Available online at www.sciencedirect.com

ScienceDirect

Structural Integrity Procedia 00 (2019) 000–000

Structural Integrity Procedia

www.elsevier.com/locate/procedia

25th International Conference on Fracture and Structural Integrity

Optimizing strengthening interventions on historic masonry walls: an experimental study

Aikaterini Marinelli[a] *, Salomi Santa[a], Andreas Spiliopoulos[b], Maria Eleni Dasiou[b]

[a]School of Engineering and the Built Environment, Edinburgh Napier University, Merchiston campus, EH10 5DT Edinburgh, Scotland
[b]School of Civil Engineering, National Technical University of Athens, Zografou Campus, 157 73 Athens, Greece

Abstract

Scotland's historic environment is an essential part of the country's cultural background and its economy. The country has a long history of building with stone and among the richest legacies of traditional and historic buildings in the United Kingdom. The effects of ageing, environmental conditions and past natural hazards can cause significant degradation, urging for action. The connection between distinct structural wall parts together with the characteristics and condition of all materials involved, define the structural response and strongly influence the extent and requirements for retrofitting interventions. This experimental study investigates a strengthening technique for rubble walls based on the insertion of a commercially available anchoring system, currently used in monuments by Historic Environment Scotland. It aims at providing quantitative data for this repair method in terms of the anchoring system's pull-out strength, paving the way for a parametric investigation of factors affecting the efficiency of the intervention towards its optimisation, in terms of both cost and structural performance.

Keywords: masonry, rubble walls, strengthening methods, transverse anchors, pull-out test

1. Introduction

Engineering problems related to conservation and restoration of Cultural Heritage are attracting increasing attention by researchers, offering opportunities for novel research and industry collaborations. Given the high demand for strategies aiming at the protection of the Structural Cultural Heritage, developing sustainable methodologies for the

* Corresponding author. Tel.: +44 (0) 131 455 2553.
E-mail address: A.Marinelli@napier.ac.uk

use of a variety of civil engineering materials and systems is fundamental for optimizing their global behaviour and standardizing intervention techniques. Such techniques should both meet the most up-to-date codification issues and comply with the philosophy and principles that have as a starting point the International Charter for the conservation and restoration of monuments and sites, known as 'The Venice Charter -1964' (ICOMOS 1965).

Whatever its scale or scope, an intervention starts eventually as a critical act of a similar nature to design (Bonelli 1963) weighting the values the historic building carries forward and fruitfully integrating them in the project. To safeguard the essence and character of historic buildings, interventions aim at the minimum disturbance of the structural scheme while preserving it for the future, through strengthening and repairs. Prescriptions and recommendations though for historic structures are mainly qualitative and offer only partial support to end users wishing to look for alternatives to well-established systems.

The rehabilitation and conservation of historic stone masonry buildings is a matter of great importance around the world, as it is related with the need to improve and extend the life of a structure for new conditions of use and to protect our cultural heritage. Historic masonry varies widely in terms of bond, type of units and mortar joints, ranging from the most rudimentary (Dark Ages) to almost sculptural effects (Baroque) (Theodossopoulos 2012).

Scotland is often referred to as 'a nation of stone', typified by its historic masonry buildings and castles. Rubble walls constitute a popular but not extensively studied structural typology, being multi-leaf walls comprising external skins of cut stones connected by an internal leaf of irregular, unsquared ones. The connection between distinct structural wall parts together with the characteristics of all materials involved, define the structural response and strongly influence the extent and requirements for retrofitting interventions. For the Scottish heritage building stock, the effect of ageing, environmental conditions and past natural hazards have caused significant degradation, urging for action (Hyslop et al. 2006, Theodossopoulos 2012). It is thus a priority for the Scottish Government to develop a long-term Infrastructure Investment Plan for restoring, enhancing and conserving the built heritage.

