12th International Conference on Structural Analysis of Historical Constructions
SAHC 2020
P. Roca, L. Pelà and C. Molins (Eds.)

LABORATORY AND IN-SITU CHARACTERISATION OF MASONRY MATERIALS IN A LARGE HISTORICAL INDUSTRIAL BUILDING IN BARCELONA

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Keywords: Masonry, MDT, Brick, Lime mortar, Core drilling, Compressive strength.

Abstract. *This paper presents an experimental campaign carried out in an historical industrial building of Barcelona from the 19th century, considering in-situ and laboratory minor destructive testing (MDT) techniques. The results obtained showed a good relationship between the in-situ MDT techniques and the tests carried out in the laboratory. The experimental results from different portions of the large-scale building allowed the discovery of different material typologies deriving from different construction phases.*

1 INTRODUCTION

The determination of the mechanical properties of existing masonry structures faces significant difficulties due to the intrinsic complexity of this composite material. However, acquiring a full knowledge of the main parameters is necessary to design adequate conservation actions for the built cultural heritage [1]. The mechanical characterisation of existing masonry structures usually requires an optimum combination of laboratory and in-situ techniques, especially in large constructions. This research presents the experimental methodology applied to an extensive campaign carried out in an historical industrial building of Barcelona built in the 19th century.

The experimental campaign resorted to minor destructive testing (MDT) techniques, both based on in-situ testing of masonry components and extraction of small samples for laboratory testing. The in-situ MDT allowed a preliminary evaluation of the variability of the properties over the large building in order to optimize the sampling and the execution of the laboratory tests. The results from different MDT techniques allowed useful cross-checking in order to keep a continuous control throughout the entire experimental program. The tests were developed on the units and mortar joints of both masonry walls and timbrel vaults, as well as on the plasters.

The main objectives were to obtain a careful characterisation of the material components in order to evaluate their strength capacity and to choose compatible restoration materials of similar properties.

The in-situ experimental characterisation was carried out by means of the Pin Penetration Test (PPT) and the Helix Screw Pull-off Test (HPT) [2] on the mortar joints and bricks, as well as the PPT and Pull-off Test (POT) [3] on the mortar plasters. The experimental characterisation in the laboratory consisted in: compressive testing of small samples of bricks extracted from walls [4]; double punch testing (DPT) of mortar joints from the walls and the timbrel vaults; DPT of plaster specimens [5]; compressive testing of core drilled masonry (CDM) samples [6], [7]; and compressive testing of ceramic tile samples from the timbrel vaults by means of a novel nonstandard setup.

2 EXPERIMENTAL PROGRAM IN-SITU

2.1 Windsor pin penetration test on mortar joints, bricks and plasters

The pin penetration test (PPT) is a MDT method developed to evaluate in-situ the compressive strength of the concrete, mortars and bricks. A previous research [3] investigated how to adapt the test to historical lime mortar joints with a low compressive strength, as well as to historical fired clay bricks.

The PPT was executed on six zones of masonry walls and four zones of mortar plasters. Figure 1 illustrates the operations. A 3 mm diameter pin, with a conical end, is inserted into the device. The retraction nut is tightened until the trigger mechanism closes to hold the spring in place and is then it completely loosened. The device is positioned perpendicularly to the surface to be tested (Figure 1a). The trigger is pulled while holding the device against the surface. After the pin is taken out, a bulb air blower is used to remove the residual material inside the hole. Then, a micrometer is inserted to the bottom of the hole using the knurled thimble on the head of the micrometer (Figure 1b). The micrometer reading is noted. The penetration is obtained by subtracting the reading from one inch (25.4 mm).

Figure 1: Pin Penetration Test operation: (A) the device is positioned perpendicularly to the surface to be tested, and, after firing the pin, (B) a micrometer is inserted to the bottom of the produced hole.

2.2 Screw (helix) pull-out test on mortar joints and bricks

The helix pull-out test (HPT) was carried out on the mortar joints and on the bricks. According to a previous research focusing on HPT in low strength mortars [3], a 3 mm diameter pilot hole was executed and preferred to the 4 mm diameter pilot one suggested by the provider.

