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N° A14-06 A NEW *IN SITU* TORSIONAL TEST TO ASSESS MASONRY MORTAR SHEAR STRENGTH

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ABSTRACT

As part of an experimental program on the lateral confinement, through jointed jackets, of traditional masonry walls, a new torsional test to assess *in situ* the bond strength of pozzuolanic mortar, typical in Roman constructions, is presented. The relevance of the mortar strength is paramount for evaluating the structural safety of existing masonry buildings and is necessary to establish if interventions are eventually due. The preliminary experimental results of this new test procedure and the relative modelling are emphasized in the paper. The test is performed through a short pipe inserted in holes predrilled in selected mortar joints, and the grip against the surface is then controlled via cylindrical expansion. After the expansion device has been blocked, the ultimate torque is determined through a dynamometric spanner. The measured torsional moment makes the back analysis of the adhesion strength possible. The instrument investigates the degradation of the mortar and its partial or complete absence, in particular in head joints, in order to establish if a simple repointing is a sufficient retrofitting.

Keywords: mortar shear strength, torsional test, in situ *test*

1 INTRODUCTION

The estimation of safety in masonry constructions, especially existing ones, is based on the mortar and units strengths. From those values the strength of the masonry can be inferred using the experimentally established tables reported in recent codes, as the EuroCode (EC) 6 (Section 3.6) or the Australian Standard 3700 (Section 3.3). On the contrary of what is typical for reinforced concrete (RC) elements, in the design of masonry walls, especially foundations, given their large cross sections, even a small amount of cohesion and adhesion can play a relevant role. Usually the tensile strength is derived by bending tests on 40×40×160 mm, the latter being the length, specimens (refer to UNI EN 1015-11), or by triplet tests (UNI EN 1052-3). However such procedures are straightforward in a new building, whereas they are not for an existing construction, especially if it is less or more degraded, suffered geotechnical or seismic distresses, or was distorted from its original configuration. The undisturbed sampling is usually impossible in masonry, therefore *in situ* tests are compulsory. The assessment of the characteristics of existing mortars is carried out by way of proper chemical-physical analyses (Baronio & Binda 1996), or mechanical tests, as the penetrometric (Gucci *et al* 1995), the bond wrench (RILEM 1994), or the shove one (Abrams & Epperson 1989). Anyway, the first is not suitable to measure the tensile or shear strength, whereas the latter two are not fit for rubble masonry, typical in Central Italy up to the beginning of the XX century. More often than not, rubble masonry with pozzuolanic mortar is built using highly irregular tuff units coursed every 60-100 cm with two or three layers of bricks. It is appropriate to highlight right now that the lime and pozzuolanic mortar is able to establish with the tuff a chemical cohesion quite similar to the fossil petrifying. As abundant archaeological testimonies prove, this makes many Roman walls, also the rubble core ones if the mortar is well distributed, almost monolithic. Although the degradation of the mortar can put at great risk such constructions, usually the adhesion between tuff and pozzuolanic mortar is very stable and only in chemically aggressive environment, or under cyclic actions, or at high stress concentrations is depleted. Consequently, to assume a zero tensile strength can prove overconservative (see § 2) and may impose retrofitting interventions whose need is not adequately motivated. This is most important when an historical building is under consideration; as a matter of fact, as theory of restoration stresses, every intervention must be minimal (Brandi 1977). The best condition would therefore be to have at disposal a tool to ascertain that, without sacrificing the safety, no action at all is necessary. At the same time one of the most limited retrofitting technique is the repointing. It would be equally recommendable to have a tool capable to measure its mechanical effectiveness, thus making further steps not needed. Only if both verifications are negative other structural upgrading, such as that presented elsewhere (Ventura 2005), can be proved convenient. Thus, the aim of this paper is to present a new device for the *in situ* assessment of the shear strength (from which derive the tensile one) of original or repointed mortar in existing walls, even the rubble ones, while at the same time permitting the inspection of the joints and establishing if they are completely filled (see § 3). The apparatus was originally conceived following those for geotechnical investigation, since in some way is similar to a scissometric test; the phase of field testing is now in course. The tool is hence a tribute to Charles Augustine Coulomb's *Essai* (1776), whose author established the more than famous law of friction and can be considered the founder of geotechnics (refer to Heyman 1972). It is exactly Coulomb's work that permits the rediscover of friction and cohesion role in masonry mechanics, a role seldom acknowledged in computing software adapted from RC. All this experimentations are part of an ongoing research about the lateral confinement of existing masonry walls, through jointed metal jackets, as an effective retrofitting technique (Ventura 2000, 2004a and b, 2005). A section of the program is currently investigating the possibility to assess concrete compressive strength through an *in situ* punching test.

