

COMPRESSION TEST OF MASONRY CORE SAMPLES EXTRACTED FROM EXISTING BRICKWORK

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Abstract

This research is focused on the experimental characterisation of the compressive behaviour of masonry in existing buildings. The proposed technique is based on in-situ core drilling of masonry members. Two walls were built making use of terracotta handmade bricks and lime mortar, without cement, to reproduce a low-strength historical masonry. Core samples were extracted from the walls and then regularized to perform a non-standard compression test in the laboratory. Stack-bonded prisms were also tested under compression. A direct comparison is made between the results from the proposed non-standard tests on core samples and the tests suggested by the available standards on prismatic samples. The proposed minor destructive technique shows to be effective for the mechanical characterisation of existing masonry structures, including historical ones.

Keywords: Masonry; Lime mortar; Historical structures; Coring; In-situ sampling; Cylindrical sample; Minor destructive testing (MDT); Compression test; Compressive strength; Young's modulus

1 Introduction

Masonry is one of the oldest construction materials that still finds wide use in the current building practice. Ancient masonry buildings represent most of the built cultural heritage and they can be found in many Mediterranean countries. The analysis of the behaviour of masonry constructions still remains a true challenge [1] since the mechanical response of this composite material is determined by the properties of the components and their complex interaction.

Compressive strength of masonry is considered by available standards as a fundamental design parameter. Several studies were performed to understand the behaviour of masonry under uniaxial compression [2-9]. These studies investigated newly built masonry and dealt with compression tests executed on EN standard wallets [10] and RILEM standard stack-bonded prisms [11].

The experimental evaluation of the compressive behaviour of masonry is even more complex in existing buildings. In this case, the large prismatic samples considered by the technical standards cannot be normally extracted due to the need to preserve the integrity of structural members. Moreover, the extraction of sufficiently intact samples is made difficult by the low strength of the materials and the poor bonding frequently shown by the mortar-unit interfaces.

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Difficulties arise even from the sampling and subsequent characterisation of the components in the laboratory, both in the case of old bricks [12,13] and historical mortars [14-17]. Due to the limited thickness of mortar beds and brick courses, it is normally impossible to extract samples sufficiently large to be tested according to standard procedures.

Recent researches have shown the great potential of Minor Destructive Tests (MDT) for existing and historical masonry buildings, consisting in the extraction of small cylindrical samples to be subjected to destructive testing in the laboratory [18-26]. The in-situ core drilling is carried out horizontally and perpendicularly to the face of a structural member, as for instance a masonry wall. The sampling procedure induces limited damage to the structure, which can be easily repaired after the inspection. The cores can be extracted from hidden parts of the historical structure. A direct evaluation of the mechanical properties of masonry can be derived from experimental laboratory tests.

Compression tests can be carried out on in-situ drilled masonry cores, as proposed by the UIC 778-3 recommendations of the International Union of Railways [22]. In the case of metric bricks, 150 mm diameter cylindrical samples of masonry can be extracted including two horizontal mortar joints and one vertical joint. The sample is centred in the middle of the vertical joint and the compression test is carried out in the same direction in which the load is applied in the original structural member. The upper and bottom parts of the lateral surface of the cylinder are regularized making use of a lead sheet between the core and concave steel plates fixed to the loading machine (Figure 1). The UIC 778-3 suggests at least three compression tests for each kind of brickwork and preferably six tests when possible. The standard also advises not to test cores with diameter smaller than 150 mm to characterise the compressive strength of masonry, since smaller samples are suitable only for the evaluation of the brick's properties. The procedure proposed by the UIC 778-3 combines the advantage of minor destructive sampling, since a limited portion of the structure is damaged by the extraction, with the possibility of testing a sufficiently complex masonry specimen, able to represent the interaction among units, horizontal and vertical mortar joints upon compression loading. For all these reasons, this method was used in previous researches to evaluate the compressive strength of clay brick masonry [20,23-24].

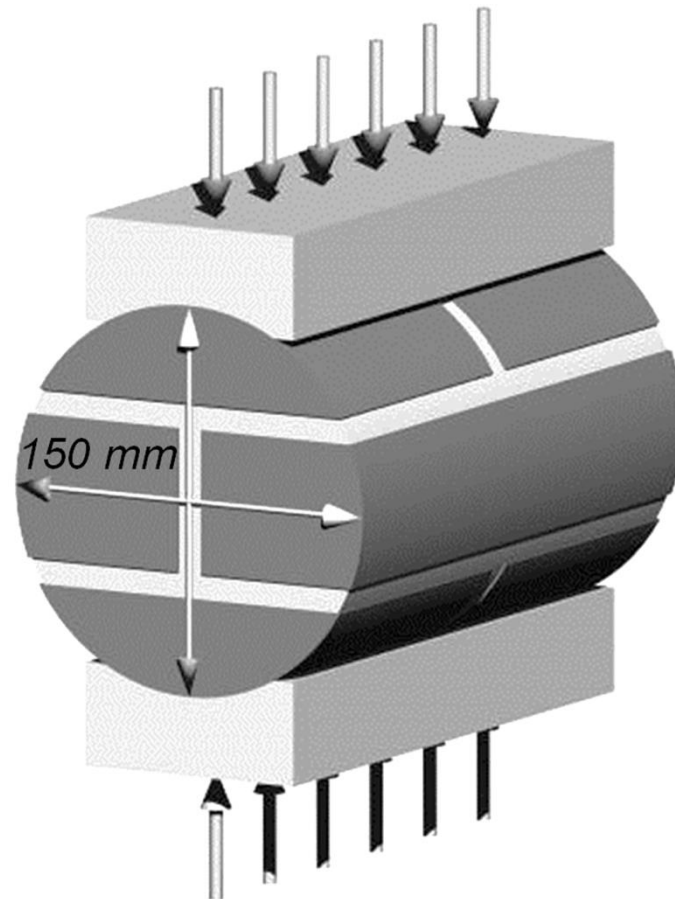


Figure 1 Compression test on brickwork core sample [22].

The present work is aimed at investigating the applicability of the aforementioned MDT to historical buildings, while also providing possible practical improvements. The study was carried out in the laboratory in order to provide a reliable calibration of the experimental method. Two masonry walls were built using solid clay bricks and lime mortar, material combination which corresponds to the vast majority of historical and existing masonry structures. After a sufficient curing time, the walls were core drilled using a novel dry extraction procedure, based on air cooling system. This is an improvement to common wet core drilling, in which water could spoil the lime mortar joints in the samples. Two different types of 150 mm diameter cylindrical samples were extracted: masonry cores with two horizontal mortar joints and one vertical (three-joint cylinders, called 3JCs) and cores including two horizontal joints without the vertical one (two-joint cylinders, called 2JCs). The curved surfaces of the extracted cores were regularized in a different way than that proposed by UIC 778-3, i.e. using cement mortar caps to produce loading planes parallel to the horizontal mortar joints [20-25]. Compression tests were carried out on both 3JCs and 2JCs. The two different types of samples were analysed in order to investigate the influence of the presence of the head joint in the core. The experimental results were compared with those obtained from stack-

bonded prisms [10-11] that were built with the same materials used during the construction of the walls.

The direct comparison between the novel non-standard testing method and well-known standard tests provides useful suggestions for experimental activities aimed at evaluating the compressive behaviour of existing masonry. The discussion of the experimental results and the comparison with analytical models are finally presented for a better comprehension of the proposed MDT.

2 Materials and test methods

The experimental program was carried out at the Laboratory of Technology of Structures and Materials of the Technical University of Catalonia (UPC-BarcelonaTech). Different masonry specimens were manufactured in the laboratory using handmade terracotta bricks and Natural Hydraulic Lime (NHL) mortar, classified as NHL 3.5 by EN 459-1 [27]. Two single-leaf walls with dimensions of $1605 \times 870 \times 145 \text{ mm}^3$ were built in order to extract fifteen 3JCs and fifteen 2JCs (see Figure 2a). Six stack-bonded prisms (SP1-SP6), with dimensions of $305 \times 297 \times 145 \text{ mm}^3$, were built following the RILEM [11] (Figure 2b). At the same time of the construction of masonry specimens, mortar prisms ($40 \times 40 \times 160 \text{ mm}^3$) were prepared according to EN 1015-11 [28] using metallic moulds. The NHL mortar prisms were tested at different ages in order to control the curing and hardening of the material until the moment of core-drilling.