In the same way, a 4 mm diameter pilot hole was preferred for bricks instead of the 5 mm one suggested by the provider [8].

The procedure for HPT is executed as follows. A pilot hole of 3 mm diameter is made in the mortar joints with a drill working at the minimum speed and with the tightening power adjusted at the weakest position. A pilot hole of 4 mm diameter is made in the bricks using a rotary-hammer drill with a masonry bit (Figure 2a). A high-strength steel helical tie with a diameter of ¼ in. (6.3 mm) is mounted into a supplementary tool. While holding it horizontally, the tool is hammered carefully until the helical tie is introduced into the pilot hole to a depth of 30 mm and results embedded in the masonry component (Figure 2b). This process allows the helical tie to rotate and cut a thread in the mortar or the unit during insertion. After insertion, a Load Test Key (LTK) is screwed onto the remaining outer part of the tie. The LTK restrains from rotating the helical tie during the test, assuring a shear failure in the tested material. The Load Test Unit (LTU) is connected to the LTK and the mechanism is rotated to screw down the tie and take up any slack. The LTU provides the contact with the material's surface by means of a steel circle. The load is applied by turning a grip lever to increase progressively the load until failure (Figure 2c). The maximum load reached during the test is recorded as the pull-out force. Figure 2 shows the test layout, as well as the sequence of the operations during the HPT.

Figure 2: Helix Pull-out Test operation: (A) drilling the pilot hole, (B) hammering the tool until the helical tie is introduced in the pilot hole, (C) loading by turning the grip lever until failure, (D) failure in the brick.

2.3 Pull-off test on mortar plasters

The pull-off test (POT) is a test developed to evaluate the adhesion strength of gypsum and lime mortar plasters [9]. The POT was executed on lime mortar plasters in the investigated building. Figure 3 shows the sequence of operations of the experimental in-situ tests. The first operation consists in removing the surface paint layer with a mechanical sanding that does not alter the physical and chemical characteristics of the lime mortar and ensures proper adhesion (Figure 3a). The plaster is cut until reaching the masonry substrate by using a core bit with 50 mm diameter (Figure 3b). After notching a number of circles, 50 mm diameter metal discs are stuck to the coating with a two components adhesive consisting of methylmetacrylate (Figure 3c). Once the adhesive has hardened, the disc is pulled off with a dynamometer by applying a perpendicular force to the surface. Two different dynamometers were used. A manual reaction dynamometer with a capacity of 500 N and a digital accuracy of 0.1 N was used in the position ZA. This position was characterised by lower adhesion strength (Figure 3d). In zones with higher adhesion strength, a different device with a mechanical dynamometer support, capacity of 5000 N and manual reading was used (Figure 3e). The pull-off load applied to the metal disc is increased steadily until failure (Figure 3f). The peak load reached during each test is recorded as the pull-off strength.

Figure 3: Pull-off test operation: (A) removing the surface paint layer with a mechanical sanding, (B) drilling the plaster until reaching the masonry substrate using a 50 mm diameter core bit, (C) sticking the metal discs, (D) manual dynamometer, (E) mechanical dynamometer support, and (F) failure of plaster substrate.

2.4 Extractions of the specimens

The masonry walls investigated were 450 mm thick, built with fired handmade clay brick units with nominal size 295.7 × 146.2 × 42.9 mm^3, and lime mortar joints with thickness variable between 12 mm and 18 mm.

The extractions of the CDM samples were done by horizontal drilling using the dry technology proposed in [6]. Figure 4 shows the sequence of operations of the in-situ extractions. Before drilling, 152.5 mm diameter core samples were marked to guarantee the correct drilling, including one vertical and two horizontal mortar joints and four bricks (Figure 4a). Twenty-one specimens were drilled in five extraction zones (Figure 4b and c). Only three out of twenty-one specimens were discarded after the extraction operations due to irregularities inside the wall. All the CDM samples had an approximate depth of 300 mm and were cut in the laboratory using a dry radial saw in order to obtain an approximate depth of 145 mm (Figure 4d). After drilling, some courses of the wall were disassembled using a chisel and a hammer to extract whole bricks and mortar joints. The selected specimens were stored and labelled carefully to preserve their integrity until taken to the laboratory.

