Doctoral School on Engineering Sciences
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Extended summary

Structural restoration of historical constructions through innovative materials: the basalt and the idea of masonry continuous stitching

Curriculum: "Architecture, Building and Structures"

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Date: 30-01-2012

Abstract. Consolidation and strengthening of bearing panels is one of the most important operations to improve seismic performance of existing masonry building, especially when these are damaged or made in bad way, far from practical laws of "rules-of-art". From the awareness that one of the worst structural defects of an historic masonry wall is the lack of monolithic behavior, arise the idea of a strengthening technique able to connect the several masonry elements, stitching them, based on the use of basalt fiber ropes. Continuous basalt fibers are obtained by melting basalt and seem to be a good alternative to glass and carbon fibers. The proposed technique allows to connect several elements in order to achieve (per realizzare) a monolithic behavior and to improve mechanical features of bearing panels, using a fire and chemical resistant material that presents a high compatibility with masonry. To assess the effectiveness of proposed technique, experimental (laboratory and in situ tests) and FEM analysis has been performed.

Keywords. Basalt fiber, masonry strengthening, stone masonry, three-leaf masonry

1 Introduction

As shown by several authors [1, 2], historical masonry buildings subjected to earthquake do not show a global structural behavior, their response to earthquake is the one offered by the number of macroelements. Masonry quality defines if this approach could be considered reasonable: in fact only good quality masonry is able to guarantee monolithic behavior.

On the contrary, if a poor quality masonry has been used, a chaotic failure has to be expected, a low earthquake could be enough to determine disastrous collapses and it is not right to reasoning about failure mechanism activation. Masonry structural effectiveness directly depends on material quality and if it has been built according to “rule of art”: when these prescriptions are followed a masonry can be considered of “good quality”. Essential features are: presence of transversal connection elements, horizontality of the courses, the stagger of the vertical joints, shape and dimension of the single units, mortar quality and mechanical resistance of single elements [3]. If the lacking of these features is recognized, every structural assessment is quite reliable and the first thing to do is to improve masonry quality.

Nowadays, there are a lot of different techniques for strengthening masonry panels. Some are traditional (and usually most invading) like grout injection, jacketing with a reinforced cement or the introduction of artificial connectors (metallic rods) and some other could be considered innovative, like the use of composite strips [4]. But when it is demanded to maintain the original aspect of the masonry brickwork, all this techniques cannot be applied. Recently, innovative reinforcing fibers and products, like basalt ones, are emerging in constructions field.

From the awareness that one of the worst structural defects of an historic masonry wall is the lack of monolithic behavior, arise the idea of a strengthening technique able to connect the several masonry elements, stitching them. The proposed technique is based on the reinforcement and connection of masonry elements using basalt fiber ropes. To assess the effectiveness of proposed technique, laboratory test (on “three-leaf” masonry samples) and in situ test (on rubble stone masonry) have been performed, above all that also FEM analysis has been developed to better understand experimental results.

2 Chemical and physical analysis and mechanical characterization of BFRP (basalt fiber reinforced polymer) rods and BF (basalt fiber) ropes

Basalt is a natural material that is found in volcanic rocks originated from frozen lava. Continuous basalt fibers are obtained by melting basalt and are characterized by high modulus, heat resistance, good resistance to chemical attack and seem to be a good alternative to glass fibers [5, 6, 7]. In construction field, basalt is proposed in form of short fibers for insulating material (basalt wool), for reinforced concrete (chopped fibers) or like reinforcing material in restoration and rehabilitation of concrete [7] and masonry structures [8], or like reinforcing material for fiber reinforced polymer (FRP) bars used in concrete technology [9]. It is also important the application in passive fire protection field [10]. Continuous basalt fibers can be processed with classic textile transformation to obtain also ropes, unlike other kinds of reinforcing fibers.

In this work test results obtained on BFRP rods and BF ropes with the aim of a physical, chemical and tensile characterization of BFRP rods and BF ropes are shown. The comparison between experimental results and the ones of other similar products shows that BFRP rods could be a good alternative to other FRP rods. Anyway, particular attention could be paid in durability features of this kind of BFRP rods and economic analysis about cost of BFRP manufacture. As regards BF ropes, the proposed protocol seems to be efficient to have a full characterization of the mechanical properties of this product and the performances showed suggest the employment in strengthening purposes. A better investigation is necessary to verify durability of BF ropes and this should represent a future development of this work.