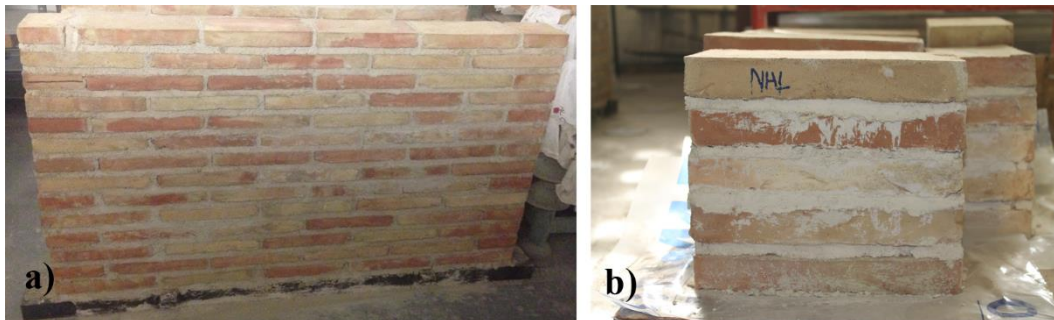


Figure 2 Masonry specimens: (a) wall and (b) stack-bonded prism.

2.1 Characterisation of material components

Handmade terracotta bricks, fired following traditional procedures, were adopted to replicate historical masonry. The nominal dimensions of the units were $305 \times 145 \times 45 \text{ mm}^3$, even though there was a small variability among bricks' dimensions due to their construction procedure. The compression test of the whole unit was carried out to evaluate the uniaxial compressive strength $f_{cb,u}$ perpendicular to the larger face of the brick. Six tests were performed according to EN 772-1 [29], using a testing machine with a load cell of 3000 kN. The average value of $f_{cb,u}$ was 30.7 MPa.

The normalized compressive strength of the units was obtained using the shape factor of 0.7 recommended by the standard, yielding 21.5 MPa. In order to obtain a complete characterisation of the brick from different types of samples, some units were cut into cubes and prisms (Figure 3a). Cubes were used to investigate the uniaxial compressive strength $f_{cb,c}$ in the vertical direction. Prisms were used to investigate the flexural strengths along the stretcher ($f_{fb,x}$) and header ($f_{fb,y}$) directions, by the three-point bending test. Due to the lack of a standard for the determination of the flexural strength on bricks, the EN 1015-11 [28] was considered as a reference. The experimental results and the coefficients of variation are summarized in Table 1.

Table 1 Mechanical properties of the brick

	$f_{cb,u}$ [MPa]	$f_{cb,c}$ [MPa]	$f_{fb,x}$ [MPa]	$f_{fb,y}$ [MPa]	$E_{bx,30}$ [MPa]	$E_{bx,60}$ [MPa]	$E_{by,30}$ [MPa]	$E_{by,60}$ [MPa]
sample	unit	cube	prism		cylinder			
	31.2	19.6	3.81	3.81	5129	6127	7572	7697
	29.4	19.5	3.67	3.53	5073	6222	11470	9103
	30.4	19.1	3.60	3.57	-	-	10335	7518
	30.3	18.3	3.52	3.74				
	34.2	16.6	3.51	3.19				
	28.9	17.5	3.59	3.32				
			3.88	4.40				
			3.48	4.73				
Average	30.7	18.4	3.63	3.79	5101	6175	9792	8106
CV	6%	6%	4%	14%	0.8%	1.1%	20%	11%

Since no reference standards are available for the assessment of the brick's Young's modulus, the authors adopted a novel approach inspired by the EN 12390-13 standard [30] for concrete. Six cylinders, with 35 mm diameter and 75 mm height, were extracted from the two lateral sides of the bricks (header and stretcher). High strength regularization caps were built on top and bottom bases of the samples in order to obtain parallel loading faces. This operation was necessary to ensure a uniform distribution of the compressive force on the sample. Two extensometers (gage length 25 mm, range +/-5 mm, full scale 10 V, linearity 0.01%) were installed on the specimen's lateral surface, in order to evaluate the vertical deformation (see Figure 3b). According to the recommendations reported in the standard EN 12390-13 [30] and in other researches [13,31], six loading-unloading cycles were performed: three cycles from 10% to 30% of the estimated failure load, followed by other three cycles from 30% to 60% of the estimated failure load. Table 1 presents the experimental values of the Young's moduli along the stretcher and header directions (E_{bx} and E_{by} , respectively). The material constituting the bricks showed a heterogeneous behaviour which was reflected in different average values and variation coefficients along the two directions.

The samples tested along the stretcher directions provided a better evaluation of the initial Young's modulus by applying the 60% of the estimated failure load ($E_{bx,60}$), while those tested along the header direction provided a better result by applying the 30% of the estimated failure load ($E_{by,30}$). This result is due to the different elastic responses of the brick along the stretcher and header directions.

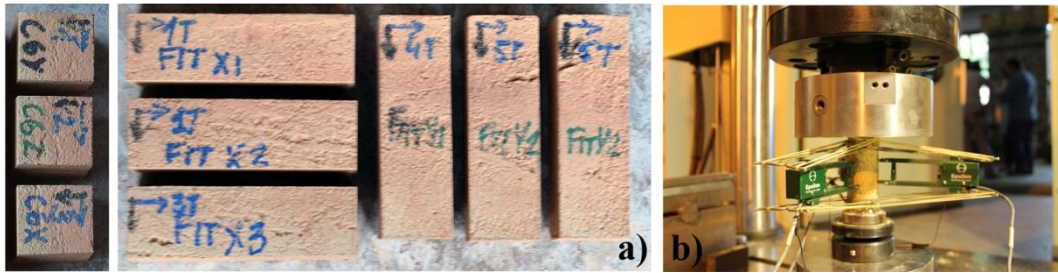


Figure 3 Cubic and prismatic specimens of brick for compression and flexure tests (a) and evaluation of the Young's modulus on cylindrical sample (b).

In order to obtain a close representation of an historical material, NHL 3.5 mortar was mixed, without using cement, in accordance with EN 459-1 [27]. A lime/washed river sand ratio of 1:3 and a water/binder ratio of 0.9 were adopted. The river sand had $0 \div 2$ mm grain size. The mortar was hand mixed in the laboratory using a trowel. The European standard for mortar testing EN 1015-11 [28] was followed to perform three-point bending and compression tests. Specimens with different ages (7, 14, 28, 42, 66, 90, 190, 260 days) were considered, in order to evaluate the development of the strength over the time. Figure 4 shows the evolution with time of flexural and compressive strengths of mortar. For each considered age of curing, three mortar prisms were tested using a load cell of 10 kN. The loading rate was kept constant during the flexure and compression tests, considering values respectively of 10 N/s and 50 N/s. The loading rates were selected to reach the failure of the sample within 30-90 seconds as prescribed by the EN 1015-11. The flexural strength of mortar (f_{fm}) was evaluated from the flexure test of the prismatic samples ($40 \times 40 \times 160$ mm³). The compressive strength of mortar (f_{cm}) was obtained, as indicated by EN 1015-11, from compression tests executed on the two halves produced by the flexure test. They measured roughly $40 \times 40 \times 80$ mm³ and were loaded with 40×40 mm² steel platens. The experimental strength values and the coefficients of variation are shown in Table 2.

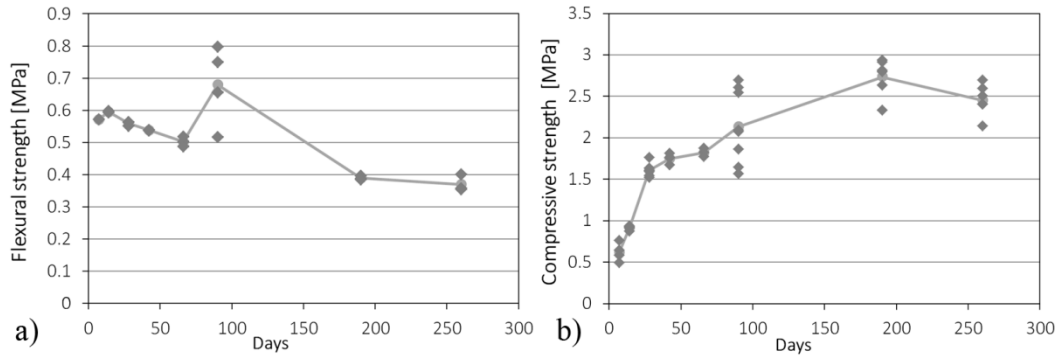


Figure 4 Evolution with time of mortar's flexural (a) and compressive (b) strengths.

Table 2 Compressive and flexural strengths of mortar prisms.

age [days]	f_{fm} [MPa]	CV [%]	f_{cm} [MPa]	CV [%]
7	0.57	-	0.62	18.3
14	0.60	0.6	0.91	2.6
28	0.56	1.2	1.61	5.3
42	0.54	0.3	1.75	3.2
66	0.50	3.0	1.82	2.8
90	0.68	18.2	2.13	20.6
190	0.39	1.5	2.73	8.2
260	0.37	7.1	2.45	7.8

2.2 Masonry core samples

Two months after the construction, two single-leaf walls were core drilled to extract cylindrical masonry specimens for the non-standard compression tests. At that time, it was supposed that the mortar had hardened enough to allow the coring operations. In order to obtain the maximum number of specimens and to avoid the disjuncting of the wall, the locations of the extractions were carefully planned. The distance between the cores was defined empirically in order to preserve the stability of the wall and the samples. [Figure 5a](#) presents the designed extraction layout.