The structural function of masonry wall panels was considered in the past as limited to the provision of resistance against only vertical compression loads, while ignoring out-of-plane forces. As a result, prior structural analysis was mainly focused on the analysis of the in-plane behaviour of masonry wall panels and strengthening techniques aiming to improve it, such as surface reinforcement using steel/aluminium meshes or composite materials, grout injection and deep repointing of mortar joints (Tomazevic et al. 1991, Stratford et al. 2004, Vintzileou 2006, Vintzileou and Miltiadou-Fezans 2008, Adami and Vintzileou 2008, Borri et al. 2014, Corradi et al. 2017).

Generally poor behaviour of masonry structures under out-of-plane load effects is due to the lack of resistance in tension, small deformation capacity and low ductility. With the out-of-plane behaviour having received less attention, there are fewer studies present in the literature (Grifftih et al. 2003, De Felice and Giannini 2007, Corradi et al. 2017), especially for multi-leaf stone masonry walls. This common in Scotland typology, in the form of rubble walls, is a cause for unsatisfactory performance under both vertical and horizontal forces. Non-uniform distribution of vertical stresses across the masonry leaves can lead to buckling effects, while the mechanical properties of the interior leaf are weak and the collaboration between external and internal ones is generally questionable (Adami and Vintzileou 2008).

Multi-leaf walls are found to be vulnerable to out-of-plane actions by soil pressure, wind or earthquake (Corradi et al. 2017). In this case, masonry mechanical parameters are not the decisive ones for the overall out-of-plane behaviour, since the level of collaboration between external and internal (rubble) leaves governs. The use of hydraulic grouts or transverse connectors to enhance this collaboration has been experimentally studied (Tomazevic et al. 1991, Grifftih et al. 2003, Corradi et al. 2008, Adami and Vintzileou 2008, Corradi et al. 2017). Continuous and efficient connections prevent out-of-plane mechanisms, so that the shear capacity of the masonry is activated instead and, under excessive loads, in-plane damage takes place (Corradi et al. 2017).

In this context, the Conservation Directorate of Historic Environment Scotland (HES), the public body responsible for caring for Scotland's historic environment, currently implement a strengthening technique for rubble walls, aiming at re-instating the collaboration between masonry leaves. This is realized through the placement of a commercially available anchoring system, using a steel bar enclosed in a mesh fabric sleeve, into which a specially developed grout is injected under low pressure. This research, coordinated by Edinburgh Napier University (ENU), aims at identifying the specific requirements of the rubble wall typology in Scottish monuments and specifying how these can be met by a strengthening system that is readily implemented and reliable.

2. Case study

2.1. The site: Bothwell castle

At the time of the research, a restoration project was under way on the Latrine Tower at Bothwell Castle, South Lanarkshire and this was used as a case study. Bothwell Castle (Fig. 1a), built on a grand scale in the late 1200s, was hotly fought over during the Wars of Independence with England and frequently passed back and forth between English and Scottish hands. The structure was conceived as a five-sided curtain wall castle dominated by a massive circular tower at the southwest angle. There were to be additional circular angle towers, a rectangular side tower and a twin-towered gatehouse. The overall plan can still be traced through excavated footings, however, only the southwest tower, south curtain wall and one of the angle towers were completed. The east side of the castle was defended by additional earthworks which survive as a banked ditch (Historic Environment Scotland 2019).

