



# Mechanical Behaviour of Metal Anchors in Historic Brick Masonry: An Experimental Approach

Rosana Muñoz<sup>1(✉)</sup> and Paulo B. Lourenço<sup>2</sup>

<sup>1</sup> Faculty of Architecture, Federal University of Bahia, Salvador, Bahia, Brazil  
munoz.rosana@gmail.com

<sup>2</sup> Department of Civil Engineering, ISISE, University of Minho, Guimarães, Portugal  
pbl@civil.uminho.pt

**Abstract.** Many historic buildings degrade and partially collapse due to the action of time and to lack of maintenance; only their façades remain. Their consolidation and reuse have fundamental importance to preserve the architectural heritage. In several cases, these buildings are made of brick masonry and interventions demand using metallic structures. The connection between the masonry, which has already lost its initial strength capacity, and the proposed structure must be carefully analysed to avoid structural damages to the building. The aim of the current study is to investigate the mechanical behaviour of metal anchors used to connect the walls to the metallic structure, whether provisionally or permanently, for shoring purposes or for building repairs, strengthening or rehabilitation ones. An experimental campaign was carried out; it included pull-out tests applied to two types of adhesive (chemical and grout) and mechanical anchors in brick masonry built in laboratory using hydraulic lime mortar and low mechanical strength bricks. Tensile force results were compared to predictive analytical formulas available in the literature. The current research contributes to the selection of the most efficient structural bond in terms of adhesion in historic brick masonry, thus contributing to the preservation of the historical, artistic and cultural heritage.

**Keywords:** Brick masonry · Failure modes · Metal anchors · Pull-out tests  
Tensile forces

## 1 Introduction

Many old buildings, which were built of brick masonry and constitute vast cultural heritage, deteriorate due to the action of time and/or men, as well as to lack of maintenance; only their façades and side walls remain. The shoring and structural reinforcement of such buildings may be conducted in several ways by using varied materials such as metallic elements, considered relevant, since they meet the requirements in terms of reversibility, compatibility and retreatability required in heritage interventions.

One fixing possibility between metallic structures and masonry walls lies on adopting metal anchors, which generally use three anchor types, namely: bonded anchors, expansion anchors and undercut anchors; the last two are called mechanical anchoring [1].

The first anchor type may use resin - thus, it is called chemical anchoring - or inorganic binders, which are often designated as grouting. The chemical anchoring often comprises two adhesive types, which are mixed during application. The grouting method often uses a cementitious grout to fill the voids in the carrier material, as well as to fix the connector. The grout presents properties similar to that of mortars or concretes, fact that enables its good performance under high temperature and humidity conditions [1]. Both bonds require a curing period for strength gain, which is short in the case of chemical anchoring.

Expansion anchors expand during installation and may be divided in two categories, namely: torque-controlled and deformation-controlled. Undercut anchors resemble miniature under-reamed piles and present expansive bottom [1]. Overall, the mechanical anchoring is based on the friction between the sides of the bore and the lugs of the connector during load transfer. Bonded and torque-controlled expansion anchors are the anchor types recommended for solid brick masonry [1].

The connection between metal structure and masonry deserves special attention, since, in practice, several internal and external factors may affect its behaviour and reduce its load capacity. Thus, the aim of the current study is to present results concerning the mechanical behaviour in terms of adhesion of three anchoring types, namely: chemical, cementitious grout-based and mechanical anchoring applied to laboratory-made masonry brick walls; as well as to compare the obtained results to predictive formulas available in the literature.

The herein performed methodological procedures included, besides the literature review on the subject, the implementation of an experimental program, which conducted tests in order to: (a) define the proportion of materials involved in the mortar to be applied to the walls; (b) characterize materials used in masonry; (c) build brick masonry walls; (d) perform tests on the masonry; and e) analyse the results by comparing the values recorded in the tests to those available in the literature.