Different types of specimens were extracted. The first type of sample, named 2JC, is a 150 mm diameter cylinder with two horizontal bed joints. The second type of sample, named 3JC, is a 150 mm diameter cylinder with two bed joints and one vertical head joint. Fifteen 2JC and fifteen 3JC were extracted for the present experimental program. Other samples, i.e. 90 mm diameter cylinders with one bed joint (1JC), were also extracted at the same time but they were used for a different research study concerning the evaluation of the shear strength of masonry through non-standard tests [26].

The extraction of cylindrical specimens from masonry structural members is a delicate operation, due to the weakness of the material components. In a previous experimental campaign [20,25], the

samples were extracted after turning the wall onto its larger face. This operation caused some difficulties, since the vertical core drilling of the horizontally laid wall induced a transversal point load, affecting the wall's integrity during the sampling procedure. In addition, the extraction was executed using a wet procedure, i.e. water was employed during core drilling to prevent both overheating of the coring bit and dust accumulation. This methodology, frequently used in concrete structures, showed some limitations for the case of masonry walls, since water sometimes washed portions of lime mortar joints away and caused the disjuncting of some core samples.

An alternative procedure was proposed in this work in order to avoid the alteration of the samples during their extraction. This requisite is very important in the in-situ sampling of historical masonry buildings, since only few specimens can be extracted and their integrity must be ensured through a reliable procedure. First of all, the wall was kept vertical during the extraction of specimens, in order to give a more realistic representation of the actual operations on existing buildings. The samples were set against a larger wall, in order to prevent their overturning during the extraction. A dry extraction procedure was employed, connecting the core-drilling machine to an aspirator that was intended to eliminate the dust and to cool the coring bit. All the specimens were extracted in three steps. First, the machine drilled the core up to half thickness of the wall (Figure 5b). Second, core drilling was interrupted to take the dust out of the coring bit (Figure 5c), either with the aspirator or with a spray compressor. Eventually, the extraction was completed until drilling across the entire thickness of the wall (Figure 5d). Making use of this careful step-by-step procedure, all the specimens were extracted without any unexpected failure (Figure 5e).

Prior to the core drilling, the wall was subjected to moderate pre-compression in order to confine properly the material during the core-drilling and to avoid the wall collapsing during the extraction. In fact, in real applications to existing masonry structures, the overload acting on the structural element provides a stabilizing effect making the core drilling operations easier. The pre-compression was applied using two steel profiles placed on the upper and lower sides of the wall, connected by four low-tensioned steel bars. Thanks to the proposed extraction procedure, all the expected 52 specimens were obtained in very good conditions.

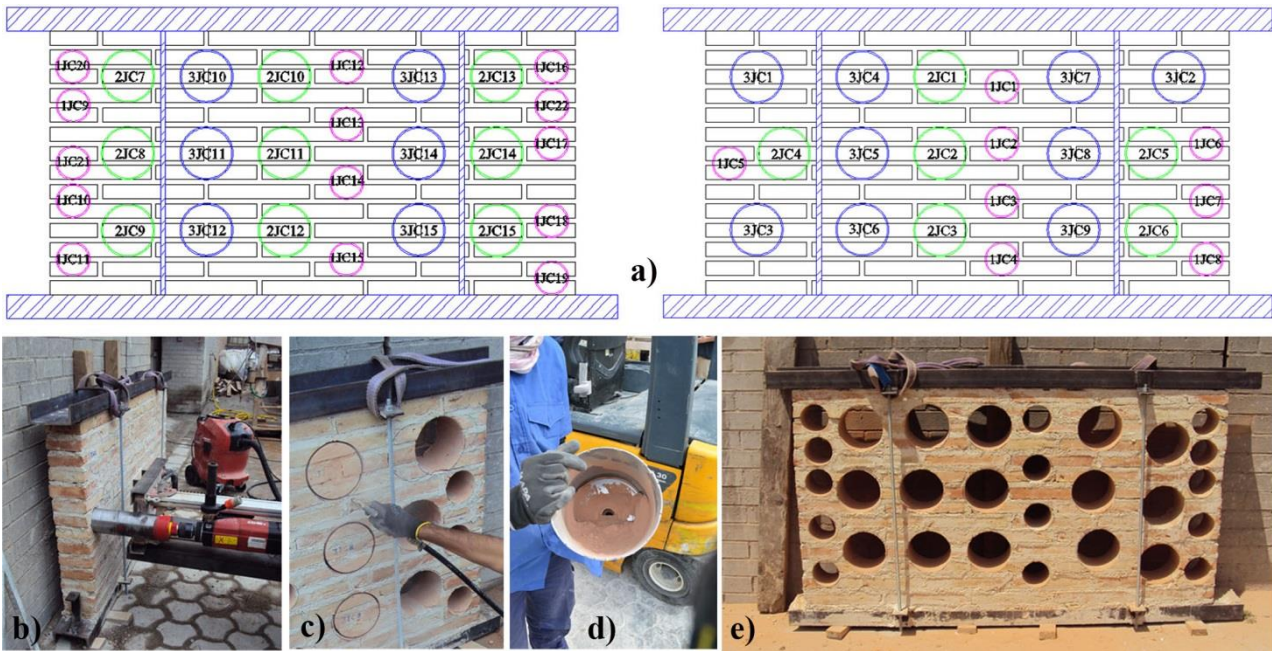


Figure 5 Layout of sampling in the two walls (a), core drilling with dry procedure (b), cleaning with spray compressor (c), dust in the coring bit (d) and wall after sampling (e).

In order to perform the uniaxial compression test on cylinders, the curved surfaces of the specimens were regularized with high strength mortar caps. Wood moulds (Figure 6a) were specifically prepared for the regularization (Figure 6b). The compressive strength of the regularization mortar is 65 MPa after 28 days, i.e. much higher than the expected strength of the masonry core samples. After pouring the mortar into the mould, the specimens were kept in laboratory conditions until the mortar cap achieved the adequate strength. After that, the specimens were extracted from the regularization moulds. The purpose of the regularization was to create two parallel loading faces and also to ensure an optimum bond between the specimen and the high-strength cap during the test. This novel solution [25] is an alternative to that proposed by UIC 778-3 [22,24] in which concave metal loading plates were recommended, together with lead sheets, to regularize the contact with the curved surfaces of the specimens. One of the main advantages of using high strength mortar caps, compared to the UIC method, is that the testing machine does not require expensive mechanical parts, like thick steel pieces gripped to the press system. In addition, the manufacturing process ensures that the mortar caps will be perfectly adapted to the irregular lateral surface of any extracted cylindrical sample, in order to guarantee a proper continuity between the regularization mortar and the extracted material.

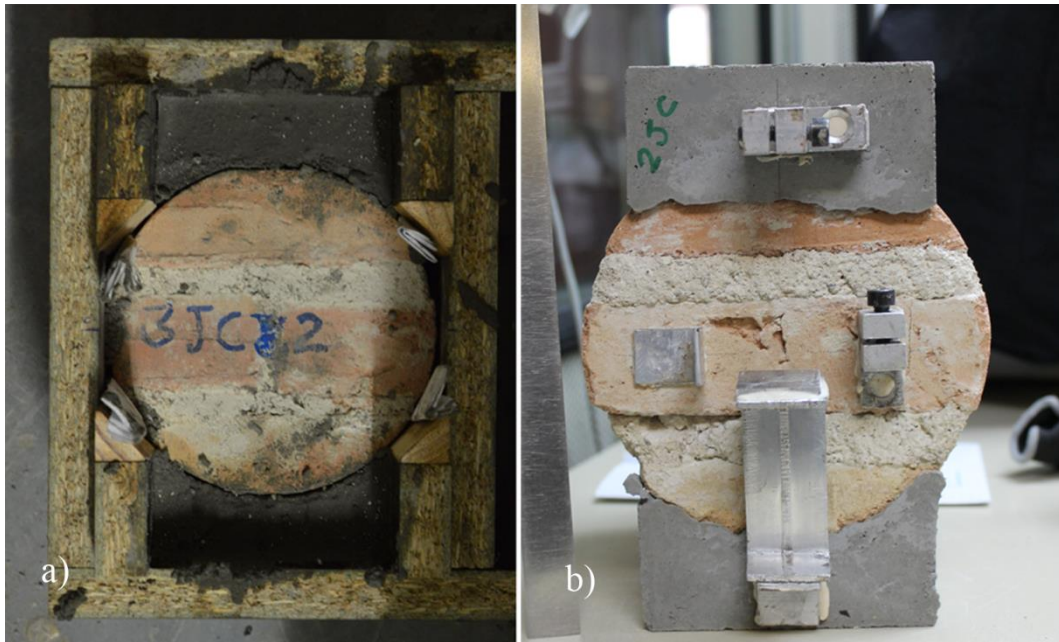


Figure 6 Regularization of cylindrical samples: (a) wood mould adopted to build the high-strength caps (b).