2 POZZUOLANIC MORTAR

The first stage of the research has been an articulated program of standard laboratory tests on traditional mortar mixes, made up by three parts of pozzuolan and one part of hydrated lime. Such volumetric proportions are similar to those of Roman historical masonries, as reported by Vitruvius (~30 b.C., section V.12.ii), although lime putty was used instead of hydrated lime. Such a mortar under the Italian Code (DM 20-11-87, and subsequent revisions, section 1.2.1) can be classified as an M4 mortar type. The average specific weight of the mortar was equal to 14.8 kN/m^3 (with a coefficient of variation equal to 2 %), very close to that of tuff stone. It is interesting to note that such specific weight is respectively lower and much lower than those of brick (~ 18 kN/m^3) or limestone masonry (~ 20-23 kN/m^3); therefore, so will be earthquake related inertia forces. In spite of this, EC8 (Section 9.2.3), and the Italian Seismic Code (OPCM 3274/2003 and subsequent revisions, Section 8.1.2), by imposing a mortar characteristic compressive strength higher than 5 MPa, forbid M4 mortars in seismic zones: this is clearly in contrast with the survival of many historical buildings. Therefore, although the recommendation of a high quality mortar is certainly shareable, and poses no problem in new constructions, it should be refined in the case of existing buildings, especially those with lower masonry specific weight. Axial compression tests were performed on mortar cylindrical specimens, whose diameter D and height L were 10 and 25 cm respectively. Consequently, mortar compressive strength f_m and elastic modulus E_m were measured following UNI 6556 standard; in particular, the elastic modulus has been computed as the mean of the three values of as many cycles with linearly increasing load (Fig. 2.1). Tests results are summarised in Table 2.1.

TABLE 2.1. ELASTIC MODULI AFTER 90 DAYS CURING

Test	Specific Weight	Compressive Strength	1st Cycle Elastic Modulus	2nd Cycle Elastic Modulus	3rd Cycle Elastic Modulus	Mean Elastic Modulus
1	15.03kN/m^3	4.68MPa	4180MPa	3759MPa	3655MPa	3865MPa
2	14.70kN/m^3	3.59MPa	4116MPa	3935MPa	3705MPa	3919MPa
3	14.50kN/m^3	3.79MPa	4190MPa	4029MPa	3905MPa	4041MPa
4	14.91kN/m^3	3.46MPa	3862MPa	4050MPa	3684MPa	3865MPa

Shear strength has been assessed by means of the so called "Brazilian", or cylinder splitting, test (Fig. 2.2). Following UNI 6135 standard, the load was applied by means of two wood pads, measuring 3×10×250 mm. The shear strength f_v, as a function of applied ultimate load P, is equal to:

