Effect of transversal steel connectors on the behaviour of rubble stone-masonry walls: two case studies in Italy

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ABSTRACT: Multi-leaf masonry walls are very common in historical constructions and have been primarily designed to resist vertical static loads. Recent earthquakes have shown their high vulnerability against dynamic horizontal and static compression loads which can easily produce the detachment of the different leaves and determine important damage and catastrophic consequences. An increasing interest in the conservation of historic masonry constructions has produced a need for new consolidation and retrofitting methods. With the aim of increasing the mechanical characteristics, the overall structural behaviour and ultimately the safety of multi-leaf masonry wall panels against out-of-plane collapse mechanisms, several reinforced techniques have been investigated. In this paper, a new strengthening system which consists in the application of a pre-loaded steel bar enclosed into a fabric protective bag-case, is investigated. The steel-bar connector is inserted into a pre-drilled hole made in the masonry in order to bond the masonry leaves and to prevent the detachment during seismic events; finally cement-based grout is injected at high pressure inside the fabric bag-case. The aim is to increase the collaboration between masonry leaves and increase the wall-capacity. The paper initially describes the reinforcement technique and its fields of application and expected benefits. In the second part, the paper addresses two case studies where this reinforcing method has been recently applied: the medieval castle of Laurenzana, located in the southern Italian region of Basilicata and a coeval 18th-century annex building nearby the Royal Palace of Capodimonte (Naples).

1 INTRODUCTION

Masonry buildings are extremely common in European historical urban centres. Natural stones, easy available from local quarries, and lime-based mortars were the materials used for masonry assemblage for centuries.

The overall behaviour of a masonry construction is often governed by the quality of the masonry material and this depends on many factors, such as the compressive or tensile strengths of components (mortar and blocks), blocks shape, number of wall leaves and the grade/level of connection between them (Binda et al. 2000, Valluzzi et al. 2005, Candela at al. 2012, Borri et al. 2015).

Multiple (double- or triple-) leaf masonry walls have been often used in historical constructions and were built using two or three leaves made of different materials such as stone, rubble or brick masonry having little or no connection and possible voids between them sometimes filled with mortar and rough stones' pieces (Corradi et al. 2008). Double-leaf walls are often used when a thickness of 35-50 cm was necessary. For thicknesses bigger than 50-60 cm a triple-leaf wall is common.

For the out-of-plane behaviour of a multi-leaf masonry wall panel, the connection between wall leaves is a critical aspect (Egermann & Newald-Burg 1994, Casolo & Milani 2013). Recent earthquakes in Italy have shown the high vulnerability of multi-leaf masonry assemblages against horizontal seismic actions producing the overturning of the outdoor masonry leaf and the resulting partial or total collapse of the entire masonry structure (Corradi et al. 2002, Augenti & Parisi 2010).

The reinforcement and consolidation of multi-leaf masonry walls constitute an important task for achieving an acceptable level of safety. These wall panels may be subjected not only on their own weight but also to the possible dynamics actions (produced by earthquakes and, more rarely, by wind). Figure 1 shows an example of an out-of-plane collapse mechanism due to the separation between two leaves produced by the Umbria-Marche seismic events of 1997-1998.

Double-or triple-leaf walls (Fig. 2a) are usually subjected to two different failure mechanisms. Figure 2b presents the out-of-plane mechanism of a double-leaf masonry wall subjected to a horizontal seismic action.

Figure 1. Example of separation between two leaves of masonry due to seismic action.

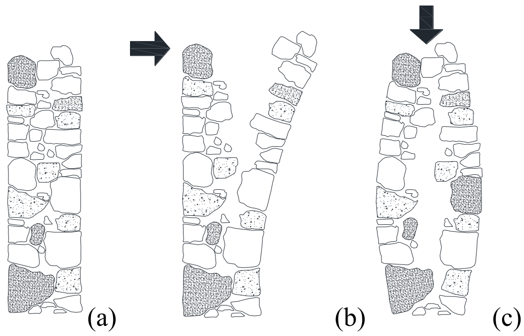


Figure 2. Leaf masonry wall failure mechanism: (a) un-loaded panel; (b) panel subjected to a horizontal load; (c) panel subjected to a compression vertical load.

