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Experimental Study on the Injected Anchors Behaviour on Historical Masonry

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Abstract The proposed paper reports the results of a research on the behaviour of injected anchors in historical masonry. The purpose of this investigation was to develop a methodology to be used as a preliminary design stage for structural interventions in order to pre-qualify the real strength of this kind of anchors. Several preliminary tests in laboratory with test specimens made of concrete and masonry and a first series of in situ tests on different types of masonry were conducted to analyse the behaviour of the anchorage and of the mortar. As this test is not included in National Standard, the studied standardised methodology could be adopted as a Guideline.

Keywords: Injected anchor, masonry reinforcement, pull-out test, Guideline.

Introduction

Injected anchors are commonly used as a strengthening method for historic and existing masonry. The present paper is focused on a particular strengthening system that consists of a flexible combination of different kinds of steel member enclosed in a fabric sleeve into which a specially developed grout is injected under low pressure. The injected anchor with sock is embedded inside a hole drilled in the masonry to be strengthened. The grouting material is injected, at low pressure, coaxially with the steel reinforcement member, though an appropriate system of injection pipes. The special sock, placed around the rebar, is gradually filled during injection, until its complete saturation, moulding itself to the substrate shape and so assuring an effective bonding to the masonry (Fig. 1).

Figure 1: Injection phases into brick masonry and stone masonry

Studies and experimentation on injected anchors have been developed in order to investigate about the capacity of injected anchors with sock in terms of adhesion and mechanical interlocking with the substrate. A second aim was to adapt this technology to the specific needs of intervention which mostly affect building belonging to our architectural heritage that must consider the aspects of "minimum intervention" and chemical and mechanical compatibility in the choice of materials and techniques involved in the restoration process. According to these requirements a new lime-based mortar more compatible with the existing substrate than a traditional cement-based mixture was studied starting from different mix designs obtaining the development of a well injectable, stable grout more compatible with the original material.

The main parameter used in the definition of these grouts was the viscosity measured by a viscosimeter type Brookfield. This apparatus measures the torque needed to realize a certain shear velocity. Mineral grouts are not Newtonian fluid and so also thixotropy takes part into rheological behaviour (Van Rickstal et al. 2003). After several tests conducted to define the two best grouts for injected anchors (Fig. 2), two recipes for grouts (Table 1) were defined in order to obtain good injection capabilities and good thixotropy during the installation process.

Table 1: Grouts component and mechanical properties after 28 days of curing

Grout	*Cement based BCM Hs*	*Lime based BCM Ls*
Cement	74%	-
Lime	-	68%
Additives	5%	5%
Inert material	21%	27%
Water/binder ratio	26%	24%
Compressive strength	55 MPa	12 MPa

Figure 2: Some phases of the laboratory tests for the definition of the correct mix design

Test Procedures and Test Setup

A standard test set up for pull-out tests has been defined: it consists of an hollow hydraulic cylinder placed in the axis of the anchor for the application of the force and of a transducer for the measurement of the displacement at the end of the anchor (Fig. 3). A data logger gives the possibility to obtain graphics and results in the form of load-displacement curves. The test rig was designed to observe failure mechanism avoiding undesirable confining and frictional effects.
All tests were carried out under monotonic tensile loading and up to collapse.

The test member is an injected anchor with an approximately bond length of two third of the entire thickness of the wall, the diameter of the drilled hole is about 3 times the diameter of the steel member. Test anchors must be embedded in boreholes made with drilling machines, working only with rotation movement in order to avoid vibration and percussion effects on masonry. The admissible grouting pressure has to be adjusted according to the state of the masonry and may vary between 1 and 3 bar. The injected cement or lime grout needs 28 days of curing before testing.

The main test parameters to consider during the execution of tests are the following:

- maximum tensile load [kN] and correspondent maximum displacement value [mm] characterized by a plastic behaviour with significant deformations till the collapse;
- value of the secant stiffness [kN/mm] at the displacement of 1 mm which is assumed for the serviceability limit state in the elastic field;
- 50% of the maximum tensile load [kN], assumed as elastic phase up to the yielding point and correspondent displacement value [mm];
- value of stiffness at the 50% of the maximum tensile load [kN/mm];
- maximum tensile load post peak and maximum tensile load ratio.