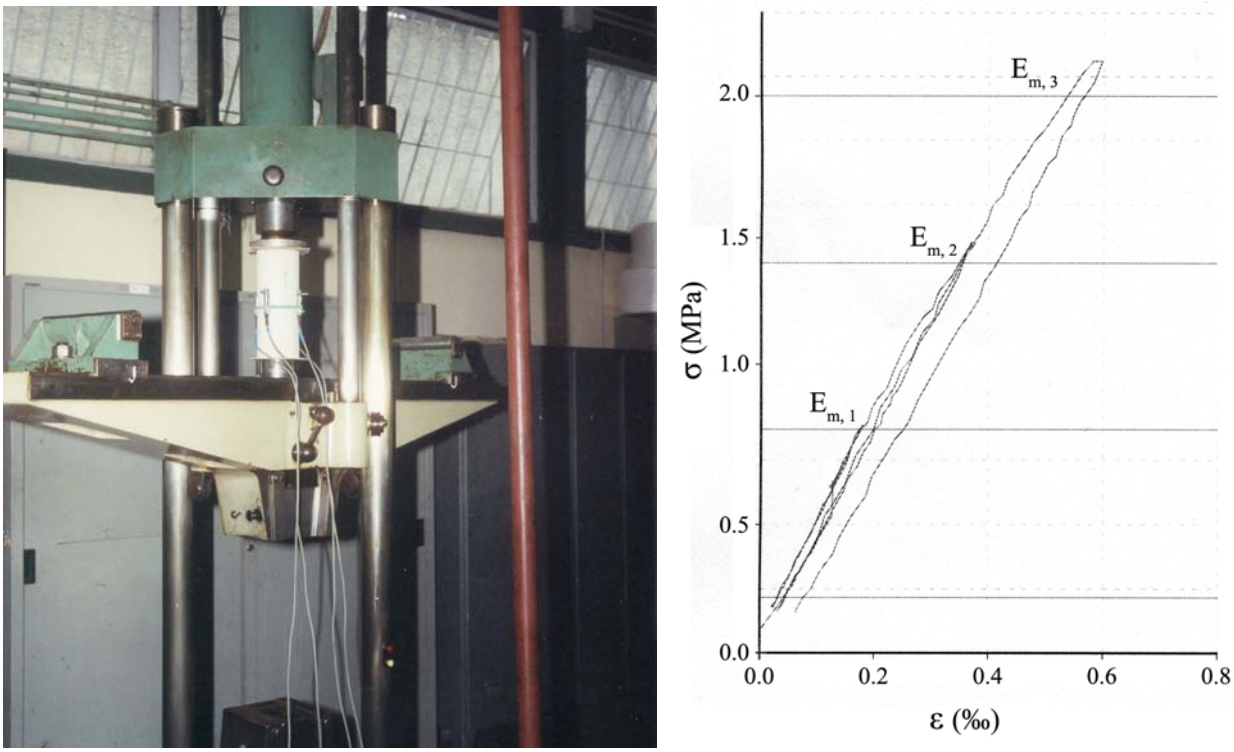
$$f_v = \frac{2P}{\pi D L} \tag{2.1}$$

with f_v average shear strength. Test outcomes are reported in Table 2.2. Finally, mean (and coefficient of variation) mechanical characteristics of pozzuolanic mortar were approximately: elastic modulus E_m = 3923 (2 %) MPa, compressive strength f_m = 3.9 (14 %) MPa, shear strength f_v = 0.53 (1 %) MPa.

TABLE 2.2. CYLINDER SPLITTING TESTS AFTER 90 DAYS CURING.

Test	Diameter×Length	Weight	Specific Weight	Ultimate load	Size at Failure	Shear Strength
1	9.7×24.9cm	27.34N	14.86kN/m^3	18.3kN	9.5×23.0cm*	0.533MPa
2	9.6×24.9cm	27.25N	15.12kN/m^3	19.0kN	9.2×24.9cm	0.528MPa
3	9.7×24.9cm	27.22N	14.80kN/m^3	20.0kN	9.5×24.9cm	0.527MPa
4	9.7×25.0cm	27.50N	14.89kN/m^3	19.2kN	9.5×25.0cm	0.515MPa

* this specimen cracked at one end during the test, thus reducing its length.



(a) (b)

Fig. 2.1. Compression test. (a): Apparatus set; (b) Stress-strain σ-ε curve.

(a)   (b)

Fig. 2.2. Cylinder splitting ("Brazilian") test. (a): Apparatus set; (b) Split specimens.

3 TORSIONAL DEVICE

3.1 Description of the device

Fig. 3.1a shows the device, made up by a 10 mm diameter pipe expandable radially by means of internal conic wedges. Its outer surface is sand-blasted in order to ensure an adequate adhesion along the 55 mm length of the shaft inserted in the 60 mm deep predrilled hole. The difference between the two measures was intentional, in order to avoid any punching contribution. For the same reason the head of the device was maintained a couple of millimetres apart from the mortar surface. The device shall be inserted in calibrated holes, carefully cleaned from any remaining dust by means of compressed air, drilled in the mortar to be assessed; its minute size reduces the disturbance and allows testing even very thin joints. Nonetheless recommended locations are were the mortar is thicker, such as intersections between horizontal and head joints or, when rubble masonry is under investigation, those points where greatest is the distance between stone units. Finally, if the mortar is exposed to the weather, it should be damped. The device has two sockets for dynamometric spanner. The former is for radial expansion, in order to get the cylindrical adhesion against the mortar, thus overcoming any surface ruggedness. Yet, it is appropriate to remember that the circumferential shear stress, which is impressed in the first setting phase, under Coulomb's hypothesis is a function of the radial stress and is independent of the contact surface. Consequently, even if the device does not completely stick to the hole the ultimate moment is unaffected, because the contributions to cylindrical shear adhesion do compensate. The achievement of the appropriate adhesion is insured by a centesimal calibre, measuring the change of the diameter during expansion, and by the dynamometric spanner measuring very small torques (starting from 0.1 Nm).