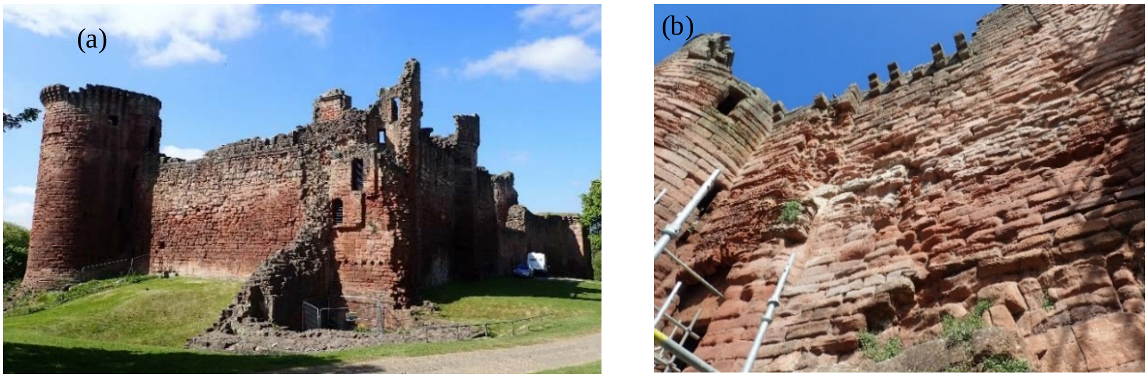

Fig. 1. (a) Overview of Bothwell Castle; (b) masonry deterioration on the South Curtain.

Bothwell was planned on an exceptionally grand scale and was executed using high quality materials with very fine detailing. As it stands, the remains of the largest tower, almost 20m in diameter with walls up to 4.6m thick, this Scheduled Ancient monument is an exceptionally important piece of Scottish secular medieval architecture (Historic Environment Scotland 2019) that came into State care in 1935. The current masonry repairs started in 2016, on the Latrine Tower, which projects from the external face of the South Curtain.

Masonry deterioration, in areas severe, represents a major conservation challenge across the site. Within the South Curtain and Latrine Tower masonry build, the majority of stones in the lower part of walls are badly decayed with surfaces eroded back and powdering, and some facing blocks entirely missing exposing wall core material (Fig. 1b). This contrasts with masonry in the upper reaches of these parts of the monument, which generally displays more superficial weathering (Historic Environment Scotland 2016).

Numerous long, vertical cracks were identified in the Latrine Tower masonry with some of them, particularly near the top, being open and widened, suggesting a lack of tying stones. These were likely to be caused by gradual loss of the facing, which is resulting in loss of support to the upper section of the wall. Combined with on-going water ingress at wall head and cyclic freeze thaw action, this would result in opening of these cracks and a potential high risk of localized collapse. Continued loss of the facing stones is the predominant issue as this exposes the weaker core material, which gradually erodes, reducing the support to the masonry above and increasing the stresses within the upper half of the structure. In this context and in order to tie the three faces of the Latrine Tower together and prevent further opening up of joint and evident cracks, a major program of carefully considered masonry repair through indenting in conjunction with introduction of small diameter helical steel bars as structural reinforcement into bed joints was proposed and approved (Historic Environment Scotland 2016).

2.2. The strengthening technique

Current practice in monuments managed by HES is based on general data existing in the literature and engineering judgement, making this experimental study significant as a starting point for the optimisation of the intervention. Previous experimental studies have addressed the importance of transversal connectors in stone masonry and the positive effects on the out-of-plane behaviour (Binda et al. 2006a, Binda et al. 2006b, Gigla 2012, Castori et al. 2017). Metallic anchors are used as a strengthening technique in historic stone masonry to cover for tensile forces that cannot be supported by the masonry itself (Gigla 2012). It is widely accepted that tying is one of the most effective interventions improving the collaboration among walls, while avoiding triggering out-of-plane mechanisms. Castori et al. (2017) in a structural analysis of transversal connectors embedded in multi-leaf masonry walls revealed that the application of mechanical connectors could produce an important increase of the masonry compressive strength.

Transversal connectors usually have the form of a metallic anchor, mostly made of stainless steel, inserted into a hole of specific diameter in which cementitious grout is injected under low pressure. They can be applied in the form of un-tensioned or pre-tensioned connectors (Gigla 1999). Such an anchoring system aims at improving the connection between masonry leaves by directly bonding them. Therefore, it can reduce the brittleness related with the traditional collapse mechanism as well as the deformation of the wall (Oliveira et al. 2012). Despite the available experimental studies and standards of reinforcing methods in brick masonry there is a lack of experimental data for historic stone masonry. Furthermore, specific applications on how to test and design strengthening systems for historic stone masonry connections are not included in the codes (Paganoni 2015).