2.3 Compression tests on masonry specimens

The core samples (2JCs, 3JCs) and stack-bonded prisms were tested under compression after eight months from the construction of the walls. The tests were carried out in two stages. The first stage of loading was executed within the elastic range of the material and was oriented to the evaluation of the elastic modulus. The first stage involved three loading-unloading cycles under load control. The Young's modulus was measured after the third loading-unloading cycle. The second stage consisted in applying a monotonic displacement, in order to explore the ultimate capacity and the post-peak behaviour of the specimens. The compression tests setups are shown in [Figure 7](#). Linear Variable Differential Transformers (LVDTs) were adopted to measure the deformation in the specimens. More detailed information on the instruments and the data acquisition system can be found in [\[32\]](#).

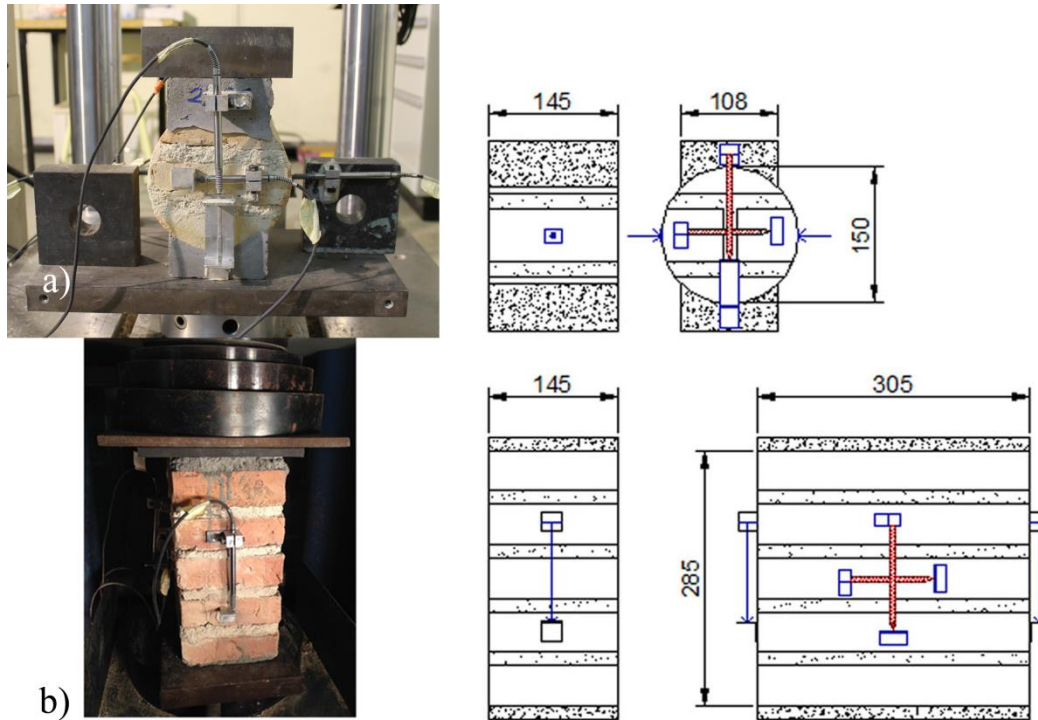


Figure 7 Experimental setups of compression tests: (a) cylindrical specimens and (b) stack-bonded prisms (dimensions in mm).

Compression tests were carried out on six 3JCs and six 2JCs extracted from the walls using a load cell of 200 kN. The guidelines UIC 778-3 [22] and previous studies [20,24,25,33,34] were taken into consideration to perform the tests. The testing procedure consisted in applying a vertical compression on the regularization caps, in order to reproduce the vertical compression loading to which the wall was subject. The cyclic loading stage was performed within the range from 5% to 20% of the maximum expected load (cautiously estimated around 100 kN), in order to preserve the material's elastic response. Concerning the subsequent loading stage, the controlled monotonic displacement was applied with a rate of 0.004 mm/sec. The cylinders were instrumented with six LVDTs (three LVDTs per lateral face, see Figure 7a) with the aim of recording both horizontal and vertical displacements and following the response of the samples both into the linear and nonlinear ranges. Two vertical LVDTs were glued to the regularization caps along the vertical axis of symmetry of the sample, having a displacement range of $\pm 5 \text{ mm}$ and a precision of $5 \mu\text{m}$. Two horizontal LVDTs were glued on bricks along the horizontal axis of symmetry of the sample, having a displacement range of $\pm 1.5 \text{ mm}$ and a precision of $1.5 \mu\text{m}$. Two external horizontal LVDTs recorded the transversal expansion of the core, having a displacement range of $\pm 5 \text{ mm}$ and a precision of $5 \mu\text{m}$. These last LVDTs were placed to check the appearance of cracks and the possible splitting of the specimen.

The experimental results of the compression tests on core samples were compared with those obtained from standard specimens, i.e. stack-bonded prisms. The compression tests on stack-bonded prisms were performed following EN 1052-1 [10] and RILEM technical recommendations [18]. A testing machine with a load cell of 3000 kN was used. Before testing, a thin cement layer was poured over the bricks to regularize the loading surface. The cyclic loading stage was performed within the range from 5% to 30% of the maximum expected load (originally estimated around 240 kN). Concerning the subsequent loading stage, the controlled monotonic displacement was applied with a rate of 0.008 mm/sec. The stack-bonded prisms were instrumented with six LVDTs, with the aim of recording both horizontal and vertical displacements. Four vertical LVDTs (one per lateral face, with a displacement range of ± 5 mm and a precision of $5 \mu\text{m}$) and two horizontal LVDTs (one per each larger face, with a displacement range of ± 1.5 mm and a precision of $1.5 \mu\text{m}$) were used to assess the elastic parameters (Figure 7b).

3 Experimental results

This section presents the main outcomes of the experimental program, with the results of the compression tests on masonry core samples and on standard specimens, i.e. stack-bonded prisms. The strength and deformation characteristics of the samples are evaluated and their peculiar modes of failure are discussed. The final comparison between the outcomes from the standard and the novel non-standard testing techniques leads to meaningful conclusions about the proposed experimental methodology.

3.1 Core samples extracted from walls

The UIC 778-3 standard [22] suggests considering the entire horizontal cross-section of the specimen to evaluate the compression strength. This work considers a second possibility, making reference to the cross-section of the regularization cap [20]. The compressive strength can thus be assessed by the two following expressions:

$$f_{C1} = \frac{F_{max}}{\phi \cdot l} \quad (1)$$

$$f_{C2} = \frac{F_{max}}{b \cdot l} \quad (2)$$

in which F_{max} is the maximum load during the test, whereas ϕ , b and l are respectively the diameter of the cylindrical specimen, the width of the regularization cap and the length of the cylinder. In this experimental program, the ratio between f_{C2} and f_{C1} resulted around 1.4.

The stress vs. strain curves resulting from the loading-unloading cycles are shown in [Figures 8a-b](#), for specimens 3JC and 2JC. The stresses are evaluated making reference to both the diametral cross-section of the specimen (σ_1) and the cross-section of the regularization cap (σ_2). The elastic modulus of each sample was assessed by considering the average displacement recorded by the two vertical LVDTs. The Young's moduli obtained from the third loading-unloading cycles are reported in [Table 3](#). The average Young's moduli for 3JC and 2JC were respectively 1824 MPa and 1813 MPa considering the entire horizontal cross-section of the sample, and 2570 MPa and 2540 MPa considering only the cross-section of the regularization cap. In both cases, the experiments showed that the influence of the vertical mortar joint on the magnitude of the Young's modulus is negligible.

As shown in [Figures 8a-b](#), the execution of loading-unloading cycles led to a compaction of the material and thus to a better control of the experimental scattering in the Young's modulus estimations. In fact, the evaluation of the Young's modulus could be difficult if such cycles were not carried out, as pointed out by previous experimental programs [\[23-25\]](#). The consideration of suitable loading-unloading cycles previous to the measurement of the elastic modulus could be proposed as a possible improvement to the UIC 778-3 testing recommendations.

The experimental stress vs. strain curves in [Figures 8c-d](#) refer to the second stage of the test corresponding to the monotonic loading beyond failure until the nonlinear range. An initial linear elastic behaviour was observed up to around 2 MPa, followed by a slight reduction of the stiffness until the peak. The average strength values were $f_{c1} = 5.96 \text{ MPa}$ and $f_{c2} = 8.40 \text{ MPa}$ for 3JC samples, whereas $f_{c1} = 7.01 \text{ MPa}$ and $f_{c2} = 9.82 \text{ MPa}$ for 2JC samples ([Table 3](#)). The peak strains corresponding to the maximum stresses of the 3JC and 2JC samples occurred within the range of 0.9% and 1.2%. The ultimate strains unfortunately could not be evaluated precisely because in many samples the instruments either detached from their supports or were removed to preserve their integrity, whilst the specimens were damaging. However, it was possible to evaluate the post-peak strains of all the samples at least until the 1.5% for 2JCs and 2.0% for 3JCs.

