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Experimental response of historic brickwork

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ABSTRACT
In historic towns of the Italian regions recently hit by earthquakes, 2016-2017, minor and monumental buildings were built with historic brick masonry, often with bricks and mortar weak to compression. Masonry buildings under seismic action are subjected to shear and bending loading with an increase of local deformation of materials. It is a well-known fact that many mechanical and geometric parameters influence the response of brickwork under loading and that they can modify the behaviour of masonry structures. This paper presents main experimental results on a large investigation focusing about historic masonry wallettes built using solid clay bricks in real scale and/or in scale 1/3rd. Specimens were subjected to compression tests, diagonal compression tests and combined compression and shear tests. Experimental results are shown and discussed with data obtained both by theoretical analysis of failure mechanisms and by finite element modelling.

1 INTRODUCTION

In recent years, earthquakes in Italy have hit masonry structures significantly; a common building technique used in field practice in many small historic centres of Italian regions such as: Marche – Umbria – Lazio ensuing dramatic consequences and destruction (Codice di Pratica Regione Marche 2007; Capozucca 2017). Historic masonry structures of buildings behaved in different ways depending on the link between cross-walls and floors, even if they are generally considered weak to dynamic actions (Tomazevic 1999). Historic masonry structures have, in many situations such as in the recent seismic events in Italy, been subjected to exceptional combined shear and compressive stresses. Masonry buildings under seismic actions are typically loaded by compression loading and shear in cross-walls. Shear walls, whether solid or pierced by window and door openings in each storey, represent the basic structural elements of a masonry structure, resisting seismic loads (Fig. 1) (Paulay 1972; Priestly and Elder 1982). In historic wall buildings subjected to seismic loads during earthquakes events of 2016-2017, relevant compression-tension strains have been registered with the deformation state of materials, bricks and mortar, increased. In particular, the compressive behaviour of historic brickwork subjected to loading, as often recorded during seismic events in Italy, influenced historic brickwork buildings' loss of resistance as tensile failure of bricks. (Fig. 1).

Figure 1. Cracking in historic building after earthquake: Pescara del Tronto, Italy.

Modern brickwork has been the object of systematic investigation over the last decades: relevant contributions are present in literature concerning the experimental behaviour under shear of masonry walls for both full-scale brickwork and in scale structures (Hendry and

Sinha 1971; Yokel and Fattal 1976; Hendry, 1978) taking in account the influence of joints and the angle between load direction and bed mortar joints (Page 1982; Samarasinghe 1981). Shear criteria of masonry have been proposed by many authors based on experimental results also considering diagonal compression tests and formulating failure hypothesis for masonry under shear and compression (Turnešec and Cačovič 1970; Hendry 1978; Drysdale et al. 1979; Mann and Muller 1980; Schubert 2002; Calderini et al. 2010;).

The behaviour of historic masonry, on the other hand, was less investigated, both experimentally and theoretically (Pina-Henriques, 2004). The focus of experimental research, in terms of historic brickwork, has focused mainly on analysing the shear behaviour (Capozucca and Sinha 2004, 2005; Capozucca 2011, 2016) and on the ability to consider the effects of shear which increases during a seismic event.

The complexity of the mechanical and geometric factors intervening in historic brickworks' resistance calls for the evaluation of actual response as a whole, analysing effects of many factors: brick strength and geometry; mortar strength; brick and mortar deformation characteristics; thickness of mortar joints; bond between mortar and bricks; etc..

In this paper, the failure mechanisms of masonry is at first theoretical analyzed considering the response of wall under compression. Successively historic brickwork are studied by experimental tests on wallettes built using historic solid bricks in real scale and in scale 1/3rd: experimental compression tests were carried out on wallettes built using different mortar joint thicknesses; tests on wallettes built with historic bricks in scale 1/3rd subjected to diagonal compression tests are also by finite element method (FEM); finally, combined compression and shear tests were carried out on wall models up to failure considering pre-compression values typical of historic building. On the basis of results obtained, the response of historic masonry has been defined through main mechanisms of failure that are present in buildings after an earthquake.

2 FAILURE OF BRICKWORK UNDER COMPRESSION

As just by experimental investigations (Sinha and Hendry 1966; Hildorf 1969) when masonry wall is loaded with compression, bricks and mortar layers undergo compressive and tensile strains to loading action.

