The Inspection by Minor Destructive Testing in Projects of Adaptive Reuse of Historical Masonry Buildings and Design of Green Rooftops in Barcelona

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Abstract. The mechanical characterisation of existing masonry in historical structures encounters several technical difficulties due to the complexity and heterogeneity of this traditional material, as well as to the need for respectful inspection activities able to preserve the cultural heritage value of the building. This paper presents and discusses different Minor Destructive Testing (MDT) techniques oriented at estimating, either in-situ or in the laboratory, the mechanical properties of masonry at the level of components, such as units, tiles, and mortar joints, and at the level of the composite material. The research addresses different issues related to the execution of laboratory tests on sampled historical materials, such as selection of the size and shape of specimens, different types of treatments for the sample, testing protocols, and experimental setup. The complementary use of Finite Element Method (FEM) models represents a valuable activity to provide a good understanding of the experimental behaviour exhibited by the specimens, and especially concerning the execution of non-standard laboratory tests. The possibility of in-situ MDT is explored considering techniques based on different portable instruments, previously calibrated through ad-hoc experimental programs under controlled laboratory conditions. The research is based on a high number of tests executed at the UPC within the context of several experimental programs linked to projects of adaptive reuse of existing masonry buildings and design of green rooftops in Barcelona.

Keywords: MDT, NDT, Inspection, Laboratory Testing, Brick, Mortar.

1 Introduction

The protection and preservation of the architectural heritage composed of brick masonry buildings require the detailed evaluation of their load-bearing capacity [1]. The careful structural assessment of existing historical buildings is particularly necessary when they are interested by refurbishment works or by projects aimed at updating or adapting the structural system to a new function, purpose, or loading scenario.

One of the first challenging activities related to this kind of studies is the inspection and characterisation of the existing masonry materials. Masonry has potentially one the most complex mechanical behaviours within the existing construction materials due to its composite nature, lack of standardization and intrinsic heterogeneity linked to its irregular character. The available international and national standards usually focus on testing procedures for new construction material. Due to it, there is a lack of technical recommendations for inspection, sampling, and testing of masonry in existing buildings. The criteria commonly used for inspection and testing of new construction materials are often not applicable to historical masonry structures. For example, the size and shape of sampled materials do not usually satisfy the standard requirements, the number of sampled specimens is limited, and the extraction of samples and subsequent execution of laboratory destructive tests may not be feasible in protected buildings. In addition to budget restrictions, a major constraint is actually posed by the heritage value of the historical structures, which requires the inspection activities to be extremely respectful and limited to the minimum necessary, as stated by the ISCARSAH guidelines on the analysis, conservation and structural restoration of the architectural heritage [2].

Minor Destructive Testing (MDT) and Non-Destructive Testing (NDT) offer an appealing solution for ensuring minimal intervention during the inspection activities, according to the modern criteria of preservation of heritage buildings. However, both MDT and NDT lead only to an indirect evaluation of the mechanical properties; therefore, their previous calibration and validation is strongly necessary to ensure the reliability of such techniques. For this reason, there is the need for ad-hoc research based on comparisons between MDT and NDT evaluations and destructive testing (DT) in the laboratory under controlled experimental conditions.

While the invasiveness of NDT is null, MDT causes little damage on the investigated structural component, leading to minor or even unnecessary repair of the tested volume after the execution of the experiments. We can subdivide MDT techniques into two main categories: i) the execution of laboratory tests on small samples extracted in-situ in a minor destructive manner, and ii) in-situ experiments directly executed on a structural component. The two approaches are often implemented together during the inspection of historical buildings. The first type of MDT techniques, whenever they are possible, can be executed only in certain parts of the structure due to the restraints posed by its heritage value, while the second type of MDT techniques can be applied for in-situ evaluations of the rest of constructed components. Both categories of MDT entail the development of specific research activity to address their relevant theoretical and technical issues, and to improve their accuracy and reliability in inspection works on historical buildings.

This paper presents an overview of recent research at UPC about the contribution to the development of DT on small non-standard specimens of sampled masonry materials, and about the calibration of in-situ MDT techniques. The current paper focuses on the compressive behaviour, while other previous research contributions at UPC addressed the evaluation of shear behaviour in existing masonry buildings [3-6]. The research addresses the recurrent issues and major challenges encountered in a series of experimental DT laboratory campaigns, including also several in-situ MDT activities; it was motivated by several projects of refurbishment and adaptive reuse of historical masonry structures, as well as of design of green rooftops in Barcelona, which were executed during the last ten years. Fig. 1 shows some of the buildings interested by these projects, such as industrial complexes from the late XIX and early XX cs., a covered market from the late XIX c., and residential palaces and buildings from the XIX and early XX cs. All the experimental campaigns were executed at the Laboratory of Technology of Structures and Materials (LATEM) of the Technical University of Catalonia (UPC-BarcelonaTech).