Consequently, the capacity of the wall to resist horizontal loads is smaller when compared with the one of a well-connected masonry wall. Multi-leaf masonry walls exhibit disadvantages also when subjected to high compression loads; this could again produce the detachment of the two leaves and the failure of the wall (Fig 2c).

Binda et al. (2006) carried out an experimental campaign and also developed a model in order to investigate the load-transfer mechanism in multi-leaf masonry walls.

In the last two decades different strengthening techniques have been proposed in order to improve the connection between wall leaves. Several researchers have studied the behaviour of the multi-leaf masonry walls reinforced by grout injections (Tomazevic et al. 1991, Silva et al. 2014). This method consists in filling the voids and cracks between the leaves using a inorganic grout (typically cement or lime-based). Vintzileou & Tassios (1995) and again Vintzileou & Miltiadou-Fezans (2008) tested in compression triple-leaf masonry panels before and after the injection. Results showed a significant increase of the masonry mechanical properties. This reinforcing method is not effective for walls with a low index of voids, due to the difficulty for the grout to spread inside the walls.

Another method to increase the level of bonding between the leaves is to insert transversal connectors. This method is not new. Artificial (Reinforced concrete) or natural (stones or bricks) transversal elements have been used in the past to strengthen multi-leaf walls.

Oliveira & Lourenço (2006) used two 10mm-diameter GFRP (Glass Fiber Reinforced Polymer) bars to connect multi-leaf masonry specimens made in laboratory. By testing these in compression, a strength increase of approx. 71% was measured compared with the unreinforced specimens.

Valluzzi et al. (2004) tested several triple-leaf masonry panels in compression after having applied a transversal confinement using two different types of steel ties. Results of the laboratory tests also show the effectiveness of the reinforced technique in terms of reduction of the panels horizontal deformations.

Pinho et al. (2015) tested rubble multi-leaf stone-masonry specimens reinforced with zinc-coated steel ties. and by applying a GFRP grid reinforced lime-based plaster. Results highlights an increase of the shear strength of approx. 200% compared with the unreinforced specimens.

This paper describes a new innovative reinforcement technique, used to improve the global behaviour of poor quality masonry made of different wall leaves, sometimes built in a different time, characterized by weak level of connection or bonding between them. The system proposed is particularly suitable for fair-faced masonry walls, because it allows keeping the fair-faced aspect and consisted in the insertion of a steel transversal connector by drilling the masonry panel. This steel element is inserted into a special fabric sleeve or bag-case, which is able to expand and adapt its shape to the surface of the hole. Before injecting the grout inside the sleeve with a small nylon tube, the steel bar can be pre-loaded in tension with a standard torque wrench.

Some of the authors of this study have investigated in the past the effectiveness of a similar reinforcement technique by laboratory and in-situ tests (Borri et al. 2012). Two case-studies will be also illustrated, discussed and commented in this paper: the medieval Laurenzana Castle and the goat house building of the Capodimonte Royal Palace.

2 DESCRIPTION OF THE REINFORCEMENT TECHNIQUE

The strengthening system (Fig. 3) consists in a steel bar inserted in a mesh fabric sleeve (bag-case). This is injected at high-pressure (3-5 atm, depending on the quality of the masonry material) using a high-strength cement-based grout. The fabric sleeve avoids unexpected and often damaging scattering and wastefulness of the grout between the masonry leaves and increases the level of connection of the injected material to the masonry surface throughout its entire length.

Figure 3. Anchor with fabric bag-case.

The reinforcement technique can be used equally on regularly shaped (perfectly cut stonemasonry, or brickwork) walls or irregular (rubble or pebble stone masonry) walls made of natural stone blocks of various sizes and shapes.

The reinforcing system is based on the use of materials easy to find on the construction market (threated steel bars, fabric bag-cases, cement-based grout) and it is described in the following paragraphs.

2.1 *Steel bar*

The nominal diameter and the material properties can be selected according the application (type of masonry, acting static loads, wall thickness, etc.). Standard bar diameters are between 16 and 20 mm. The bar is usually threated to improve bonding with the grout and allow the application of the pre-load. In order to apply a horizontal compression stress on the masonry, steel bar can be pre-loaded in tension by tightening of the free part of the anchorage. In this application, steel bar used are characterized by a design tensile ultimate and yield strength of 750 and 650 N/mm^2, respectively. In order to guarantee durability of the intervention stainless steel AISI 304 is usually used to manufacture the element.

