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EXPERIMENTAL TESTS AND THEORETICAL ISSUES FOR THE IDENTIFICATION OF EXISTING BRICKWORK

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Abstract

The assessment of masonry structures ask some mechanical parameter to be defined, at least the compressive strength. Several theoretical approaches have been developed but their application to existing masonry seems to be unsatisfactory. Therefore, experimental approaches give a fundamental contribution to the identification of the parameters provided that proper calibration allows a reliable estimation of the experimental error. In this paper, the calibration of compressive tests on large diameter cylinders, drilled from brickwork and loaded on the lateral surfaces, is discussed on the bases of both experimental and theoretical issues. The technique reproduces the brickwork collapse mechanism and gives reliable estimates of the brickwork compressive strength.

Introduction

A large number of old masonry structures, such as arch bridges, tunnels, historical and ordinary buildings, are still in service for which the assessment of the safety level with respect to modern standards is a primary need. Whatever the mechanical model for the structure and the material constitutive model, assessment procedures require some mechanical parameter to be defined, at least the compressive strength f_c, sometimes the elastic parameters (E and ν) and others for more detailed models. The available experimental and theoretical approaches present advantages and uncertainties and the estimate of the global error, and therefore of the reliability of the analysis, remains quite difficult.

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The experimental approach to existing masonry relies on Non Destructive Tests (NDT) and Moderately Destructive Tests (MDT), facing some conceptual deficiency for some technique, a limited data base for the test calibration and large errors due to specific technical problems for other techniques. Small diameter (70-90 mm) drillings and flat jacks (ASTM 1991) are typical examples. Other NDT approaches proposed, such as radar and sonic testing (Colla 1998, Bensalem 1998 among others) due to the high intrinsic inhomogeneity of masonry, still need a detailed calibration and do not seem to be capable to provide quantitative estimates of the brickwork mechanical parameters.

Deformation and failure theories, on the other hand, have been developed since the late sixties with the aim of defining constitutive models and failure criteria based on the mechanical properties of bricks and mortar (Hilsdorf 1969, Francis 1971, Khoo 1973, Atkinson 1983, Shrive 1983, Biolzi 1988). The basic assumption looks at masonry as an unlimited layered continuum in plane strain conditions, thus assuming uniform stress distributions in the materials; due to the elastic mismatch between bricks and mortar, brickwork collapse is attained when a tensile limit condition is met in the brick. Unluckily, these approaches do not give satisfactory estimates of the experimental data, neither of the measured compressive strength nor of the elastic modulus.

In this work an experimental procedure for solid clay brickwork, i.e. compressive tests on large diameter cylinders (ϕ = 150 mm) loaded on the lateral surface proposed by UIC (UIC 1995), is discussed and calibrated. The advantages of this technique are: *i*) the brickwork bond is represented in the specimen; *ii*) the load direction is the same as in the actual brickwork. The calibration of the test shows that: *i*) the collapse mechanism of the specimen is similar to the collapse mechanism of brickwork; *ii*) the effect of local concentrations of stresses, due to the testing setup, on the measured compressive strength seems to be of minor importance; *iii*) a calibrated formula for the compressive strength (and elastic modulus) to be used for practical applications and an estimate of the inherent error can be deduced.

Testing procedures

The UIC 778-3R guidelines (UIC 1995) require a ϕ= 150 mm diameter cylinder to be drilled including the basic brickwork bond, Figure 1. The specimen is loaded on the lateral surface, i.e. in the same way as in the original structure, recording both the vertical and horizontal displacements. The compressive strength f_c of brickwork is simply assumed as the ratio between the collapse load F_{coll} and the horizontal cross section $\phi\, l$, Figure 2, being l the cylinder length; the characteristic value of the compressive strength f_{ck} is given as 1.1 times the minimum value of the collapse load $(F_{coll})_{min}$. The elastic modulus is calculated referring to a reduced section $0.75\phi l$ and to loads at 1/10th ($F^{0.1}$) and 1/2 ($F^{0.5}$) of the limit load:

$$f_c = F_{coll} / \phi\, l, \qquad f_{ck} = 1.1\, (F_{coll})_{min} / \phi\, l \qquad \textbf{[1.a, b]}$$

$$\varepsilon_h = u_h / \phi, \qquad \varepsilon_v = u_v / \phi \qquad \textbf{[2.a, b]}$$

$$\Delta\varepsilon_h^{0.1\text{-}0.5} = (u_h^{0.5} - u_h^{0.1}) / \phi, \qquad \Delta\varepsilon_v^{0.1\text{-}0.5} = (u_v^{0.5} - u_v^{0.1}) / \phi \qquad \textbf{[3.a, b]}$$

$$E = 4(F^{0.5} - F^{0.1}) / 3(u_v^{0.5} - u_v^{0.1})l, \qquad \nu = (u_h^{0.5} - u_h^{0.1}) / (u_v^{0.5} - u_v^{0.1}) \qquad \textbf{[4.a, b]}$$

being ε_v and ε_h the vertical and horizontal strains and u_v and u_h the related displacements.