Fig. 1. Some of the buildings interested by refurbishment and adaptive reuse projects in Barcelona, including industrial complexes from the late XIX and early XX cs. (first four pictures on top), covered market from the late XIX c. (fifth picture on top), and residential palaces and buildings from the XIX and early XX cs. (bottom figures).

2 Adaptive Reuse of Historical Buildings and Design of Green Rooftops

Adaptive reuse is a quite traditional approach in architecture to repurpose an existing structure for a new use, e.g. converting its original function to something useful for the surrounding urban environment. Adaptive reuse can be intended as one of the possible forms of historical preservation of the built heritage, as it can breathe new life to sites that otherwise might be left to decay or, in worst cases, might be demolished due to unrestricted urban sprawl. As expected, this approach may entail changes of loading scenarios over walls and vaults, with higher magnitudes of forces applied compared with the original ones, as well as alterations of the structural system due to the reduction of cross-section of the load-bearing elements, e.g. due to the creation of new openings or widening of existing ones. Fig. 2a shows the adaptive reuse project of the industrial complex of Can Batlló, where the original textile factory from the late XIX c. will host the new Archive of the City of Barcelona [7].

An emerging trend in many cities, such as in Barcelona [8], is the adaptive reuse of the flat rooftops of existing urban buildings to host green living roofs covered with vegetation and a growing medium, usually planted over a waterproofing membrane. The action of integrating vegetation in existing buildings is a nature-based solution that currently constitutes a very useful strategy to deal with climate change mitigation and adaptation at urban scale, helping to lower urban air temperatures and mitigate the heat island effect. Among other advantages, there are those of absorbing rainwater, creating habitat for wildlife, providing insulation and pleasing open-air spaces for buildings' inhabitants. The design of green rooftops in existing buildings clearly involves adding extra weight on top of the load-bearing structural system, and therefore it is necessary to evaluate if the masonry walls are able to withstand higher stress levels. Fig. 2b shows the Xifré's Rooftop

"Floating" Wild Garden in Barcelona, 2021 New European Bauhaus Award [9], built on top of "Casa Xifré", a catalogued and protected historical palace built between 1836 and 1840 near to the old seaport.

These projects aim to achieve the maximum social, environmental and energy performance, transforming the historical buildings or part of them to new functions, while respecting the heritage value of the construction. Extensive experimental programs were implemented aimed at a detailed mechanical characterisation of historical materials to support subsequent structural analyses, in order to evaluate carefully the load bearing capacity of the structural members. The precise evaluation of the compressive strength of masonry is a governing issue of paramount importance in these types of projects, as common objectives are minimising the possible alterations to the existing heritage structures as well as strengthening interventions, and the relevant costs.

(a) 

(b) 

Fig. 2. Adaptive reuse project of the industrial complex of Can Batlló in Barcelona (top figures, downloaded from [7]), and Xifré's Rooftop "Floating" Wild Garden, 2021 New European Bauhaus Award (bottom figures, courtesy of MataAlta Studio [9]).

3 Laboratory Testing of Brick Samples

3.1 Brick Units Extracted from Walls

The experimental characterisation of brick units has always been a subject of scientific debate, as the available standards report different assumptions about technical aspects that are very influent on the evaluation of the compressive strength. Possible examples are the choice of the shape and size of specimens, the preparation of bearing surfaces treatments of the specimen prior to compressive testing, and the definition of the experimental setup. This context shows a lack of consensus about common criteria and testing procedures for the units, both historical (like handmade) and modern ones (like hydraulic pressed or extruded). It is worth noticing that the value of compressive strength of masonry units can strongly depend on the reference standard applied [10].

Extracting a number of entire units for laboratory testing may be difficult in historical buildings, as this operation might leave important damage on the existing walls (Fig. 3a). Although a reliable estimation of the compressive strength should consider a number of tests able to provide statistically significant results, the sampling of bricks can usually involve a small number of units in real-life projects. In addition, the units can have limited thickness (e.g. usually 40 ÷ 50 mm in Barcelona) and it is not possible to extract samples that correspond to that suggested in the standards. This context leads to devise a compressive test using a non-standard specimen. A good solution is the use of non-standard $40 \times 40 \times 40$ mm^3 cubic specimens for the assessment of the compressive strength of bricks extracted from existing masonry buildings.

An experimental program executed at UPC correlated the brick compressive strength derived from small cubic specimens with that obtained from the $100 \times 100 \times 40$ mm^3 specimens recommended by the European standard EN 772–1 [11].

