Cyclic behavior of non-reinforced and confined masonry

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SUMMARY:
The confined masonry technology is appealing since it allows to combine the well-known building practice of masonry with the ductility characteristics of r/c frames. A research program has been started which aims to investigate the increase in ductility of regular masonry walls obtained by the use of the technology that characterizes the confined masonry. A comparison between regular and confined masonry walls subjected to shear load applied at the top has been achieved by means of experimental tests. The specimens are built in 1:2 scale, 1.85 m wide, 1.50 m high and 0.15 m thick. The hollow bricks have 45% of vertical holes and dimensions of 18x15x25 cm. The shear load is applied in both directions with cycles of increasing amplitude on panels under compression. The results in term of force-displacement path are shown, highlighting an improvement in ductility.

Keywords: Confined masonry, Shear testing, Seismic performance

1. INTRODUCTION

As is well-known from the literature, the term “confined masonry” is generally used to identify several types of masonry constructions strengthened by elements of reinforced concrete or wood (Brzev, 2007). During the last hundred years confined masonry constructions have been widely used especially in the developing countries located in areas with high seismic risk. The main use of this technology is in the suburban areas of the cities, in which there is a wide presence of the so called “non-engineering constructions”. This is due to the good compromise between the technological easiness of construction and the structural response to seismic action.

In recent years these characteristics have led to a growing interest of the scientific community to the study and analysis of the confined masonry by means of accurate observations and surveys of crack patterns in the buildings hit by earthquakes (Brzev *et al.*, 2011), and by means of experimental tests (Tomaževič and Klemenc, 1997, Zabala *et al.*, 2004).

The confined masonry technology has characteristics in common with both non-reinforced (regular) masonry buildings and frame constructions in reinforced concrete. In fact it is characterized by load-bearing masonry walls, made with clay brick or cement blocks, and by vertical and horizontal confining elements of reinforced concrete on each side of the panel. In such a way a response behaviour as a composite panel can be obtained. Confined masonry buildings subjected to seismic actions have ductility capacity greater than regular masonry buildings due to the reinforced concrete elements, with consequent increasing of energy dissipation. The horizontal and vertical confining elements are effective in improving the stability and integrity of the masonry walls for actions both in the plane and out of plane of the wall.

2. EXPERIMENTAL SETUP

2.1. Specimen realization and measuring system

The experimental tests shown in the present paper were carried on in order to investigate the mechanical characteristics of confined masonry panels. In particular, the main goal was to compare two typologies of masonry panels: one is built in regular masonry (Fig. 1a) and the other with confined masonry (Fig. 1b). A total of four panels were built, two for each typology. They are 1:2 scale models of a typical load bearing masonry wall used in a residential building: more details will be reported in the following. The panels were 1.85 m in length, 1.50 m in height and they had a thickness of 0.15 m. They were realized with clay bricks with a 45% percentage of vertical holes volume and overall dimensions 30x18x15 cm.

The characteristic compressive strength of bricks is f_{bk} = 22.30 N/mm^2; they can be considered as belonging to Category I. The walls were realized with a designed masonry mortar class M15 (i.e. the compressive strength is 15.0 N/mm^2). The thickness of both vertical and horizontal mortar joints was 1.0 cm.

The panels had on the top a confining element cast in reinforced concrete with cross-section of dimensions 15x15 cm. The reinforcement consisted of four longitudinal bars 8 mm in diameter and stirrups 6 mm in diameter spaced 100 mm. On the bottom a confining element in r.c. with cross section dimensions of 15x50 and same reinforcing of the previous was realized; it had eleven holes 19 mm in diameter in order to connect it to the steel base with M18 steel bolts class 10.9.

The two confined masonry panels had two vertical confining elements. These were realized in reinforced concrete with cross-section dimensions of 15x51 cm and reinforced with four longitudinal bars 8 mm in diameter and stirrups 6 mm in diameter spaced 100 mm. The concrete used for confining elements had characteristic value of compressive strength R_{ck} = 30 N/mm^2 and aggregate with maximum dimension of 20 mm; the grade of the steel used for reinforcing was B450C.