2.2 *Fabric bag-case*

The fabric bag-case is manufactured with a particular fabric sleeve, capable to expand and adapt itself to the hole's surface and irregularities. The fabric of the case is made of a particular porous membrane, specially designed to hold the grout. The fabric bag-case characteristics also allow an effective mechanical bond to the masonry substrate, moreover the grout can leaks superficially, because of the substrate porousness, and act as a direct-contact binder with the original masonry. Figure 4 shows different phases of the grout injection in the bag-case.

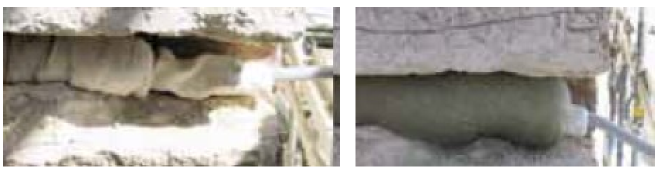


Figure 4. Different phases of the grout injection of the fabric bag-case.

Table 1. Mechanical characteristics of the grout as declared by the producer.

Mean compressive strength [N/mm^2]	Mean flexural strength [N/mm^2]	Young's modulus [N/mm^2]
51.5	4.5	28000

2.3 *Grout*

The material used for the injection is a commercially available high-strength cementitious grout specially designed to be injected into the fabric bag-case. The injection material is a ready-to-use grout containing graded aggregates and other constituents which, when mixed with water, produces grout that exhibits no shrinkage. Table 1 shows the mechanical characteristics of the grout injected into the sock, according to the producer data sheet.

3 PROCEDURE FOR REINFORCING A MASONRY WALL

The procedure for reinforcing a masonry wall panel using the system suggested in this paper is carried out in the following stages:

- drilling the masonry panel using a machine equipped with diamond bits (Fig. 5a), which work only with rotation movements in order to avoid percussion and vibration effects on the masonry. Hole's diameter is evaluated according to the anchors size: it is usually about three times the steel bar diameter. It is important to use the correct borehole diameter in order to guarantee an easy insertion of the anchor equipped with fabric bag-case; moreover the adherence surface is strictly influenced by the drilling diameter;

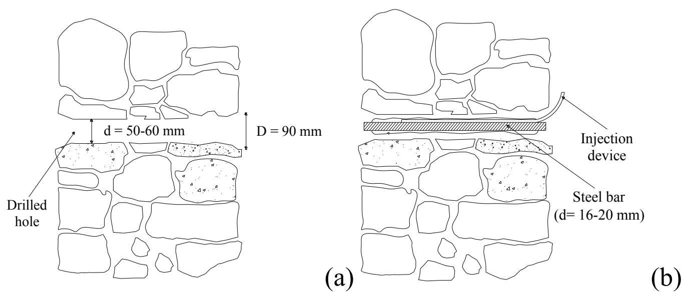


Figure 5. Reinforcement procedures: (a) drilling the masonry; (b) application of the anchor in the drilled hole.

- the reinforcement, made of the steel bar, supplied with the special fabric bag-case, is assembled on-site, and then applied inside the holes (Fig. 5b). The connection between the different parts is obtained with full strength couplers and special turnbuckles in case of tendons designed to contain the drift of pushing elements such arch and vaults;

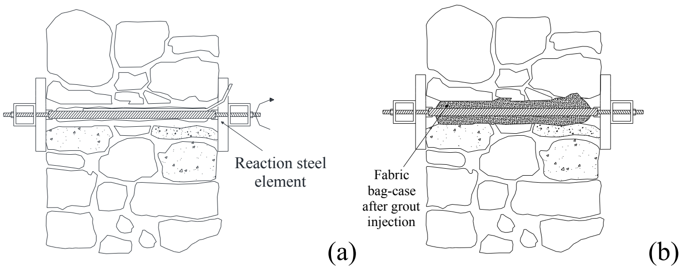


Figure 6. Reinforcement procedures: (a) pre-stress of the steel bar using a torque wrench which applied load on reaction steel element; (b) grout injection.