The timbrel vaults of the industrial building were composed of two layers of fired handmade clay tiles. Their bond was staggered through the thickness of the vault in order to prevent the alignment of the tile joints. The components used in the vaults were tiles with nominal size of 294.3 × 145.3 × 20.8 mm^3. The lime mortar joints had thickness of 17 mm in the 1^{st} timbrel vault and of 10 mm in the 2^{nd} timbrel vault.

Figure 5 shows the sequence of operations of the in-situ extractions, executed from the top of the timbrel vaults by removing first the pavements and then the vault filling (Figure 5a). The mortar joints between tiles were marked with a radial saw (Figure 5b) and then extracted carefully with a chisel and a gauging trowel (Figure 5c and d).

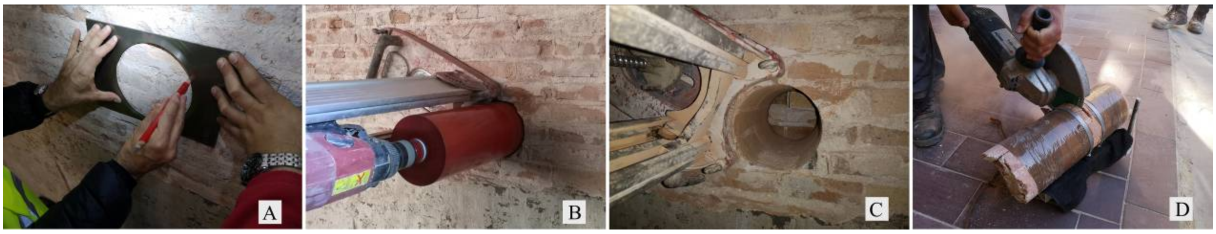

Figure 4: The sequence of operations of the cylinder extractions: (A) marking the core perimeter before extraction, (B) drilling, (C) hole in the wall after extraction, (D) cutting the specimen with a dry radial saw until obtaining an approximate depth of 145 mm.

Figure 5: The sequence of operations of the extractions of samples from the timbrel vaults: (A) removing the pavements and the vault filling, (B) removing the mortar between tiles by using a radial saw, (C) extracting the tiles with a chisel, (D) extracting the tiles with a gauging trowel.

3 EXPERIMENTAL PROGRAM IN THE LABORATORY

3.1 Compressive tests on brick specimens

The specimens considered for the experimental programme were prepared according to the procedures specified in standard EN 772-1:2011+A1 [4]. The use of a grinder fitted with a diamond-impregnated head could guarantee the flatness and parallelism of the faces. The specimens were cut from the bricks using a table saw equipped with a water jet, and air conditioned in a dry mode at a constant temperature of 105°C. Two types of specimens were obtained from every extraction zone, i.e. a specimen measuring 100 × 100 × 40 mm^3 (identified as “CB_10”) fulfilling the standard requirements, and 40 × 40 × 40 mm^3 cubes (identified as “CB_C4”) as a nonstandard size that allows a considerable increase of the number of available samples.

The specimens were tested under uniaxial compression by using two hydraulic testing machines, with a capacity of 3000 kN for CB_10 specimens, and a capacity of 200 kN for CB_C4 samples. The tests were executed under load control with a rate of 0.15 MPa/s with duration of the test higher than 60 seconds.

3.2 Compressive tests on tile specimens

The characterization of the clay tiles from the timbrel vaults is not possible according to the European standard EN 772-1:2011+A1 [4] or American ASTM C67 [10] due the reduced thickness of the units. To overcome this problem, the proposed solution consisted in assembling two specimens with a cement mortar layer allowing the connection between the samples. This strategy allowed the reduction of the slenderness of the specimen (Figure 6a).