The shear load consisted in an horizontal force applied at the top of the wall by means of a system of steel plates. The load was applied in cycles of increasing amplitude by means of an oleo-dynamic jack. A load cell was placed between the jack and the wall in order to measure the actual shear force. The wall was vertically pre-stressed with a compressive load applied through four steel bars; each bar was equipped with a load cell which allowed to measure the vertical load redistribution during the test. (Fig. 3).

(a) (b)

Figure 1. Regular masonry specimen (a) and confined masonry specimen (b)

Due to the brittle nature of the structural elements, the cyclic action imparted by the jack was applied at the top of the specimen through a system of steel elements, rods and plates: in this way the load applied to the wall was always a compression and never a tension. This allowed to avoid localized fracture which could compromise the experimental test. The transmission of the force from the jack to the specimen was achieved by means of a strut and tie system to avoid the occurrence of localized moments due to the deformation of the specimen.

Figure 2 shows the measuring devices installed on the specimens in order to monitor the state of tension and deformation of the panels during the test.

Eight linear voltage displacement transducer (LVDT) were used as follows:
- one to measure the top wall displacement (LVDT-t);
- one to measure the displacement at the base of the wall (LVDT-b);
- two to measure the vertical displacements (LVDT_v1 and LVDT_v2);
- four to measure the displacement along the diagonal of both faces (LVDT_d1_1, LVDT_d1_2, LVDT_d2_2, LVDT_d2_1).

Moreover five load cells were used. One was used to measure the shear load applied on the top of the specimen by the jack (LC); the other four were used to measure the axial load applied through the four pre-stressed vertical bars (LC-1, LC-2, LC-3, LC-4): in particular LC-1 and LC-2 were on side a and LC-3 and LC-4 were on side b.