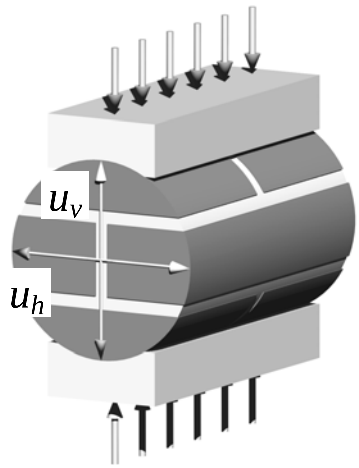

Figure 1. Test arrangement

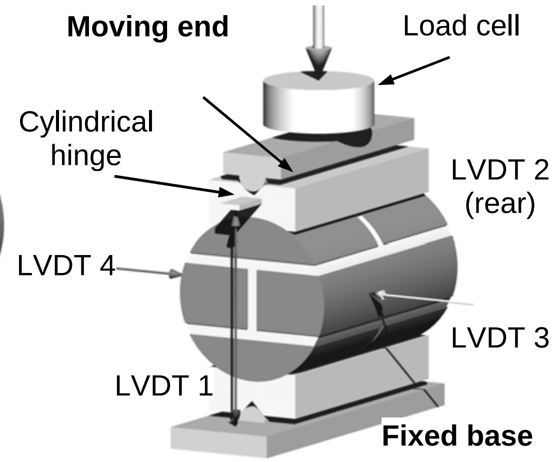

Figure 2. Details

The testing setup is presented in Figure 2; minor details are omitted for simplicity (Brencich 2004). The load measuring device is a C5 class *HBM-RTN* load cell with a 0.01% precision in-between the upper plate and the testing machine. The upper and lower plates are connected to a stiff frame with cylindrical hinges that allow the load line to be identified. Displacements are measured by means of LVDTs with a 0.001mm precision; the displacement of the upper plate is measured at the two ends of the specimen (LVDTs n. 1 and 2); lateral ones are recorded at the centre of the cylinder (LVDTs n. 3 and 4), so that u_v, eq. (2) and (3), is directly the sum of devices 3 and 4.

The moving end of the machine, and the whole load process, is displacement controlled, the load being measured by the load cell. A 2 mm thick lead sheet between the specimen and the loading plates was used to smooth the lateral surface of the cylinder.

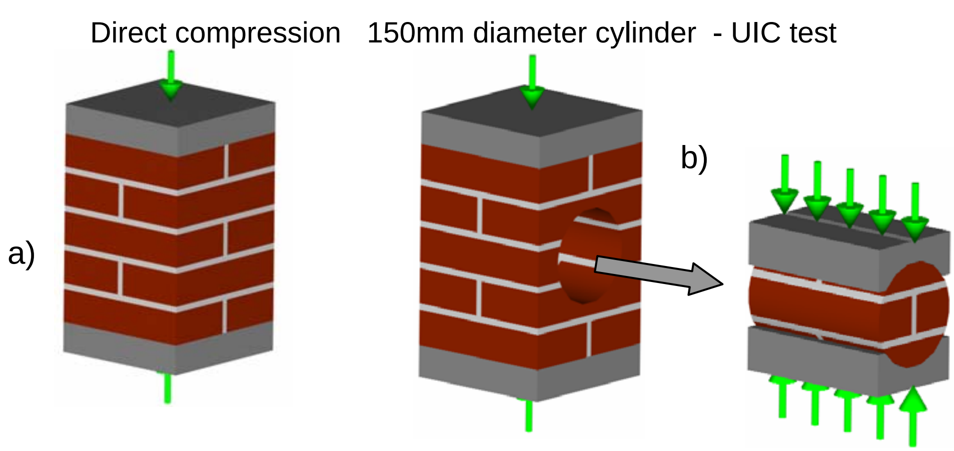

Figure 3. Identical specimens for: a) direct concentric compression; b) UIC (1995) tests.