The specimens were cut from the clay tile using a table saw. Two specimens were obtained for every clay tile measuring $100 \times 100 \times t$ mm^3, were t is the thickness of the specimen (identified as “CB-F”). These two specimens were assembled using a mould designed and built specifically for this research. The cement mortar was kept 10 mm away from the contact with the testing machine plates. The specimens were grinded on loaded faces to ensure a uniform distribution of compression forces (Figure 6b). The specimens were tested under uniaxial compression using a hydraulic testing machine with a capacity of 200 kN. The loading rate under displacement control was 0.025 mm/s to ensure a duration of the test higher than 60 seconds (Figure 6d).

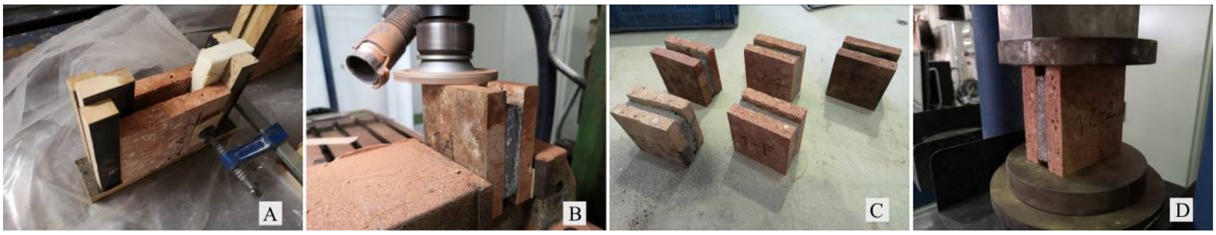

Figure 6: The sequence of operations of compressive tests on tiles: (A) two specimens assembled with an intermediate cement mortar layer, (B) grinding on the side surfaces, (C) tile specimens in test position, (D) execution of the test.

3.3 Double punch tests on mortar joints and plasters samples

The mortar bed joints extracted between the units, as well as the plaster samples, had low consistency and cohesion. This fact, usual in historical structures, made the preparation of regular specimens difficult. For this reason, it was not possible to test mortar slabs with exact dimensions of 50×50 mm^2 as recommended by the German standard DIN 18555-9 [5]. A gypsum powder layer with a thickness of 1 mm was interposed between the specimen and the loading punches, which had a diameter of 20 mm.

The specimens were tested under uniaxial compression using a hydraulic testing machine with a capacity of 10 kN. The loading rate under load control ensured that the test would last approximately 60 seconds. After the DPT, the specimens showed a crushed central part shaped like a sandglass between the loading punches and radial cracks toward the outer perimeter.

3.4 Compressive strength of core drilled specimens

Once brought to the laboratory, two high strength mortar caps were casted on top and bottom of the CDM cores by using a special mould. The mortar caps created two flat surfaces allowing a distributed load, as proposed in [6] and [7] and unlike the UIC leaflet [11] recommendation on the use of steel concave plates and lead sheets in contact with the sample. The sizes of the caps were about 110 mm width and 150 mm length.

The specimens were tested under uniaxial compression using a hydraulic testing machine with a capacity of 3000 kN. The force was applied perpendicularly to the horizontal joints. The tests were carried out in two stages. The first stage was oriented to the study of the elastic behaviour of the masonry and consisted in the application of three loading/unloading cycles under load control ranging from 5% to 20% of the estimated maximum load. Its value was determined by using the expression proposed by the Eurocode 6 (EC6) [12] to obtain the characteristic compressive strength of masonry, f_c, using the normalised compressive strength of the units, f_b, and the mortar, f_m. The Young's modulus was calculated for the loading branch of the third cycle. The second stage of the test was aimed to characterize the compressive strength of masonry. The cylinders were tested under displacement control, at a rate of 0.004 mm/s. The compressive strength was calculated as the ratio between the maximum load and the cross-section of the mortar caps [13].