The current study contributes to the selection of the most efficient type of fixing using mechanical and adhesive anchors in solid brick masonry. It is worth emphasizing that this anchoring type is recommended to strengthen old structures, since it implies low aesthetic impact and minimal intervention. The loss of original fabric is limited, and anchors can be easily removed and replaced. Still, one much relevant aspect is durability, meaning that depending on the application (short term or long term), selection can consider electroplated zinc coated (short term application), hot dip galvanized (ten times longer expected life than zinc coated) or stainless steel (long term, in this case AISI 316 type is recommended) to minimize corrosion problems.

## 2 Theoretical Aspects of Resistance of Metal Connections to Tension Loads

The use of metal anchoring in masonry is based on the transfer of tension. In practice, the use of anchors is often associated with aspects such as the stabilization of cracked or deformed masonry; the connection between new and old structures or structural elements; the transmission of tensile forces, for example, during construction; the strengthening of walls and foundations; and the strengthening to help supporting dynamic loads [2].

Masonry strengthening through metal connectors subjected to tensile forces has been carried out for centuries and is widely accepted in the conservation of cultural-heritage buildings. Some analytical formulas of estimated tensile strength values, obtained through pull-out tests applied to adhesive and mechanical anchors, were developed based on possible connection failure types.

### 2.1 Characteristic Strength for Adhesive Anchors

The main failure types for adhesive anchors are [3]: (a) failure of the metal part; (b) pull-out failure of the anchor; (c) brick breakout; (d) pull out of one brick.

The characteristic strength of the first failure type (herein called T1), which refers to the connector, is given by [4, 5]:

$$N_{Rk} = 0.75.A_s.f_u \quad (1)$$

The failure of the metal part is rarely observed in masonry; it happens in cases showing significant anchoring depth and masonry strength [6]. The characteristic strength shown in Eq. (1) is given by the effective cross-section area of the screw ( $A_s$ ) and by the ultimate tensile stress ( $f_u$ ) of the steel [3, 4, 7]. The ACI 318 recommends using the coefficient 0.75 [5], whereas the ACI 530 suggests using the yield strength ( $f_y$ ) instead of the ultimate tensile strength, as well as applying the reduction coefficient 0.90 [8], as seen in Eq. (2).

$$N_{Rk} = 0.90.A_s.f_y \quad (2)$$

The second failure type, i.e., the pull-out failure of the anchor - herein called T2 - happens between the adhesive and the surface or between the adhesive and the connector, in chemical anchors [9]. In case this failure type happens, the TR 029 [4], the fib Bulletin 58 [10] and the EN 1992-4 [11] recommend adopting the uniform adhesion tension model to describe the behaviour of the interface between the connector and the grout (see Eq. (3)) [12], and between the grout and the concrete (see Eq. (4)) [13]. Some of these models were specifically developed for reinforced concrete; however, it is possible to make analogies when addressing masonry.

$$N_{Rk} = \tau.\pi.d.h_{ef} \quad (3)$$

$$N_{Rk} = \tau_o \cdot \pi \cdot d_o \cdot h_{ef} \tag{4}$$

Both strengths depend on the effective anchoring length ( $h_{ef}$ ) and take into consideration different diameters such as  $d$  (connector) and  $d_o$  (bore). Equation (3) uses the nominal value  $\tau$  at the connector/grout interface, whereas Eq. (4) uses the  $\tau_o$  value at the grout/concrete interface. The disadvantage of this method lies on the scarce information about bond strength at the interface, since it is affected by internal factors, which are difficult to be controlled, as well as by external factors such as the bore condition during installation.

The concrete cone failure formula presented in Eq. (5) [4] is used to calculate the characteristic strength for the brick breakout failure type - herein called T3.

$$N_{Rk} = k \cdot (f_{ck \text{ cube}})^{0.5} \cdot h_{ef}^{1.5} \cdot \frac{A_{c,N}}{A_{c,N}^0} \tag{5}$$

This type of failure, which generally happens at short anchoring depths and in low-strength concretes, is influenced by the concrete strength, by the proximity to other connectors and edges, as well as by the presence of cracks [9].