A careful preparation of the cubic specimens is necessary prior to testing, disregarding those with material imperfections (inclusions and voids) and checking carefully the aggregate diameter (Fig. 3b) according to the suggestions of the standard for concrete EN 12390–1 [12]. The observed failure mode in both specimens followed an hourglass shape (Fig. 3c) with separation of the outer parts. The acceptability of the failure modes in cubic specimens was evaluated according to the standard for concrete EN 12390–3 [13]. Fig. 3d shows the histogram and probability distribution function for the values of the ratio between the compressive strengths of the standard and non-standard specimens, based on 461 compressive tests on specimens derived from 11 types of units, including different manufacturing technologies such as handmade, mechanically extruded, and hydraulic press moulded bricks. Historical handmade units extracted from real buildings of Barcelona were also included in the statistical sample. The experimental research allowed the assessment of a correlation coefficient to convert the strength of the non-standard cubic specimen to that of the normalized 100 × 100 × 40 mm^3 specimen. The average value of this coefficient was 1.65, while for design purposes one may reduce this value up to 1.45 considering the -1σ standard score, or to 1.32 corresponding to a 5% percentile [14].

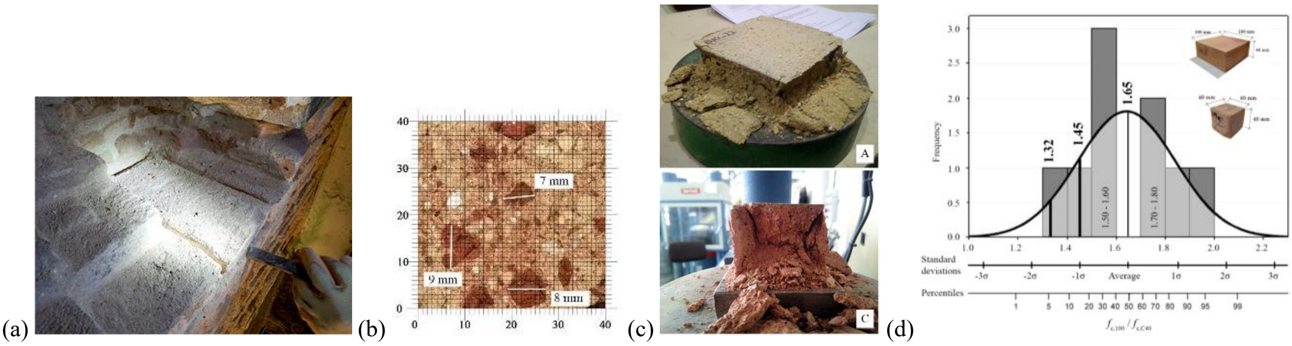


Fig. 3. Extraction process of bricks from existing masonry walls (a), control of the size of the aggregate in cubic specimen (b), types of failure in standard 100 × 100 × 40 mm^3 specimens and in non-standard cubic specimens with 40 mm side (c), and histogram and probability distribution function for values of the ratio between the compressive strengths of the standard and non-standard specimens (d) [14].

Another experimental program at UPC focused on the influence of the confinement exerted by the platens of the loading machine on the brick during the execution of the compression test, by varying the cross-section aspect ratio and the bearing surface treatment of the specimens, see Fig. 4a-b [10]. The experimental campaign was based on 458 tests including both mechanically extruded and handmade units, considering different standard specimens, such as whole or half brick, standard 100 × 100 × 40 mm^3 and non-standard 40 × 40 × 40 mm^3 specimens. Different standard bearing surface treatments were explored, i.e. grinding, capping with cement mortar or gypsum plaster, placing with birch plywood or fibreboard. In addition, two novel bearing surface treatments were proposed, i.e. covering with gypsum powder, and placing two oiled PTFE leaves.

In the case of full and half bricks, a complex compressive behaviour was observed depending on the assumed surface treatment, with specimens grinded, capped with gypsum plaster or capped with gypsum powder exhibiting a hardening response without identifiable maxima in the stress vs. displacement curves. These curves were analysed in detail as they present a series of singular points that can be correlated to the observed material condition throughout the execution of the experiment. The point of the maximum of the second derivative of the stress vs. displacement curves was considered as the most significant as it corresponds to cracks' widening in the specimen accompanied by significant lateral expansion, see Fig. 4c.