4 DISCUSSION OF THE RESULTS

4.1 Summary of in-situ and laboratory experimental results

Table 1 reports a summary of the in-situ experimental results on mortar joints (MJ), bricks (B) and plasters (P) for the PPT and HPT, as well as the POT results in lime mortar plasters (P) on masonry wall (zone A and B) and at the bottom of the timbrel vaults (zone D).

Table 2 reports a summary of the experimental compressive strength, f_b', of 49 CB_10 and 98 CB_C4 brick specimens, as well as of 22 clay tile specimens obtained from two zones (F1 and F2). It also reports a summary of the experimental compressive strength results, $f_{m,DPT}$, of 193 DPTs on mortar joint (MJ) specimens, and 94 DPT of plaster (P) specimens obtained from the different zones. Finally, Table 2 presents the values of the experimental compressive strength, f_{c150}, and the experimental Young's Modulus, E_{c150}, of 18 CDM specimens.

Table 1: Experimental results on mortar joints (MJ), bricks (B) and plasters (P) from the PPT, HPT and POT tests, in terms of the average values (Av) and coefficients of variation (CV), for six zones of masonry walls (Z1, Z2, Z2bis, Z3, Z4 and Z5) and four zones of plasters (ZA, ZB, ZC and ZD).

		Z1	**Z2**	**Z2bis**	**Z3**	**Z4**	**Z5**	**ZA**	**ZB**	**ZC**	**ZD**
		Lime Mortar Joints (MJ) / Plasters (P)									
PPT	Av	10.4	10.6	10.4	11.3	10.4	9.8	9.9	7.4	5.6	7.0
[mm]	CV	4.5%	4.8%	4.3%	7.7%	8.3%	5.9%	8.4%	15.2%	8.2%	9.5%
HPT	Av	415	405	455	531	435	765	-	-	-	-
[N]	CV	35.5%	34.3%	24.0%	33.3%	18.0%	20.0%	-	-	-	-
POT	Av	-	-	-	-	-	-	77	295	-	350
[N]	CV	-	-	-	-	-	-	38.6%	94.4%	-	49.5%
		Fired Handmade Clay Brick (B)									
PPT	Av	6.6	6.2	5.9	5.8	5.9	6.0	-	-	-	-
[mm]	CV	23.6%	13.3%	16.7%	11.3%	11.6%	15.2%	-	-	-	-
HPT	Av	1700	2005	1665	1625	1795	1670	-	-	-	-
[N]	CV	14.1%	13.7%	9.2%	16.5%	20.2%	10.3%	-	-	-	-

Table 2: Experimental compressive strength averages values (Av) and coefficients of variation (CV) on brick specimens (CB_10, CB_C4), tile specimens (CB_F1, CB_F2), mortar joint specimens (MJ), plaster specimens (P) and Core Drilled Masonry (CDM) samples obtained on six extraction zones of masonry wall (Z1, Z2, Z2bis, Z3, Z4 and Z5), on two extraction zones of timbrel vaults (F1 and F2) and on t five extraction zones of plasters, three from wall (ZA, ZB and ZC) and two from the bottom of the timbrel vaults (ZD and ZE).

			Z1	Z2	Z2bis	Z3	Z4	Z5	F1	F2
Brick f_b'	**CB_10**	Av [MPa]	26.2	46.0	33.7	32.7	25.0	30.5	-	-
		CV	21.3%	21.3%	13.6%	13.4%	16.8%	22.7%	-	-
	CB_C4	Av [MPa]	15.0	25.3	14.8	16.4	13.6	17.8	-	-
		CV	16.5%	29.5%	21.0%	26.4%	25.2%	24.0%	-	-
Tile f_b'	**CB_F**	Av [MPa]	-	-	-	-	-	-	22.8	22.2
		CV	-	-	-	-	-	-	21.8%	19.7%
DPT $f_{m,DPT}$	**MJ**	Av [MPa]	1.1	0.4	0.5	0.4	1.4	1.8	0.7	4.0
		CV	30.8%	33.7%	32.5%	25.0%	33.3%	33.4%	31.4%	45.2%
CDM f_{c150}		Av [MPa]	6.4	-	7.0	6.4	5.3	7.8	-	-
		CV	4.0%	-	9.8%	9.5%	21.1%	9.4%	-	-
		E [MPa]	2,673	-	4,378	2,804	2,297	3,523	-	-
		CV	18.0%	-	1,5%	10.4%	21.9%	18.2%	-	-