Equation (5) depends on the  $k$  value, which is  $7.2 \text{ N}^{0.5}/\text{mm}^{0.5}$  for cracked concrete and  $10.1 \text{ N}^{0.5}/\text{mm}^{0.5}$  for non-cracked concrete [4] or  $7.7 \text{ N}^{0.5}/\text{mm}^{0.5}$  and  $11.0 \text{ N}^{0.5}/\text{mm}^{0.5}$ , respectively, according fib Bulletin 58 [10]; as well as on the concrete strength values obtained in 200 mm cubes ( $\text{N}/\text{mm}^2$ ); and on the effective anchoring length  $h_{ef}$  (mm). This equation may take into consideration the overlap of areas, when there are two or more adjacent connectors, through the reduction factor  $A_{c,N}/A_{c,N}^0$ . The  $A_{c,N}^0$  concrete area of an individual connector located far away from the edges on the concrete surface is given through  $9 \cdot h_{ef}^2$  [4–7], when the cone is idealized as a pyramid whose height is equal to the embedment depth ( $h_{ef}$ ), as shown in Fig. 1.

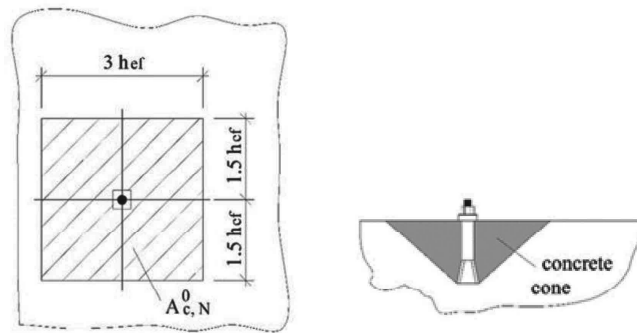


Fig. 1.  $A_{c,N}^0$  area of an individual connector and concrete cone

The characteristic strength of an anchor or a group of anchors in case of pull-out of one brick (T4), when vertical joints are designed to be filled with mortar, is calculated as follows:



$$N_{Rk} = 2.l_{brick} \cdot b_{brick} \cdot (0.5 \cdot f_{yko} + 0.4 \cdot \sigma_d) + b_{brick} \cdot h_{brick} \cdot f_{yko} \quad (6)$$

Wherein:  $l_{brick}$  = brick length;  $b_{brick}$  = brick width;  $h_{brick}$  = brick height;  $\sigma_d$  = design compressive stress perpendicular to the shear; and  $f_{vko}$  = initial shear strength according to EN 1996-1-1 [14]: 0.2 N/mm<sup>2</sup> for mortar strength from M2.5 to M9; and 0.3 N/mm<sup>2</sup> from M10 to M20.

## 2.2 Characteristic Strength for Mechanical Anchors

With respect to the mechanical anchoring, when it comes to load capacity, the following failure types may happen: failure of the anchor, as it was already discussed (see Eqs. (1) and (2)); cone; pull-out; and cracked cross-section of the material [8].

As for cone failure, herein called T5, the characteristic strength may be calculated through [8]:

$$N_{Rk} = k \cdot (f_{ck})^{0.5} \cdot h_{ef}^{1.5} \quad (7)$$

According to the fib Bulletin 58, the k value should be 7.0 N<sup>0.5</sup>/mm<sup>0.5</sup> for cracked concrete and 11.0 N<sup>0.5</sup>/mm<sup>0.5</sup> for non-cracked concrete [10]. Also, can be used 7.7 N<sup>0.5</sup>/mm<sup>0.5</sup> and 11 N<sup>0.5</sup>/mm<sup>0.5</sup>, respectively, according to the EN 1992-4 [11]; or yet; 7.2 N<sup>0.5</sup>/mm<sup>0.5</sup> and 10.1 N<sup>0.5</sup>/mm<sup>0.5</sup> [7], as already mentioned.