The calibration of the test is performed comparing the test data with the compressive strength of the brickwork, obtained through concentric load tests on prisms of the same masonry; specimens have been produced in couples, one for drilling the cylinder and the other for direct testing, Figure 3. Tests are compared two-by-two.

Table 1: Bricks and mortars properties		Av. value [N/mm^2]	n. of samples	C.o.V.	Char. Value[1] [N/mm^2]	Char. / Average
Brick 1*	Compressive strength – direct	20.2	20	17%	13.6	0.67
	Tensile strength – TPB	5.0	10	6.5%	4.30	0.86
	Elastic modulus	15930	20	32%	5930	0.38
Brick 2$^+$	Compressive strength – direct	32.5	12	17%	26.0	0.80
	Tensile strength – TPB	0.8	6	10%	0.7	0.84
	Elastic modulus	26200	12	30%	13070	0.50
Mortar 1*	Compressive strength – direct	11.9	25	3%	11.5	0.97
	Tensile strength – TPB	3.8	13	8%	3.5	0.92
	Elastic modulus	1520	25	3%	2440	0.97
Mortar 2*	Compressive strength – direct	8.9	32	5%	8.5	0.96
	Tensile strength – TPB	3.3	16	4%	3.2	0.97
	Elastic modulus	1300	32	17%	1080	0.83
Mortar 3$^+$	Compressive strength – direct	<6.9>	13	10.6%	5.7	0.83
	Tensile strength – TPB	<1.4>	6	6.4%	1.25	0.89
	Elastic modulus	<5.635>	4	3.6%	5.298	0.94
* Genoa	$^+$Palermo	[1] Gaussian distribution assumed				

Three types of solid clay brickwork have been used:

i) BRICKWORK 1: Brick 1+Mortar 1;

ii) BRICKWORK 2: Brick 1+Mortar 2;

iii) BRICKWORK 3: Brick 2+Mortar 3.

Table 1 shows the data for the materials deduced according to (prEN771-1 1999, prEN 772-1 1999, prEN 1052-1 1998). Mortar 1 (cement-lime) and Mortar 2 (white cement – lime) are com-mercial Italian products for which the producer did not provide the exact proportions, while Mortar 3 is a 1:1:5 mortar with water/ /cement volume ratio = 0.7.

Test results

Figures 4 to 7 show the stress-strain curves and the collapse mechanisms of the specimens; Table 2 provides the experimental data (Prism 3 for BRICKWORK 1 and Cylinder 3 for BRICKWORK 3 are missing because of technical problems during the tests). Stresses are calculated as suggested by UIC, i.e. dividing the peak load by the horizontal section ϕl, eq.s (1-4).

The response of prisms and cylinders shows that: *i*) the peak load and the (elastic) initial stiffness are different but the ratio between the cylindrical tests and the prism data seem to be quite constant, Table 2; *ii*) the elastic (initial) stiffness seems to be different but with a constant ratio; *iii*) the post peak response is quite similar for prisms and cylinders; *iv*) cylinders exhibit a longer softening phase as a consequence of the confining effect of the loading plates.