			ZA	ZB	ZC	ZD	ZE
DPT $f_{m\ DPT}$	**P**	Av [MPa]	1.6	3.9	3.0	7.1	7.5
		CV	17.6%	33.1%	56.8%	29.6%	27.9%

4.2 Compressive strength from in-situ MDT and laboratory results

Table 3 presents the comparison between the in-situ and the laboratory tests results for lime mortar joints and bricks. The laboratory strength values for bricks were normalized with the application of the shape coefficient of 0.7, as proposed by EN 772-1:2011+A1, to the CB_10 specimens, $f_{b'}$. The reduction factor of 0.7 given by the standard UIC 1995 was applied to the laboratory strength of the mortar specimens, $f_{m,DPT}$. The HPT results were expressed in terms of the tangential stress, τ_H, corresponding to the pull-out force, F, and derived from the embedment length and the external diameter of the helix, D_e, as given by Equation 1 [14].

$$\tau_H = F / (\pi \cdot D_e \cdot L) \quad (1)$$

The variation trends of HPT results in terms of pull-out forces are fairly consistent with ranges of variations of the depth measurements obtained with PPT, as well as strengths derived from DPT for lime mortars. The HPT allowed the identification of significant in mortar performance except in the Z5 zone. The PPT showed the same result, with Z5 exhibiting a higher resistance to penetration. The variation trends of the PPT also showed good agreement with the DPT in plasters (ZA, ZB and ZC).

It is worth to mention that HPT and PPT on tested mortars provided a better agreement between them than with the DPT values. This disagreement is attributed to the fact that the specimens were dried and better conditioned when brought to the laboratory and therefore had a different moisture contents compared to the mortars in their original location. As for the bricks, the HPT and PPT values were very close to each other in spite of the variations of the laboratory compressive strengths, not allowing to identified a clear relationship between on site and laboratory results.

Figure 7a shows the comparison between the HPT results and the laboratory results for this campaign, together with those reported in previous research studies by Pelà et al. [2] and de Vekey et al. [8]. Figure 7b shows the same results for bricks tested in this campaign, together with literature values of units of compressive strength over 10 MPa according to Ferguson [15]. The HPT on mortars provides a good relationship with the laboratory values for this campaign, as well as with the values reported in the previous researches, especially for low strengths. However, the case of bricks no clear relationship is obtained between HPT and compressive strength test as already observed by Ferguson [15]. As explained by de Vekey et al. [8], the stress could exceed the elastic limit of the tie when the material tested had a compressive strength over 10 MPa. Actually, reliable relationships for historical masonry constituents are still under investigation.

