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EXPERIMENTAL CALIBRATION OF IN-SITU SAMPLING AND TESTING OF HISTORICAL MASONRY

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Abstract. *The mechanical characterization of existing masonry is a difficult task due to the heterogeneous and composite character of the material. In most cases, the historical structure cannot be damaged during the in-situ sampling procedure due to its cultural, historical and economical value. Non-destructive testing techniques have been proposed to minimise the damage during the inspection. Another possibility is the extraction of small samples to be subjected to destructive testing in laboratory.*

This paper presents the results of an experimental program aimed at calibrating a non-standard testing method for the determination of the mechanical response of existing masonry. Cores of 150 mm diameter were extracted from a masonry wall built in the laboratory. The upper and lower portions of the cylinder were properly regularized to create two plane parallel surfaces. The specimen was tested under compression. The results are discussed and compared with those derived from conventional compression tests on stack prisms, built with the same materials.

The outcomes of the research show that the test provides an estimation of the compressive strength of the composite material, comparable with that obtained through the standard method. The proposed experimental technique can be helpful for the inspection and the analysis of structures of the built cultural heritage.

1 INTRODUCTION

Masonry constructions constitute the great majority of the existing built heritage in Europe, including monuments of huge historical and architectural value. Given the age of many of these constructions, the demand for safety assessments and restoration projects is pressing and constant.

The evaluation of masonry structures requires some mechanical parameters to be defined, being the compressive strength one of the most important ones. Even if the structure of masonry is rather simple, the determination of the mechanical properties is really complex, due to highly nonlinear response of the material and lack of standardization. Also, the strength obtained by tests is strongly dependent on the modality of the experiment.

Nondestructive Testing (NDT) is an interesting approach for the evaluation of existing structures, since the structural components are not damaged during the testing activities [1]. However, the mechanical characteristics of masonry can be estimated indirectly. Thus, it is advisable to consider also Minor Destructive Testing (MDT) in order to obtain the properties more directly from laboratory tests on small masonry samples.

This work presents the calibration of a methodology to extract samples from existing walls and test the obtained specimens in the laboratory. In particular, the research is intended to give a contribution to the development of a particular non-standard technique for the determination of the response of existing masonry under compression. The samples are cylinders of 150 mm diameter extracted by a core drilling machine. The curved surface of the specimen is regularized to create two planes parallel to the bed joints of the masonry, as shown in Figure 1. In this way, a vertical compression can be applied over the regularization planes in order to reproduce on the sample the compression loading to which the wall is subjected. The test can represent the complex interaction among units, horizontal and vertical mortar joints. The testing method was proposed by the UIC 778-3R recommendations [2]. Additional studies assessing the applicability of the test can be found in references [3,4].

Compression tests on stack prisms were also carried out in the laboratory, in order to have a reference for a better calibration of the new test and to provide a direct comparison between the results from standard and non-standard techniques. The reference standard for the development of the compression test on stack prisms was the EN 1052-1 [5].

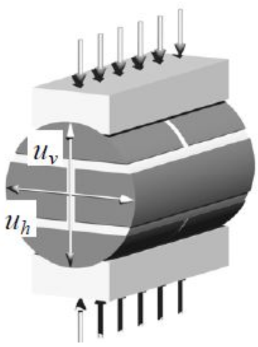

Figure 1: UIC test arrangement.

2 EXPERIMENTAL INVESTIGATION

2.1. Materials

The materials used in the research were chosen in order to reproduce those employed in historical masonry of low mechanical properties. Hydraulic lime mortar without cement content was used in the research. Such traditional material is frequent in historical masonry. The aggregate used was washed river sand with 0-5 mm diameter. The binder/sand volumetric ratio chosen was 1:3, in order to provide a good representation of an ancient mortar.

The mortar flexural strength (f_{mf}) and compressive strength (f_{mc}) were measured according to EN 1015-11 [6], respectively on 3 prismatic samples with dimensions 40 × 40 × 160 mm^3 and on the 6 fragments produced by the flexural test, capable of providing 40 × 40 × 40 mm^3 cubes of solid material. The results obtained at 61 days from mortar pouring are reported in Table 1.