The specimens with grinded surfaces showed the highest compressive strength values, which are strongly influenced by the slenderness of the specimen. Capped specimens exhibited different levels of confinement depending on the properties of the capping material. The novel proposed treatment based on two oiled PTFE leaves proved to be an advantageous technique for the evaluation of the unconfined compressive strength of solid fired clay units, as it exhibited similar compressive strength values regardless of the specimen shape. The influence of the aspect ratio of the cross section of the specimen on the determination of the compressive strength was quantified by means of the average of the ratios obtained for the different treatments considered. The ratio between the compressive strengths of the half and the entire unit resulted equal to 0.73 for handmade bricks, and close to 1.00 for extruded bricks as also found by other authors [15].

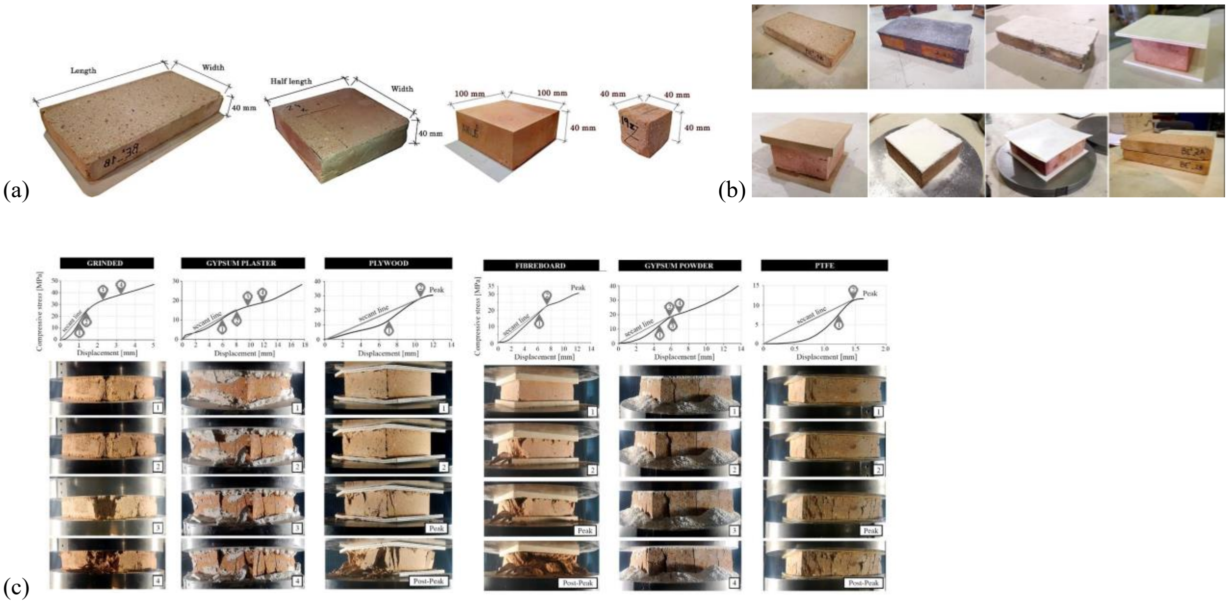


Fig. 4. Specimens with different cross section aspect ratio (a), different considered bearing surface treatments for compressive testing of brick samples (b), and identification of singular points on the stress-displacement curves for different bearing surfaces treatments and correlation with damage states (c) [10].

3.2 Tiles Extracted from Timbrel Vaults

The experimental evaluation of the compressive strength of thin tiles, recurrent elements used in the construction of timbrel vaults (also known as *Catalan* vaults), entails technical difficulties during both in-situ sampling and laboratory testing. Tiles are produced in a similar way to solid bricks, with similar dimensions in terms of length and width, but with thickness lower than 40 mm. Such thin unit cannot be tested as it is, as either buckling or confinement problems would emerge depending on the compression loading direction.

As an alternative to the testing of a single tile specimen, a novel setup was proposed [16] consisting in an assembled specimen of two portions of a same tile, bonded with a layer of cement mortar that is not in contact with the platens of the hydraulic press (Fig. 5a). The test on the assembled specimen allowed the reduction of the slenderness of the specimen until values similar to those recommended by the European standard EN 772–1 [11]. This method was used for the characterisation of the tiles of timbrel vaults in historical buildings in Barcelona, after having being validated by careful analysis with nonlinear numerical models (Fig. 5b). Further validation was provided by comparison with additional experiments on modern handmade bricks with known compressive strength characteristics, which were progressively grinded so that they presented the same thickness as the real tiles of the inspected timbrel vaults. The failure mechanism of the specimen involved the splitting of the tile into two parts (Fig. 5c).