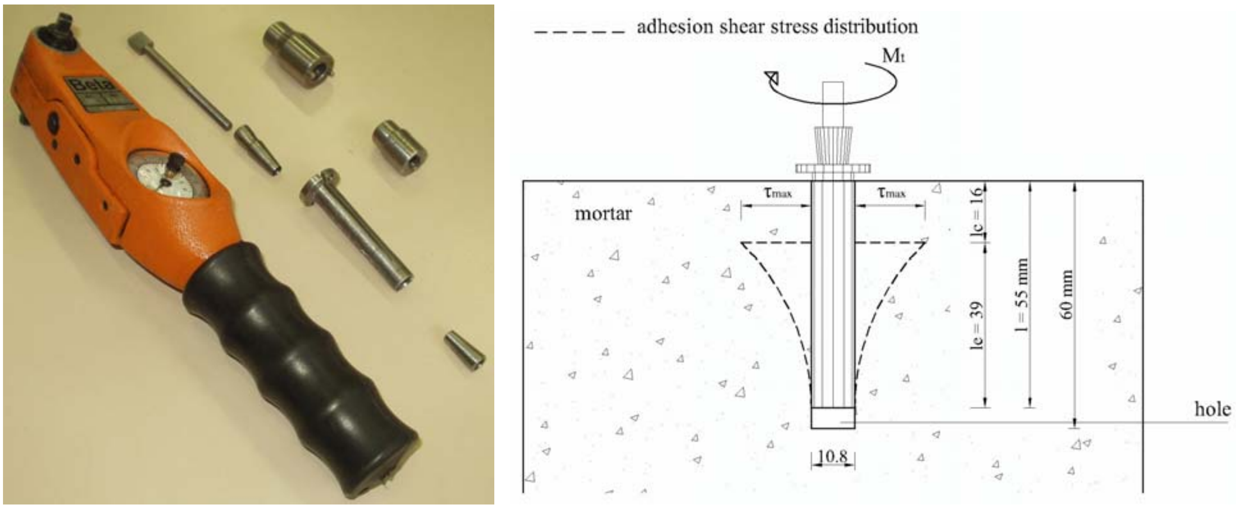
(a)  (b)

Fig. 3.1. Torsional device. (a): view; (b) vertical section with adhesion shear stress distribution.

When the first dynamometric spanner starts to register, as showed in Fig. 3.2a, the calibre is zeroed and a raising torque is applied up to an increase of the diameter of a few tenths of millimetre. This is usually achieved for a moment of the order of 1/5 of the torque producing the splitting of the specimen. Then, through proper blockage pivots, the expansion is stopped and using the second socket the torsional test is performed (Fig. 3.2b). The value of the mortar mean adhesion is computed from the ultimate torque, registered by the needle of the device when the cylindrical fissure slippage failure is triggered.

(a)  (b)

Fig. 3.2. (a): device expansion and calibre controlled reset; (b): torsional test.

3.2 Interpretation of initial expansion and of the torsional test

The calibration of the initial device expansion is here interpreted recurring to the theory of the expansion of a cylindrical cavity in an elastoplastic half-space (Vesic 1972). The same theory was used to study the behaviour of a piezometric tip as a modification of the Dutch static penetrometer (Ventura 1982). Following that theory, the radial elastic normal stress σ_{ri}, applied by a pressiometer-like tool, is equal to:

$$\sigma_{ri} = \frac{E_m \, \Delta r}{r_i} \tag{3.2}$$

r_i being the inner radius of the cavity, where the expanding device is encased and Δr the radius increase. The radial plastic normal stress σ_{rf} is instead equal to:

$$\sigma_{rf} = 2\, f_v \ln\left(\sqrt{\frac{E_m}{3\, f_v}}\right) + \frac{2}{3}\, f_v \tag{3.3}$$