Table 1: Experimental strengths of mortar and bricks.

Mechanical characterization			
Mortar		Bricks	
f_{mf} (MPa)	f_{mc} (MPa)	f_{bf} (MPa)	f_{bc} (MPa)
0.60	1.60	3.68	25.51

Hand-cut solid clay bricks with dimensions 276 × 133 × 43 mm^3 were used. The bricks compressive strength (f_{bc}) was determined according to European standard EN 772-1 [7] on 3 bricks, which were regularized by polishing of the two faces in contact with the plates of the load machine. The test is performed in the same direction as the load acts the wall. The results obtained are shown in Table 1. The flexural strength was evaluated making reference to the standards available for concrete units EN 772-6 [8].

2.1 Masonry samples

Three masonry stack prisms (see Figure 2a) were built using the materials described above. Each prism consisted of five stacked units separated by four mortar joints approximately 10 mm thick, resulting in a total nominal height of 280 mm. The lowest and uppermost bricks were coated with a layer of high-strength cement mortar, to ensure the flatness of the loading surfaces, as established by EN 1052-1 [5]. Immediately after the construction, the prisms were covered with polyethylene sheets for three days in order to prevent the premature drying out of the masonry during this time. Subsequently, the masonry was kept in laboratory conditions until it reached an age of 61 days.

Figure 2: (a) Stack prism and (b) wall used for core drilling.

A wall with dimensions 1.5 × 0.75 × 0.276 m^3 was built using the same materials adopted for the construction of the stack prisms. The Flemish bond was adopted, as shown in Figure 2b. The wall was built over a metal beam to permit its displacement during the following phases of the campaign. Care was taken to maintain a constant thickness of the mortar joints, each approximately 10 mm thick, and the planarity of bricks layers. At the end of the construction, a layer of mortar was placed above the last line of bricks, to permit the location of another metal beam, useful during the phase of extraction of specimens, and the wall was kept in laboratory conditions.

After 28 days of curing, 24 specimens were extracted from the wall using a core drilling machine. The smallest specimens were used for another experimental campaign, while the largest ones, with a diameter of 150 mm, were used for the investigation presented. Two types of cylindrical specimens of 150 mm diameter were extracted, the first formed by four brick pieces, two horizontal mortar joints and a vertical mortar joint while the second by three bricks and two horizontal mortar joints. The location of the extractions is shown in Figure 3a.

Before proceeding with the extraction, the wall was taken out of the lab and turned onto its larger face, see Figure 3b. To ensure the integrity of the wall during this phase, a low pre-compression force was exerted, using the two metal beams located at the bases and connecting them with metal bars bolted to the beams.

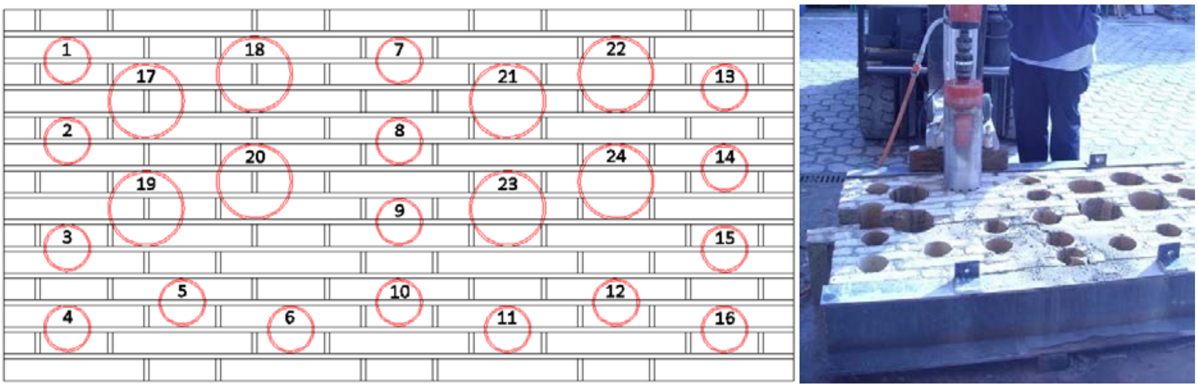

Figure 3: (a) Location of cylinders in the wall, (b) extraction of specimens.