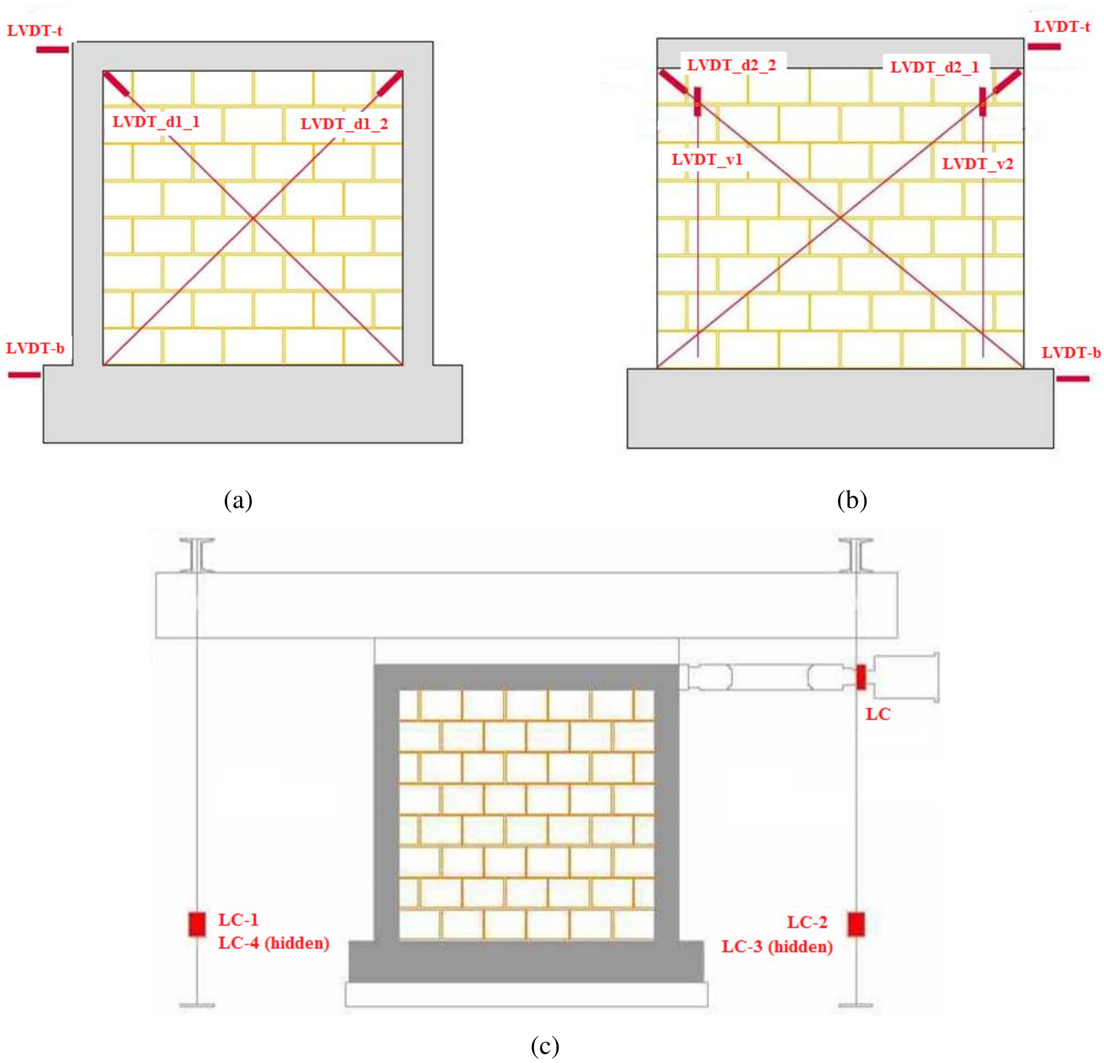

Figure 2. Layout of the measuring system: LVDT on side a (a) and on side b (b), load cells (c) (side a in view).

2.2. Experimental test program

The experimental tests, performed in displacement control, consisted of the following phases:
- pre-compression: the vertical bars were tensioned to obtain a compressive tension on the horizontal cross section of the specimen slightly greater than 0.30 MPa. This pressure is equivalent to that acting on the base of a three level residential building with walls spaced 3-4 m. The axial load applied to the bars was about 90 kN;
- horizontal cyclic load with small amplitude: this phase was necessary to avoid as much as possible the effect of the tolerances of the connections, especially those in the system connecting the reinforced concrete base of the specimen to the steel base and those connecting the steel base to the ground;
- horizontal cyclic load at increasing amplitude: the value of the load applied to the specimen increased until the collapse of the specimen was reached.

In the following the results of the experimental tests obtained for one of the regular masonry specimen (A3) and one of the confined masonry specimen (A4) are reported. Only the results concerning the third phase (application of horizontal cyclic load at increasing amplitude) is shown.

3. EXPERIMENTAL RESULTS

The tests carried out on regular masonry panel A3 (Fig. 3a) showed a good behavior under cyclic actions.

The early cracks occurred at the ends of the diagonals (Fig. 3b) and then diffused towards the center of the panel, involving a limited region (Fig. 3c-f). The crack pattern suggests a mode of failure for shear load, although a mixed mechanism for sliding shear and diagonal shear is also present.

The ultimate load for regular masonry panel was about 100 kN (Fig. 3h), which is about 50% greater than the load associated with a diagonal shear mechanism and of the same order with the load associated with a bending mechanism; the value obtained in the test may be due, besides the safety factor implied by the building code (to account for the variation due to resistance of constituting materials and the modality of realization), to the high compressive strength of the clay bricks used (which are used to build regular masonry structures in highly seismic zones) and to the careful construction of the specimen, which were built inside the laboratory used for the tests. The displacement of the top of the specimen under ultimate load was less than 10 mm (Fig. 3g).

Also in specimen A4 (Fig. 4a), built in confined masonry, the early cracks appear at the end of diagonals and then diffuse toward the center of the panel following the diagonal. The crack pattern is a classical one, with crossing diagonal cracks throughout the panel. The cracks cross the entire section of the specimen. Moreover, in the test the lateral confining element were interested by cracks at middle height (Fig. 4b).