Along the surface between the external most elastic region and the inner most plastic one, it is possible to assume that the respective radial stresses coincide. Therefore, it is possible to write

$$\sigma_{ri} = \sigma_{rf} \qquad \Rightarrow \qquad \frac{E_m \, \Delta r}{r_i} = 2\, f_v \ln\left(\sqrt{\frac{E_m}{3\, f_v}}\right) + \frac{2}{3}\, f_v \tag{3.4}$$

The initial radial strain, disregarding the gaps, is usually approximately equal to $\Delta r/r_i \approx 0.1\%$. Once the device is blocked the torsional test can be performed. Its modelling is analogous to that used to interpret tests on soil anchor ties (Ventura 1985a) or to assess the clamp degree in bulkheads or in piles sets, as dolphin piles, subjected to horizontal actions (Ventura 1985b). In Fig. 3.1b the adhesion shear stress distribution in the mortar is represented. Initially the mortar behaves elastically and adhesion can be assumed along the whole height of the pipe. When the adhesion shear strength is reached, the mortar does crack. Therefore, an upper part of the device shaft, whose length is ℓ_c, is more or less free; in the remaining length ℓ_e the mortar is still adherent and the stress distribution can be assumed exponential. The steel device can be modelled as cylindrical De Saint Venant beam undergoing torsion: the total shear stress τ in a generic point of the cross section is tangent to the circumference whose centre is coincident with torsion centre. The latter is coincident with the centroid of the cross section, whose circular shape rules out any warping. When considering the outer most circumference, τ is therefore equal to:

$$\tau = \frac{M_t}{I_p} r = \frac{2 M_t}{\pi r^3} \tag{3.5}$$

with *r* radius of the cross section and $I_p = \pi r^4/2$ polar moment of inertia with respect to the centroid. The torsional rotation angle θ between two cross sections, distant one from the other ℓ_c, is equal to:

$$\theta = \frac{M_t \, \ell_c}{G_s \, I_p} = \frac{2 M_t \, \ell_c}{G_s \, \pi r^4} = \frac{\tau \, \ell_c}{G_s \, r} \tag{3.6}$$

with G_s steel shear modulus. It is important to bear in mind that the steel bolt is still elastic, while the mortar is already in the plastic (cracked) range. As assumed the shear stress τ, at the interface between mortar and device, varies exponentially along the shaft height, measured by the abscissa z, following the equation:

$$\tau(z) = \frac{e}{e-1} \tau_{\max} \left(1 - e^{-\frac{z}{\ell_e}} \right) \tag{3.7}$$

where τ_{max} is the maximum shear stress. Integrating the elementary reaction of the mortar $dM_z = \tau(z)\, r\, dA$, upon the infinitesimal area $dA = 2\pi r\, dz$, one gets the reaction torque M_z:

$$M_z = 2\pi r^2 \frac{e}{e-1} \tau_{\max} \int_0^{\ell_e} \left(1 - e^{-\frac{z}{\ell_e}} \right) dz \approx 3.67 \, \tau_{\max} \, \ell_e \, r^2 \tag{3.8}$$

Imposing the equilibrium between applied torque and reaction torque, it is possible to get the shear strength f_v:

$$\tau_{\max} = f_v = \frac{M_t}{3.67 \, \ell_e \, r^2} \tag{3.9}$$

Writing down the compatibility equation among the two rotations one gets:

$$\theta_e = \theta_p \qquad \Rightarrow \qquad \frac{M_t}{3.67 \, G_m \, \ell_e \, r^2} = \frac{2 M_t}{G_s \, \pi r^4} \ell_c \tag{3.10}$$