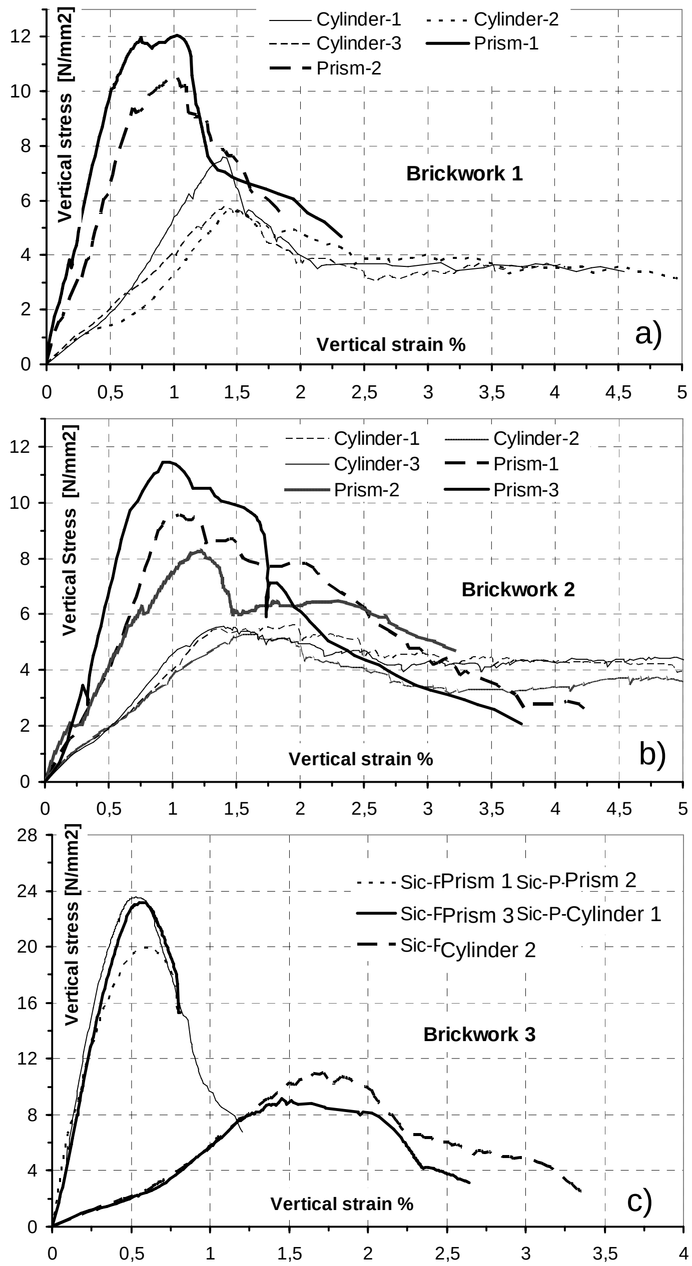

Figure 4. Stress-strain curves for brickwork.

Figures 5 and 7 show that the collapse mechanism of Brickworks 1 and 2 is quite the same for prisms and cylinders; when (Brickwork 3) high strength bricks (engineering bricks) are used, Figure 3, the cylinder collapse mechanism is different from that of the prisms: the brick/mortar interface collapses and the lateral parts of the cylinder detach from the specimen before cracking is activated in the central joint, while this does not happen in the prisms of the same masonry, i.e. the cylinders seem to collapse because of the stress concentration induced by the loading plates. The latter conclusion needs a wider data base to rely on before general conclusions are derived.

The tests show similar post-peak descending branches for prisms and cylinders and significant inelastic strains, more pronounced for cylinders due to the confining effect of the loading plates. Figure 5.a shows the typical collapse mechanism at approx. 80% of the peak load when the central vertical mortar joint cracks along its whole length showing that inelastic strains have been developed; Figure 5.b shows the specimen at collapse; Figures 5.c-5.e show the final stage: i) a crack is found in the vertical joint, at the mortar/brick interface or inside the joint; ii) the lateral parts of the specimen are detached, due to the ends of the loading plates, Figure 5.b. Figures 6 show a different mechanism for type 3 brickwork.