- the steel bar, installed inside the hole, can be pre-loaded using a torque wrench (Fig. 6a); a reaction steel frame is used to keep applied the pre-load.
- grout is then injected through the plastic injection device at high-pressure values between 3 and 5 bars (Fig. 6b). The value of the grouting pressure depends on the quality of the masonry and on the vertical compression stress acting on it at the level of the application of the connector. For good quality masonry walls subjected to high compression stresses, it is possible to use a high pressure value. The effective anchor's length is another aspect to consider: this depends on the thickness of the wall. The injection should be done gradually until the anchor is fully injected;
- after the injection grout is cured for 28 days;
- the reaction steel element used to pre-load the reinforcing bar is removed;
- masonry joints are repointed on both sides of the drilled hole (Fig. 7). The reinforcing intervention is completely invisible.

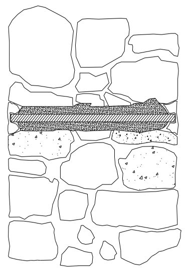


Figure 7. Restoring of the masonry on both sides of the drilled hole.

As a result of these operations, each leaf of the wall is connected to the adjacent one. Upon completing the operations described above the system is perfectly incorporated into the wall but not visible from outside respecting the original fair faced of the strengthened building and capable of improving the panel mechanical characteristics (compression strength, shear strength, monolithic behaviour and improving against out of plane failure mechanism).

4 FIELDS OF APPLICATION AND EXPECTED BENEFITS

As already stated, the proposed reinforcement technique is suitable for multi-leaf masonry panels, mainly stonemasonry walls. It complies with the values underlying the protection of historical buildings:

- "long lasting", since the materials used have a high resistance to chemical and physical aggression;
- "compatible" with preservation of the original material, as it is able to adapt and integrate perfectly inside the wall;
- Intended to integrate the structure without transforming it.

The possible advantages from the mechanical point of view are:

- Improved the transversal connection between the different masonry leaves of the wall;
- improved the monolithic behaviour against out of plane mechanism produced by horizontal loads (Fig. 8a);
- improved the monolithic behaviour against mutual horizontal detachments caused by high compression loads (Fig. 8b);
- improved mechanical characteristics in terms of compressive and shear strength.

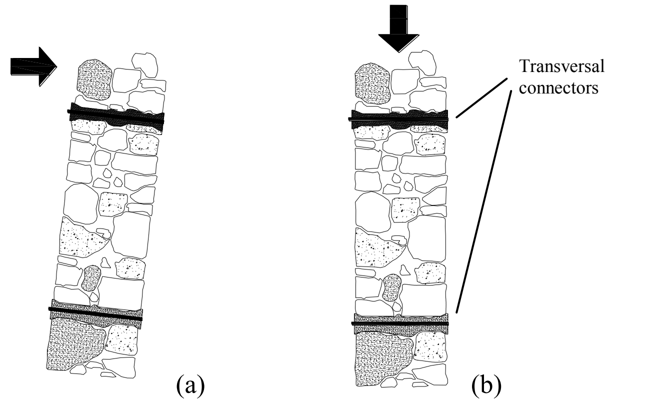


Figure 8. Leaf masonry wall behaviour expected after the reinforcement: (a) panel subjected to a horizontal load; (b) panel subjected to a compression vertical load.

The reinforcement has been designed considering the overturning mechanism of the monolithic masonry wall and using a theoretical approach to evaluate the collapse - load factor (α). The overturning moment ($M_{R(A)}$) causing the rotation of the wall about the hinge A is:

$$M_{R(A)} = \alpha \cdot (W \cdot y_G + F_V \cdot h_V + P_S \cdot h) \quad (1)$$

The resisting moment ($M_{S(A)}$), withstanding the panel rotation, is given by the following:

$$M_{S(A)} = W \cdot \frac{s}{2} + F_V \cdot d_V + P_S \cdot d \quad (2)$$

In Figure 9a, W is the weight of the masonry wall panel and y_G is the distance of the panel's centroid from hinge in A and s is the wall thickness. F_V is the vertical load due to the presence of a floor or roof and h_v and d_V are the vertical and horizontal distances from the point of application of load to the point A. P_S is the vertical load due to the weight of the floor above the masonry wall and h and d are the vertical and horizontal distances from the load to the point A. Combining equations (1) and (2), the collapse – load factor is equal to:

$$\alpha = \frac{W \cdot \frac{s}{2} + F_V \cdot d_V + P_S \cdot d}{W \cdot y_G + F_V \cdot h_V + P_S \cdot h} \qquad (3)$$