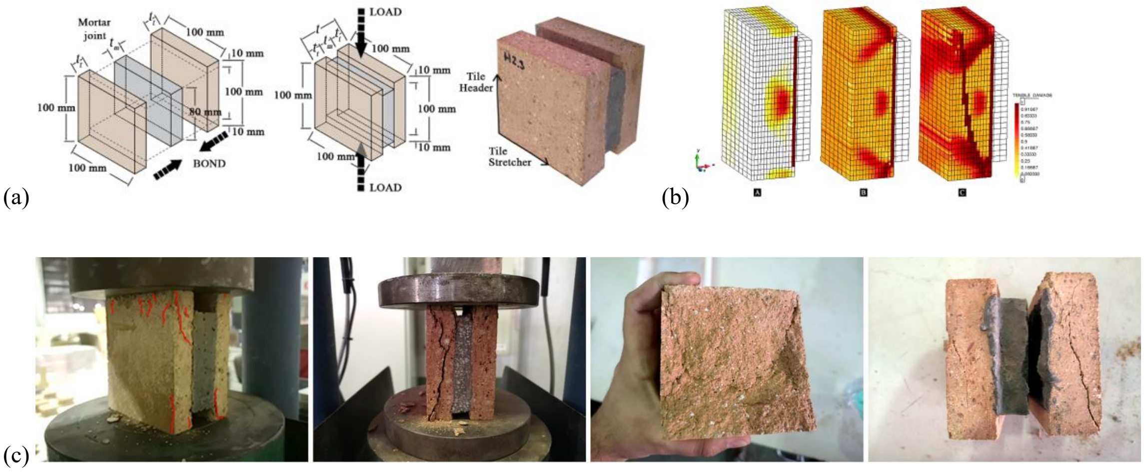


Fig. 5. Proposed method for compression testing of thin tiles extracted from masonry timbrel vaults (a), comparison of failure modes derived from nonlinear FEM analysis results (b), and experimental evidence in the laboratory (c) [16].

4 Laboratory Testing of Mortar Samples

4.1 Mortar Joints Extracted from Walls

The laboratory evaluation of the compressive strength of mortar samples extracted from existing buildings cannot be executed following the European standard EN 1015-11 [17], as these regulations refer to the prismatic 40 mm thick specimens of mortar for new construction, while the mortar joints in existing walls have usually lower thickness, e.g. 10 ÷ 15 mm. One possible alternative is extracting mortar joints from existing walls and testing them in the laboratory under the Double Punch Test (DPT) setup, proposed by the German standards DIN 18555-9:2019-04 [18] and the International Union of Railways (UIC) Leaflet 778-3R [19]. The DPT considers specimens with dimensions around 50 × 50 mm^2, with circular loading area between punches with 20 mm diameter (Fig. 6a). Due to the irregular upper and lower faces of the extracted mortar joint sample, a gypsum powder layer with a thickness of 1 mm is interposed between the specimen and the loading punches to regularise the bearing surfaces and ensure a homogeneous loading.

The DPT technique was extensively applied in inspection works of existing buildings in Barcelona, whenever brickwork can be disassembled in some hidden small wall portions, without damaging excessively the structure. The detailed modelling of the DPT by means of FEM models contributed to the understanding of the specimen's behaviour. Fig. 6b shows a FEM elastic analysis indicating that the horizontal stress in the central section of the mortar sample can be estimated as 5% of the vertical pressure [5]. This result evidences that the strength value obtained from the DPT may be higher than the mortar uniaxial compressive strength due to the confinement exerted by the loading punches. The failure mode of the joint specimen is given by the tensile failure of the external ring surrounding the loaded area (Fig. 6c), as also observed in [20]. Fig. 6d shows a nonlinear FEM analysis of the DPT at failure, displaying a remarkable agreement with the experimental evidence [21].

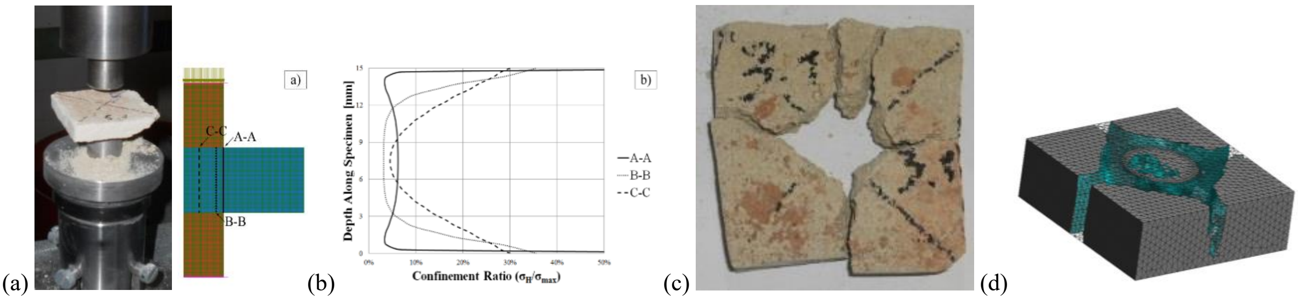


Fig. 6. DPT testing setup (a), FEM elastic analysis of the confinement effect in the mortar joint specimen (b) [5], experimental evidence of the failure mode after DPT (c), and failure mode derived from FEM nonlinear analysis [21].