3 Laboratory experimental experience

To assess the effectiveness of proposed technique, laboratory tests on masonry samples have been performed. The masonry reproduced was the "three-leaf" wall, a masonry typology often found in Italian historical building heritage, where an inner core of rubble material is included between two outer brick shell. If "three-leaf" masonry presents poor or absent connection between the external leaves due to the lack of elements so long to crossing wall section, it could result very weak under eccentric and horizontal loads. In fact, it could meet problems of buckling of the external shell due to its slenderness and of weak resistance to action that could involve out-of-plane mechanisms due to a global behavior nearest to two thin panels than a monolithic one.

3.1 First experimental campaign

3.1.1 Experimental program

Six "three-leaf" masonry samples have been made, and tested under compression load. The masonry wallets were cured outdoor in the same condition for about 90 days. Two of them were tested without treatment, while the remaining four, before testing, have been artificially damaged. After that, two of the damaged sample were tested while the remaining two have been strengthened using the proposed technique. Vertical compression tests have been performed under load control.

3.1.2 Strengthening technique description

The main operative phases for a correct execution of the intervention are:

- execution of crossing hole by means of drill equipped with a bit long as the wall depth;
- cutting of the bed mortar joints creating a groove at least 10 mm high and about 30-40 mm deep on the two wall faces;
- removal of powder or rubble by air, not water: the groove should be kept dry for the use of resin in successive phase;
- placing of a first layer of tixotropic epoxy resin;
- placing of the basalt fiber rope;
- placing a second layer of tixotropic epoxy resin over the rope to cover it sufficiently and holding of rope ends;
- placing a final layer of mortar in the last available 15–20 mm, to restore original appearance and homogeneity.

3.1.3 Results and discussion

The proposed technique aims to connect outer brick masonry shell to exclude buckling failure and to impart monolithic behavior, without modify masonry original aspect. It consists in insertion of basalt fiber ropes in the mortar bed joints previously partially cleared out and refilled with tixotropic epoxy resin. Respect insertion of steel or FRP bars, as in re-pointing application [11, 12, 13], come out the opportunity of working with a lighter and versatile material (bringing time and money saving) and able to connect the masonry elements also in the panel depth direction. The proposed technique is able to change the failure mode of "three leaf" masonry wall, exploiting material properties, and to determine a transverse strain reduction under compression load: in brief it is able to impart to masonry monolithic behavior.

3.2 Second experimental campaign

3.2.1 Experimental program

To better assess the effectiveness of the technique of basalt fiber continuous stitching, should be useful perform further experimental experiences. In particular it needs to take a deeper look into the reinforcing ropes disposal and improve the technique reversibility excluding resin use. Then, to have a condition better comparable to historical construction, bricks with lower mechanical features than previous ones, and an air lime-based mortar has been chosen. In the second experimental campaign twelve "three-leaf" masonry samples have been made, and tested. Six of them were tested under vertical compression load, while the remaining six were tested under in plane shear load. Within every group of six wallets, two of them were tested without treatment, the remaining four have been strengthened using the proposed technique.

3.2.2 Strengthening technique description

The intervention on the strengthened ones has been performed following two different disposals of the reinforcing ropes: placed only in the horizontal mortar joints or also in the vertical one, creating a grid. The operative phases are the ones described in 3.1.2 excluding the use of epoxy resin. Obviously, the grid disposal of reinforcing ropes requires the cutting of the bricks placed between vertical joints.

3.2.3 Results and discussion

Also after these further compression tests, the proposed technique seems to be able to change the failure mode of "three-leaf" masonry wall, exploiting material properties. The reinforce is able to produce a great transverse strain reduction under compression load: respect to unreinforced ones the samples strengthened using horizontal disposal show a reduction of about 70% of this parameter, and for the grid ones the reduction is of about 80%. As regards shear tests, the most interesting results it is the fact that the application of reinforced ropes makes the sample able to show a bigger pseudo-ductility respect unreinforced condition. Also in this case the technique in able to impart to masonry monolithic behavior and the global behavior does not look like several thin panels but closer to the one of a monolithic body.