Assuming:

$$G_m = \frac{E_m}{2(1+\nu)} = \frac{E_m}{2(1+0.25)} = 0.4 E_m \tag{3.11}$$

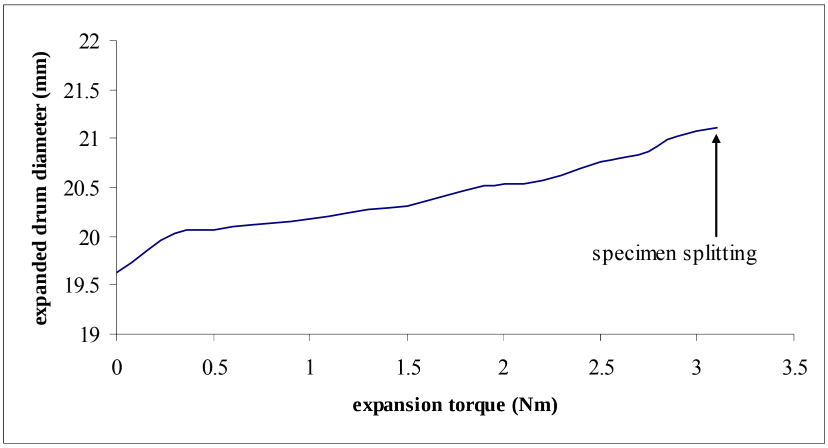
from Eqn. (3.10) it is possible to calculate:

$$\ell_e(\ell-\ell_e)=0.43\,r^2\frac{G_s}{G_m}\approx r^2\frac{G_s}{E_m} \tag{3.12}$$

The three Eqn. (3.4), (3.9), and (3.12) are a set that, having measured Δr and M_t, make the computation of E_m, f_v and ℓ_e possible. However, in the framework of this research the task was made easier by the measured value of E_m (see § 2), from which it was possible to set $\ell_e \approx 39$ mm. Thus, based on these values, the shear strength of the mortar was evaluated using the sole Eqn. (3.9).

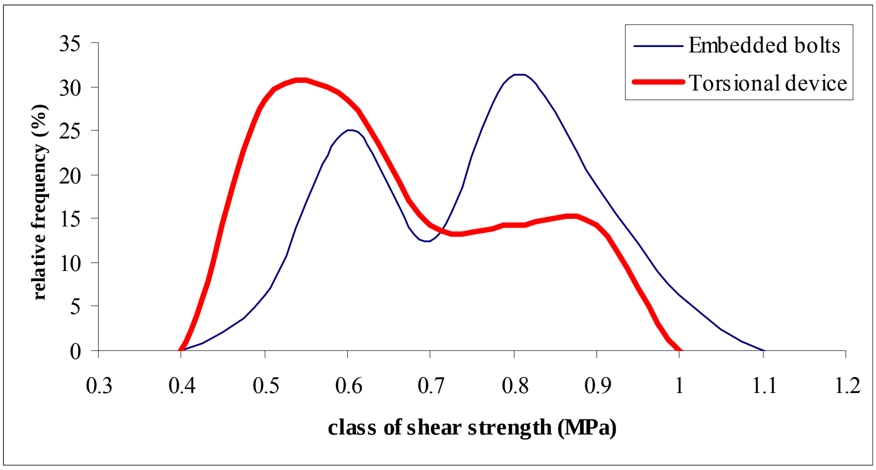
3.3 Torsional tests

Torsional tests were performed on pozzuolanic mortar specimens both cubic, with a 16 cm edge, and cylindrical, with a 10 cm diameter and a 25 cm height (Fig. 3.4a). In either case 8 mm diameter bolts were embedded in the fresh mortar for 55 mm. The diameter of the bolt was chosen smaller than the nominal one of the torsional device pipe because due to the screw-threaded surface of the former, with a 1.27 mm pitch, had an area equal to 1.32 times the latter. After a 90 days curing, a direct torsional test was performed in order to measure the ultimate torque and then compare it with that obtained through the new device. The torque has been applied upon the hexagonal nut and counter-nut, 2 mm apart from the face of the specimen, by means of a dynamometric spanner. The moment operated was counter-clockwise in order to avoid any punching contribution. The mean value of this ultimate torque M_t has been equal to 2.3 Nm (with a standard deviation of 0.41 Nm). The interpretation based on Eqn. (3.9) was performed assuming $\ell_e \approx \ell = 55$ mm, because it was observed that the crack propagation was hampered by the screw-threading. Therefore, the average shear strength f_v was equal to 0.71 MPa (see Fig. 3.4b). The torsional tests with the new device were performed on the same specimens where the bolts where embedded, drilling holes in the other faces. Quite an effort was put in the research of the most appropriate finish of the pipe outer surface. Initially different grades of knurl were tested; also different values of the expansion torque, ranging between 0.5 and 1.0 Nm, were experienced in order to check that the ultimate torque was not dependent upon the expansion. This proved true. However, the knurled finish was in the end discharged because the surface was too rough and after the first expansion its spikes depleted the mortar characteristics and produced a wide scatter in the results. Therefore, the sand-blasted solution was preferred, and only those outcomes are reported. The first radial lateral expansion was usually equal to 0.4 mm, the whole being therefore 0.8 mm, and was obtained under an average torque of 0.6 Nm. Such a figure is much lower, usually 20-25%, than the one producing the splitting of the specimen (e.g. refer to Fig. 3.3). The diameter of the device after the initial expansion was therefore ordinarily equal to 10.8 mm. Fig. 3.2b shows the torsional test performed using the described torsional device. The average ultimate torque M_t obtained was equal to 2.58 Nm (with a standard deviation equal to 0.55 Nm); the average shear strength f_v being therefore 0.62 MPa. Thus, the assessment through the torsional device is intermediate between this based on the bolts and that computed from cylinder splitting test (Table 3.1).