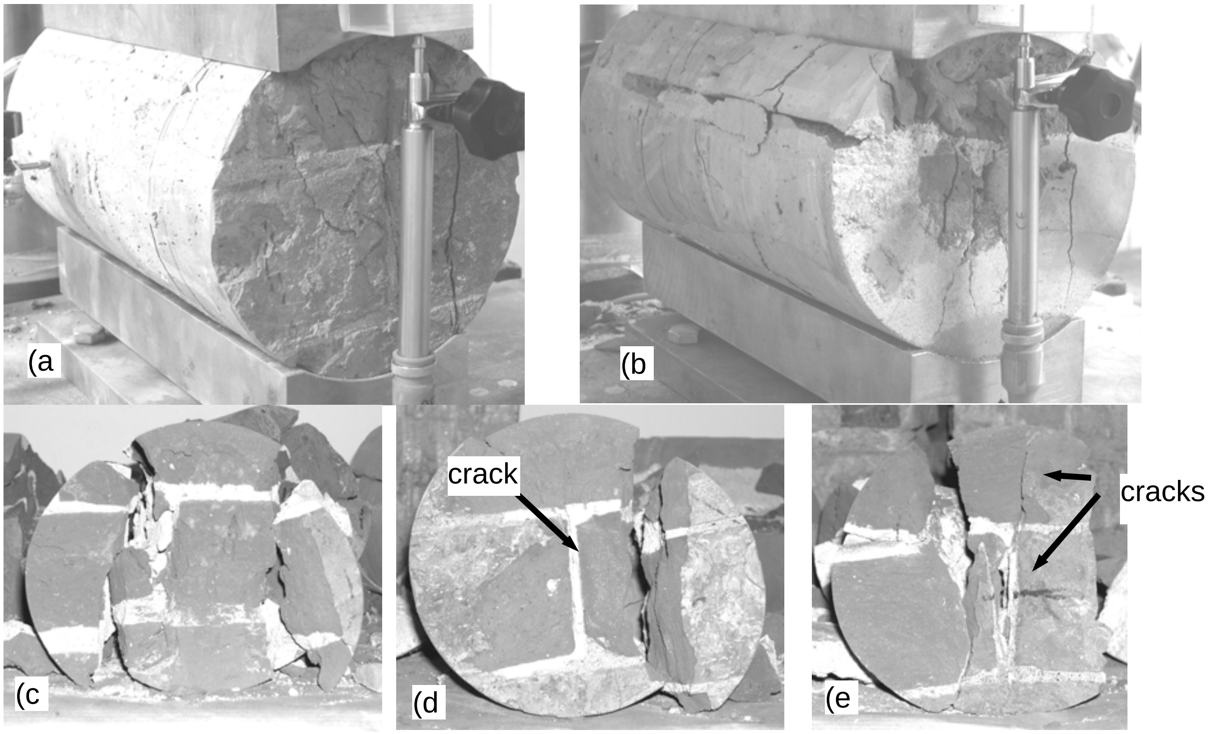

Figure 5. BRICKWORK 1 and 2: typical crack pattern at: a) 80% of the maximum load; b) end of the test; c), d) and e) typical collapse mechanisms: opening of the vertical joint and splitting of the lateral part of the cylinder (after peak load).

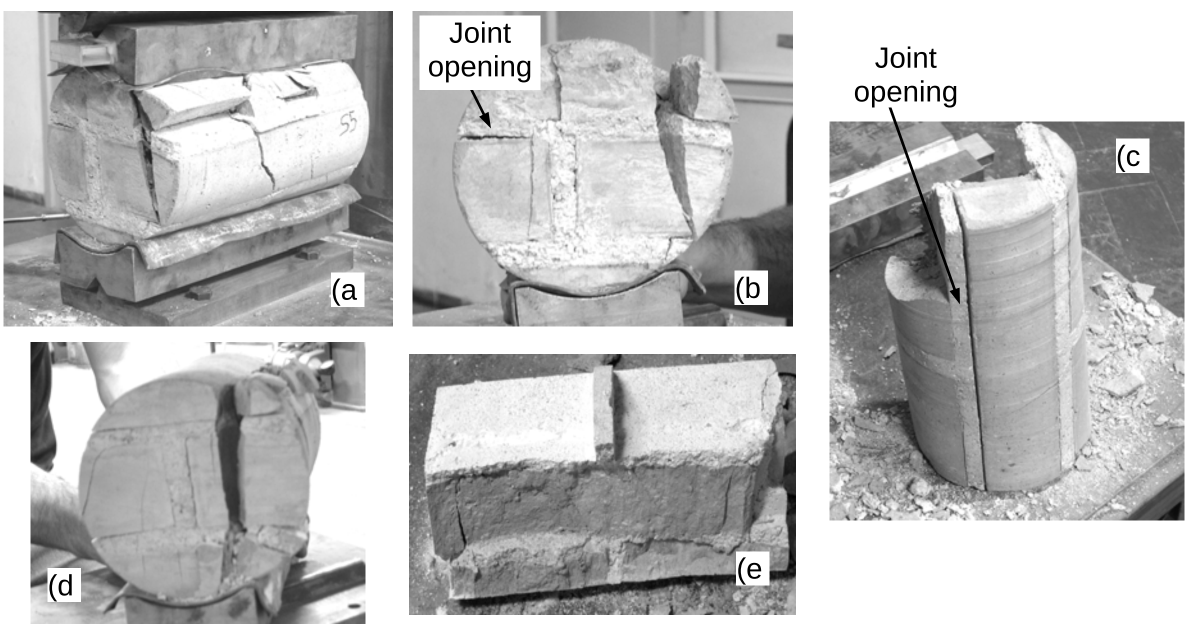

Figure 6. BRICKWORK 3: typical crack pattern at the maximum load. Cyl. 1: a) the lateral parts detach and b) the brick/mortar interface collapses before collapse is activated; c) detachment of the joint. Cyl. 2: d) the same collapse mechanism as for Cyl. 1; e) detachment of the horizontal joints.