The response of brickwork under compression is more greatly influenced by tensile strength of brick**,** f_{bt}, than by compressive strength f_b (Hildorf 1969). Being Poisson's ratios of brick and mortar different, they can have different transverse strains only if they are free to move. Bond and friction between brick and mortar layers, produce shear stress state at the surface interface; hence, bricks and mortar layers are subjected to a triaxial state of stress. The effect equivalent to the confinement of mortar bed joints allows mortar layers to sustain higher compressive load.

Strength of brickwork under compression depends on the Young's modulus and Poisson's ratio of brick and mortar; coefficient of friction, f, at the brick and mortar interface and, also, thickness of mortar joints. Usually, failure of brickwork compression occurs if value of principal stress is greater than tensile strength of bricks.

Theoretical analysis for calculating failure conditions of compression loaded brickwork has been developed by Hendry and Sinha (1966). It may be considered the following normal stresses: compressive stress, σ_x; lateral tensile stress, σ_y, for brick correlated with mortar lateral stress σ_{y1}; the axis x as normal on bed mortar joint and y (or y_1) in the horizontal plane of brick (or mortar). The analysis calls for knowledge of the following mechanical and geometric parameters: E_m, E_b, E_w, respectively, Young's modulus of mortar, brick and brickwork; Poisson's ratios ν_m, ν_b, ν_w; cross section area of mortar layer and brick, A_m, A_b and thicknesses t_m, t_b. If the mortar and brick are free to expand, strains will be $\nu_m \cdot \sigma_x / E_m$ for mortar and $\nu_b \cdot \sigma_x / E_b$ for brick, obviously in absolute value. Because they are not free to expand, the strain value will be in the brickwork: $\nu_w \cdot \sigma_x / E_w$.

The following equations of elastic compatibility and equilibrium may be deduced:

$$\nu_b \cdot \frac{\sigma_x}{E_b} - \nu_w \cdot \frac{\sigma_x}{E_w} = \frac{\sigma_y}{E_b} \tag{1}$$

$$\nu_m \cdot \frac{\sigma_x}{E_m} - \nu_w \cdot \frac{\sigma_x}{E_w} = \frac{\sigma_{y1}}{E_m} \tag{2}$$

$$\sigma_y \cdot t_b - \sigma_{y1} \cdot t_m = 0 \tag{3}$$

Knowing the thickness of mortar joint, t_m, thickness of brick, t_b, and mechanical parameters of mortar and brickwork, it is possible to obtain the following relation between normal compressive stresses, σ_x , and tensile stress, σ_y, for the brick:

$$\sigma_y = k \cdot \sigma_x \tag{4}$$

being k a dimensional coefficient:

$$k = \frac{t_m}{t_b} \cdot \left(E_m \cdot \frac{\nu_w}{E_w} - \nu_m \right) \tag{5}$$

For a brickwork wallette, in general, failure under compression can happen for different failure mechanisms: loss of strength due to tensile stress or compressive stress state. Although rare, shear mechanisms may be enounced. As known these failure mechanisms may be expressed by relation between normal and shear stresses related to principal stresses.

Assuming that shear stress on the brick surface may be approximatively expressed as follows, neglecting the bond:

$$\tau \cong f \cdot \sigma_x \tag{6}$$

the relations obtained by Mohr's circle allow to evaluate the principal stress:

$$\sigma_{II} = \frac{\sigma_x - \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x + \sigma_y}{2} \right)^2 + (f \cdot \sigma_x)^2} \tag{7}$$

for compressive stress; introducing Eq. (4) in Eq. (7), the principal stress becomes:

$$\frac{\sigma_{II}}{\sigma_x} = \frac{1-k}{2} + \sqrt{\left(\frac{1+k}{2} \right)^2 + f^2} \tag{8}$$

The tensile principal stress is:

$$\frac{\sigma_I}{\sigma_x} = \frac{k-1}{2} + \sqrt{\left(\frac{1+k}{2} \right)^2 + f^2} \tag{9}$$

Finally the following ratio between ultimate shear stress on brick surface and compressive stress on brickwork is:

$$\frac{\tau_{u,b}}{\sigma_x} = \sqrt{\left(\frac{1+k}{2} \right)^2 + f^2} \tag{10}$$

Each value of k coefficient allows to calculate three failure mechanism curves of brickwork through the Eqs. (8), (9) and (10).