The correspondent nominal shear values [MPa] are obtained from the same load parameters.

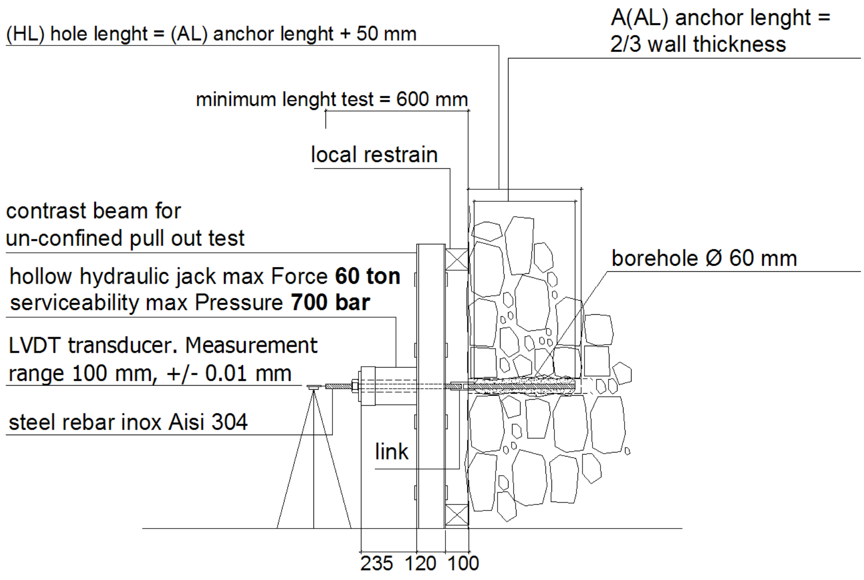


Figure 3: In situ test layout – unconfined test rig

Test Members

Preliminary laboratory tests have been performed on standard masonry members (2.0x1.7x0.75 m) made of solid bricks (250x120x60 mm) and poor mechanical resistance joint mortar (M2.5 with fc<4MPa). The test members were built on a set of bearing steel beams: vertical load was applied by prestressing threaded rods between the bearing beams and the top steel beams obtaining a compressive load of 0.2 MPa on the specimens simulating a real compressive stress state (Fig. 4) (Bassini, 1998).

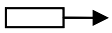
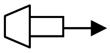
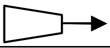
Figure 4: Test setup on laboratory specimens

After the first phase conducted in laboratory, a second phase of in situ tests have been performed on six different sites (defined in Table 3 as A, B, C, D, E, and F) representative of the two main types of masonry substrate: brick masonry and stone masonry. These kinds of masonry are typical of the northern Italy in the Alpine region.

Results

The great number of tests (more than 100 tests, including preliminary laboratory and in-situ tests during three years of activity) led to the definition of parameters that are fundamental for the design of injected anchors with socks, as the bond strength at the bar-injected grout interface and at the injected grout-substrate interface. Table 2 reports the mean values of bond strength obtained from tests made with different anchorage lengths as a function of the anchor's shape and with different types of injected grouts, cement grout BCM Hs and lime grout BCM Ls. For each value listed in Table 2, three tests were conducted for an amount of more than 20 pull out tests.

Table 2: Shear Tensile Strength; Laboratory tests on brick wall specimens [MPa]

Failure mechanism	*Bulb shape*	*Mortar joint compressive strength*	*Cement based BCM Hs*		*Lime based BCM Ls*	
			inner	*outer*	*inner*	*outer*
Adhesion	 F	< 4	5.62	1.81	2.77	0.89
Adhesion and undercut	 F	< 4	5.02	1.62	3.01	0.90
Mechanical interlock	 F	< 4	3.20	1.03	4.01	1.29

The first phase of experimental tests on standard masonry was integrated with a second set of in-situ tests in order to create a database representative of the different types of masonry usually found in the existing buildings in Italy. Also, in this second stage of the research, specific values of the bond strength at the steel member-injected grout interface and at the injected grout-substrate interface have been obtained with tests done on different substrates made of brick and stone masonry. Table 3 gives indications about the mean values of bond strength resulting from tests, as a function of the substrate characteristics and, in particular, of the type of resistant elements, of the grout for the joints and of the masonry texture. Two different materials were considered for the injected grouts, namely cement grout BCM Hs and lime grout BCM Ls. As the anchor system tends to fail in the substrate, leaving the anchor body intact, the design procedure should concentrate primarily on determining the properties of the substrate (strength of the parent material).