In the above context, the strengthening technique implemented at Bothwell castle relies on indenting and the installation of a reinforcement and anchoring system by Cintec™ (Fig. 2a). Indenting of decayed stones which are structurally defective and introducing stainless steel helical bars into bed joints provide bearing and support for facing masonry from the base up and also tie the structure back together again, curtailing the tendency to spread and crack (Historic Environment Scotland 2016). After drilling a hole at an appropriate location into a joint, the system works by introducing there a helical bar enclosed in a mesh fabric sleeve into which a specially developed cementitious grout is later injected under low pressure (Fig. 2). The flexible sleeve loosely surrounds the helical bar and expands to fill the cavity as the grout is injected. During this process, it shapes itself into the hole and a mechanical bond is created between the elements (Cintec™ 2018).

However, despite the common perception that these anchors achieve a better connection between adjacent wall leaves, there is a lack of data regarding the pull out-resistance of such anchors used in historic rubble walls. The need for a parametric study to evaluate factors affecting the efficiency of the intervention (bar diameter, anchorage length, properties of grout and characteristics of rubble) was identified as a topic of common interest between HES and ENU.

Fig. 2. (a) Cintec™ anchoring system; (b) installation of anchoring system and (c) injection of cementitious grout in the fabric sleeve, at the Latrine Tower, Bothwell castle.

3. Experimental investigation

3.1. Specimen specifications

It is reported that it is very difficult to produce walls representative of historic stone masonry buildings in a laboratory (Vintzileou 2006). Nevertheless, experimental tests are often necessary to determine the properties of such masonry and the efficiency of proposed interventions. In order to measure the force required to pull out an anchor from a stone masonry wall installed as described above (Fig. 2c), a pull-out test was performed to investigate the anchor/masonry substrate bond behaviour. Based on the case study previously described, materials and techniques involved in masonry repairs at Bothwell castle were reproduced in a laboratory environment, the 'Heavy Structures' Laboratory at the School of Engineering and the Built Environment, ENU. The design of the wall specimen constructed in the laboratory was finalized considering the principles of the intervention method followed by HES as well as laboratory space and equipment restraints.

The stone currently used as a substitute stone at restoration works on the Latrine Tower at Bothwell castle is a local red sandstone, Locharbriggs. A wall specimen of 1m^3 (1mx1mx1m) made of Locharbriggs sandstone and appropriate natural hydraulic lime was constructed by qualified HES stonemasons, using the technique for stone bonding in historic rubble walls (Fig. 3). A 0.93m long, AISI 304 stainless steel threaded M16 anchor by Cintec™ (Fig. 2a) was placed centrally in the wall specimen, inserted in an appropriately predrilled hole (d=45mm) at a mortar joint, having an anchorage length of 0.6m. Cintec™'s Presstec™ grout, a pure mineral grout tested in accordance with the DIN standards, was injected into the fabric sleeve under low pressure.