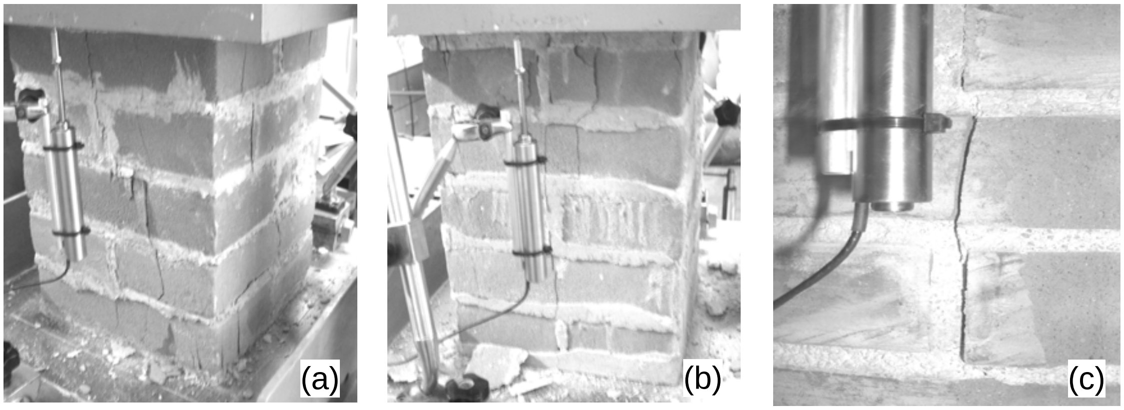

Figure 7. BRICKWORK 1 and 2: cracking of prisms at approx. 80% of the peak load.

Table 2. Summary of the experimental data.

		Prism 1	Cyl. 1	Prism 2	Cyl. 2	Prism 3	Cyl. 3
BRCWRK 1	f_c [N/mm^2]	12.1	7.6	10.6	5.7	/	5.8
	E [N/mm^2]	20550	6820	15560	5140	/	4070
	f_c prism/cyl.	1.6		1.9		/	
	E prism/cyl.	3.0		2.8		/	
BRCWRK 2	f_c [N/mm^2]	9.6	5.6	8.2	5.3	11.5	5.6
	E [N/mm^2]	12900	4000	9500	3400	19300	5080
	f_c prism/cyl.	1.7		1.6		2.1	
	E prism/cyl.	3.2		2.8		3.7	
BRCWRK 3	f_c [N/mm^2]	20.0	9.1	23.6	11.0	23.2	/
	E [N/mm^2]	29000	9400	23560	7000	31080	/
	f_c prism/cyl.	2.2		2.1		/	
	E prism/cyl.	3.1		3.4		/	

Numerical approach: FEM models

FEM models usually fail in reproducing the whole collapse mechanism because of numerical instabilities arising when cracking is spread throughout the brickwork. The tests show that the pre-peak and post-peak phases exhibit large cracking, responsible of the non linear load-displacement response; since the simulation of these phases is quite difficult for FEM models, the numerical approach can be used to better understand the activation of cracking and the first steps of its evolution only. The main results of FEM analysis (Brencich 2004) for a brickwork similar to the one tested in this work are briefly summarized.

Figure 8 shows the load-displacement curve of the FEM model; on the right-hand side the load-displacement (vertical) curve shows that the specimen does not exhibit a macroscopic non linear behaviour, whilst the lateral displacement, left-hand side of Figure 8, shows a curve with two distinct parts: at step 4 the stiffness decreases as cracking is activated in the vertical joint, Figure 5.b; after step 4, stiffness remains approximately constant at the reduced value while cracks propagate inside the bricks, Figure 9; the gradual activation of the central core of brickwork that had been already detected during the tests can be recognized.