In Fig. 2 adimensional diagrams of the failure mechanisms for masonry are shown having introduced tensile and compressive strength for brick: f_{bt} , f_b. The coefficient of friction between brick and mortar in the case of historic masonry may be equal to 0.70÷0.74 (Capozucca 2011, 2017) so that, if the mechanical parameters shown in Eq. (5) are known by experimental tests, the main failure mechanisms of masonry under compression can be evaluated by adimensional diagrams of Figure 2.

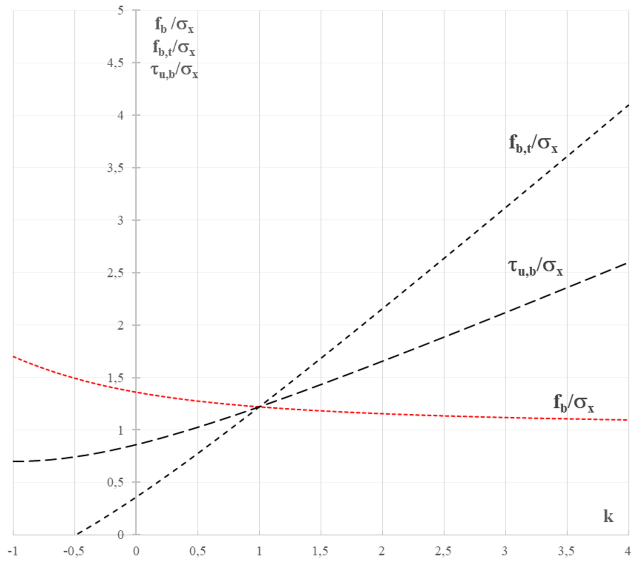


Figure 2. Adimensional diagrams of the failure mechanisms for masonry.

3 EXPERIMENTAL TESTS ON HISTORIC WALLETTES

Compressive and tensile strength of bricks are two fundamental mechanic parameters useful to describe behavior at failure of historic brickwork. Compression was experimentally evaluated on real scale brick samples and on 1/3 scale samples. Eight historic brick samples measuring approximately 120mmx120mmx50mm (Figs. 3(a), (b)) were subjected to compression to failure in order to determine resistance to compression f_b. A sample failure can be seen in Fig. 3(b). Experimental results confirm the vast variability of resistance in the case of solid historic bricks: mean experimental resistance is equal to f_b= 15.40N/mm^2.

(a) (b)

Figure 3 - (a) Specimens of historic bricks subjected to compression tests; (b) view of compression failure.

Tensile strength, f_{bt}, was experimentally evaluated on samples obtained by real scale historic bricks. The samples shown in Fig. 4, measuring approximately 115mm · 115mm· 50mm, underwent diagonal compression to failure. The diagonal tensile strength of the brick was experimental evaluated using *Brazilian test* on a square brick sample and average value, and determined using the following expression, is equal to $f_{bt,av} = \frac{2 \cdot P}{\pi \cdot D \cdot t} = 1.51 N/mm^2$. It can be noted that the brick's tensile resistance is equal to $f_{bt} \approx 1/10 \cdot f_b$.

Compression tests on 1/3rd scale bricks (Fig. 5) were carried out to evaluate, in particular, Young's, E_b, and Poisson's ratio, ν_b.

Figure 4. Square historic brick model under diagonal compression at failure.

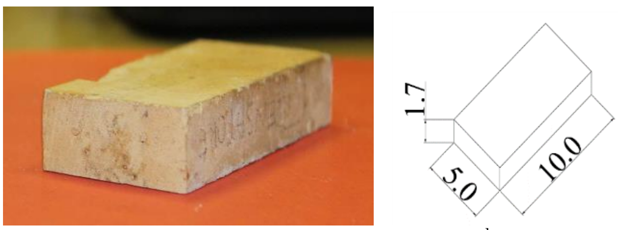


Figure 5. Clay historic brick in scale 1/3rd with average dimensions (cm).