The pull-out failure in the mechanical anchoring, herein called T6, happens at moderate embedment depths in low-strength concretes or bores presenting diameter greater than that of the connectors [9], and depends on anchor type and shape [7]. The characteristic strength may be calculated through [11]:

$$N_{Rk} = k \cdot \pi \cdot (d_h^2 - d^2) \cdot \frac{f_{ck}}{4} \quad (8)$$

Equation (8) depends on k - whose values should be 7.5 N<sup>0.5</sup>/mm<sup>0.5</sup> for cracked concrete and 10.5 N<sup>0.5</sup>/mm<sup>0.5</sup> for non-cracked concrete [11] -, as well as on the concrete strength and on the supporting area of connector  $A_h$ , which takes into consideration the connector head ( $d_h$ ) and connector ( $d$ ) diameters.

Another failure type typical of mechanical anchoring, which happens in the cross section, may be avoided during the installation of the connector by providing sufficient distance from the edges and between connectors [10]. After the presentation of the state-of-the-art, the following section will describe the experimental campaign developed at University of Minho, in Guimarães, Portugal.

## 3 Experimental Campaign

Pull-out tests were carried out on solid brick walls built in the Structural Laboratory – LEST, at University of Minho, as well as other materials and masonry characterization tests, in order to enable the mechanical characterization of the three anchoring methods proposed in the current study (mechanical, chemical and cementitious grout-based).

### 3.1 Material Characterization

The materials used to build the walls comprised: (a) NHL 3.5 hydraulic lime mortar and sand derived from a quarry, with 1:2.5 volume proportion, according to Veiga and Santos [15]; and (b) solid bricks ( $0.065 \times 0.095 \times 0.200 \text{ m}^3$ ). The anchors were supplied by HILTI Portugal and the herein used cementitious grout was Mapefill P, produced by MAPEI. This choice was based on the main goal of working with old masonry. Table 1 presents the mechanical characterization of the materials used to build the walls (average values), as well as the coefficient of variation (expressed in percentage, in parentheses), which followed the reference standard recommendations [16–19]. The results of the studied mortars are within the range of values set by Veiga [20] about mechanical requirements for mortars adopted in restoration processes.

**Table 1.** Mechanical characterization of the materials using in the experimental campaign.

Material	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Mortar (28 days)	1.4 (10.5)	0.4 (14.1)	2.2 (4.7)
Brick	19.9 (4.5)	2.1 (16.3)	9.7 (6.9)

### 3.2 Masonry Construction and Mechanical Characterization

Two walls (0.40 m wide, 0.80 m long, and 1.20 m tall) were built for each anchoring type (six, in total) in order to perform the pull-out tests. The bricks were arranged according to recommendations by Segurado [21] for old masonry.

Walls were also built to allow characterizing the studied masonry according to compression, tension and shearing. In order to do so, axial and diagonal compression tests were conducted according to reference standards [22–25]. Table 2 shows average test results and the coefficients of variation expressed in percentage, in parentheses.

**Table 2.** Average wall strengths.

Compressive strength (MPa)	Tensile strength (MPa)	Shear strength (MPa)
9.8 (2.6)	0.1 (12.8)	0.2 (12.8)

### 3.3 Pull-Out Tests Applied to Walls

The anchoring types adopted in the present study were HUS 3 (mechanical); HIT-HY 270 and HIT-V-8.8 M10  $\times$  19 anchor (chemical); Mapefill P grout and HIT-V-8.8 M10  $\times$  190 anchor (cementitious grout). It is worth highlighting that, when the bores were drilled, and the anchoring was placed, as well as during the pull-out tests, the wall was subjected to compressive stress 0.2 MPa in order to reproduce the confinement effect associated with the vertical compression found on a real façade.

The anchors were placed 28 days after the walls were built. After the chemical and grout-based anchoring curing period was over, pull-out tests were carried out by keeping the actuator in horizontal position and connected to the anchor through a swivel specially developed for the test (Fig. 2).