5 Laboratory Testing of Masonry Core Samples

Sections 3 and 4 have presented different available DT techniques for the experimental evaluation of the compressive strength of masonry components, such as units and mortar joints. The values derived from these experiments can be introduced in available expressions for the assessment of the compressive strength of the composite material, such the equation provided by the European standard [22]. However, previous studies on solid handmade bricks and lime mortar masonry [23-24] demonstrated that approximate empirical expressions, based on separate compressive strengths of masonry components, might underestimate the actual compressive strength of the composite material. Although a more precise evaluation should consider DT of portions of walls, their sampling is almost impossible in historical structures, as it would entail the partial dismantlement of a rather big volume of the existing brickwork.

Different research studies investigated the possibility of in-situ core drilling (Fig. 7a-b) and subsequent DT of cylindrical specimens in the laboratory (Fig. 7c). Core samples with 150 mm diameter can include either four brick segments, two mortar bed joints and one head joint, or three brick segments with two mortar bed joints. The experimental programs executed in the laboratory at UPC allowed first to choose the correct sampling technique for historical masonry, e.g. moving from traditional wet core drilling to a novel dry extraction procedure [4,25], based on air cooling system, in order to avoid the alteration of the mortar joints in the sample due to the use of water. The laboratory experimental campaigns analysed different typologies of masonry, i.e. composed of handmade solid bricks and either hydraulic or lime mortar in order to replicate a recurrent historical material, including compression testing of standardised prismatic wallettes and non-standard core samples for comparison [4,25-26]. Then, another campaign addressed the evaluation of the compressive strength in smaller 90 mm core samples, which include two brick segments and one bed joint, determining size-effect empirical correlations based on the comparison with experimental results obtained from the 150 mm diameter cylinders [27]. The development of nonlinear FEM simulations of the test complemented the experimental results with additional insight into the behaviour of the core sample under compression loading, highlighting, for instance, that the outer parts outside the regularization caps provide a limited contribution to the strength of the specimen (Fig. 7d, [24]).

All these synergistic research activities allowed the optimal calibration and validation of the compression test on masonry core samples, which was extensively applied in almost all the inspected historical buildings of Barcelona subjected to adaptive reuse and covered with living gardens. The adopted MDT technique combines a rather clean and minimally invasive in-situ sampling activity (Fig. 7a-b), with a direct precise estimation of the compressive strength of the composite masonry material.

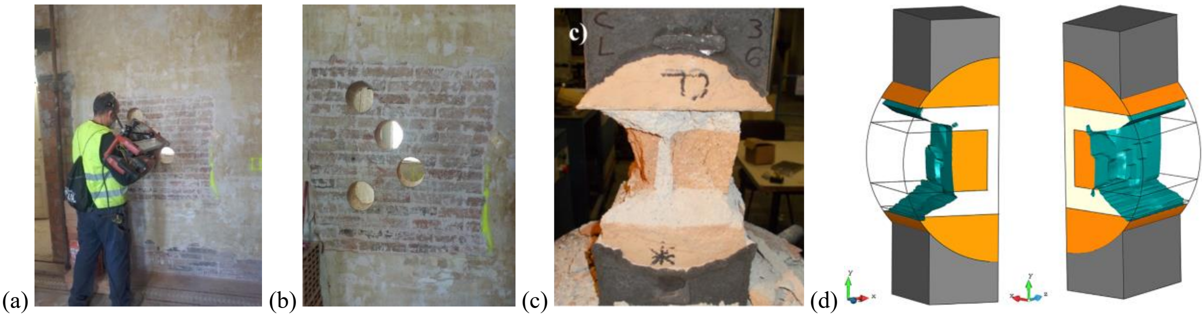


Fig. 7. In-situ core drilling of cylindrical masonry samples (a) inspected wall after sampling (b), experimental failure mode in a 150 mm diameter cylindrical specimen (c), and failure mode derived from FEM nonlinear analysis [26].