The main experimental results obtained are the following: compressive strength $f_b \approx 21.76 N/mm^2$ with deformation equal to approximately $\varepsilon_{b,u} \approx 1.83 \cdot 10^{-3}$; the elastic modulus for $P_{max} \approx 18.5kN$ was estimated to be equal to approximately $E_b \approx 12.0 \cdot 10^3$ N/mm^2 and finally Poisson's ratio was estimated to be $\nu_b \approx 0.15$.

Variability in the compressive strength of historic bricks is evident in the analysis of brickworks' behaviour under loading; this important response variability, influences resistance of the structural elements with the formation of possible local cracking mechanisms.

On the basis of the experimental data obtained, the reference values related to the mechanical parameters of historic brick contained in Table 1 can be considered.

Table 1. Exp. mechanical parameters of historic bricks.

Compressive Strength f_b (N/mm^2)	Tensile Strength f_{bt} (N/mm^2)	Young's Modulus E_b (kN/mm^2)	Poisson's ratio ν_b (kN/mm^2)
15.4÷28.0	1.5÷2.8	12.0	0.15

Wallettes built using real scale historic bricks on historic is described below. A typical wallette with historic bricks is shown in Fig. 6 before compression tests and the failure cracking after reaching maximum load. Experimental tests have been developed considering wallettes with different joints thickness 4mm-8mm and 12mm respectively for W1, W2 and W3 samples. From the experimental compression test on wallettes with historic bricks it can be observed that once again failure appears with a development of tensile cracking parallel to the load axis, following the tensile strains orthogonal to the principal compression strains.

Figure 6. Brickwork wallette with historic brick.

The average resistance values obtained from tests on historic wallettes are shown in Table 2. It can be noted that, the response of the historic brick wallette, in terms of resistance, proved to be inhomogeneous without a clear influence of mortar joint thickness. This result is principally due to the different strength of historic bricks; they, in fact, contrary to modern ones, have very different resistance capacities according to the composition of the material adopted. It must also be observed that, in general, the resistance capacity of historic masonry bricks is lower than that of modern bricks with a reduction equal to 40%.

Table 2. Experimental results from compression tests on wallettes.

Specimens	Wallettes with historic bricks			
	P_u (kN)	P_u (kN)	f_w (N/mm^2)	$f_{w,av.}$ (N/mm^2)
W1	366.5	270	7.69	8.22
W2	358.6	355	10.11	
W3	354.2	241	6.86	

4 EXPERIMENTAL TESTS OF WALLETTES WITH HISTORIC BRICKS IN SCALE 1/3RD

One-third-scale model historic bricks were used in the experimental tests evaluating the response of historic brickwork under loading to analyze the failure mechanisms and influence of material's mechanic and geometric parameters. Simple compression tests, diagonal compression tests and, finally, combined compression and shear tests are described below.

Mortar used in the testing of in scale brickwork is that typical of historic Italian brickwork, in volume 1:1:5 of cement, lime and sand. Deformation measurements during the course of compression testing on cylindrical mortar specimens allowed the evaluation of the following intervals of Young's modulus $E_m \approx 3.0\cdot10^3 \div 10\cdot10^3$N/mm², and Poisson's ratio $\nu_m \approx 0.18 \div 0.25$.

Compressive tests were carried out on wallettes built with historic bricks (Fig. 7) obtained from sawing full-scale bricks measuring approximately 200mm·200mm·50mm (Capozucca 2017).

Compression tests were carried out to evaluate both strength, f_w, and elastic moduli: Young's modulus E_w and Poisson's ratio ν_w. The thickness of the mortar joints was equal to 4÷5mm. The average compressive strength obtained by experimental tests on two wallettes increasing compressive load normal to bed mortar joints, was equal to about $f_w \approx 9.0$N/mm^2.

Figure 7. Wallettes with solid bricks in scale.

In order to have all the values of the meaningful moduli, E_x, $E_{y,}$, ν_{xy}, ν_{yx}, and seeing that the brickwork was orthotropic material, compression tests were carried out on small wallettes with compressive forces in the two directions: parallel to the bed joint (y direction) and vertically, (x direction) perpendicular to the mortar bed joint. The mechanic parameters in Table 3 were obtained by the experimental tests on small wallettes.