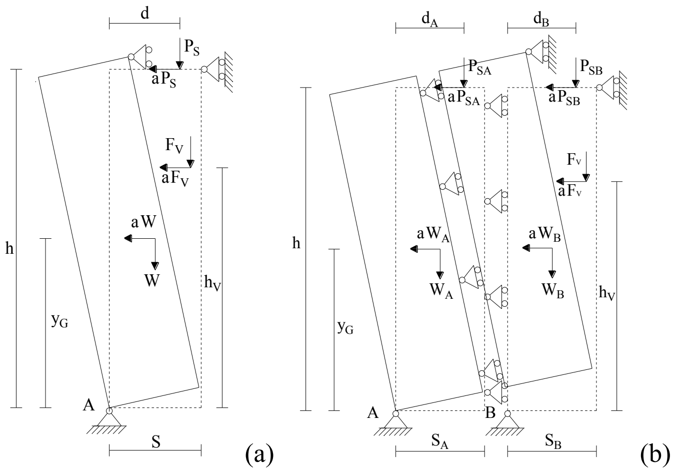


Figure 9. Overturning mechanism: (a) monolithic masonry wall. (b) double-leaves masonry wall.

Figure 9b shows the overturning mechanism for a double-leaf masonry panel. The collapse – load factor is given here by:

$$\alpha = \frac{W_A \cdot S_A + W_B \cdot S_B}{2[(W_A + W_B) y_G + F_V \cdot h_V + (P_{SA} + P_{SB})h]} + \\ + \frac{P_{SA} \cdot d_A + P_{SB} \cdot d_B + F_V \cdot d_V}{(W_A + W_B) y_G + (P_{SA} + P_{SB})h} \qquad (4)$$

5 CASE STUDIES ON THE APPLICATION OF THE REINFORCEMENT TECHNIQUE

In this section two real case studies, in which the above defined reinforcement technique has been used, are described. Two different historic masonry buildings have been reinforced with the above described technique in order to improve their mechanical behaviour and preserve them from possible damage and failure.

5.1 *Laurenzana Castle*

The castle is located on the cliff top of the village of Laurenzana in the southern Italian region of Basilicata. It was built approx. around 1150 after the Normans conquest on a previous Longobard fortress. The castle (Fig. 10) was conceded to Basilian monks as hermitage. For a time, it was occupied by Muslim forces from Africa. By the middle of the 13th century, the castle was used by the Swabian rulers, then the Angevins, then the Aragonese.

After 1454, it became a feudal property of different aristocratic families. In 1483, the owner, Raimondo Orsini Del Balzo, began converting it into a residence. It then passed to the families of the Dukes of Belgioioso, who owned it till the early 1800s. The castle was inhabited until the early decades of the twentieth century and its abandonment was emphasized after the Second World War with several collapses such as the west façade and the roofs. The castle is listed in the Italian inventory of cultural property.

Figure 10. Laurenzana castle.

The existing walls are made of barely cut stone-masonry bonded with a weak (pulverulent) lime-based mortar, often damaged from excessive water action. The walls are made of 3 adjacent masonry leaves (triple-leaf walls) with a total thickness varying between 100 and 169 cm. The strengthening intervention has interested these massive walls, which are located near the main entrance of the castle (Fig. 11). The masonry arrangement is shown in Figure 12. Stones with larger dimension of approx. 35 cm were used together with smaller pinning stones, needed to increase the stability of larger stones. The three masonry leaves are weakly connected to each other. In order to increase the transversal connection of the different layers the technique described in the previous paragraphs has been choice by the authors. Twenty eight connectors GBOS 20-60 P characterized by steel bar with nominal diameter of 20 mm have been placed in a hole with diameter of 60 mm while the both sides of the hole were characterized by a diameter of 90 mm (Fig. 13a) to allow the prestress of the bar.

Figure 11. Main entrance of the castle where the connectors have been applied.

Figure 12. Masonry arrangement of the Laurenzana castle.

