Testing methods for the assessment of material properties in historical masonry structures: a review

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Abstract. The current state of testing methods for assessing the mechanical properties of old masonry buildings is reviewed, with a focus on the methods adapted for heritage structures. For these buildings, an accurate assessment is needed in order to minimise the interventions extent while ensuring an adequate structural safety level. As old masonries are non-homogenous and exhibit a highly anisotropic behaviour, numerous parameters are required for correctly simulating the behaviour under a given load scenario. In earthquake-prone areas, numerous failure patterns, in-plane and out-of-plane, can occur for the structural walls, each of them depending on different characteristics of the material. If for new masonries the testing procedures are standardised, for old buildings less standardised tests exist, while investigations are often based on modified or empiric methods. The testing methods can be classified as destructive, minor-destructive and non-destructive. The destructive methods are the most precise but are extremely intrusive and may not be acceptable for heritage listed buildings. The non-destructive methods mostly provide qualitative results. The minor-destructive tests are often the most adapted for the study of historical buildings, as they can provide relevant information while affecting only in a limited extent the existing elements.

1. Introduction

For the evaluation of the vulnerability of the existing buildings, an important aspect is the correct assessment of the mechanical properties of the materials. Masonry is a highly anisotropic material. Moreover, in old buildings, multiple changes often occurred through time (local degradations, reparations or modifications using different materials etc.). As the material characteristics are not uniform as would be for new constructions, there are numerous uncertainties regarding these properties. It is difficult to define, in a unique way, the procedures and techniques to be used in an experimental program. For a particular case, some types of tests might not be acceptable at all, if they were to alter the architectural or cultural value of the building, such as wall paintings.

Also, if for the modern materials the codes contain some correlations between properties measured separately on brick and mortar and the global properties of masonry, these cannot always be used for historical structures.

In highly seismic areas, the various in-plane and out-of-plane failure patterns need to be considered. These are governed by various characteristics of the masonry, such as the compression strength and elastic moduli of the blocks and mortar, the friction coefficient of the interface, the bond strength in tension or shear, the past actions that might have partially broken this bond in various areas etc.
In this context, the present study, aimed at reviewing the current methods in assessing material properties for old masonry buildings, is of particular interest. Only by understanding the advantages and shortcomings of various methods, practicing engineers can correctly establish relevant survey and testing programs for a given project, that respect the specific architectural and cultural values. For the researchers, this could be a starting point in improving the existing methods or establishing new testing procedures, more adapted towards assessing the vulnerability of historical monumental buildings.

2. Testing methods for assessing the mechanical properties of masonry

The testing methods can be classified as destructive, minor destructive and non-destructive. Many methods are standardised, while some, in particular the non-destructive ones, are not.

2.1. Destructive methods

The destructive methods are the most precise but are extremely intrusive and may not be acceptable for heritage listed buildings. They are based either in extracting large specimens from the existing buildings and testing these using standard procedures used for new buildings, or in performing tests directly in-situ.

2.1.1. Laboratory testing on large samples

Consists in using the standardized methods for new buildings (such as [1-8]). But, in place of constructing the samples in the laboratory, as would be done for new buildings, they are extracted from the existing building and transported before being tested. In order for the results to be relevant, several tests should be performed for each material characteristic (compression, bending, shear). Some of the required samples, are very large, such as 1.2x1.2 m for [7]. The number of extracted samples must also account for the risk of damaging them during extraction, transport or handling, in particular for masonry with weak mortar. Therefore, this approach is highly intrusive and rarely acceptable for heritage buildings.

2.1.2. Shear-compression test in-situ

The shear-compression test consists of the application of an increasing shear force on a masonry wall subjected to constant compression stress, figure 1. This in-situ test is not standardized. The test is performed by separating the panel from the masonry (side and above) and applying a certain level of axial compression loading or separating the panel from the masonry (left-right) using the real value of the compression effort due to the gravitational loads that can be measured by performing single-jack test. The typical dimension of the tested masonry panel is 90x180 cm [9, 10].

Figure 1. In situ shear tests done by UTCB for a 20th century building in Constanta.
2.1.3. **Diagonal compression test in-situ.** This type of test is performed in-situ and is based on the standardized method that is performed in the laboratory to determine the diagonal compression strength [7]. The tested masonry panel must have dimensions greater than or equal to 1.2 m x 1.2 m, and the width between 25cm and 70 cm. The panel is separated by the adjacent masonry on three sides. The test results are influenced by the quality of the wall and especially by the local defects [9].

2.2. **Minor destructive methods**

Minor-destructive tests can be performed relatively easily and have a small impact on the construction, but they provide only local information and the results obtained are quite scattered.

2.2.1. **Tests using flat jacks** consist in performing a split, perpendicular to the direction of the stresses to be measured, followed by the introduction into the split of a flat press, in order to generate a pressure inside the split, until the initial state of deformations is restored, figure 2 [11, 12]. The initial state of deformations is determined by extensometer measurements, performed before splitting. Based on this test several parameters can be established: the existing compressive stress, the compression strength, the $\sigma$-$\varepsilon$ law and the modulus of elasticity, the shear strength against sliding in the horizontal bed joint [13].

![Figure 2. Flat jack tests performed on a 19th century masonry building in Bucharest.](image)

2.2.2. **Shove tests** are used in order to establish the shear strength against sliding in the horizontal bed joint for a given vertical compression level, figure 3. The method consists in imposing the sliding of a brick between two horizontal mortar layers [14]. The bricks adjacent to the tested one are removed and a hydraulic press, acting horizontally on the brick, is installed. The force corresponding to obtaining movement in the testing brick gives the measure of the shear strength against sliding in the bed joint. As the shear force depends on the adherence between bricks and mortar as well as on the friction force under vertical loads, the tests should be performed both at the ground floor level (where the compressive stress from gravitational loads is maximum) as well as under window openings (where the value is nearly zero). Even if the shear strength of a single mortar joint does not fully represent the shear resistance of a horizontal wall, this test provides the most accurate and direct estimate of shear strength in the horizontal joints that can be made in-situ.