Table 3. Young's modulus and Poisson's ratio.

Young's modulus E_y (N/mm^2)	Poisson's modulus ν_{yx}	Young's modulus E_x (N/mm^2)
4584	0.25	5384

Diagonal compressive tests on two specimens of brickwork with bricks in scale 1/3rd were carried out to evaluate the tensile capacity of wallettes. Figure 8 contains the dimensions of the specimen and the set-up of the measurement equipment on one side.

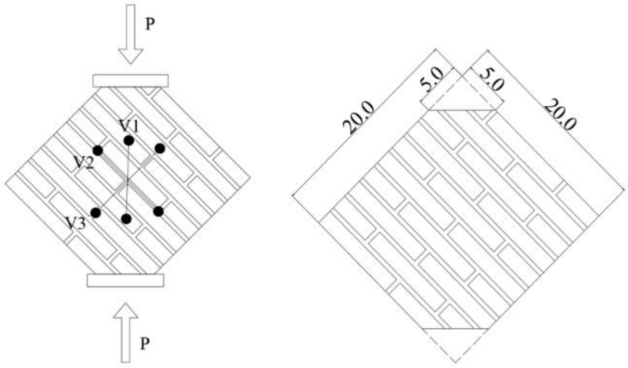


Figure 8. Wallette with solid bricks under diagonal compression test.

Evaluated according to ASTM E 519 standards, the experimental values for the average tangential stresses to failure are $\tau_u \approx 1.14$N/mm^2 ÷ 1.15N/mm^2 for the two wallettes. These values do not differ much from resistance $f_{w,t} \approx 1.0$ N/mm^2 obtained considering the test as Brazilian test for theoretical diameter D=210 mm equal to length of one side.

A numerical analysis was conducted by FEM on the specimens subjected to diagonal compression by adopting a linear elastic analysis and using three dimensional modelling by code Ansys. Generally, when modelling masonry elements two approaches are used: either micro or macro-modelling (Gambarotta and Lagomarsino 1997; Lourenço 2002; Milani et al. 2006). Each of the wallettes studied with diagonal load was studied using macro-modelling, assuming masonry both as an isotropic and orthotropic material. Assuming masonry as an orthotropic material appears to be more congruent to the different elastic properties in the two main directions, parallel and perpendicular, to the mortar bed joints.

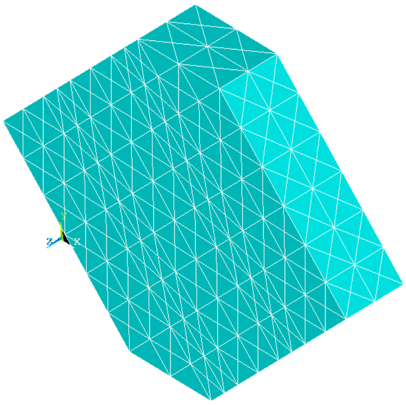
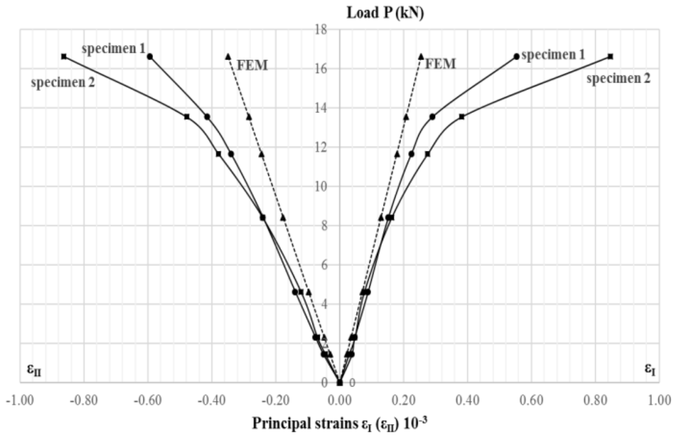
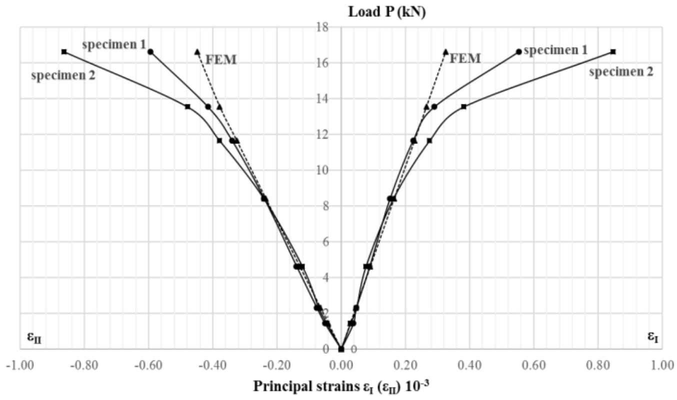


