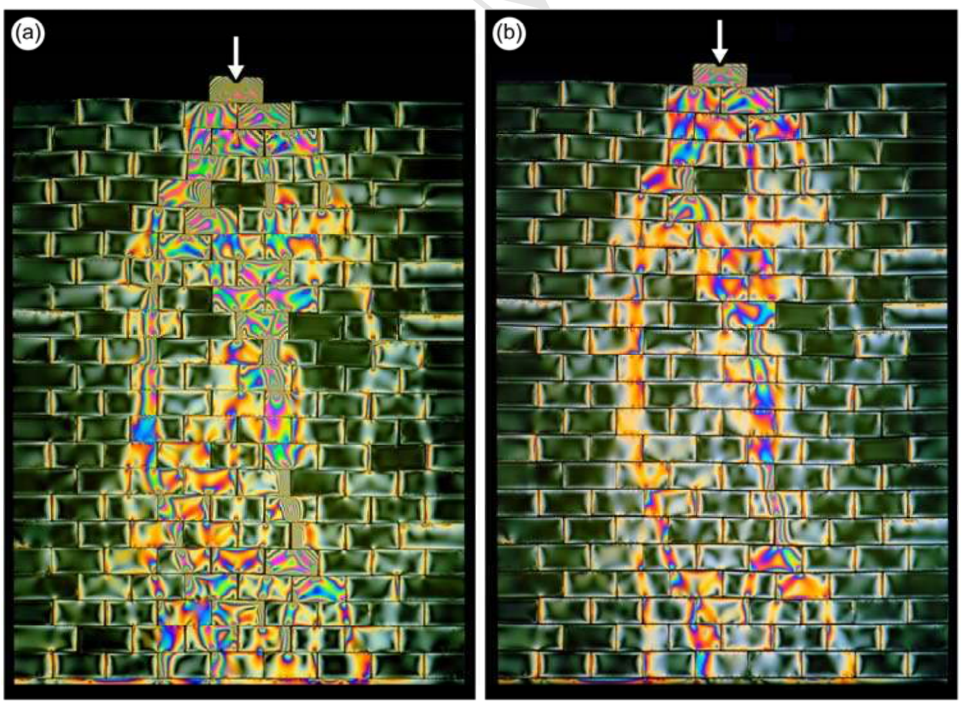

Fig. 10 – Photoelastic fringes of a model of dry masonry detected with a circular transmission polariscope at white light and at 400 N of vertical load. Material used is PSM-9 (the white arrow denote the applied vertical load). (a) dry masonry; (b) mortar courses are simulated with paper layers. Part (b) shows that the intensity of transmitted forces is lower than in part (a), but localization of 'stress streams' appears even greater where mortar is simulated.

References

Alberti, L.B. (1452) *De re aedificatoria*. Facsimile ed. H-K. Luecke (Munich, 1975). For translations, see J. Leoni The architecture of Leon Battista Alberti in Ten Books (London, 1755) and J. Rykwert, N. Leach and R. Tavernor (Cambridge, Mass., 1988).

Bertoldi, K., Bigoni, D. and Drugan, W.J. (2008) Nacre: an orthotropic and bimodular elastic material. *Composites Sci. Tech.*, 68, 1363-1375.

Bigoni, D. and Capuani, D. (2002) Green's function for incremental nonlinear elasticity: shear bands and boundary integral formulation. *J. Mech. Physics Solids* 50, 471-500.

Bigoni, D. and Capuani, D. (2005) Time-harmonic Green's function and boundary integral formulation for incremental nonlinear elasticity: dynamics of wave patterns and shear bands. *J. Mech. Physics Solids* 53, 1163-1187.

Clarke, S. and Engelbach, R. (1930) *Ancient Egyptian masonry: the building craft*. Oxford University Press.

Coker, E.G. and Filon, L.N.G. *A treatise on photo-elasticity*. Cambridge University Press.

Da Silva, M. and Rajchenbach, J. (2000) Stress transmission through a model system of cohesionless elastic grains. *Nature* 406, 708-710.

Drescher, A. and de Josseiling de Jong, G. (1972) Photoelastic verification of a mechanical model for the flow of a granular material. *J. Mech. Phys. Solids* 20, 337-351.

Frocht, M.M. (1965) *Photoelasticity*. J. Wiley and Sons, London.

Gao, H.J., Ji, B.H., Jager, I.L., Arzt, E. and Fratzl, P. (2003) Materials become insensitive to flaws at nanoscale: Lessons from nature. *Proc. Nat. Acad. Sci. United States America*, 100, 5597-5600.

Geng, J., Howell, D., Longhi, E., Behringer, R.P., Reydellet, G., Vanel, L, Clément, E. and Luding, S. (2001) Footprints in sand: the response of a granular material to local perturbations. *Phys. Rev. Letters* 87, 035506.

Geng, J., Reydellet, G., Clément, E. and Behringer, R.P. (2003) Green’s function measurements of force transmission in 2D granular materials. *Physica D* 182274-303.

Johnson, K.L. (1985) *Contact Mechanics*. Cambridge University Press.

Mainstone, R.J. (1970) Brunelleschi’s dome of S. Maria del Fiore and some related structures. *Trans. Newcomen Soc.* 107-126.

Zhu, Y., Shukla, A. and Sadd, M.H. (1996) The effect of microstructural fabric on dynamic load transfer in two dimensional assemblies of elliptical particles. *J. Mech. Phys. Solids* 44, 1283-1303.