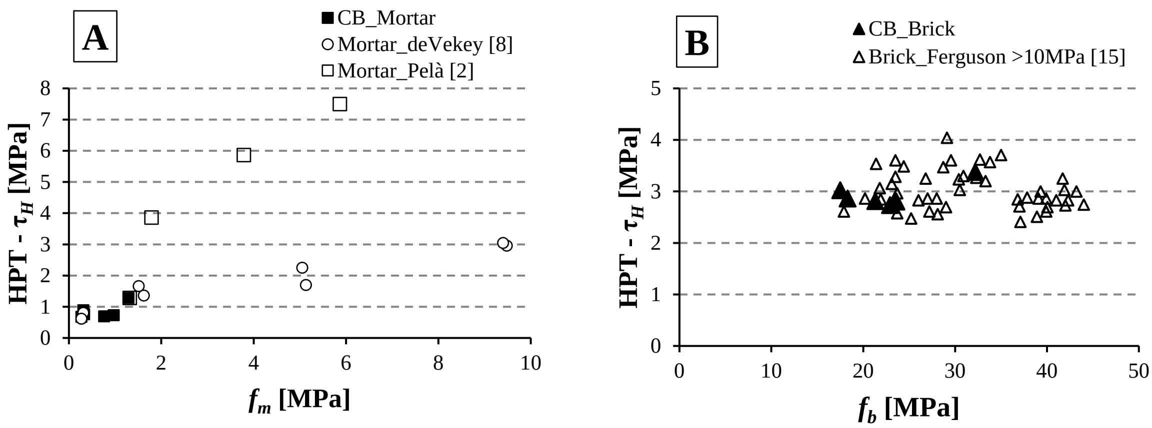

Figure 7: (A) Tangential stress of HPT on mortar joints compared with Pelà et al. [2] and de Vekey et al. [8] values. (B) Tangential stress of HPT on bricks compared with Ferguson values [15].

Table 3: Comparison among in-situ MDT and laboratory results on lime mortar joints, bricks and lime plasters.

		Z1	Z2	Z2bis	Z3	Z4	Z5	ZA	ZB	ZD
		Lime Mortar Joints (MJ) / Plasters (P)								
DPT f_m	Av [MPa]	0.76	0.27	0.33	0.31	0.97	1.29	1.12	2.73	4.97
PPT	Av [mm]	10.4	10.6	10.4	11.3	10.4	9.8	9.9	7.4	7.0
HPT τ_H	Av [MPa]	0.70	0.68	0.77	0.89	0.73	1.29	-	-	-
		Fired Handmade Clay Brick (B)								
Brick f_b	Av [MPa]	18.3	32.2	23.6	22.9	17.5	21.3	-	-	-
PPT	Av [mm]	6.6	6.2	5.9	5.8	5.9	6.0	-	-	-
HPT τ_H	Av [MPa]	2.86	3.38	2.80	2.73	3.02	2.81	-	-	-

4.2 Relationship between CB_10 and CB_C4 brick specimens

Another stage of the experimental campaign considered compression tests on nonstandard specimens measuring 40 × 40 × 40 mm^3, CB_C4. The average values of experimental compressive strengths of the CB_C4 samples ($f_{b\ C4}$) have been related with the standard CB_10 ones ($f_{b\ 10}$). Table 4 reports the ratio between the uniaxial compressive strengths (f_{b_C10} / f_{b_C4}). The given ratios resulted between 1.71 and 2.28. In average, the f_{b_10} strength was equal to 1.90 $f_{b\ C4}$ with CV equal to 11%.

Table 4: The relationship between the experimental compressive strength of the nonstandard specimen CB_C4 and the standard specimen CB_10.

			Z1	Z2	Z2bis	Z3	Z4	Z5	
Brick	**CB_10**	Av [MPa]	26.2	46.0	33.7	32.7	25.0	30.5	
	CB_C4	Av [MPa]	15.0	25.3	14.8	16.4	13.6	17.8	**Average**
	$f_{b\ CB\_10}$ / $f_{b\ CB\_C4}$		1.74	1.82	2.28	1.99	1.84	1.71	**1.90 [CV 11%]**

4.3 Evaluation of masonry compressive strength from available analytical equations

The characteristic compressive strengths of masonry, f_c, has been evaluated from the experimental average compressive strengths, f_{c_exp}, and the empirical equation provided by Eurocode 6 [12], f_{c_EC6}, and American Requirements for Masonry Structures (ACI 530.1-05) [16], f_{c_ACI}. The characteristic f_{c_exp} values were calculated according to the procedures described in EN 1052-1 [17] using the CDM experimental values, f_{c150}. Accordingly, the f_{c150} values have been divided by 1.2 for inspection zones with less than five specimens. The f_{c_exp} corresponded to the 5% fractile value based on a confidence level of 95% if there were five or more specimens. The f_{c_EC6} and f_{c_ACI} were obtained through the Equations 2 and 3 respectively. Eurocode 6 relates the characteristic compressive strength of masonry with the characteristic compressive strength of brick, f_b, and mortar, f_m, using as a constant K the value 0.55, and ACI equation relates it to the compressive strength of the unit, f_b.