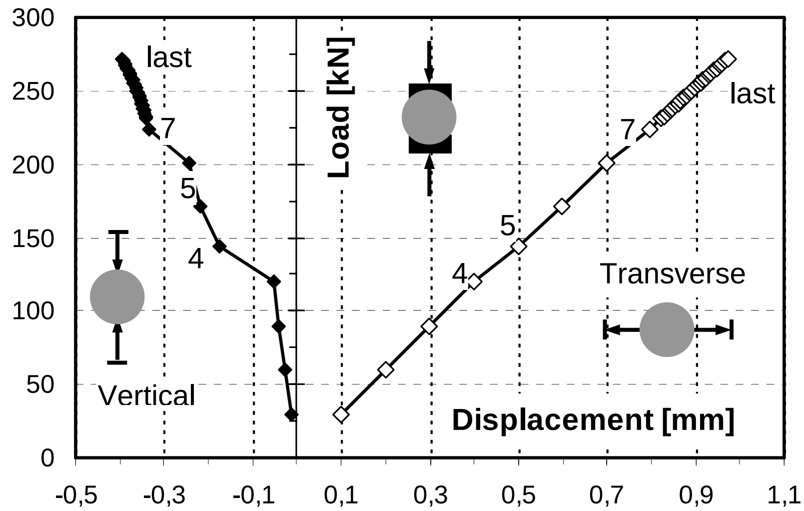

Figure 8. Load-displacement response of the FEM model.

The distribution of the vertical and horizontal stressses at approx. 80% of the peak load is displayed in Figures 10. The vertical stresses, Figure 10.a, are mainly concentrated in a sand-glass shaped central core, large 3/5th of the whole cross section, with a not uniform distribution. Figure 10.b shows concentrations of horizontal stress in the upper and lower bricks close to the edges of the loading plates explaining the observed crack patterns and the detachment of the lateral parts of the cylinders (Figures 5.c-5.e and 9).

The FEM model, although not capable of reproducing the entire loading process, helps in understanding the onset of cracking in the specimen. Figures 9 show the crack pattern at approximately 80% of the peak load for the tested prisms, where cracking clearly originates from the central mortar joint. Some ongoing numerical analysis (Corradi 2006) suggests that this is caused by a concentration of tensile stresses in the brick, in the part close to the vertical joint, due to the brick/mortar elastic mismatch. The comparison of the crack pattern of Figures 5, 6 and 7 with the results of the numerical analysis shows that the brickwork collapse mechanism is reproduced by the large diameter cores but for the stress concentrations due to the loading plates, Figure 10.b. Therefore, a calibration of the test can be performed providing reliable estimates of the actual brickwork compressive strength.

Discussion and Conclusion

The compression tests on the cylinders show a collapse mechanism similar to that of solid clay brickwork prisms, both in the crack evolution and in the stress/strain response; the post peak phase is much more ductile -see (Brencich 2005) for a definition of brickwork ductility- than what is found for brickwork prisms due to the confinement of the loading plates. Nevertheless, the ratio between the compressive strength and the elastic modulus measured on the cylinders and on prisms, the latter representing the reference masonry, is reasonably constant. Due to the large differences in the post peak phase, no information on masonry ductility can be deduced from the cylinder tests.