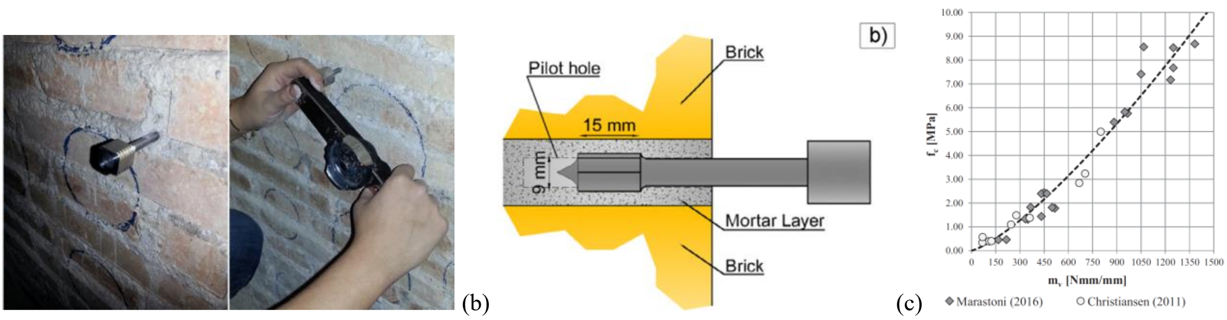
6 In-Situ Minor Destructive Testing of Bricks and Mortar Joints

In-situ MDT techniques constitute a valuable option for the inspection of masonry components in heritage buildings, as they are minimally invasive and their impact on the investigated structure is negligible. In-situ MDT by portable testing equipment can also represent a complementary activity to the sampling of small specimens for laboratory DT, when the repetitiveness of the measurements in many locations of the building is advisable for a reliable statistical evaluation of the investigated mechanical properties. There exists a wide range of portable devices, based on different technology and operations, allowing the indirect evaluation of the compressive strength of the material by means of empirical correlations with the physical magnitude directly measured by the probe.

In-situ MDT techniques were extensively used in many case studies in Barcelona, like those presented in Fig. 1, as they allow obtaining an insight about the quality of the materials used in the historical construction. The extensive execution of in-situ MDT provides clear indications about the variability of masonry properties among walls of the same building located at different floors, or, in big industrial heritage complexes, among walls pertaining to different buildings.

The careful calibration of in-situ MDT devices is essential for obtaining accurate and reliable results in the characterisation of existing masonry. For this reason, different experimental programs were carried out at UPC to derive empirical correlations from MDT measurements and laboratory DT on bricks and mortars of different strengths. Three types of MDT portable testing equipment were investigated, i.e. the Torque Penetrometric Test (TPT), the Pin Penetration Test (PPT), and the Helix screw Pull-out Test (HPT).

The TPT consists in hammering a steel nail, specifically shaped with four protruding teeth, into a mortar joint and then applying a torque by means of a dynamometric key, until reaching the failure of the material (Fig. 8a). Concepts of fracture mechanics were used for the micro-mechanical analysis of the stress state induced by the instrument on the investigated mortar, which were further validated through the execution of experimental tests in the laboratory [28]. The application of the TPT technique is particularly appealing in historical masonry buildings, as it is rather quick for execution of in-situ MDT evaluations. In addition, the TPT allows an in-depth assessment of the strength of existing mortar (Fig. 8b), which is often deteriorated or even replaced by restoration repointing on the exposed superficial surface of the wall. Experimental programs executed at UPC and UNIBO allowed the derivation of an empirical correlation between the standard compressive strength of mortar and the TPT measurements for a range of mortar strengths representative of those usually encountered in historical construction (Fig. 8c).



(a) (b) (c)

Fig. 8. Toothed nail inserted into the mortar joint and execution of the TPT using the torque wrench (a), longitudinal section of the toothed nail (b), and empirical correlation between the standard compressive strength of mortar and the TPT measurements (c) [28].

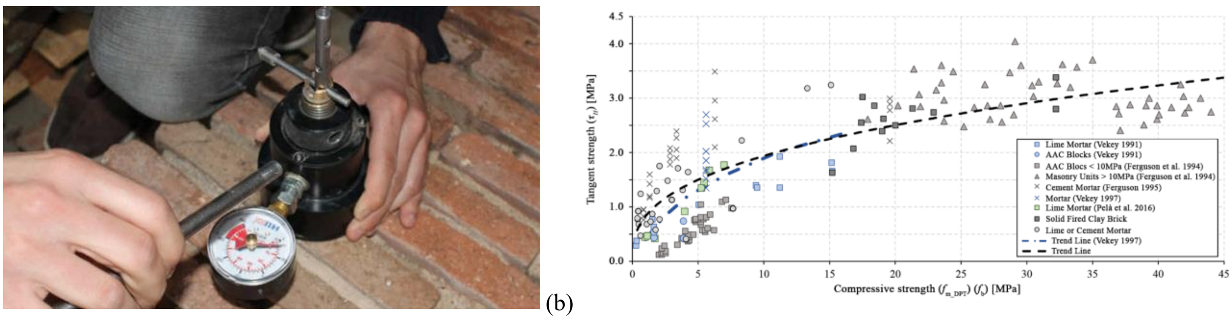
The PPT technique, also known as Windsor probe, consists in driving a 3-mm diameter and 30.5-mm long pin into a mortar joint or a brick through a spring-loaded device (Fig. 9a). After striking the inspected material, the pin leaves an indentation whose depth of penetration is measured by a micrometre and is inversely proportional to the compressive strength of mortar.