Figure 9. FE triangular mesh of brickwork.

Orthotropic quality is also linked to the form and proportion of the units and to the manner in which they are set-up. The masonry panel, assumed continuous and orthotropic, was modelled using a Solid185 element. The mechanical parameters are those evaluated experimentally (Tab. 3). For the wallettes, analysed according to the hypothesis that the material is continuous and isotropic, a triangular mesh Solid65 element was used (Fig. 9). The experimental values (Tab. 3): $E_{y,w}$=4584N/mm^2 and ν_w=0.25, assuming the material as homogeneous. In the numerical analysis diagonal compression load was applied by increasing step up to an ultimate value equal to P_u=16.60 kN. Deformations ε_1 along compressed diagonal and the principal strains ε_I and ε_{II} with inclination equal to θ in relation to the mortar bed were detracted. The theoretical results obtained using FEM are compared with those obtained by experimental tests; in Fig. 10(a) and (b) load diagrams, P, versus principal strains, ε_I and ε_{II} are compared respectively, in the case of isotropic material and orthotropic.



(a)



(b)

Figure 10. Comparison between theoretical and experimental diagrams load, P, versus principal strains ε_I, ε_{II}: (a) isotropic and (b) orthotropic material.

We can note how, elastic analysis, in the case of orthotropic material, leads to a congruent comparison between experimental and numerical values. Thus, we can underline how in analysis using FEM, masonry material as orthotropic, produces more reliable results.

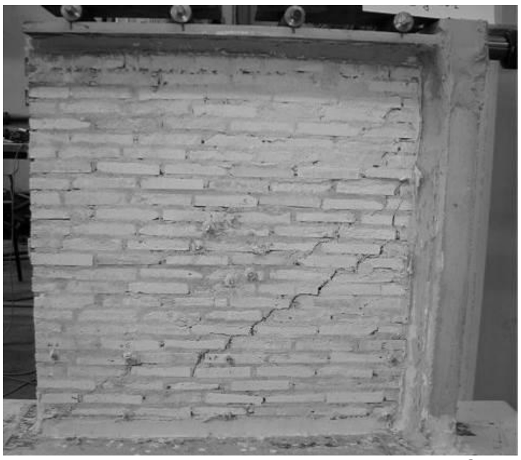
4.1 Combined compression and shear tests on historic walls

Single-story brickwork structures were built with historic bricks in 1/3rd scale and tested varying compression stress from 0.3 to 3.0N/mm^2 (Capozucca 2017). In this paper we analyze, in particular, wall models subjected to three compression stress values typical in the masonry walls of historic buildings in many of the central regional towns of Italy recently hit by earthquakes (Capozucca 2005, 2011). The walls tested measured approximately 630mm·630mm·50mm. In literature there are a series of experimental research tests carried out on brick wall models which clearly show that the strength of full scale in shear can be conveniently predicted through testing on small scale models (Hendry and Sinha 1971). Walls W1s-W3s were subjected to relatively low values of pre-compression, respectively, equal to 0.50 N/mm^2 and 0.30N/mm^2 and they reach failure with cracks in the mortar joints (Fig. 11).

Wall W2s was subjected to a higher pre-compression value equal to 0.75N/mm^2; here failure occurred with cracks through the mortar joints and bricks.