Figure 4: (a) Three and two joint cylindrical masonry samples, (b) mould used for the regularization of the specimens, (c) regularized specimen ready to be tested.

After the extraction, the cores were cut into two parts, obtaining two specimens of a length of 130 mm. A total of 6 samples with two joints and 5 with three joints (Figure 4a) were used to perform a non-standard compressive test. In addition to the compressive strength, the possibility of measuring the masonry Young's modulus and Poisson's ratio was also investigated.

Each specimen was regularized with cement mortar caps, using a wooden mould especially designed (see Figure 4b and Figure 4c). The purpose of this particular kind of regularization is to ensure an optimal transmission of the compression force from the testing machine to the specimen through a cap perfectly adherent, in order to avoid any stress concentration.

2.3. Testing setup and procedures

The three stack prisms were subjected to compression test, see Figures 5a-b. Six LVDTs were used to measure vertical and horizontal displacements. Five initial loading cycles under force control were executed in a range of load between 10 kN and 100 kN. The test was then performed under displacement control in order to follow the post peak response of the masonry. The load was applied at a rate of 0.003 mm/sec. The LVDTs were removed from the structure shortly after reaching the maximum load, so as not to be deteriorated.

The cylindrical specimens regularized were tested under compression. The UIC 778-3R recommendations [2] and previous studies [3,4] were taken into consideration to perform the test. The test procedure consisted of applying a compressive load on the regularization caps and perpendicular to the bed joints. Both the vertical and horizontal displacements were recorded through 4 LVDTs. Two LVDTs were disposed vertically, on the bases of the cylinder, attached on the caps of regularization mortars. Two other LVDTs were located horizontally along the diametral direction of the specimen, fixed on two metal supports, see Figure 5c. In all the tests the load was applied under displacement control, at a rate of 0.006 mm/s, until a very low level of residual strength, in order to follow the post peak response of brickwork. The tests were conducted at the same age of the compressive tests on stack prisms, i.e. at 61 days.

Figure 5: (a, b) Stack prisms and (c) regularized cylindrical specimen before the test.

3 RESULTS AND DISCUSSION

3.1 Results of the tests on stack prisms

The load-displacement curves of the stack prism 2 (Sp2) and stack prism 3 (Sp3) are shown in Figure 6. In the last part of the test, consisting in leading to failure the specimens by applying a load under displacement control, some LVDTs fell down because of cracks and others were removed not to be deteriorated. For this reason, it was not possible to evaluate the post peak response of specimens.

The samples were tested under initial loading cycles, showing typical nonlinear elastic behaviour of masonry under compression. At the last cycles, the material became more compact and consequently stiffer due to the micro-cracks and voids closure. Taking into account this not merely elastic initial response, it was decided to calculate the values of the Young's modulus as a secant modulus in the more linear branch of the last loading cycle. Table 2 shows the compressive strength (f_c) and the Young's modulus (E) obtained in the tests.

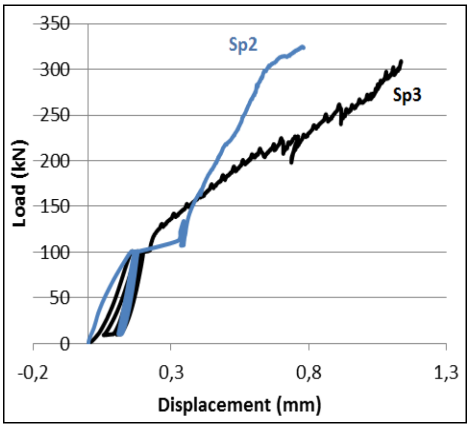

Figure 6: Load-Displacement curves of stack prisms 2 and 3

Table 2: Compressive strength and Young's modulus of the stack prisms.