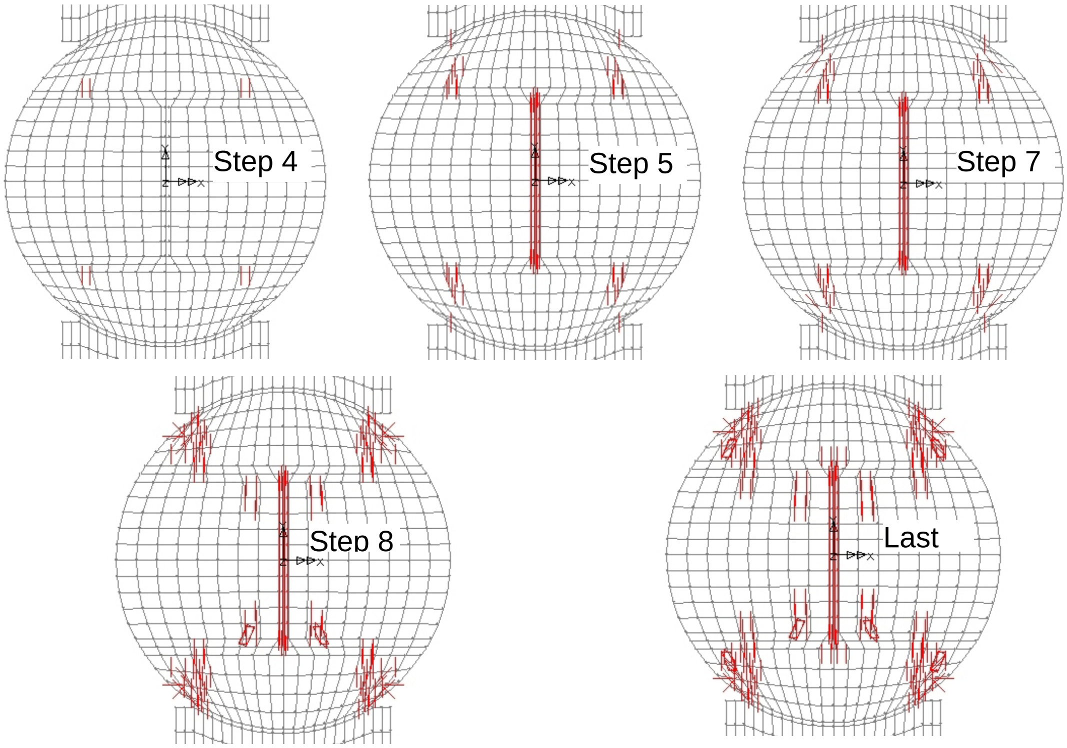

Figure 9. Crack pattern evolution during the load process

On the bases of the results summarized in Table 2, a first calibration of the test can be given by formulas:

$$f_c^{prism} \cong 1.8\, f_c^{cyl} \qquad \textbf{[5.a]},$$

$$E^{prism} \cong 3E^{cyl} \qquad \textbf{[5.b]}$$

valid for bricks with compressive strength not larger than 25-30 N/mm^2, as already found by some of the authors in a previous research (Brencich 2004). For higher compressive strengths, Table 2, the calibration coefficients seem to be higher, but a general conclusion cannot be derived at this stage of the research.

The C.o.V. of the compressive strength is approx. 30% for both the cylinders and the prisms (7% for the cylinder and 24% for the prism tests if the anomalous prism n. 1 of Table 2 is not considered), which is rather typical for small brickwork assemblages (Ellingwood 1985, Dymiotis 2002). Assuming a Gaussian distribution, the characteristic values for the compressive strength is:

$$f_{ck}^{prism} \cong 1.3 \langle f_c^{cyl} \rangle, \qquad \textbf{[6]}$$

being $\langle f_c^{cyl} \rangle$ the average value of the cylinder tests. It seems that there is no reason for referring to the minimum experimental value, eq. (1.b); if large dispersion of experimental data are found, the coefficient of eq. (6) can be modified according to the standard semi-probabilistic approach to material strength on the bases of the number of tests performed.

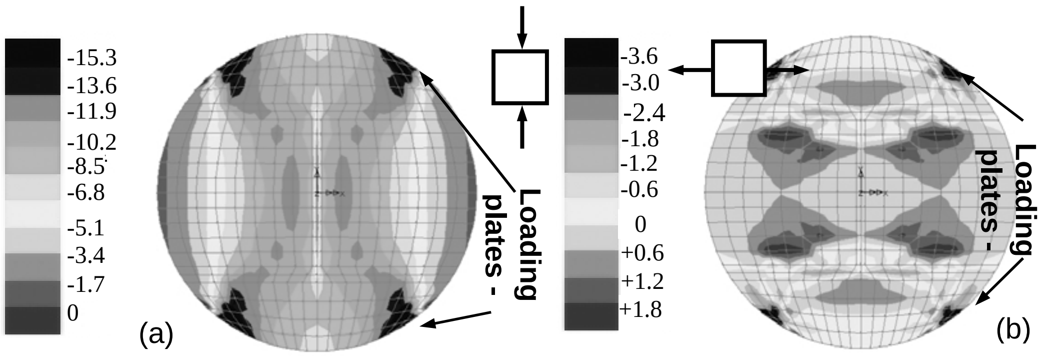

Figure 10. a) Vertical and b) horizontal stresses [MPa], 80% of peak load

The C.o.V. of the elastic modulus is approx. 57%; this value shows that no reliable information can be deduced from the large cylinder test on material stiffness; similar results had been obtained by the authors in a previous calibration campaign (Brencich 2004). This result is not unexpected: the elastic modulus is an average property on the whole structure, i.e. a global parameter, while experimental tests are always local measurements that, in the specific case, only partially reproduce the brickwork bond. The experimental setup, for example the lead sheets in-between the loading plates and the specimen, and geometric irregularities of the cylinder are only a couple of reasons explaining the large variability in the elastic modulus measurements. For these reasons, eq. (5.b) should be applied very carefully for the identification of the Young's modulus.

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