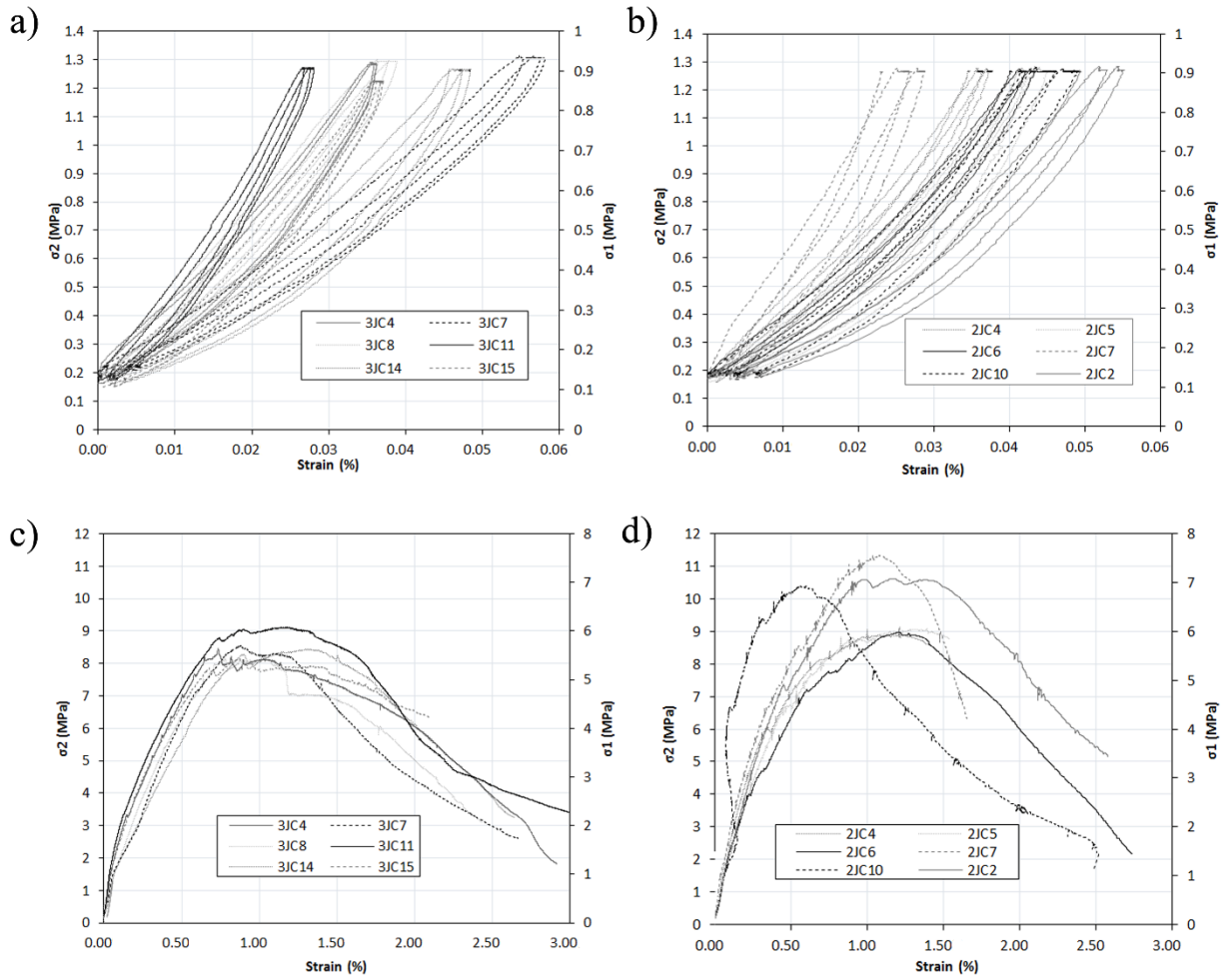


Figure 8 Stress vs. strain experimental curves of masonry core samples: elastic responses of (a) three-joint and (b) two-joint cylinders; strength and nonlinear responses of (c) three-joint and (d) two-joint cylinders.

Table 3 Compressive strengths and Young's moduli of core samples and stack bonded prisms.

<i>3JC</i> <i>sample</i>	E_1 [MPa]	E_2 [MPa]	f_{c1} [MPa]	f_{c2} [MPa]	<i>2JC</i> <i>sample</i>	E_1 [MPa]	E_2 [MPa]	f_{c1} [MPa]	f_{c2} [MPa]	<i>stack</i> <i>bonded</i> <i>prism</i>	f_c [MPa]	E [MPa]
<i>3JC4</i>	1912	2726	5.94	8.47	<i>2JC2</i>	1435	2027	7.06	9.97	<i>SP1</i>	5.00	2220
<i>3JC7</i>	1370	1930	6.05	8.52	<i>2JC4</i>	1964	2749	6.53	9.14	<i>SP2</i>	5.43	2541
<i>3JC8</i>	1760	2483	5.84	8.24	<i>2JC5</i>	1617	2262	6.50	9.09	<i>SP3</i>	6.08	2169
<i>3JC11</i>	2522	3560	6.46	9.12	<i>2JC6</i>	1601	2241	6.41	8.97	<i>SP4</i>	6.41	2628
<i>3JC14</i>	1444	2036	5.97	8.42	<i>2JC7</i>	2757	3857	8.10	11.33	<i>SP5</i>	6.54	4053
<i>3JC15</i>	1937	2686	5.51	7.64	<i>2JC10</i>	1504	2105	7.44	10.41	<i>SP6</i>	5.43	3519
<i>Avg</i>	1824	2570	5.96	8.40	<i>Avg</i>	1813	2540	7.01	9.82	<i>Avg</i>	5.82	2855
<i>CV</i>	22.8%	22.8%	5.7%	5.7%	<i>CV</i>	27.3%	27.3%	9.5%	9.5%	<i>CV</i>	10.6%	26.7%

Specimens 3JC and 2JC exhibited a qualitatively similar mechanical response to compressive loading. Their damage patterns were characterised by vertical cracks starting from the edges of the regularization cap and propagating throughout the height of the specimens (Figure 9a-b). Vertical cracks were observed in 3JCs at the mortar-brick interface of the vertical joint, as previously observed by other authors [24]. At the end of the compression tests, the typical sandglass failure was observed in all of the specimens (Figure 9c-d). The high-strength mortar was not affected by compressive damage after the tests, proving to be a suitable material for the regularization caps.

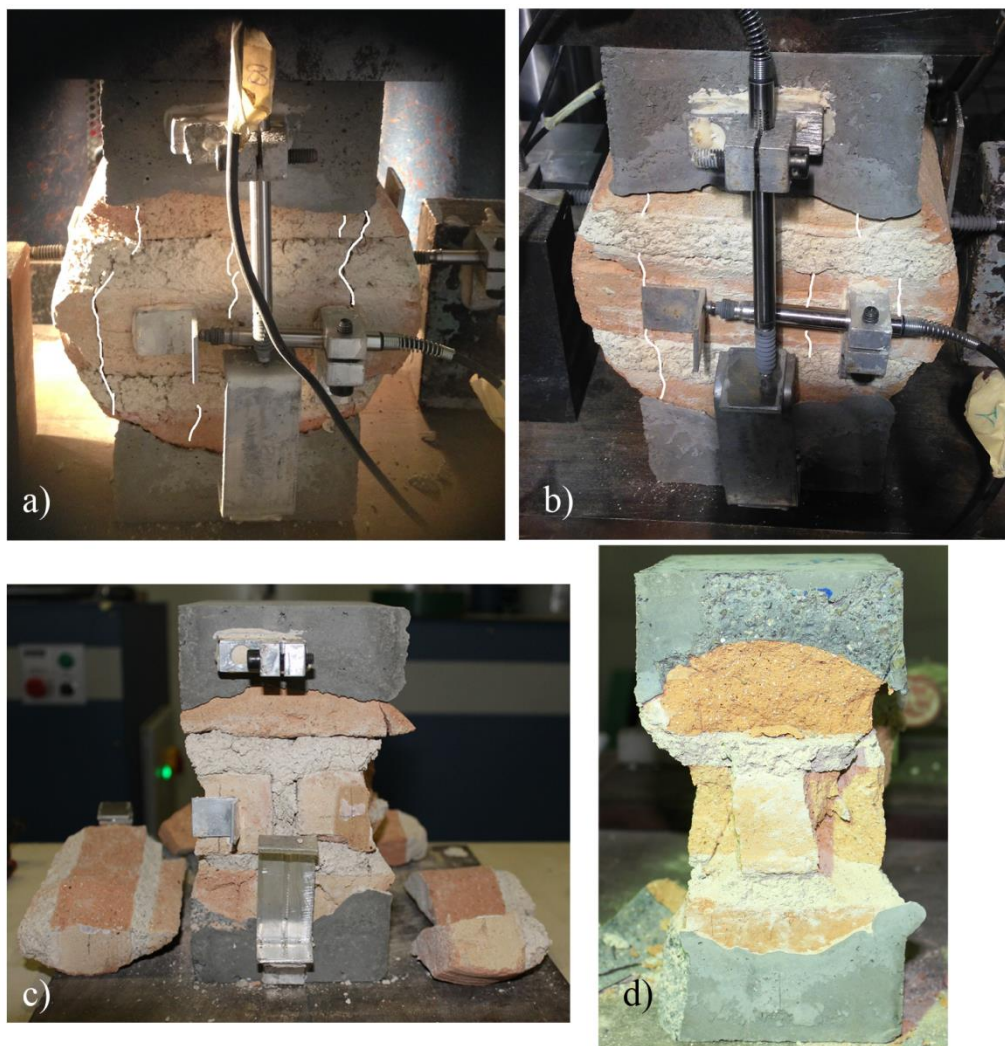


Figure 9 Crack patterns at the peak load and core samples after failure. Three-joint cylinders (a,c) and two-joint cylinders (b,d).