$$f_{c\_EC6} = \mathrm{K} \cdot f_b^{\,0.7} \cdot f_m^{\,0.3} \text{ [in } MPa\text{]} \quad (2)$$

$$f_{c\_ACI} = \mathrm{A} \cdot (400 + \mathrm{B} \cdot f_b) \text{ [in } psi\text{]} \quad (3)$$

The Young's modulus of masonry, E_c, has been also analysed. The Eurocode 6 suggests that E_{c_EC6} is 1000 times the compressive strength, while ACI 530.1-05, E_{c_ACI} suggests that is 700 times the compressive strength. The experimental values of Young's modulus, E_{c_exp}, were obtained as explained in Section 3.4 testing the CDM specimens.

Table 5 reports a summary of the experimental and empirical evaluations of the masonry compressive strength and Young's modulus. The Eurocode 6 provides values lower than the experimental ones, while the ACI 530.1-05 results are higher than the experimental ones. The only good agreement between laboratory and analytical evaluations has been found for specimens of zone Z4 for EC6 equation, and of zone Z5 for the ACI equation. Previous research [18] provided good relationships between the empirical and experimental strengths for lime mortars with 2 MPa strength. Table 5 also presents that the Young's modulus estimated from the standards is overestimated compared with the experimental ratios E_c/f_c ranging between 475 and 759.

Table 5: Experimental and empirical compressive strengths, f_c (MPa) and Young's moduli, E_c (GPa).

		Z1	Z2bis	Z3	Z4	Z5
Masonry f_c [MPa]	f_{c_exp}	5.4	5.9	5.9	4.4	7.2
	f_{c_EC6}	3.9	3.6	3.4	4.0	5.0
	f_{c_ACI}	6.4	7.5	7.3	6.2	7.0
Masonry E_c [GPa]	E_{c_exp}	2.7	4.4	2.8	2.3	3.5
	E_{c_EC6}	3.9	3.6	3.4	4.0	5.0
	E_{c_ACI}	4.5	5.2	5.1	4.4	4.9
E_{c_exp} / f_{c_exp}		**500**	**759**	**475**	**523**	**486**

5 CONCLUSIONS

This paper has presented the experimental results from in-situ and laboratory minor destructive testing (MDT) of the masonry materials of an industrial 19^{th} c. building of Barcelona. Tests on samples made possible to determine the compressive strengths of bricks, tiles, mortars and masonry.

The following conclusions can be drawn from the research:

- The laboratory testing on novel types of specimen shows consistent results. In particular, the research proposes a novel methodology for the characterisation of the thin-tile of timbrel vaults.
- Tests on the nonstandard 40 × 40 × 40 mm^3 brick specimens showed similar scattering than the standard 100 × 100 × 40 mm^3 ones. Moreover, a clear correlation could be found between the compressive strength obtained with the two specimens. However, further investigation should be done to analyse the influence of the specimen size and shape on the compressive strength.
- The empirical equations provided by the building codes yielded values that overestimated or underestimated the compressive strength obtained from the extracted cylindrical cores.
- The in-situ MDTs have provided clear correlation trends in the evaluation of the mortar strength. In particular, and for the case of mortars, the sufficient sensitivity of HPT and PPT test allow the possibility of relating their results with experimental laboratory values.
- The in-situ MDT results for the evaluation of the clay bricks still do not show sufficient sensitivity to the variation of the material strength. More research is necessary in order to improve the application of HPT and PPT for a more reliable in-situ characterization of bricks.

Acknowledgements. The authors gratefully acknowledge the financial support from the Ministry of Science, Innovation and Universities of the Spanish Government (MCIU), the State Agency of Research (AEI) as well as that of the ERDF (European Regional Development Fund) through the project SEVERUS (Multilevel evaluation of seismic vulnerability and risk mitigation of masonry buildings in resilient historical urban centres, ref. Num. RTI2018-099589-B-I00). Support from MCIU through a predoctoral grant awarded to the first author is also gratefully acknowledged.

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