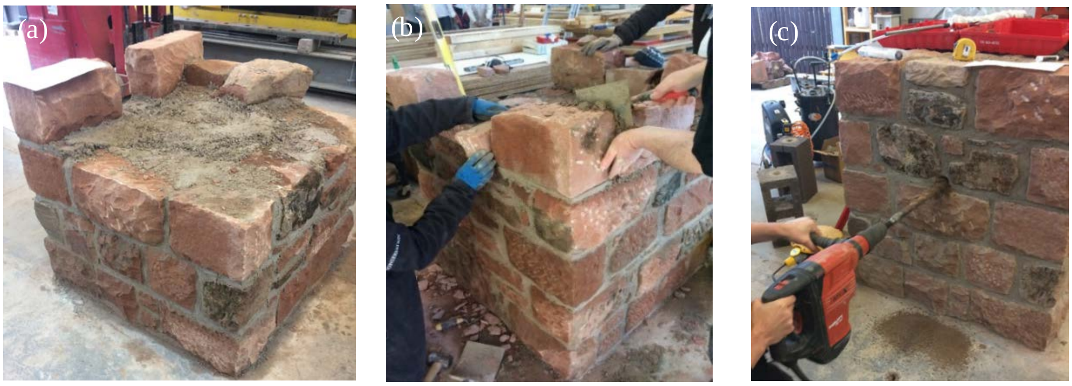

Fig. 3. Wall specimen preparation at ENU structural laboratory: (a) Core of the wall filled with mortar and rubble; (b) building process by HES stonemasons and (c) drilling process in preparation of the anchoring system's installation.

Fig. 4. Wall specimen preparation at ENU structural laboratory: (a) cleaning the hole in preparation of the anchoring system's installation; (b) injection of the cementitious grout in the fabric sleeve.

Although the use of cementitious grout in historic stone masonry structures should be further investigated due to the potential incompatibility with stone units, in this configuration the fabric sleeve does not allow the grout to spread freely into the masonry wall. Relevant mechanical properties of materials involved in this investigation were either provided by suppliers (Cintec™ 2015) or determined experimentally by standard tests (Table 1).

Table 1. Mechanical properties of materials involved in testing.

Material	Yield proof stress (MPa)	Tensile strength (MPa)	Compressive strength (MPa)
AISI 304 stainless steel	450	700	-
Presstec™ grout	-	4.5	51.5
Locharbriggs sandstone	-	-	47.3
Lime mortar	-	-	3

3.2. Test setup

The bonding behaviour between the masonry wall and the anchoring system is investigated by means of a pull-out test. The focus is on the performance of the anchor and the damage caused to the stone masonry wall. The testing process involves attaching an apparatus (hydraulic jack) at the edge of the anchor, which is then pulled at a loading rate to determine the characteristics of the fixing.

A steel frame was appropriately designed to secure the wall specimen in position as well as support the testing equipment, which involved an ENERPAC RCH-306 hydraulic cylinder, a load cell and linear variable differential transformers (LVDT) (Fig. 5a). The test was conducted under a load control mode, with the pull-out load being applied in steps of approx. 5kN/min through the hydraulic cylinder connected to a manual pump. Two LVDTs over a gage length of 50mm were placed horizontally to measure the displacement of the anchor, mounted on a purpose made plate positioned as close as possible to the wall specimen (Fig. 5b). Such a test is considered complete when either failure occurs in the parent material (wall specimen) or when a specific displacement is reached, reasonably specified at 10mm (Paganoni and D'Ayala 2014, Paganoni 2015).

Fig. 5. (a) Overview of the experimental configuration for the pull-out test; (b) detail of the measuring equipment for anchor displacement (LVDTs).

4. Experimental results

Experimental data regarding the pull-out resistance of anchors embedded in historic masonry wall is scarce. However, possible failure modes of grouted anchors in historic stone masonry can be predicted by comparing with failure modes of anchors embedded in concrete (Paganoni and D'Ayala, 2014). In this experimental study, failure was initially observed at the bond between the grouted anchor and the parental material and only later cracks were developed on the surface of the wall (Fig. 6). It can be observed that horizontal cracks extended from the hole to both sides of the wall, but no cracks reached its rear elevation.

Fig. 6. (a) Detail of the pull-out failure mode observed; (b) development of horizontal cracking at front elevation and (c) left-side elevation.

The overall pull-out behaviour of the anchor is illustrated in Fig. 7, in terms of force exerted (load in kN) versus average LVDT measurements (slip in mm). Results are presented here up to a meaningful slip of 10mm, which corresponds to approx. 60% of the total load carrying capacity of the anchor. The maximum load achieved was 36.68kN, at a point of anchor slip equal to 1.62mm. It is worth noting that for load levels around 35 kN and slip approx. 1mm, it became evident that it was hard to increase the load sustained, which remained relatively stable for a range of slip measurements between 1mm and 3mm. After the attainment of the maximum load within a period of small load fluctuations as described above, during which the anchor kept its capacity due to friction and mechanical interlocking, the load continued dropping while LVDT measurements increased, until the point of complete failure by pull-out.