3.2 Stack-bonded prisms

The experimental stress vs. strain curves for the stack-bonded prisms are presented in Figure 10. The samples showed an initial linear elastic behaviour up to around 2 MPa. For higher stress values,

their stiffness decreased due to the opening of the first cracks, until reaching the maximum strength. The Young's moduli were evaluated from the third loading-unloading cycle, similarly to the procedure explained in Section 3.1 for core samples. The mean Young's modulus was 2855 MPa whereas the average compressive strength was 5.82 MPa. The strains of stack-bonded prisms corresponding to the peak stresses occurred within the range of 0.35% and 0.8%. A summary of the experimental results is reported in Table 3.

The stack-bonded prisms exhibited similar crack patterns. The cracks were mainly vertical, starting from the upper bricks and propagating throughout the height of the specimens (Figure 11a-b). At the peak load, major cracks appeared in the central part of the specimens (Figure 11c). At the end of the tests, the specimens were taken out of the loading machine and showed splitting through their thickness.

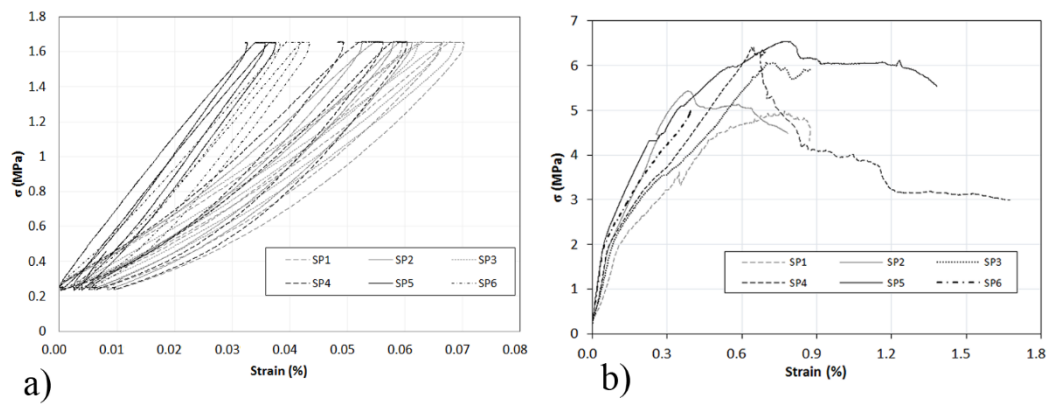


Figure 10 Stress vs. strain experimental curves of stack-bonded prisms: (a) elastic response; (b) strength and non linear response.

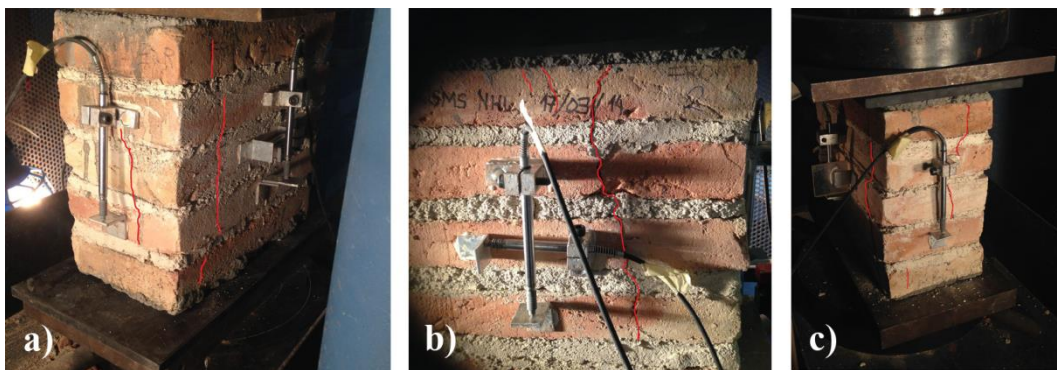


Figure 11 Crack patterns in stack-bonded prisms SP2 (a), SP4 (b) and SP6 (c)

3.3 Comparison between standard and non-standard compression tests

Figure 12 shows the comparisons among the Young's moduli and compression strengths obtained from the tests on stack-bonded prisms and core samples. The correlation between the results on standard prismatic samples and the outcomes of the non-standard tests on core drilled specimens is useful to better understand the investigated MDT.

The lowest values of the Young's modulus are provided by the evaluations on core samples considering the stress σ_1 , i.e. the one related to the entire diametral cross-section of the specimen (2JC- E_1 and 3JC- E_1). A good agreement can be observed among the Young's moduli of stack-bonded prisms and core samples considering the stress σ_2 , i.e. the one related to the cross-section of the regularization cap (2JC- E_2 and 3JC- E_2), with a coefficient of variation of only 6%.

A good agreement can be observed among the compressive strengths of stack-bonded prisms and core samples considering the stress σ_1 (2JC- f_{c1} and 3JC- f_{c1}), with a coefficient of variation of only 10%. The average of the compressive strengths f_{c1} and f_{c2} of 3JCs is 15% lower than that of 2JCs, showing the effect of the presence of the head joint on the resistance of the sample.

The average compressive strength f_{c1} of 3JCs is very similar to that of the stack-bonded prisms (+2%). The average compressive strength f_{c1} of 2JCs is higher than that of the stack-bonded prisms (+20%).

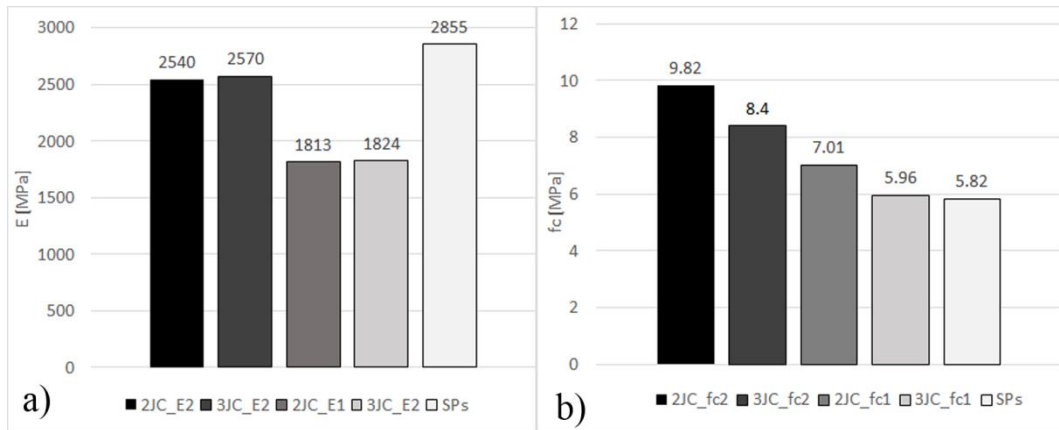


Figure 12 Comparison between standard and non-standard compression tests: (a) Young's modulus; (b) compressive strength.

4 Comparison with analytical and empirical models

The experimental results were compared with analytical and empirical expressions proposed by current technical standards and researches available in the literature [35].