Specimen	F_{max} (kN)	F_c (MPa)	E (MPa)
Sp1	328.28	8.84	—
Sp2	308.96	8.32	3545.65
Sp3	324.83	8.75	5013.36
Average	320.69	8.64	4279.51

The cracking of specimens was predominantly vertical, as expected from a compression test, see Figure 7. Mortar joint expansion could be clearly observed during the test. The regularization cement mortar proved to be suitable, as it was demonstrated by its undamaged state at the end of the test.

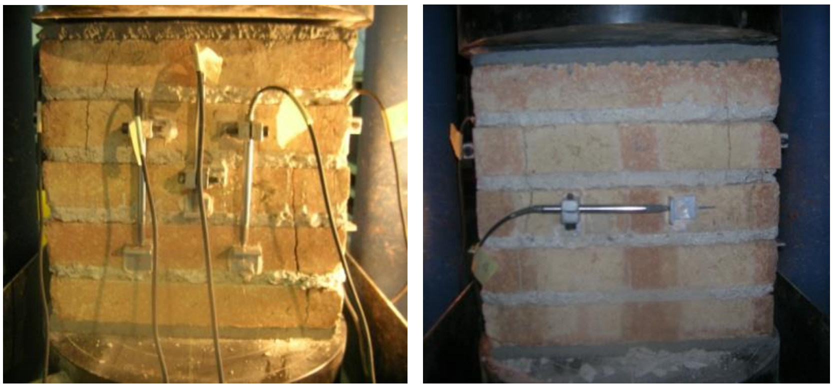

Figure 7: Damage in stack prisms after testing.

3.2 Results of the tests on cylindrical specimens

The vertical stress-strain curves of the cylindrical specimens with three joints and two joints are shown in Figures 8a and 9a. As for the three joint specimens, the experimental responses are similar. It can be noted an initial lineal behavior until about 15% of the maximum strength, followed by a change of slope, with a higher growth of deformation with the load increase. It can be observed the presence of a sudden fall in the initial loading branch, corresponding to the appearance of the first crack. After this point, the cylinder can still resist higher loads, until reaching the maximum compression load. After the peak stress, the unloading branch shows a deformation increase with the decreasing stress. The post-peak part of the curve presents an uneven trend due to the propagation of cracks across the specimen.

The curves of the two joint specimens show also similar overall trend, even if they differ in the initial response. The curves of the specimens 21a, 23a and 23b show an initial lineal behavior until about 15% of the maximum strength, while specimens 21b, 24a and 24b show an initial non-linear branch, probably due to an accommodation of LVDTs, followed by a linear branch until about 35-40% of the maximum stress. After this different initial part, all the curves show a change of tendency, with higher growth of deformation with the load increase. As in the curves of three joint specimens, it can be noticed a sudden fall of load which indicates the initiation of cracking and a subsequence strength recover until reaching the maximum compression load. Only the specimen 24b does not show a clear peak and descending branch. All the curves show an uneven trend after the first crack appearance, more pronounced than in the three joint specimens. The deformation increases gradually with the stress decrease in the unloading branch. It was not possible to evaluate the unloading branch of the specimen 21b because the LVDTs detached from the supports.