4 FEM analysis

A finite element model was developed to simulate the behavior of "three-leaf" masonry specimens subjected to laboratory compression tests in the first experimental campaign. The objective of this investigation is to better study the effectiveness of continuous basalt fiber stitching reinforcement on the behavior of masonry and obtain further information with the aim of optimization of intervention design. Finite element model has been developed using the modelling strategy called "micro-modelling" where brick units and mortar in the joints are represented by different elements with different mechanical features. Two different models have been used: the first characterized by elastic materials constitutive laws, and used in small displacements analysis; the second, used in large displacements analysis, characterized by the use of specific contact element located at interface between outer shell and inner core, to better represent outer shell buckling phenomena. The model captures different features of the experimental response of "three-leaf" walls in integer and damaged condition several instances. The comparison between numerical and experimental stress–strain diagrams shows a good agreement, both in vertical and transverse strain. In reinforced condition, the model is not able to completely reproduce the stiffness increase observed during tests. Finally, an important information has been obtained for design purpose: the reinforcing ropes seem to be subjected to load not higher than the rupture one, excluding brittle and unexpected failure.

5 In-situ diagonal compression tests

Last experimental experience developed with the aim of a complete investigation about efficiency of proposed technique, was the execution of in-situ diagonal compression tests in Onna (L'Aquila). The area in which the experimental tests were carried out is characterized by "poor" masonry, built with rubble stones and air lime-based mortar. Two different masonry panels has been selected for tests and two samples has been obtained from each panel: in all four diagonal compression tests has been done. Within every sample couple a panel has been tested in unreinforced condition, while the other after the intervention trough basalt fiber stitching. Comparing the obtained results, come out as the intervention, discarding masonry crumbling and reducing smeared cracking, contributes to the increase of the tensile strength of masonry and it is able to impart a monolithic behavior to the masonry panel.

6 Conclusion

This work presents the results of an experimental and analytical program with the aim of investigate the strengthening of masonry walls through the employment of basalt fiber ropes, used for stitching masonry panel.

First an experimental work with the aim of investigate chemical, physical and mechanical features of basalt fiber products is presented, in particular test results obtained on BFRP rods and BF ropes are shown. The comparison between experimental results and the ones obtained on similar products shows that BFRP rods could be a good alternative to other FRP rods. As regards BF rope, it seems to be a product suitable to be successfully exploited in masonry strengthening. In particular, an innovative technique that aims to strengthening irregular and poor masonry trough continuous basalt fiber stitching able to encage and connect masonry component has been proposed.

The first results on "three-leaf" masonry walls show that the proposed technique is able to change the failure mode of "three leaf" masonry wall, exploiting material properties, and to determine a transverse strain reduction under compression load: in brief it is able to impart to masonry monolithic behavior. Still it has looked as necessary to develop further experimental experience to assess the effect of changing reinforcing ropes disposal and improve the technique reversibility excluding resin use. In the followings experimental experiences (compression and shear tests), the obtained results confirmed the efficiency of the proposed technique to impart to masonry monolithic behavior.

Then, numerical simulations have been performed, to better study the effectiveness of continuous basalt fiber stitching reinforcement. FEM analysis and experimental results seems to be in good agreement to demonstrate in particular the transverse strain reduction under compression load.

Finally, also in-situ diagonal compression tests executed on rubble stone masonry in Onna (L'Aquila), confirms what seen in laboratory on "three-leaf" masonry samples. In conclusion, come out as the intervention, discarding buckling collapse and better exploiting material properties, contributes to impart a monolithic behavior to the masonry panel. Moreover other advantages are represented by the fact that:

- the application is very fast and so cheap;
- the material used (basalt) presents an high compatibility with masonry: stone stitches stone;
- the reinforce is reversible;
- it is invisible, respectful of masonry original aspect;
- it improves but not replaces original materials;
- it is safe for operators, not providing the use of resin or other dangerous materials.

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