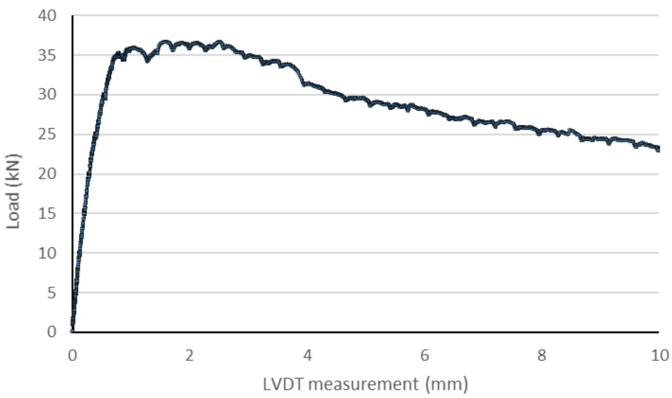

Fig. 7. Load vs. Displacement (anchor slip) curve for the pull-out test performed.

The bearing capacity of the anchor is dependent on the geometry and characteristics of the grouted fabric sleeve, as any failure mode not directly involving failure of the threaded bar would rely on the compressive strength of the cementitious grout. If the grout around the threated bar crushes and sliding begins, friction becomes the main mechanism that controls the behaviour of the anchor. Furthermore, although the threads of the steel bar are symmetrical in shape and spacing, it is not the same for the grouted fabric sleeve which fills the random voids within the masonry wall (Paganoni 2015). This means that sliding can be activated before mechanical interlocking and it is generally difficult to evaluate the bearing mechanism of the anchor as the presence of voids in the masonry and the degree of cementitious grout penetration is unknown (Paganoni 2015). In terms of interpretation of the results, it is therefore reasonable to consider a maximum load level for all practical purposes (at 35 kN for this case), instead of an absolute maximum load value.

As the anchor was removed from the wall specimen at the end of the test, it was confirmed that it had experienced pull-out together with its surrounding fabric sleeve, mainly as a rigid body. There was only a small part of the sleeve missing (around 10cm), towards the end (inner side) of the anchorage length (Fig. 8a). The wall was then carefully demolished and a visual analysis took place, layer by layer, to document fully the failure mode. No crack pattern was found within the volume of the wall and the remains of the grouted fabric sleeve were found as expected at the end of the hole, firmly attached to the parent material (Fig. 8b,c).

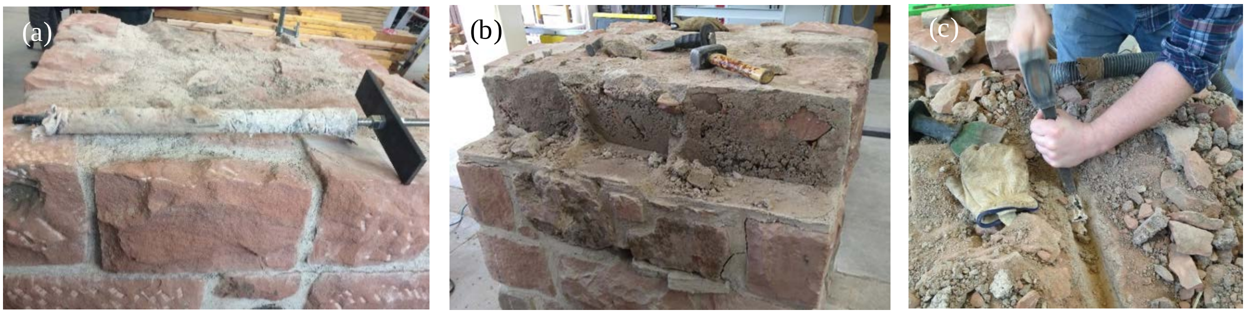

Fig. 8. (a) Condition of the anchoring system after complete pull-out; (b) careful demolition of the wall specimen for visual inspection; (c) remains of the fabric sleeve attached to parent material.