The experimental compressive strengths of the different samples (e.g. prismatic and cylindrical) were compared with the predictions from the expressions provided by Hilsdorf [2], Khoo & Hendry [36] and Ohler [37], as well as recommendations by European CEN [38], American ACI [39],

Italian DM [40], Italian Circolare [41] and Spanish CTE [42] standards. Making use of the strength values of the material components, the strength of masonry was evaluated for the different expressions. The compressive strength of the brick used in calculations was that of the whole unit, as generally required by the standards (Table 1). The tensile strength of the brick was obtained from the flexural one (Table 1) using the expressions proposed by the CEB-FIP Model Code [43]. The adopted mortar's compressive strength was that determined experimentally on half prisms at the age of 260 days (Table 2). A summary of the results is shown in Table 4, where the experimental results are both expressed in terms of mean (f_c) and characteristic (f_{ck}) values to allow a more direct comparison with analytical and empirical estimations. The 5% characteristic values were evaluated accounting for the limited number of samples [40], i.e. six for the present experimental program. The analytical models proposed by Hilsdorf, Khoo & Hendry and Ohler derive from equilibrium and were formulated using failure theories based on the strength of brick and mortar under multiaxial stress. The CEN, ACI and Spanish CTE equations have an empirical nature and are based on statistical analyses of experimental data. The Italian DM and Circolare provides tables with strength values for masonry as function of the characteristics of the unit and the mortar. The analytical models proposed by Hilsdorf, Khoo & Hendry and Ohler can be compared with the experimental mean values, whereas the empirical estimations from building codes can be correlated with the experimental characteristic values. The only exception is the Italian Circolare that suggests a mean value of compressive strength, referring to existing masonry buildings. The analytical models consider as input parameters the compressive strengths of brick and mortar, the tensile strength of brick and the geometry of units and joints. In turn, the estimations from code regulations are based on the compressive strengths of brick and mortar (CEN, DM, CTE) or on the sole compressive strength of the brick (ACI). The only exception, again, is given by the Italian Circolare which is based on the level of knowledge of the investigated existing structure. For the present research, the level of knowledge adopted for the application of the Italian Circolare was assumed to be the highest possible among those considered in it.

Table 4 Experimental results vs. analytical predictions: compressive strength.

Sample	$f_{c,exp}$	$f_{ck,exp}$	$f_{c,Hilsdorf}$	$f_{c,Khoo-Hendry}$	$f_{c,Ohler}$	$f_{ck,CEN}$	$f_{ck,ACI}$	$f_{ck,DM}$	$f_{c,CIRC}$	$f_{ck,CTE}$
3JC- f_{C1}	5.96	5.17								
3JC- f_{C2}	8.40	7.28								
2JC- f_{C1}	7.01	5.46	6.80	7.55	6.40	6.16	6.46	5.64	6.00	5.97
2JC- f_{C2}	9.82	7.65								
Prism	5.82	4.33								

The experimental Young's moduli E_{exp} of the different samples (e.g. prismatic and cylindrical) were compared with the predictions from the expressions provided by the European CEN [44], the American ACI [39] standards and the simple one-dimensional homogenization method represented in Figure 13 using spring-like elements (respectively E_{CEN} , E_{ACI} and E_{1D} in Table 5). The one-dimensional homogenization method can represent the interaction of bed and head mortar joint with the units by means of the definition of a proper series-parallel system. The model requires the elastic moduli of the material constituents as input data [45]. It allows a direct comparison with the results obtained from LVDTs readings that were recorded during the experiments.

The Young's modulus of bricks was 8500 MPa in the calculations, being a representative value according to the obtained experimental range (Table 2). As for the Young's modulus of mortar, a precise experimental value was not available due to well-known complexities related to the evaluation of mortar's elastic parameters [46]. A value of 700 MPa was assumed in the calculations, corresponding to around 300 times the compressive strength of mortar [47]. Table 5 presents a summary of all the comparisons. The simple proposed homogenization method provides very good estimations of the Young's modulus of masonry, with relative errors of -9%, -7% and -5% for 3JCs, 2JCs and stack-bonded prisms, respectively. On the other hand, the CEN expression, suggesting the ratio between masonry's Young's modulus and compression strength of 1000, clearly overestimates the experimental ratios, which vary within a range of $259 \div 491$. Also the ACI expression, which considers a ratio of 700, overestimates the experimental Young's moduli.

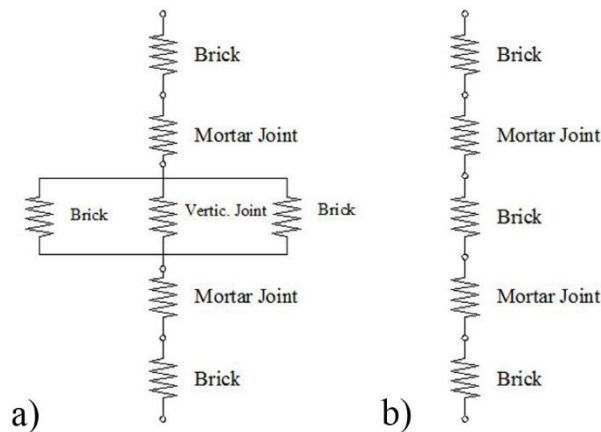


Figure 13 Representation by spring-like elements of the 1D homogenization method adopted for (a) three-joint cylinders and (b) two-joint cylinders and stack-bonded prisms.

Table 5 Experimental results vs. analytical predictions: Young's Modulus.

Sample	$E_{\text{exp}}/f_{c,\text{exp}}$	E_{exp}	E_{CEN}	E_{ACI}	E_{ID}
3JC-E1	306	1824	5960	4172	2342
3JC-E2		2570	8400	5880	2331
2JC-E1	259	1813	7010	4907	2385
2JC-E2		2540	9820	6874	2385
Prism	491	2855	5820	4074	2696

5 Conclusions

The research has presented a novel MDT based on in-situ core drilling of existing masonry structures. The aim has been the characterisation of the mechanical behaviour of masonry in compression by laboratory testing on core samples, without inducing too much damage to the existing structure during the sampling.

In view of the results obtained from the present investigation, it is possible to draw the following conclusions:

- The non-standard compression tests on masonry core samples can provide a good evaluation of the actual mechanical parameters of the inspected material.
- The extraction of masonry cylinders using a novel dry coring technique has ensured the successful completion of the sampling process without damaging the specimens. This approach has revealed to be more appropriate for lime mortar masonry than the wet coring procedure usually adopted for concrete structures and cement mortar masonry. Another remarkable advantage of the dry coring technique is that it can be effectively carried out both from the interior and the exterior of existing buildings. On the other hand, the wet core drilling is usually unfeasible from the interior of the historical buildings due to the massive use of water that may damage wooden floors, paintings, etc.
- The compressive strength of masonry can be evaluated by the compression test on cylindrical specimens. This work has presented a direct comparison with experimental tests on prismatic specimens, as those normally suggested by building codes for new masonry. The relationships obtained between standard and the novel non-standard tests are related to the specific material combination investigated, i.e. solid clay bricks and NHL mortar. The authors are currently carrying out additional laboratory investigations in order to extend the experimental database for other types of materials and specimens. Another research is ongoing about the numerical simulation of the tests in order to obtain a better understanding of the effective relationship between the compressive strength of prismatic and core samples.

- The evaluation of the Young's modulus of masonry cores must be experimentally evaluated after applying a series of loading-unloading cycles in the elastic range. The assessment of the elastic parameters has resulted more in agreement with that of prismatic samples when the cross-section of the regularization cap is considered in the calculations.
- The comparison with empirical and analytical expressions has allowed a useful comparison of available equations for the estimation of strength and elastic parameters of masonry. The available closed form expressions for the assessment of the Young's modulus have largely overestimated the experimental results of the investigated type of masonry, made of bricks and NHL mortar. On the other hand, a simple one-dimensional homogenization method can be helpful to estimate the Young's modulus of masonry, if the elastic properties of components are known.

The novel MDT, based on is-situ drilled masonry core samples, has shown to be a promising approach for a more reliable assessment of the compressive behaviour of historical masonry.

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References

- [1] Roca P, Cervera M, Gariup G, Pelà L. Structural analysis of masonry historical constructions. Classical and advanced approaches. *Arch Comput Method Eng* 2010; 17:299-325.
- [2] Hilsdorf HK. Investigation into the failure mechanism of brick masonry loaded in axial compression. in *Designing, Engineering and Constructing with Masonry Products*. In: Johnson FB, editor. Houston: Gulf Publishing; 1969.
- [3] Samarasinghe W, Page AW, Hendry AW. A finite element model for the in plane behavior of brickwork. *Proceedings of the Inst Civ Eng* 1982; 73:171-178.
- [4] McNary WS, Abrams DP. Mechanics of masonry in compression. *J Struct Eng-ASCE* 1985; 111(4):857-870.