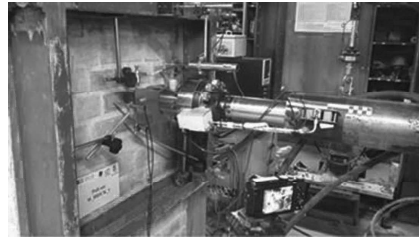


Fig. 2. Pull-out test applied to brick masonry

## 4 Results, Analyses and Conclusions

Table 3 presents the force and displacement results recorded in the pull-out tests, as well as the estimated characteristic strengths, which were calculated based on failure type, as it was addressed in Sect. 2. The failure type identification was based on the displacement results recorded through five LVDTs placed on the walls, as well as through the visual inspection performed during and after the pull-out test (see Figs. 3, 4, 5, 6, 7 and 8).

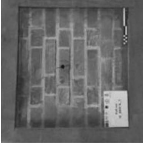
The current study adopted  $k$  values  $7.2 \text{ N}^{0.5}/\text{mm}^{0.5}$  (for adhesive anchoring) and  $7.0 \text{ N}^{0.5}/\text{mm}^{0.5}$  (for mechanical anchoring) as formula parameters in order to investigate the most unfavourable situation; as well as bond strength ( $\tau$  and  $\tau_o$ ) equal to  $2.3 \text{ MPa}$  [4]. The compressive strength value presented in Table 2 was adopted for  $f_{ck \text{ cube}}$ , whereas the value  $0.2 \text{ N}/\text{mm}^2$  was adopted for  $f_{yko}$ , and the value set by the EN 1996 1-1 standard was adopted for  $\sigma_d$  [14]. As the anchor was centred and more than  $3h_{ef}$  away from the edges, the  $A_{c,N}/A_{c,N}^0$  ratio was one.

The average pull-out force was  $25.06 \text{ kN}$  (CoV 11%) in the chemical anchoring;  $21.68 \text{ kN}$  (CoV 30.1%) in the grout-based anchoring; and  $12.72 \text{ kN}$  (CoV 1.8%) in the mechanical anchoring. Adhesive anchors showed better results than the mechanical one, with emphasis on the chemical anchoring. The difference between resin and grout bonds was approximately 16%.

The coefficient of variation in the grout-based anchoring showed significant result variability, which may be explained through factors such as: (a) internal voids; (b) absorption, in a differentiated way, of part of the grout water by the substrate, which changed the strengths; (c) manual grout application; (d) inadequate bore cleaning and/or wetting in some masonry; among others.



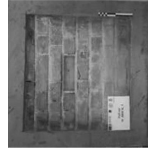
The predictive formulas available in the literature were inadequate for the herein developed study. Thus, it is necessary to conduct additional research in this field, mainly with respect to the value of the constants use in formulas and interface strengths.

**Table 3.** Experimental values of the pull-out test applied to brick masonry and values recorded through predictive formulas.

Wall panel	Type of fastener	Maximum axial load obtained on pull-out $N_p$ (kN)	Horizontal displacement at $N_p$ (mm)	Type of failure	Image of failure	Nominal load value $N_c$ (kN)	$N_c/N_p$ (%)
W_Brick_2	Chemical	27.00	3.06	T3	 <b>Fig. 3. Failure T3</b>	0.59	2.2
W_Brick_6	Chemical	23.11	2.84	T2 (adhesive/substrate)	 <b>Fig. 4. Failure T2</b>	16.47	71.3
W_Brick_3	Grout	26.29	10.02	T2 (anchor/grout)	 <b>Fig. 5. Failure T2</b>	27.46	104.5

*(continued)*

Table 3. (continued)

Wall panel	Type of fastener	Maximum axial load obtained on pull-out $N_p$ (kN)	Horizontal displacement at $N_p$ (mm)	Type of failure	Image of failure	Nominal load value $N_c$ (kN)	$N_c/N_p$ (%)
W_Brick_4	Grout	17.06	2.02	T4	 <p><b>Fig. 6. Failure T4</b></p>	27.84	163.2
W_Brick_1	Mechanical	12.55	2.17	T5	 <p><b>Fig. 7. Failure T5</b></p>	21.91	174.6
W_Brick_5	Mechanical	12.88	2.05	T5	 <p><b>Fig. 8. Failure T5</b></p>	21.91	170.1

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