The HPT technique is based on the measurement of the pull-out force required to extract a high-strength steel helical tie with a 6 mm diameter, also known as Helifix, stuck into the material with a prescribed depth. The helical tie is hammered into a prepared hole and then is extracted using a proof loading device with a screwed gripper (Fig. 10a).

A first experimental program was carried out at UPC to correlate empirically the PPT penetration depth and the HPT pull-out force with the strength derived from DPT on mortar joints extracted from walls, which were built on purpose in the laboratory [29]. A second research at UPC provided a further detailed calibration of both MDT methods by means of an extensive experimental campaign including both bricks and mortar joints from eight different masonry walls of seven existing historical buildings in Barcelona, and two different types of masonry walls built in the laboratory. The campaign included the execution of laboratory DT on 125 bricks and DPT on 398 mortar joints, as well as 398 PPT and 343 HPT in-situ MDT tests in heritage buildings in Barcelona. Fig. 9b and Fig. 10b show the empirical correlation laws obtained between the DPT compressive strength of mortar and the TPT and HPT measurements, based on an extensive experimental database including both the tests developed at the UPC and those available in the scientific literature [30].

(a) (b)

Fig. 9. Example of in-situ execution of the PPT in a heritage building (a) [29], and empirical correlation between the DPT compressive strength of mortar and the PPT measurements (b) [30].



(a) (b)

Fig. 10. Example of in-situ execution of the HPT in a heritage building (a) [29], and empirical correlation between the DPT compressive strength of mortar and the HPT measurements (b) [30].

7 Conclusions

This paper has highlighted the importance of the inspection activities in existing historical buildings aimed at the experimental evaluation of the compressive strength of masonry, as well as that of its separate components, i.e. bricks, tiles, and mortar joints. We have focused our attention on the great potential of MDT, including both the approaches combining the in-situ sampling of small non-standard samples of materials and subsequent DT in the laboratory, and those techniques consisting in in-situ direct testing of structural members by portable measurement devices. The adoption of the former or the latter MDT option depends on many factors, among which the level of protection and heritage value of the investigated building, the accuracy required, the size of the investigated construction, and the resources available in the project.

Different recent projects in Barcelona, consisting in refurbishment and adaptive reuse of historical masonry buildings, as well as in design of green rooftops, have highlighted the importance of the careful experimental evaluation of the mechanical properties of existing masonry. In particular, the compressive strength constitutes a governing parameter in the structural assessment to quantify the current safety level of the building and to envisage up to which extent the structural interventions are feasible and compatible with the modern criteria for the preservation of heritage structures. The accurate assessment of the compressive strength of masonry is of paramount importance in projects of adaptive reuse of existing historical buildings and industrial heritage complexes, in which the refurbishment works often involve structural alterations inducing higher stress levels in the existing load-bearing structural members, such as widening existing openings or increasing variable loads. The design of green rooftops also requires a precise preliminary evaluation of the masonry compressive strength in order to quantify the amount of extra load that the walls can bear and the optimal location of the new weighty elements, such as flowerbeds, dunes, and benches. Evaluating with accuracy the compressive strength is essential to reduce the uncertainties in design, minimise the structural interventions, reduce the cost of the structural works, and preserve the building's heritage value.

The paper has presented an overview of laboratory experimental programs that contributed to increase the knowledge about DT of non-standard small specimens, such as core samples of masonry, small samples of brick or tile assemblages, and small pieces of mortar joints. The paper has also addressed the calibration of in-situ MDT based on TPT, PPT, and HPT techniques. The results derived from a number of real case studies, complemented with additional laboratory tests on supplementary specimens of different properties and controlled characteristics, have provided a meaningful experimental database as well as helpful empirical correlation functions for inspection activities linked to preservation works in historical buildings. The execution of FEM analyses has been also very useful to provide a correct understanding of the novel non-standard testing procedures and to optimise the novel experimental setups.

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