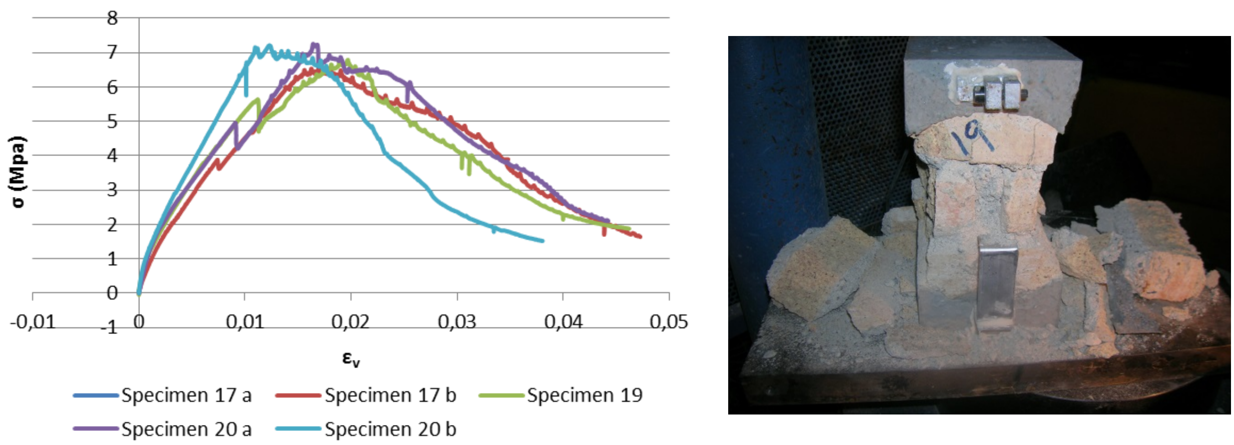

Figure 8: Stress-strain curves of three joint specimens (a) and mode of failure (b).

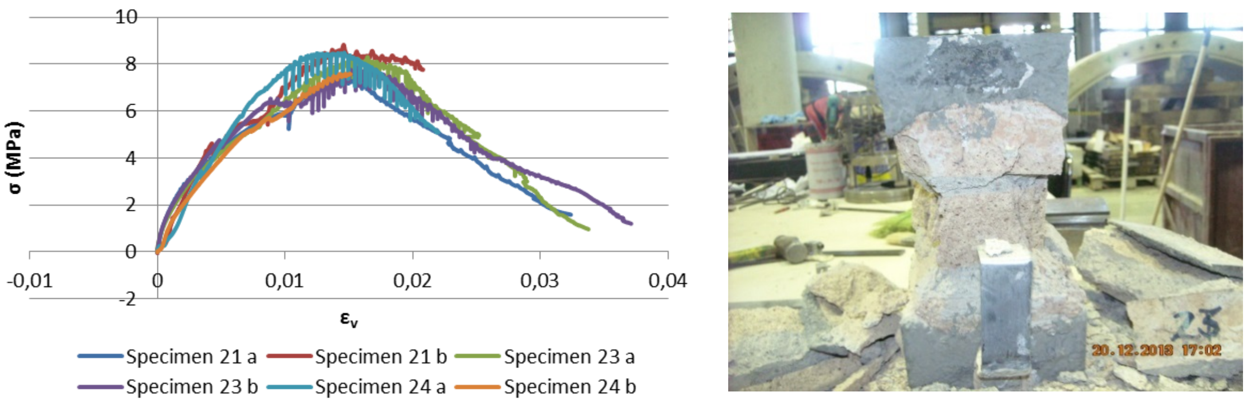

Figure 9: Stress-strain curves of two joint specimens (a) and mode of failure (b).

Regarding the failure mode, in both the three and two joint specimens it was essentially the same, as it can be seen in Figures 8b and 9b. The first crack was vertical and collinear with the edge of the upper and lower regularization caps. Then, the crack enlarged and a symmetrical one appeared in correspondence of the other edge of the regularization caps. Finally, the splitting of the lateral parts occurred. Comparing the observation of damage with the graphs in Figures 8-9 it is possible to deduce that such cracking process begins before reaching the ultimate failure load. At the end of the test, the remaining part of the specimen was a prism with upper and lower sections equal to those of the regularization caps, whereas the section at the middle height was smaller. In addition to this main damage, the specimens presented micro-cracks distributed through the cylinder. After testing, the remaining samples were inspected and manipulated and were found to be extremely damaged, which was expected from the fact that the test was continued until a very low level of residual strength. The regularization mortar caps were usually intact at the end of the test, see Figure 10a. Some specimens experienced the cracking of the edge of the cap due to the propagation of the vertical lateral crack previously mentioned, see Figure 10b. The detachment of the lateral portions of the cylinder at failure was also observed in previous studies [3,4]. Such type of failure was due to the lower confinement to which they are subjected, since the width of the regularization caps is lower than the diameter of the cylinder. Nevertheless, in the current study neither the opening of the vertical joint nor the net debonding between the brick-mortar interface were observed, as opposite to previous studies [3,4].