Table 3: Shear Tensile Strength in situ tests on several masonry type [MPa]

Failure mechanism	*Mortar joint*	*Cement based BCM Hs*		*Lime based BCM Ls*	
	compressive strength	*inner*	*outer*	*inner*	*outer*
A. Solid limestone	<< 4	1,34	4,15	0,85	2,64
B. Berbenno stone	<< 4	-	-	0,29	0,90
C. Credaro stone	<< 4	0,53	1,64	0,45	1,38
D. Bricks 300x150x50 mm	c.a. 4	0,76	2,34	0,47	1,47
E. Bricks 260x130x80 mm	6÷9	1,39	4,30	0,87	2,71
F. Zorzino Limestone	> 8	1,64	5,09	1,11	3,45

The maximum tensile force can be related to nominal shear strength for the inner interface as shown in Fig. 5 (but the same is valid also for the outer interface), where the maximum force is plotted in a logarithmic scale vs the maximum shear strength at inner interface. One can observe that a regression exponential line describes the phenomenon with good accordance. Fig. 6 shows the relation between the maximum tensile force and the geometric anchor length ratio vs the maximum shear strength and compressive resistance ratio. It can be observed that these values present a linear regression line and the stiffness of BCM Hs anchors is 4 times greater than that of BCM Ls.

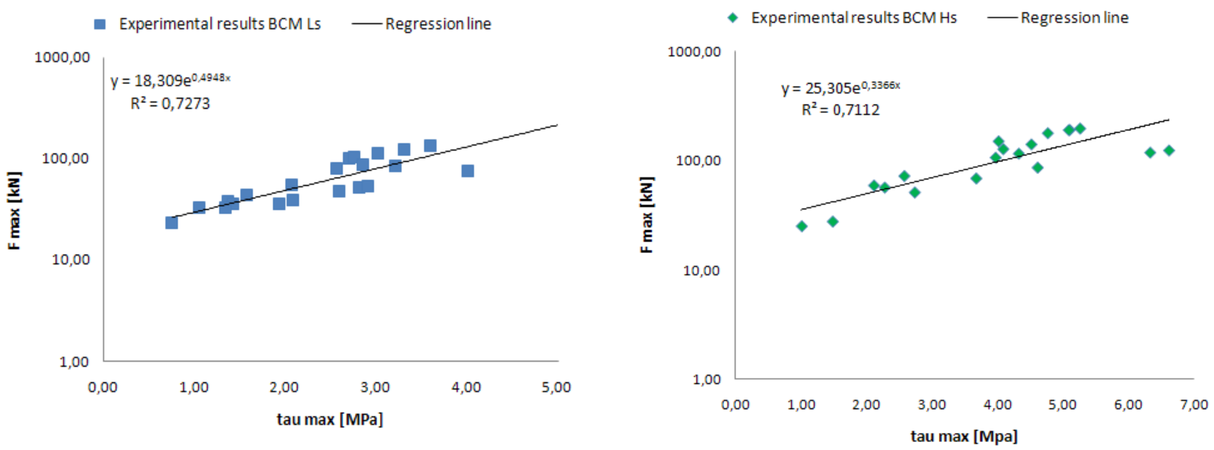


Figure 5: Comparison diagram between BCM Ls lime base grout and BCM Hs cement base grout