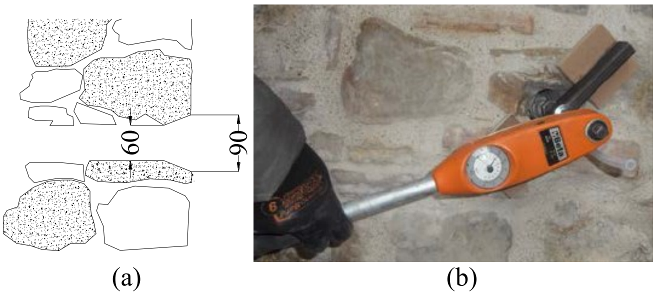


Figure 13. (a) Geometry of the of the hole drilled in the masonry (dimension in mm). (b) pre-stressing of connectors.

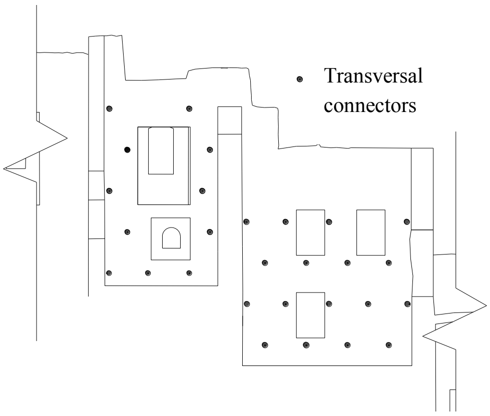


Figure 14. Arrangement of the position of the connectors.

The length of the bars varied between 960 and 1650 mm and the mutual distance in the horizontal and vertical direction between the connectors was around 1500 mm and they have been placed in according with the geometry in Figure 14. The holes have been drilled with drilling machines with diamond bits that work only with rotation movement in order to avoid vibration and percussion effects on the masonry panels. The anchors, supplied with the special sock, are installed inside the holes and pre-stressed with 3.92 kN using a torque wrench which applied load on reaction steel elements (Fig. 13b) and the grout has been injected inside the sock with a pressure between 3.0 and 3.5 bar.

Finally, the grout was cured for 28 days, the reaction steel elements were removed and the both sides of the hole have been restored.

5.2 *Goat house of the Royal Palace of Capodimonte*

The goat house of the Royal Palace of Capodimonte is a stonemasonry construction made in the same period of the Royal Palace. The house is located inside the Capodimonte park. In 1738, Charles VII ordered the construction on the Capodimonte hill which has been completed in 1840 by Ferdinand II (Fig. 15). The building is listed in the Italian inventory of cultural property of national significance.

Figure 15. View of the goat house nearby the Royal Palace of Capodimonte.

Figure 16. Tuff masonry arrangement of the goat house of the Royal Palace of Capodimonte.

In 1861, after the Italian unification, the Royal Palace passed to the House of Savoy. In the early 20th century, the palace became the residence of the Dukes of Aosta and later, in 1920 it became the property of the Italian state. Finally, from 1950 it has been used as museum.

The goat house is a two storey building made of tuffstone masonry walls and vaults (Fig. 16). Tuff was the typical stone of the area coming from local quarries. Double-leaf wall panels were used when a thicknesses between 46 and 55 cm was required. For larger thicknesses (between 57 and 103 cm) completely disconnected triple-leaf masonry have been used during the construction phases. All walls were assembled using barely cut tuffstone bonded with a very weak lime-based mortar and externally plastered.

The ground floor was used for housing the animals while the first floor as a residence for the farmers. In order to increase the transversal connection of the two disconnected layers, the same technique used in the previous building has been considered.

16mm-diameter steel-connectors (type GBOS 16-50 P) have been used (Fig.17a) to bond the masonry leaves together. A total of 78 50mm-diameter holes were drilled on the building perimeter walls. To allow the application of a tensile pre-load on the steel bar, holes were enlarged near the wall surface to a diameter of 90 mm (Fig. 17b). The length of the bars varied between 420 and 990 mm depending on the thickness of the wall panels and the centre-to-centre distance in the horizontal and vertical direction between the connectors was approx. 2000 mm. Figure 18 shows the arrangement in the north-east façade. A professional non-percussion rotary hammer drill with an active vibration control system and a 90 mm-diameter diamond core drill bits hole cutter were used to drill the holes (Fig. 19).