Figure 10: Typical regular failure at the end of the test (a) and failure with crack involving the cap (b).

3.3 Discussion of results

This section presents the comparison between the results of tests performed on stack prisms and cylinders drilled from masonry. Whereas the compression strength in prisms can be calculated in a simple way, the strength of cylinders must be evaluated more carefully making reference to the peculiar failure observed.

Some previous studies [3,4] proposed to calculate the compressive strength of masonry from cylindrical specimens as the ratio between the collapse load F_{max} and the horizontal cross section $\phi \cdot l$, being ϕ the diameter and l the length of the cylinder. Applying this method, the entire horizontal cross section of the specimen is considered resistant until reaching the maximum load. However, the experimental evidence from the current research showed that the specimens experienced cracking and subsequent detachment of the lateral parts of the specimens, with consequent reduction of the cross-section during the test. Therefore it can be deduced that the effective resistant cross-section of the cylinder may be smaller than the total one, with a minimum size given by the width of the regularization mortar caps. In this study, the compressive strength was deduced also as the ratio between the collapse load F_{max} and the horizontal cross section of the regularization mortar layer, $b \cdot l$, being b the width of the mortar caps. The strength calculated with reference to the whole section of the specimen $A_1 = \phi \cdot l$ and the strength calculated with reference to the section of the regularization cap $A_2 = b \cdot l$. are indicated respectively as f_{c1} and f_{c2} .

As should be expected, the average compressive strength obtained for two joint specimens resulted higher than that of three joint specimens. Table 3 presents the compressive strengths of both the three and the two joint specimens. It can be seen that the average value of compression strength fc_1 obtained by testing three joint cylinders (6.84 MPa) is lower than that of the standardized test on stack prisms (8.64 MPa). On the contrary, the average value of compression strength fc_1 determined by testing two joint cylinders (8.10 MPa) is closer to the value obtained from stack prisms. When the reduced resisting cross section $b \cdot l$ is considered in calculations, the average value of compression strength fc_2 obtained by testing three joint cylinders (8.55 MPa) is very similar to that of the standardized test on stack prisms (8.64 MPa). On the contrary, the average value of compression strength fc_2 determined by testing two joint cylinders (10.12 MPa) is the 17% higher than the value obtained from stack prisms.

Table 3: Compressive strength and Young’s modulus of three joint specimens.

Specimen	F_{max} (kN)	f_{c1} (MPa)	f_{c2} (MPa)	E (MPa)
17a	123.95	6.36	7.95	1385.54
17b	128.05	6.57	8.21	925.31
19	132.42	6.79	8.49	2274.10
20a	141.45	7.25	9.07	1676.81
20b	140.64	7.21	9.02	1990.86
Average	133.30	6.84	8.55	1650.52

Table 4: Compressive strength and Young’s modulus of two joint specimens.

Specimen	F_{max} (kN)	f_{c1} (MPa)	f_{c2} (MPa)	E (MPa)
21a	144.41	7.41	9.26	2859.93
21b	172.07	8.82	11.03	1105.93
23a	161.93	8.30	10.38	3149.13
23b	152.81	7.84	9.80	3105.79
24a	165.61	8.49	10.61	994.76
24b	150.40	7.71	9.64	986.13
Average	157.87	8.10	10.12	2033.61

As for the determination of the Young’s modulus (E), previous studies [3,4] considered a reduced section $0.75 \cdot \phi \cdot l$ in calculations and made reference to the loads at 1/10 and 1/2 of the maximum load. Since this approach provided very small values for the present research, a different method was considered in this study. Stress-strain graphs of each specimen were analyzed and it was noted that the initial part of compression stress-vertical strain curves followed two main trends. In the majority of cases the curve started with a linear behavior until about 15% of the maximum stress reached, while in some cases it showed an initial nonlinear branch, followed by a linear one until about 35-40% of the maximum stress (Specimens 21b, 24a, 24b). The Young's modulus was thus calculated as the secant modulus inside the elastic branch, i.e. between 0 and 15% or between 0 and 35% of the maximum load, based on the trend followed by the curves. The ordinary equation obtained by the Hooke's law was applied and the area used for the calculation was that of the regularization mortar layer A_2. Tables 3 and 4 present the Young's moduli of both three and two joint specimens. The Young's moduli measured in cylinders showed large scattering and, in average, lower values than prisms. With regard to the Poisson's Coefficient (ν), the results obtained gave higher values than those expected and were characterized by a large dispersion. It was not possible to compare the results with others, since also in refs. [3,4] they are not reported, maybe due to similar complexity encountered during the experimental program. An ongoing research project is helping to improve the experimental setup and the interpretation of test results.