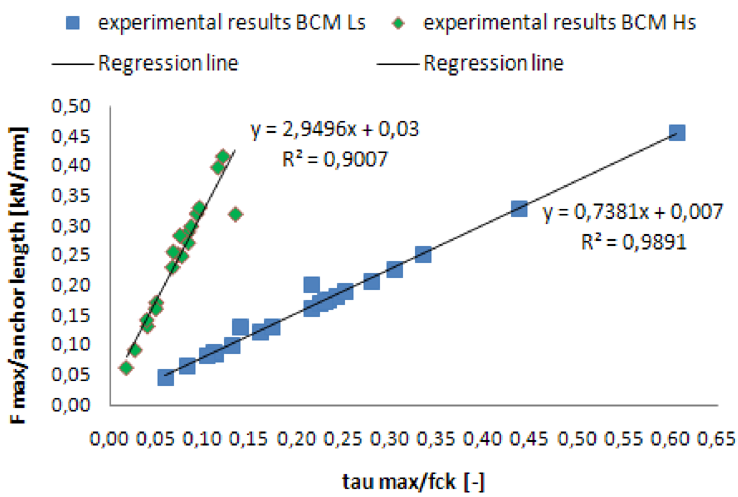
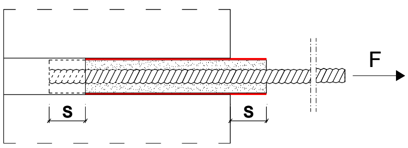


Figure 6: Comparison diagram between BCM Ls lime base grout and BCM Hs cement base grout

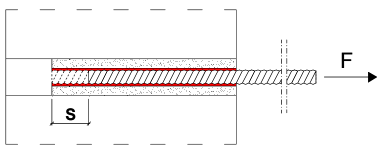
Mechanism of failure

Force-transmission between the surrounding masonry and the tensile element includes two intersections: the outer intersection between borehole surface and injected mortar plug and the inner intersection between injected mortar plug and tensile element (Gigla, 2004). Four different types of failure were observed (Fig. 7), even if the last one it was not so usual (occurred only one time):

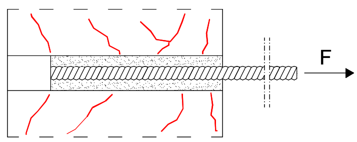
a. failure of the interface between the injected mortar plug and borehole surface;
b. failure of the interface between steel member and injected mortar plug;
c. surrounding masonry tensile failure;
d. steel failure (anchor loaded until tensile strength).



(a) failure between sock and borehole



(b). poor shear strength of injected mortar



(c) exceeded tensile strength of masonry

Figure 7: Main failure mechanism observed

Concluding remarks

Shear strength was considered as a nominal value obtained starting from the tensile force divided by the two shear surfaces: the inner one at the interface between sock and borehole and the outer one between the steel m and the grout injected.

Table 4 shows the values of the ultimate bond strength at the interface between borehole surface and injected mortar plug and between injected mortar plug and tensile element, for the different resistance mechanisms observed during the laboratory tests and for the different masonries investigated during the situ tests. In particular, the nominal values of the joint mortar adhesion is related to the type of structural units and to the performance of the joint mortar that was investigated by using a penetration test (Sala 2008).

Table 4: Shear Tensile Strength – all tests [MPa]

Interface	*Cement based BCM Hs*		*Lime based BCM Ls*	
	Laboratory tests	*In situ tests*	*Laboratory tests*	*In situ tests*
Inner: steel rebar-injected mortar plug	1.47÷6.62	1.64÷5.09	1.92÷7.26	0.89 ÷3.45
Outer: injected mortar plug-substrate	0.47÷2.13	0.53÷1.64	0.62÷2.34	0.29÷1.11

The parent material properties and, in particular, the mortar strength strongly affects the performance of injected anchors. For the assessment of the behaviour of injected anchors with sock, it is recommended to carry out preliminary on-site pull-out tests in order to check the anchor efficiency up to a maximum tensile load 20% higher than the design force. The shear strength ratio of injected grouts is about 2 in spite of a compressive strength ratio equal to 5÷6. Lime based grouts are, no doubts, the most compatible with the original materials present in ancient masonry; they also have good mechanical characteristics for this type of application. Moreover their specific application for the injection of anchors with sock, with the contribution (taking advantage) of the mechanical interlock mechanism, can increase results normally expected if only adhesion is contemplated.

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