(a)  

(b)

Fig. 3.3. Expanding the torsional device up to splitting the specimen.

(a)  

(b)

Fig. 3.4. (a): Mortar specimens with embedded bolts. (b): Relative frequencies of shear strength classes for tests on embedded bolts and using the torsional device.

TABLE 3.1. CYLINDER SPLITTING, EMBEDDED BOLTS AND TORSIONAL TESTS MEAN AND STANDARD DEVIATION SHEAR STRENGTH.

Test	Mean	Standard Deviation
Cylinder splitting (“Brazilian”)	0.53MPa	0.01MPa
Embedded bolts	0.71MPa	0.13MPa
Torsional device	0.62MPa	0.13MPa

3.4 In situ torsional tests

Fig. 3.2 presents the use of the torsional device on the mortar joints of ashlar and rubble tuff masonry walls (Ventura 2005). The tests have been performed in holes drilled at the base and the top of head joints; this permitted, at the same time, to verify that perpend joints were completely filled. The measured values agreed quite well with laboratory ones, although the number of tests performed is still too low. However, a wider experimental research is in an advanced stage of preparation; this will consider also non pozzuolanic mortars, more usual when far away from pyroclastic quarries.

(a)  (b)

Fig. 3.2. *In situ* torsional tests on tuff masonry walls. (a): ashlar; (b): rubble course.

4 CONCLUSIONS

While verifying the safety of existing constructions, interventions should be limited for both economic and cultural reasons. Mortar cohesion and adhesion can play an important role, due to the considerable size of the walls cross sections, significantly contributing to overall shear and tensile resistance. However, in order to take into account such contribution an accurate measure of its strengths is compulsory, and this should be taken *in situ*. At the same time it should be also verified that the mortar is appropriately distributed, especially in head joints which have a crucial function under horizontal, earthquake related, actions. Thus, within the framework of a wider experimental research on the seismic strengthening of masonry walls through jointed metal jackets (Ventura 2005), a new device for field torsional tests has been developed. The apparatus makes the investigations possible also in the case of rubble masonry, and is able to check the effectiveness of sensitive retrofit techniques, such as the repointing. Tests have been performed on pozzuolanic mortar mixes, traditional in Central Italy especially in Rome and nearby. In order to make a comparison possible, standard tests, such as axial compression and cylinder splitting, were performed. Moreover, additional experiments were carried out unscrewing, after 90 days, bolts embedded in the fresh mortar. Finally torsional tests were performed using the proposed device. First of all a parametric research was carried out, in order to establish the necessary initial expansion. Then the actual tests were executed.

A first set of them, using a knurled device outer surface was discharged. Then a sand blasted finish was adopted. Laboratory results of the first expansion were interpreted at the light of the Vesic (1972) theory of a cavity expanding in a elastoplastic half-space, while the torsional test modelling was performed in accordance to similar geotechnical problems. The average shear strength computed from these latter tests was intermediate from the values obtained from the embedded bolts (slightly higher) and from the cylinder splitting, or so called "Brazilian" (slightly lower) test. A field experimental campaign on masonry walls, both constructed using the same mortar of the specimens and being part of existing building, is now in course.

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