4 CONCLUSIONS

The present research evaluated the compressive behaviour of a masonry wall built in laboratory. Standard tests on stack prisms were performed, in order to determine the compressive strength, the Young's modulus and the Poisson's coefficient. Subsequently, compressive tests on cylinders extracted from the wall and with the lateral surfaces regularized were carried out, to estimate the same properties. A number of conclusions were drawn from these experiments:

- With regard to the test on stack prisms, the results obtained gave an average compressive strength of the masonry examined of 8.64 MPa. Thus, it has been also established that relatively high masonry strength can be obtained using conventional hydraulic lime mortars and moderately strong units. Specifically, it was possible to achieve a compression strength nearly 5.5 times higher than the compressive strength of the mortar, at only 61 days of curing. For what concerning the Young's modulus, it was determined taking into consideration the value referred to the more linear branch of the last loading cycle curve, obtaining a value of about 4300 MPa, with a E/f_c ratio of 500.

- The attempt to find a correlation between the standard tests on stack prisms and the test proposed by the UIC 778-3R guidelines [2] has been partially satisfied. The tests permitted to obtain a reliable estimation of the compressive strength, giving values comparable with those of stack prisms, but it was not possible to evaluate a direct correlation of the Young's moduli and the Poisson's coefficients, due to the large dispersion of results. Furthermore, it was detected that both the UIC guidelines and the previous studies should be complemented by additional researches in order to provide clear rules of general applicability for the performance of the test and for the analysis of results. This suggests that further investigations are necessary in order to calibrate adequately the test. A combined experimental-numerical approach is currently in progress to better understand the stress distribution across the specimen during the loading and the development of cracking phenomenon.
- Even if a wider database is necessary to derive general conclusions, the results obtained are encouraging. Once refined, the test could represent a valid technique to

permit the characterization of the compression properties of existing masonry elements.

ACKNOWLEDGEMENTS

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REFERENCES

[1] D.M. McCann, M.C. Forde, Review of NDT methods in the assessment of concrete and masonry structures. *NDT & E International*, 34, 71–84, 2001.

[2] UIC – International Union of Railways, Leaflet 778-3R, Recommendations for the inspection, assessment and maintenance of masonry arch bridges. UIC, Paris, 1995.

[3] A. Brencich, E. Sterpi, Compressive Strength of Solid Clay Brick Masonry: Calibration of Experimental Tests and Theoretical Issues. Structural Analysis of Historical Constructions: 757-765. Editors: Lourenço P. B., Roca P., Modena C., Agrawal S, New Delhi, 2006.

[4] Bilello C., Brencich A., Corradi C., Di Paola M. and Sterpi E. (2007). Experimental tests and theoretical issues for the identification of existing brickwork. *10th North American Masonry Conference*. St. Louis, Missouri, USA.

[5] CEN, EN 1052-1 - Methods of test for masonry - Part 1: Determination of compressive strength, European Committee for Standardization, Brussels, Belgium, 2001.

[6] CEN, EN 1015-11, Methods of test for mortar masonry - Part 11: Determination of flexural and compressive strength of hardened mortar, European Committee for Standardization, Brussels, Belgium, 2007.

[7] CEN, EN 772-1, Methods of test for masonry units - Part 1: Determination of the compressive strength, European Committee for Standardization, Brussels, Belgium, 2002.

[8] CEN, EN 772-6, Methods of test for masonry units - Part 6: Determination of bending tensile strength of aggregate concrete masonry units, European Committee for Standardization, Brussels, Belgium, 2002.