(a) (b)

Figure 17. (a) 16 mm-diameter steel connector before insertion; (b) hole countersinking.

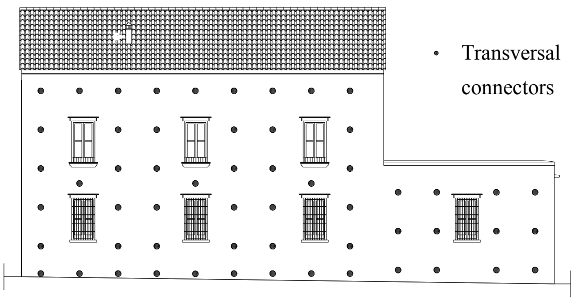
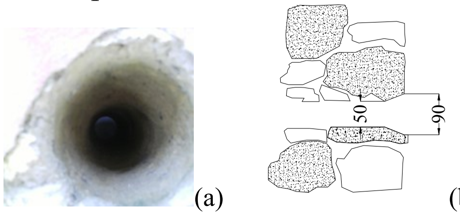


Figure 18. Arrangement of the connectors.

The steel bars, supplied with the special fabric bag-case, are then installed inside the holes (Fig. 20a). A tensile pre-load of 7.84 kN was also applied using a standard torque wrench. It was possible to keep the steel bars under loading using a reaction steel element (Fig. 20b). Finally the cement-based grout has been injected inside the fabric bag-case at pressure of 2.5 bar (Fig. 21a). The grout was cured for 28 days (Fig. 21b). At the end of this period, the reaction steel element was removed and the surface of hole repointed with new mortar to be invisible.



(a) (b)

Figure 19. (a) View of a hole realized on the goat house building; (b) Geometry of the of the hole drilled in the masonry (dimensions in mm).

(a) (b)

Figure 20. (a) Insertion of the steel bar; (b) pre-load application.

(a) (b)

Figure 21. (a) Grouting operation; (b) the reinforcement during curing time.

6 CONCLUSIONS

This paper describes an innovative technique for reinforcing historic masonry wall panels. The method is intended mainly for multi-leaf stonemasonry walls, often subjected to catastrophic out-of-plane mechanisms when stressed with horizontal dynamic actions or serious vertical compression static loads.

By applying a threaded 16 or 20mm-diameter steel bar inserted into a fabric bag case injected at high-pressure using a high-strength cement-based grout, it is possible to increase the collaboration between adjacent masonry leaves. In order to improve the level of connection between the different masonry leaves, before injecting the grout material, the steel bar can be also pre-loaded using a standard torque wrench and . This will produce a tensile stress in the steel bar and a subsequent horizontal compressive stress in the masonry material.

The main result is the improvement of the connection between the masonry leaves. This can highly contribute to increase the wall-capacity against seismic out-of-plane horizontal forces.

The strengthening technique can be applied on listed masonry buildings because it is not produce transformations in the structure and preserve its original aspect and it is long-lasting thanks to use of very durable materials (inorganic mortars, stainless steel).

Two case-studies, where the reinforcement technique has been applied, have been studied and described in the paper in order to verify if the reinforcement technique can be effectively applied on a real structure. The historic constructions are the Laurenzana Castle, built in 1150 by Normans and the goat house, an annex building of the Royal Palace of Capodimonte. The masonry arrangement of both constructions is constituted by a barely cut stone-masonry bonded using a weak lime-based mortar. At the castle, twenty-eight 20mm-diameter steel connectors were used to reinforce a wall of a surface of 85.1 m^2. The connectors' nominal centre-to-centre distance in the horizontal and vertical directions was 1500 mm. In the annex building of the Royal Palace of Capodimonte, seventy-eight connectors made of 16mm-diameter steel threated bars have been installed. For the north-east façade fifty-seven 16mm-diameter steel connectors have been applied to strengthen a total surface of 255.2 m^2.

An accurate analysis of the application procedures has demonstrated the feasibility of the reinforcement technique for on-site scenarios. In detail, no difficulties were found both in the application of the tensile pre-load on the steel bar and in the injection of the fabric bag-case. Also the small steel reaction-frame was able to keep on acting the tensile pre-load.