The ultimate load for confined masonry panel was about 200 kN (Fig. 4h), which roughly double the ultimate load for regular masonry specimen. The mechanism associated to ultimate load appear to be diagonal shear (Fig. 4c-f). The displacement of the top of the specimen under ultimate load was about 18 mm (Fig. 4g), which is considerably higher than that of regular masonry specimen.

The improvement in the mechanical behavior of the confined masonry over the regular masonry can be appreciated by comparing the force-displacement curve measured during the test and shown in Fig. 5a-b: for confined masonry, the cycles reach greater values of shear load and displacement and the area enclosed by the curve (proportional to the dissipated energy) is larger.

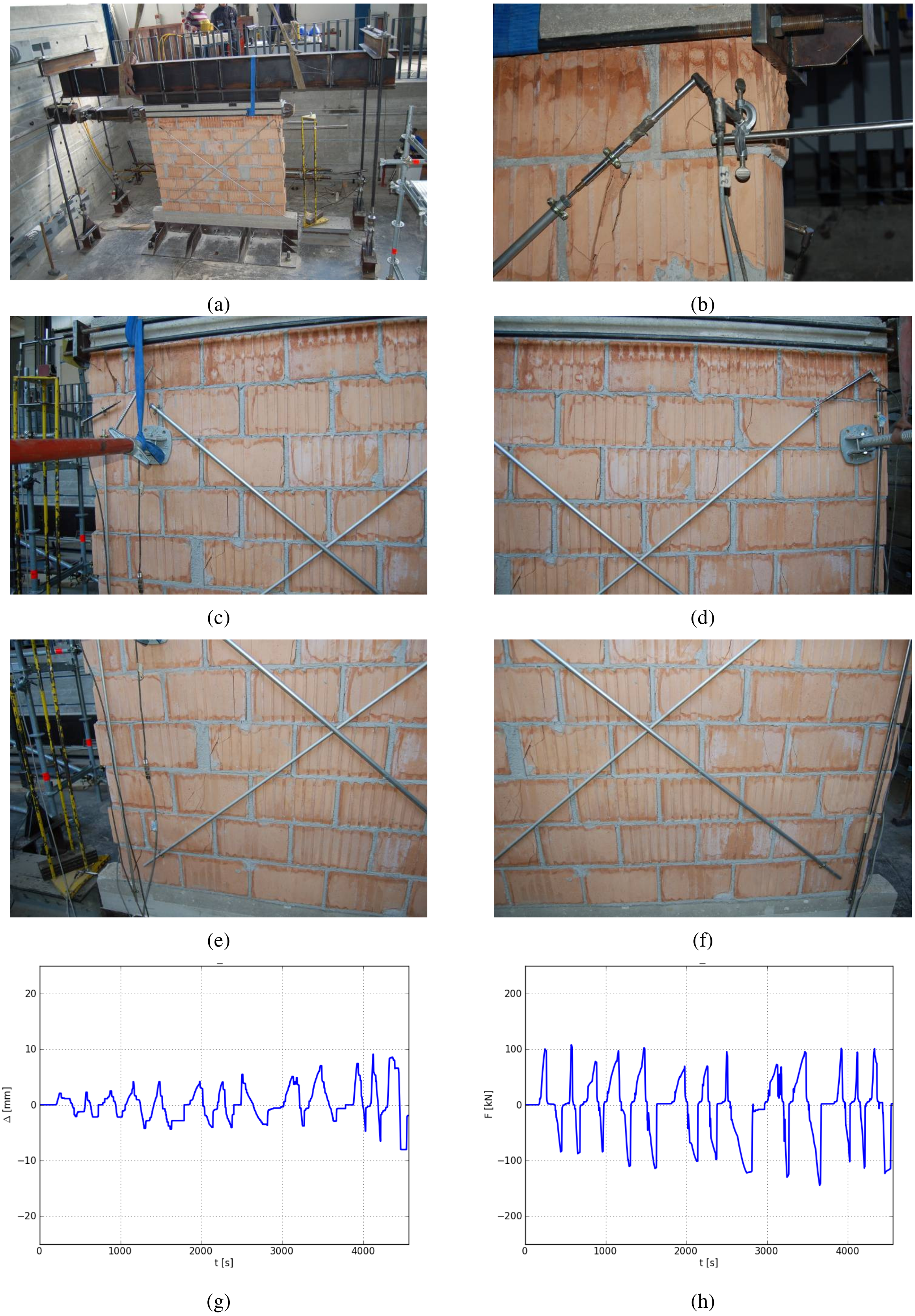

Figure 3. Test on regular masonry specimen: view of the panel (a), particular of crack (b), overall view of final crack pattern (c-f), top displacement (g) and applied force (h) time histories.