- [5] Binda L, Fontana A, Frigerio G. Mechanical behavior of brick masonries derived from unit and mortar characteristics. Proceedings of the 8th International Brick and Block Masonry Conference, London; 1988, p. 205-216.
- [6] Anthoine A. In-plane behavior of masonry: a literature review. Report EUR 13840 EN. Commission of the European Communities JRC. Ispra: Institute for Safety Technology; 1992.
- [7] Aprile A, Benedetti A, Grassucci F. Assessment of cracking and collapse for old brick masonry columns. *J Struct Eng-ASCE* 2001; 127(12):1427-1435.
- [8] Vermelthfoort AT. Brick-mortar interaction in masonry under compression. PhD Thesis. Eindhoven University of Technology; 2005.
- [9] Drougkas A, Roca P, Molins C. Compressive strength and elasticity of pure lime mortar masonry. *Mat Struct* 2016; 49:983-999.
- [10] CEN BS EN 1052-1. Methods of test for masonry - Part 1 : Determination of compressive strength; 1999.
- [11] RILEM. Technical recommendations for testing and use of constructions materials: LUMB1 – Compressive strength of small walls and prisms, London: Chapman & Hall; 1994.
- [12] Lourenço PB, Fernandes FM, Castro F. Handmade clay bricks: chemical, physical and mechanical properties. *Int J Archit Herit* 2010; 4(1):38-58.
- [13] Binda L, Baronio G, Ferrieri ED. Durability of brick masonry surface treatments to salt crystallization. Proceedings of 11th Int Brick & Block Masonry Conference, Shanghai; 1997, p. 732-747.
- [14] Binda L, Papayianni I, Toumbakari E, Hees RV. Mechanical tests on mortars and assemblages. In: Characterization of Old Mortars with Respect to their Repair - Final Report of RILEM TC 167-COM 57-76; 2002.
- [15] Válek J, Veiga R. Characterisation of mechanical properties of historic mortars – testing of irregular samples. In: Brebbia CA, Torpiano A, editors. Structural Studies, Repairs and Maintenance of Heritage Architecture IX, Southampton: WIT Press; 2005, p. 365-374.
- [16] Drdácký M. Non-Standard Testing of Mechanical Characteristics of Historic Mortars. *Int J Archit Herit* 2011; 5(4-5):383-394.
- [17] Drdácký M, Mašín D, Mekonone MD, Slížková Z. Compression tests on non-standard historic mortar specimens. Book of abstract Historical Mortars Conference, Lisbon; 2008.
- [18] Benedetti A, Pelà L. Experimental characterization of mortar by testing on small. Proceedings of 15th International Brick and Block Masonry conference, Florianópolis: UFSC; 2012.
- [19] Pelà L, Benedetti A, Marastoni D. Interpretation of experimental tests on small specimens. In: Jasienko J, editor. 8th International Conference on Structural Analysis of Historical Constructions, Wrocław: DWE; 2012.
- [20] Pelà L, Roca P, Benedetti A. Mechanical characterization of historical masonry by core drilling and testing of cylindrical samples. *Int J Archit Herit* 2015; DOI:10.1080/15583058.2015.1077906.
- [21] Benedetti A, Pelà L, Aprile A. Masonry properties determination via splitting tests on cores with rotated mortar layer. Proceedings of 8th international seminar on structural masonry, Istanbul; 2008, p. 1-8.
- [22] UIC – International Union of Railways: UIC 778-3R. Recommendations for the assessment of the load carrying capacity of the existing masonry and mass-concrete arch bridges. Paris: UIC; 1995.

- [23] Brencich A, Corradi C, Sterpi E. Experimental Approaches to the compressive response of solid clay brick masonry. 13th International Brick and Block Masonry Conference, Amsterdam; 2004, p. 1-10.
- [24] Brencich A, Sterpi E. Compressive strength of solid clay brick masonry: calibration of experimental tests and theoretical issues. In: Lourenço PB, Roca P, Modena C, Agrawal S, editors. Structural analysis of Historical Constructions, New Delhi; 2006.
- [25] Pelà L, Peverini A, Garijo L, Roca P. Experimental calibration of in-situ sampling and testing of historical masonry. In: Peña F, Chávez M, editors. Proceedings of 9th International Conference on Structural Analysis of Historical Constructions, Mexico City: UNAM; 2014, p. 1-12.
- [26] Marastoni D, Pelà L, Benedetti A, Roca P. Combining Brazilian tests on masonry cores and double punch tests for the mechanical characterization of historical mortars. *Constr Build Mater* 2016; 112:112-127.
- [27] CEN. BS EN 459-1. Building lime Part 1: Definitions, specifications and conformity criteria, Brussels: Comité Européen de Normalisation; 2010.
- [28] CEN. BS EN 1015-11. Methods of test for mortar for masonry - Part 11. Determination of flexural and compressive strength of hardened mortar, Brussels: Comité Européen de Normalisation; 2007.
- [29] CEN. EN 772-1. Methods of test for masonry units. Part 1: Determination of the compressive strength, Brussels: Comité Européen de Normalisation; 2000.
- [30] CEN. EN 12390-3. Testing hardened concrete – Part 3: Compressive strength of test specimens, Brussels: Comité Européen de Normalisation; 2000.
- [31] Binda L, Mirabella Roberti G, Tiraboschi C. Problemi di misura dei parametri meccanici della muratura e dei suoi componenti (in Italian). In: *La Meccanica delle Murature tra Teoria e Progetto*, Messina: Pitagora; 1996, p. 45–54.
- [32] Canella E. Experimental characterization of the compressive behaviour of brick/lime mortar masonry. Master Thesis. University of Ferrara and Technical University of Catalonia; 2015.
- [33] Bilello C, Brencich A, Corradi C, Di Paola M, Sterpi E. Experimental tests and theoretical issues for the identification of existing brickwork. North American Masonry Conference, St. Louis; 2007.
- [34] Brencich A, Sabia D. Experimental identification of a multi-span masonry bridge: The Tanaro Bridge. *Constr Build Mater* 2008; 22:2087-2099.
- [35] Drougkas A, Roca P, Molins C. Numerical prediction of the behavior, strength and elasticity of masonry in compression. *Eng Struct* 2015; 90:15–28.
- [36] Khoo CL, Hendry AW. Strength tests on brick and mortar under complex stresses for the development of a failure criterion for brickwork in compression. *Proc Br Ceram Soc* 1973; 21:57–66.
- [37] Ohler A, Zur berechnung der druckfestigkeit von mauerwerk unter berücksichtigung der mehrachsigen spannungszustände in stein und mortel (in German). *Bautechnik* 1986; 63:163–8.
- [38] CEN. EN 1996-1-1: rules for reinforced and unreinforced masonry, Brussels: Comité Européen de Normalisation; 2005.
- [39] ACI. ACI 530.1-11. Building code requirements and specification for masonry structures and related commentaries; 2011.
- [40] D.M. 14 gennaio 2008. Norme tecniche per le costruzioni; Cap. 11: Materiali e prodotti per uso strutturale (in Italian); 2008.
- [41] CIRCOLARE 2 febbraio 2009 n. 617. Istruzioni per l'applicazione delle Nuove norme tecniche per le costruzioni di cui al decreto ministeriale 14 gennaio 2008 (in Italian); 2009.

- [42] CTE DB-SE-F. Seguridad estructural: Fábrica - Anejo C: Valores de resistencia característica a compresión; 2009.
- [43] CEB-FIP. Model Code 1990. Comité Euro-International du Béton; 1990.
- [44] CEN. EN 1996-1-1: rules for reinforced and unreinforced masonry, Brussels: Comité Européen de Normalisation; 2005.
- [45] Pande GN, Liang, JX, Middleton J. Equivalent elastic moduli of brick masonry. *Comput Geotech* 1989; 8:243-65.
- [46] Binda L, Tiraboschi C, Abbaneo S. Experimental Research to Characterise Masonry Materials. *Masonry International* 1997; 10(3):92-101.
- [47] Kaushik HB, Rai DC, Jain SK. Stress-Strain Characteristics of Clay Brick Masonry under Uniaxial Compression; *J Mater Civil Eng* 2007; 19(9):728-739.

Tables captions

Table 1 Mechanical properties of the brick

Table 2 Compressive and flexural strengths of mortar prisms

Table 3 Compressive strengths and Young's moduli of core samples and stack bonded prisms.

Table 4 Experimental results vs. analytical predictions: compressive strength

Table 5 Experimental results vs. analytical predictions: Young's Modulus

Figures captions

Figure 1 Compression test on brickwork core sample [22].

Figure 2 Masonry specimens: (a) wall and (b) stack-bonded prism.

Figure 3 Cubic and prismatic specimens of brick for compression and flexure tests (a) and evaluation of the Young's modulus on cylindrical sample (b)

Figure 4 Evolution with time of mortar's flexural (a) and compressive (b) strengths..

Figure 5 Layout of sampling in the two walls (a), core drilling with dry procedure (b), cleaning with spray compressor (c), dust in the coring bit (d) and wall after sampling (e).

Figure 6 Regularization of cylindrical samples: (a) wood mould adopted to build the high-strength caps (b).

Figure 7 Experimental setups of compression tests: (a) cylindrical specimens and (b) stack-bonded prisms (dimensions in mm).

Figure 8 Stress vs. strain experimental curves of masonry core samples: elastic responses of (a) three-joint and (b) two-joint cylinders; strength and nonlinear responses of (c) three-joint and (d) two-joint cylinders.

Figure 9 Crack patterns at the peak load and core samples after failure. Three-joint cylinders (a,c) and two-joint cylinders (b,d).

Figure 10 Stress vs. strain experimental curves of stack-bonded prisms: (a) elastic response; (b) strength and non linear response.

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