(a) W1s - pre-compression 0.50 N/mm^2

(b) W2s - pre-compression 0.75 N/mm^2



(c) W3s - pre-compression 0.30 N/mm^2

Figure 11. Wall specimens under compression and shear tests: (a) W1s - pre-compression 0.50 N/mm^2; (b) W2s - pre-compression 0.75 N/mm^2; (c) W3s - pre-compression 0.30 N/mm^2.

Table 4 shows the main values of shear stress at failure. In the case of wall W1s the first crack occurs in the vertical joints; then horizontal cracks also appear along the diagonal of the wall, forming stepped cracks. The two parts of the panel followed to slip but the horizontal force did not increase significantly. It can be noted that when the first crack occurred, behaviour became non-linear to complete failure, achieved at horizontal force F=20.8kN. As seen in the case shown in Fig. 9, principally, the cracks followed the joints, so it suggests that failure criterion to be adopted is Mohr-Coulomb, a frictional one (Capozucca 2017).

Table 4. Experimental results of shear strength.

Brickwork wall models	W1s	W2s	W3s
Precompression stress σ_v (N/mm^2)	0.50	0.75	0.30
Average shear strength τ_n (N/mm^2)	0.66	0.68	0.54

In wall W2s no evident cracks formed before failure. Therefore, there is no ‘plastic’ range and diagonal cracking occurs suddenly when horizontal load achieved F≈21.4kN. Fig. 11 shows how the crack crossed both joints and bricks in this case, hence the material behaved as a homogeneous continuum. This suggests that failure criterion to be adopted is diagonal tensile failure (Capozucca 2017).

5 DISCUSSION ON FAILURE MECHANISMS

Experimental results on historic brick wallettes allow us to discuss failure mechanisms. Fig. 2 contains dimensionless diagrams relative to the three mechanisms theoretically foreseen by Eqs. (8), (9) and (10) for the value of coefficient k; coefficient k can be evaluated from the aforementioned experimental data to determine the possible failure mechanism by compression of wallettes with historic bricks. Referring to the experimental tests described on masonry wallettes with bricks in scale 1/3rd, the following historical masonry values can be adopted: brick compression strength, f_b=15.4N/mm^2, and tensile $f_{b,t}$=1.5N/mm^2; Young’s modulus of mortar E_m≈5.0kN/mm^2, and Poisson’s ratio of mortar ν_m≈0.20; masonry compressive strength f_w =

9.0N/mm^2, tensile $f_{w,t}$ =1.0N/mm^2 with Young's modulus $E_w \approx$ 4.60 kN/mm^2, and Poisson's ratio $\nu_w \approx 0.20$. A coefficient value k approximately equal to zero is obtained from Eq. (5) for the parameters listed above: $k^* \approx 4.1 \cdot 10^{-3}$. From the diagrams in Fig. 2 it can be seen that failure of masonry by compression is conditioned by tensile cracking for coefficient values -0.50< k<1. For coefficient value k* the value of maximum compression stress on the wallette, may be evaluated. This failure mechanisms may be developed to analyse the damage due to increase of compression that may happen during earthquake that determines masonry bricks' failure by tensile strain, as it occurs during seismic events. Comparing the theoretical value of compressive stress using a FEM analyses of the walls subjected to shear tests, W1s and W2s, can be useful. From the results shown in Figs. 12 and 13, it can be inferred that by effect of the deformation state induced on the materials by compression and shear-bending, for horizontal load F that exceed initial cracking in the mortar joints, local stresses in the most compressed area of walls W1s and W2s reaches values about equal to the theoretically ultimate stress such as to cause the tensile crash of the bricks. Combined shear and compression-tension failure mechanisms were registered in laboratory (Fig. 11) on panels W1s and W2s with pre-compression values 0.50 and 0.75N/mm^2.

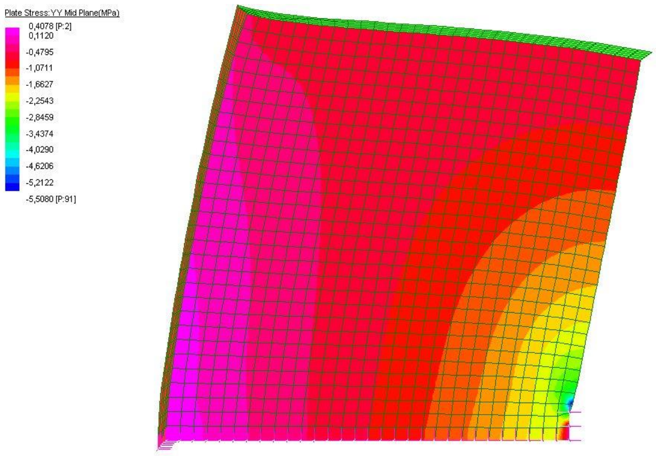


Figure 12. FE shape and vertical compression stress distribution with horizontal force F=15.6kN orthotropic material (wall W1s).