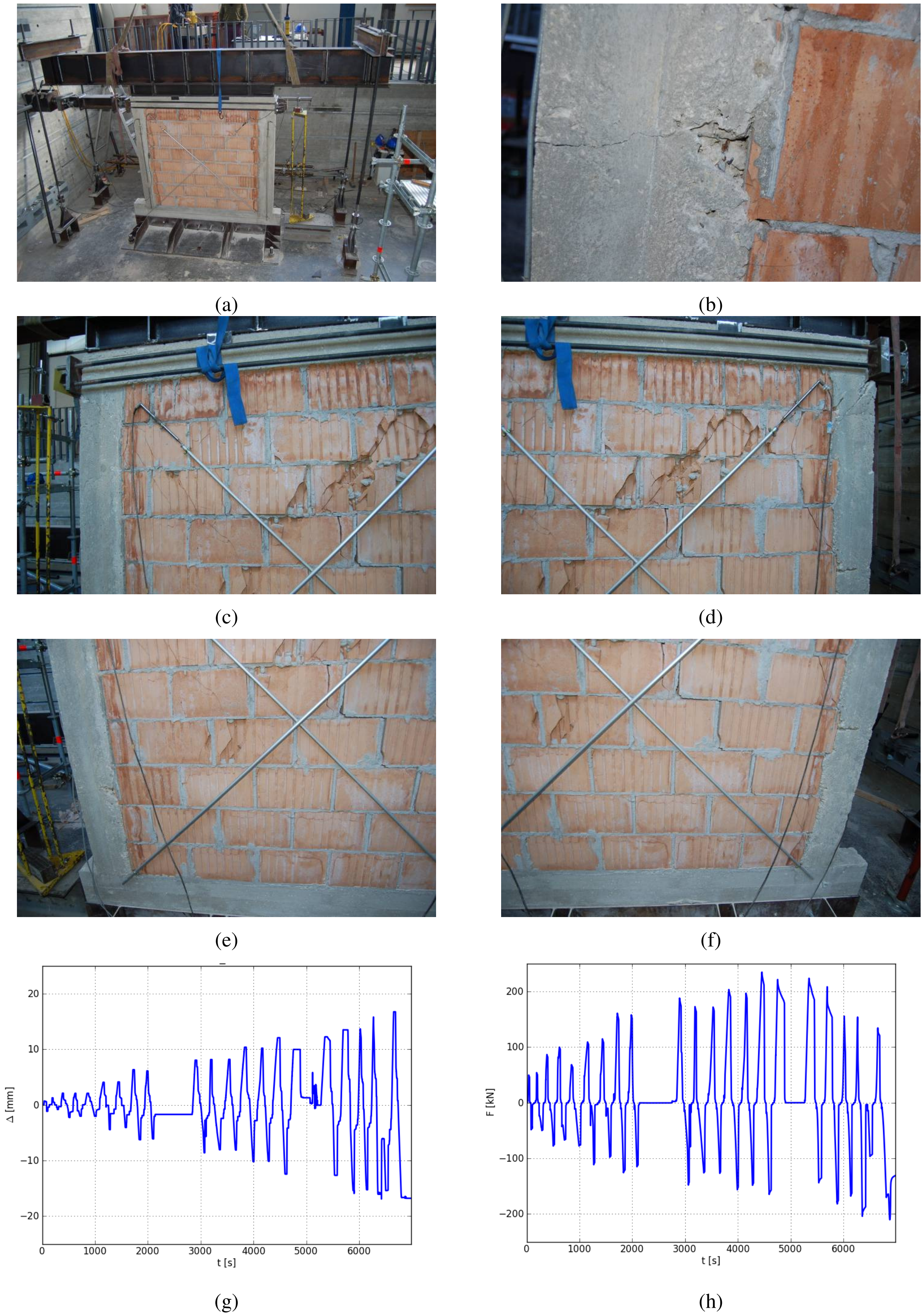

Figure 4. Test on confined masonry specimen: view of the panel (a), particular of crack (b), overall view of final crack pattern (c-f), top displacement (g) and applied force (h) time histories.

In order to estimate the dissipation of energy during the test, the work done by the shear load was calculated. In particular the work done at time $t = t_k = k \cdot \delta t$ (with δt denoting the sampling interval) by the applied load has been evaluated through the following:

$$L(t) = \int_0^t F(\tau)d\tau \Rightarrow L_k = \sum_{i=1}^{k} F_i \cdot (\Delta_i - \Delta_{i-1}) \tag{3.1}$$

In the Eqn. 3.1 F_i is the force applied by the jack and measured by the load cell LC (see Fig. 2) and Δ_i is the displacement measured by the transducer placed at the top of the specimen (LVDT-h in Fig. 2): both measure are taken at time t_i. The energy dissipated in a half-cycle in found (???) by the intersection with the vertical axis in Fig. 5c-d.

The improvement of the mechanical behavior of confined masonry over regular masonry is shown by the quality of hysteretic cycles. The dissipated energy is more than 100% greater in the case of the confined masonry specimen than in the case of the regular masonry specimen realized .