4. Discussion and Conclusions

Over the last decades, several new materials and application techniques have been developed to strengthen and repair historic stone masonry buildings. Such a technique, based on the use of transverse connectors (metallic anchors surrounded by a fabric sleeve into which cementitious grout is injected under low pressure) is currently used in Scottish monuments managed by HES. It is generally accepted that this kind of anchoring system improves the connection between masonry leaves, reduces the brittleness related with traditional collapse mechanisms and reduces the deformation of the wall (Oliveira et al. 2012).

On the other hand, it can be argued that metallic anchors can instigate local failures because of the higher stiffness of steel in comparison to the stone masonry elements (D'Ayala and Paganoni 2011). Furthermore, the installation of anchors is not an easy task since drilling holes into masonry can induce a stress re-distribution in the area around the hole leaving this area uncompressed (Corradi et al. 2017). It is also challenging to prove physical and mechanical compatibility between masonry and the strengthening system, for an intervention that in any case appears highly invasive. HES have decided to restrict insertion of anchors to bed joints, where adverse impact on highly significant historic fabric would be minimal. Of the options appraised, given that in historic structures the structural condition is often so poor that intervention is necessary to prevent major loss, this was considered the most acceptable (Historic Environment Scotland 2016).

In this context, an experimental study aiming at investigating the effectiveness of a transverse anchor as reinforcement of a stone masonry wall specimen was performed at ENU, by means of a pull-out test designed around requirements of a case study of restoration works at Bothwell Castle, Scotland. The performance of the anchorage system was approximated by a load-displacement curve, on which characteristic stages can be identified such as appearance of relative movement, achievement of maximum load, achievement of maximum displacement and ultimate failure. Close examination of the failure mode was also performed to shed light into the bonding mechanism between the masonry wall and the anchoring system.

Despite limitations, results obtained and observations made can be used towards quantifying the efficiency of the intervention and informing design decisions. This study is planned to act as a starting point for a wider parametric investigation of this intervention commonly used by HES. The objective is to conduct a combined experimental and numerical study to evaluate factors affecting the efficiency of the intervention (such as bar diameter, anchorage length, properties of grout and rubble), for a range of wall boundary conditions, having as a basis a numerical model of the pull-out test calibrated to the above experimental results. In this context, it is anticipated that design guidelines for an efficient and economic design of this strengthening intervention will be given. Further requirements such as minimising intrusiveness, compatibility of materials and durability will also be addressed.

Acknowledgements

Historic Environment Scotland and Edinburgh Napier University are gratefully acknowledged for supporting this research. The authors wish to record their appreciation to Dr Kashif Ashraf, Senior Structural Engineer at HES and Ms Frantzeska Nanopoulou, Structural Engineer at HES, for their expertise and facilitation of this project.

References

Adami, Ch.-E., Vintzileou, E., 2008. Interventions to historic masonries: Investigation of the bond mechanism between stones or bricks and grouts. Materials and Structures, 41 (2): 255.

Binda, L., Saisi, A. and Tedeschi, C., 2006a. Compatibility of materials used for repairs of masonry buildings: Research and applications. In: Fracture and Failure of Natural Building Stones, S.K.Kourkoulis (Ed.), Springer Netherlands, pp.167-182.

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

Bonelli, R., 1963. Il restauro architettonico. In: Enciclopedia Universale dell'arte, Sansoni (Ed) Florence: vol.XI.

Borri, A., Castori, G., Corradi, M., Sisti, R., 2014. Masonry wall panels with GFRP and steel-cord strengthening subjected to cyclic shear: an experimental study. Constr Build Mater 56: 63.