The failure mechanism is combined; it is characterized by loss of resistance both for shear with slipping in the mortar joints, and by the bricks' loss of tensile strength in the area with greater compression. At lower pre-compression levels, panel W1s with pre-compression stress 0.30/mm^2, the combined mechanism is not registered experimentally and the masonry's prevalent loss of resistance is shear of the mortar joints.

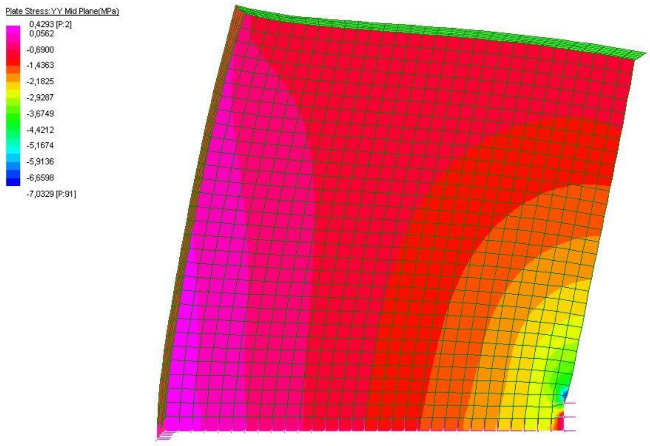


Figure 13 - FE shape and vertical compression stress distribution with with horizontal force F=19.0kN - orthotropic material (wall W2s).

6 CONCLUSIONS

Failure mechanisms of historic brickwork have been analyzed in this paper considering experimental tests and results carried out with a large campaign of test on brickwork and on solid brick and mortar materials.

The experimental results are discussed considering a theoretical analysis of failure mechanisms by compression and also numerical analysis by FEM. Main results may be summarized as follows:

- thickness of mortar bed joints does not have a particular influence on the compression strength of historic brickwork as it does on modern brickwork;
- failure mechanism registered on historic walls subjected to seismic loading, is linked to a double loss of resistance: shear failure in mortar joints and cracking of bricks in areas where deformation increases due to compression;
- tensile failure mechanism of bricks appears in the combined compression and shear tests on wall models with pre-compression values from 0.50N/mm^2; these value of normal stress is a typical compression value for historic masonry walls;
- FE analysis of historic brick masonry in elastic field as orthotropic continuous material allows the correct estimation of deformation and stress state in masonry by using experimental data which takes into account the different mechanical proprieties of masonry.

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LIST OF SYMBOLS

$_{exp,\ av}$ = index for experimental value; index for average value
f_b = compressive strength of brick
f_{bt} = tensile strength of brick
f_m = compressive strength of mortar
f_{fm} = flexural tensile strength of mortar
f_w = compressive strength of masonry
σ_x = compressive stress on brick
σ_y = lateral stress on brick
σ_{y1} = lateral stress on mortar
τ = shear stress on brick surface
E_m = Young's modulus of mortar
E_b = Young's modulus of brick
E_w = Young's modulus of masonry
ν_m = Poisson's ratio of mortar
ν_b = Poisson's ratio of brick
ν_w = Poisson's ratio of masonry
t_m = thickness of mortar
t_b = thickness of brick
f = coefficient of friction
ε_v, ε_o = vertical and horizontal strain
ν_{xy}, ν_{yx} = Poisson's ratios of masonry-orthotropic material
E_x, E_y = Young's moduli of masonry-orthotropic material
F = exp. lateral load in shear tests
P = compressive force on masonry parallel bed mortar joints
ε_I, ε_{II} = principal tensile and compressive strain
σ_I, σ_{II} = principal tensile and compressive stress

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