An experimental investigation is actually ongoing in laboratory to measure the increase in terms of compressive vertical capacity of double-leaf stone-masonry wall panels. These further results will be used to have a better understanding of the effectiveness and feasibility of the proposed reinforcement technique.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Augenti, N. & Parisi, F. 2010. Learning from construction failures due to the 2009 L'Aquila, Italy, earthquake. *Journal of Performance of Constructed Facilities* 24(6): 536-555.

Binda, L., Pina-Henriques, J., Anzani, A., Fontana, A. & Lourenço, P.B. 2006. A contribution for the understanding of load-transfer mechanism in multi-leaf masonry walls: Testing and modelling. *Engineering Structures* 28(8): 1132-1148.

Binda, L., Saisi, A. & Tiraboschi, C. 2000. Investigation procedures for the diagnosis of historic masonries. *Construction and Building Materials* 14(4): 193-233.

Candela, M., Cattari, S., Lagomarsino S., Rossi, M., Fonti, R. & Pagliuca, E. 2012. In-situ test for the shear strength evaluation of masonry: the case of a building hit by L'Aquila earthquake (Italy). In *Proc. 15th World Conference on Earthquake Engineering (WCEE 12) 24-28 September 2012,* Lisbon, Portugal.

Borri, A., Corradi, M., Castori, G. & De Maria, A. 2015. A method for the analysis and classification of historic masonry. *Bulletin of Earthquake Engineering* 13: 2647-2665.

Borri, A., Savelli, R. & Poverello, E. 2013 Diatoni artificiali attivi a espansione: alla ricerca di un comportamento monolitico del pannello murario. In *proceedings of 15th Italian National Conference of Earthquake Engineering (ANIDIS)*, Padua (Italy). (only available in Italian).

Casolo, S. & Milani, G. 2013. Simplified out-of-plane modelling of three-leaf masonry walls accounting for the material texture. *Construction and Building Materials*, 40: 330-351.

Corradi, M., Borri, A. & Vignoli, A. 2002. Strengthening technique tested on masonry structures struck by the Umbria-Marche earthquake of 1997-1998. *Construction and Building Materials* 16(4): 229-239.

Corradi, M., Tedeschi, C., Binda, L. & Borri, A. 2008. Experimental evaluation of shear and compression strength of masonry wall before and after reinforcement: Deep repointing. *Construction and Building Materials* 22: 463-472.

Egermann, R. & Newald-Burg, C. 1994. Assessment of the load bearing capacity of historic multiple leaf masonry walls. In *Proc. 10th Int. Brick and Block Masonry Conf.,* Calgary, Canada: 1603-1612.

Oliveira, D.V. & Lourenço, P.B. 2006. Experimental behaviour of three-leaf stone masonry walls. *In proceedings of the conference and brokerage event: The construction aspects of built heritage protection.* Dubrovnik, Croatia, *14-17 October 2006.*

Pinho, F.F., Lúcio, V.J. & Baião, M.F. 2014. Rubble stone masonry walls strengthened by three-dimensional steel ties and textile reinforced mortar render, under compression and shear loads. *International Journal of Architectural Heritage* 9(7): 844-858.

Silva, B., Dalla Benetta, M., da Porto, F. & Modena, C. 2014. Experimental assessment of in-plane behaviour of three-leaf stone masonry walls. *Construction and Building Materials*, 53: 149-161.

Tomazevic, M., Weiss, P., Velechovsky, T. & Apih, V. 1991. The strengthening of stone masonry walls with grouting. In *Structural repair and maintenance of historical buildings. Vol. 2: dynamics, stabilisation and restoration*: 215-225.

Valluzzi, M.R., Binda, L. & Modena, C. 2005. Mechanical behavior of historic masonry structures strengthened by bed joints structural repointing. *Construction and Building Materials* 19: 63-73.

Valluzzi, M.R., Da Porto, F. & Modena, C. 2004. Behaviour and modelling of strengthened three-leaf stone masonry walls. *Materials and Structures* 37: 184-192.

Vintzileou, E. & Tassios, T.P. 1995. Three-leaf stone masonry strengthened by injecting cement grouts. *Journal of Structural Engineering* 121(5): 848-856.

Vintzileou, E. & Miltiadou-Fezans A. 2008. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime based grouts. *Engineering Structures* 30(8): 2265–2276.