Castori, G., Borri, A., Corradi, M. and Luca, R., 2017. Structural analysis of transversal steel connectors applied on multi-leaf walls. In: Conference Proc. of the 13th Canadian Masonry Symposium at Halifax, Canada.

Cintec™ Worldwide, 2018. The System: Anchoring principle and how it works. [accessed online 30/4/2019] Available at http://cintec.com/reinforcement-anchoring/ the-system/anchoring-principle-and-how-it-works/.

Cintec™, 2015. Masonry anchoring and reinforcement systems. [accessed online 1/5/2019] Available at http://cintec.com/wp-content/uploads/2015/04/contractors-notes-2009-LR1.pdf .

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. Constr. Build. Mater 22: 263.

Corradi, M., Borri, A., Poverello, E., Castori, G., 2017. The use of transverse anchors as reinforcement of multi-leaf walls. Materials and Structures, 50: 114.

D'Ayala, D., Paganoni, S., 2011. Assessment and analysis of damage in L'Aquila historic city centre after 6th April 2009. Bulletin of Earthquake Engineering, 9(1), pp.81-104.

De Felice, G., Giannini, R., 2001. Out-of-plane seismic resistance of masonry walls. J Earthq Eng 5 (2): 253.

Gigla, B., 1999. Field pull-out tests of supplementary injection anchors in historic masonry. Transactions on the Built Environment, WIT Press, Vol. 39, pp.95-105.

Gigla, B., 2012. Structural Design of Supplementary Injection Anchors Inside Masonry. In: Proc. of the 15th International Brick and Block Masonry Conference, Florianopolis, Brazil.

Griffith, M.C., Magenes G., Melis, G., Picchi, L., 2003. Evaluation of out-of-lane stability of unreinforced masonry walls subjected to seismic excitation. J Earthquake Eng 7 (1): 141.

Historic Environment Scotland, 2019. Bothwell castle [accessed online 30/4/2019] Available at http://portal.historicenvironment.scot/ designation/SM90038.

Historic Environment Scotland, 2016. Bothwell castle, Latrine tower: proposed masonry repairs – supporting statement [accessed online 30/4/2019] Available at http://portal.historicenvironment.scot/document/600002805.

Hyslop, E., McMillan, A., Maxwell, I., 2006. Stone in Scotland, UNESCO Publishing.

ICOMOS, 1965. The Venice Charter 1964 [accessed online 29/4/2019] Available at https://www.icomos.org/charters/venice_e.pdf.

Oliveira, D., Silva, R., Garbin, E. and Lourenço, P., 2012. Strengthening of three-leaf stone masonry walls: an experimental research. Materials and Structures, 45(8), pp.1259-1276.

Paganoni, S., 2015. Dissipative anchor devices for the seismic retrofit of heritage buildings. Doctor of Philosophy (PhD). University of Bath.

Paganoni, S., D'Ayala, D., 2014. Testing and design procedure for corner connections of masonry heritage buildings strengthened by metallic grouted anchors. Engineering Structures, 70, pp.278-293.

Stratford, T., Pascale, G., Manfroni, O., Bonfiglioli, B., 2004. Shear strengthening masonry panels with sheet glass-fiber reinforced polymer. J Compos Constr 8 (5): 434.

Theodossopoulos, D., 2012. Structural design in building conservation, Routledge.

Tomazevic, M., Weiss, P., Velechovsky, T., Apih, V., 1991. The strengthening of stone masonry walls with grouting. Structural repair and maintenance of historical buildings II: Proc. of 2nd Int. Confer., Spain, pp.215.

Vintzileou, E., 2006. Grouting of three-leaf stone masonry: types of grouts, mechanical properties of masonry before and after grouting. In: Proc. of Vth Inter. Conf. on Structural Analysis of Historical Constructions, New Delhi, India.

Vintzileou, E., Miltiadou-Fezans, A., 2008. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime based grouts, Eng Struct 30 (8): 2265.