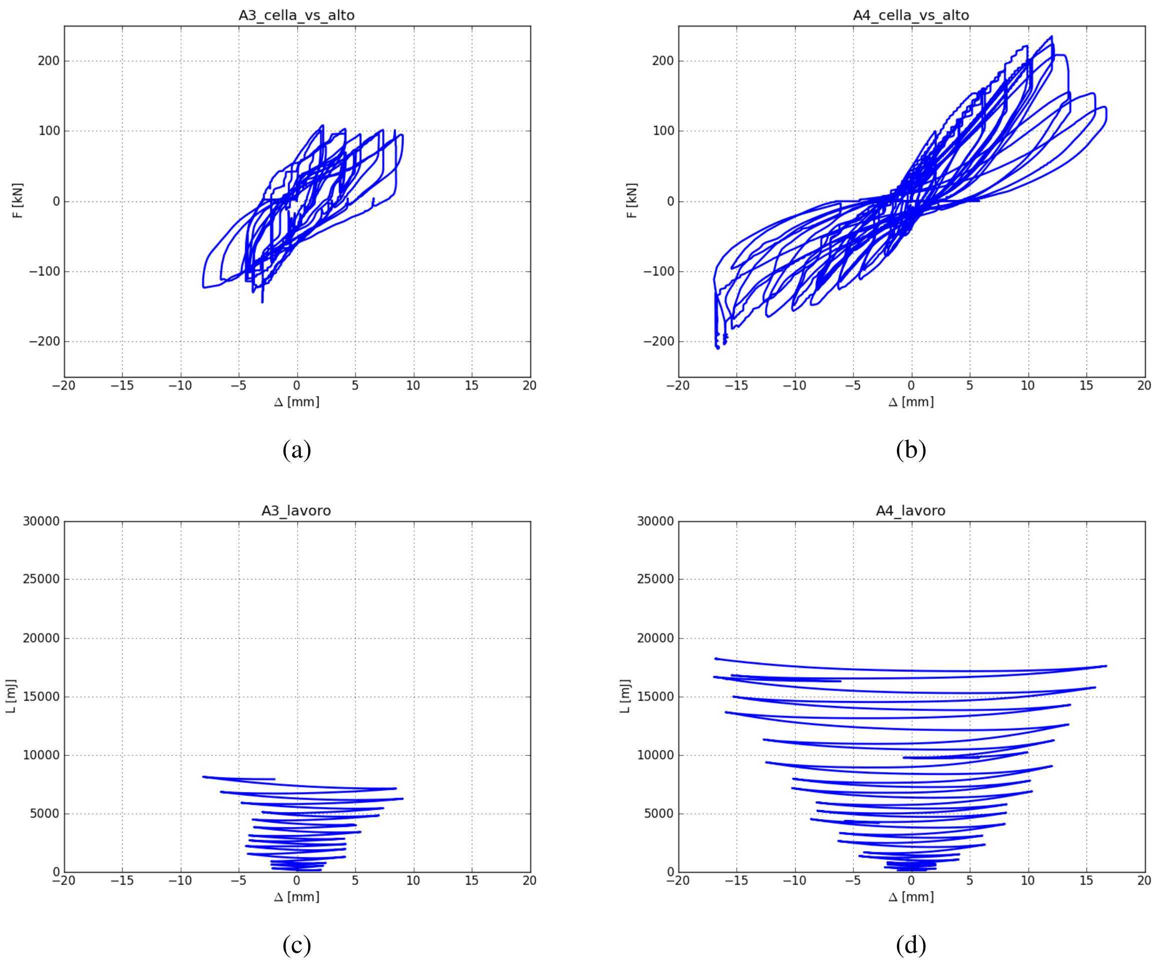

Figure 5. Force-displacement relation for regular (a) and confined (b) specimen and work done by shear force in regular (c) and confined (d) specimen.

Summarizing, the specimen in confined masonry (A4) has shown a good mechanical behavior since:
- it shown stable cycles in terms of shear load-displacements;
- the ultimate shear load increased more than 100% with respect to the one of regular masonry specimen, reaching a value of 200 kN;
- the ultimate displacement was about 50% greater than in the case of regular masonry, reaching a

value of 15 mm;
- the increase in dissipated energy was more than 100%.

The experimental tests confirmed that the contribution of the confining elements is fundamental to increase the value of both the ultimate shear load and the ultimate displacement and therefore to increase the ductility of the masonry and to dissipate more energy under cyclic loads.

It seems possible to design structures built in confined masonry using the tested materials adopting behavior factor higher than that used for regular masonry: Eurocode 8 (EN 1998-1) suggest to use q = 3.0 instead of the value q = 2.0 which is reserved to structures in regular masonry.

4. CONCLUDING REMARKS

The paper presents the results obtained in experimental tests on masonry panels built both in regular masonry and in confined masonry.

The panels were loaded with a shear force at the top applied in cycles on increasing amplitude. The results showed that the masonry panels had mechanical behavior and strength as expected: in particular the strength was sensibly greater than expected, although the failure mechanism is eminently brittle.

The panels built with confined masonry showed an increased strength and ductility, respectively about 100% and 50%. This is possible only with an accurate design of the coupling between the masonry wall and the confining reinforced concrete elements (geometrical dimensions, concrete resistance and reinforcement characteristics): in fact it must be ensured an effective overall behavior (between the masonry and the confinement) especially in the elastic-plastic phase. In particular the evolution of crack pattern in the masonry must be controlled by the confining elements which must contribute to the dissipation of energy with the development of plastic zones.

Although the specimen tests were rather few, the obtained results highlight that the increase of performance which can be obtained in masonry through confinement, well assessed in literature with reference to units of ordinary bricks, can be expected also when the units of masonry are clay bricks with high compressive strength: this could allow to use this technology in more daring structures. Moreover, the results, even if more experimentation is necessary, suggest that in designing structures in seismic areas an increased behavior factor may be used.

AKCNOWLEDGEMENT
This research was partially supported by the “Cassa di Risparmio di Perugia” Foundation within the “Bando 2010” funding.

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