![Figure 3. Shove tests done by UTCB for a 20th century building in Constanta.](image)
2.2.3. **Splitting tests on masonry cores with inclined mortar joint** are a recently proposed (unstandardized) method for establishing the shear strength in mortar joints [10], [15, 16]. For these tests, cores with a diameter between 70 mm and 110 mm are extracted from the existing walls, figure 4. Cores are extracted in such way so that the mortar layer is near the centre of the section. The cylinders are then placed horizontally in a vertical press and tested under axial force. The inclination of the mortar joint in relation to the direction of application of the axial force is varied between 45° and 60°. Based on the Mohr-Coulomb criteria, the shear strength is computed. A special problem in the case of the poor quality of the mortar is the extraction and transport of intact specimens.

![Figure 4. Extraction of cores from a 19th century masonry building in Bucharest.](image)

2.2.4. **Bond wrench tests** are standardised tests performed based on [17] or [18]. The method consists in fixing a standardized wrench on the top brick of an assembly then twisting until failure. Based on this test, the adherence strength in the mortar layer under tensile stresses in bending can be assessed. The test can be performed in-situ at the top of the walls or below window openings. Otherwise, they can be performed in laboratory on reconstituted walls using bricks extracted from the building and replicated similar mortar (discussed further below). It is to be noted that for low-strength mortar it is recommended that samples of only 2 bricks and 1 mortar layer are used.

2.2.5. **Pull-out tests** consist in inserting a screw (typically a 60 mm one), by drilling, into the mortar bed joint, for a depth of 35 mm. A correlation was observed between the shear strength developed by the small cylinder around the screw and the compressive strength of the mortar. Therefore, the force required to pull out the screw gives a rough estimate of the strength of the mortar. The advantage of the test is that it can be used for standard 10 mm mortar joints and the damage done while testing is minor and easily repaired.

2.2.6. **Extracting bricks and mortar samples** from the wall is one method that is less intrusive than extracting large panels. For instance, if a given wall is deemed to be jacketed with reinforced concrete, the extracted bricks create useful connection points between the jacket and the existing wall (figure 5). Bricks and mortar can be tested in the laboratory using standardized methods for new buildings. Also, based on the analysis of the mortar, a similar formulated mortar can be created such that wall panels using the extracted bricks and the similar mortar can be constructed and tested. The usual tests are discussed further below. It is important to mention that it is very difficult to reconstitute a mortar if the original formula is unknown. The chemical analysis of existing mortars [19] can lead to inaccurate results if the original ingredients are not available and no check can be made for soluble lime or silica parts in the aggregates. Even if all of the ingredients are known, the reconstituted mortar might exhibit different properties from the one in the building, since the original air content, water/binder ratio and sand grading cannot be fully determined. Finally, even if the reconstituted mortar were to have the same compressive strength and elastic moduli as the original, many failure patterns of masonry structures are governed by the bond strength between mortar and bricks. Tests on reconstituted samples should always be compared with tests on intact elements extracted from the existing building.
2.2.7. *Tests on blocks* can be performed as for new buildings. Based on the standard tests [20-23], the compressive strength of blocks made either from masonry or natural stone can be measured. For masonry units, the splitting tensile strength can be obtained. A special attention must be given to the preparation of the blocks extracted from the work prior to testing [24].

2.2.8. *Tests on mortar* can be performed as for new buildings using standardized methods [25-27]. For lime-based mortars, a particular attention must be given to the curing time and conditions. The minimum time should be 90 days (as compared with 28 days for cement-based mortars). The curing conditions should be, if possible, adapted so that they reproduce the climate from the location of the existing building, as curing conditions highly influence the properties of the mortar at early stages.

2.2.9. *Tests on reconstituted samples from bricks and mortar* can be performed using the standardized methods for new buildings [1-8]. As for the reconstituted mortar, a long curing time is needed for the lime-based mortars, of at least 90 days, before tests can be performed.

2.3. *Non-destructive methods*

The non-destructive methods do not compromise the existing masonry constructions and can be carried out quickly and with relatively low costs. The use of non-destructive methods allows both detection and localization of defects. As there are numerous methods, we chose to focus on those mentioned in [28] as reliable for assessing the existing buildings. Unfortunately, the non-destructive methods do not provide any exact values of the parameters of the masonry necessary to establish the vulnerability, so they must always be accompanied by minor destructive or destructive methods. It is recommended to combine different non-destructive methods in order to obtain information as relevant as possible.

2.3.1. *Acoustic emission (AE)* is a non-destructive method that is based on recording the elastic waves released when sudden redistribution of stresses occurs in the material. AE sensors are very sensitive and can record extremely low motions that are transmitted to the surface of the masonry when cracks occur or grow and can provide useful information regarding the strength and risk of failure of a component. This method has been successfully used for historical monumental masonry constructions that have been subjected to numerous seismic actions [29]. The method allows to identify cracks and deteriorations in the walls and to evaluate the stability of the structure based on the evolution of the degradation phenomena.
2.3.2. Ultrasonic pulse velocity tests are used to check the quality of existing masonry based on the velocity of ultrasonic pulses passing through the material. The equipment includes a pulse generator, a transducer that transforms electronic pulses into mechanical pulses and a reception circuit. Generally, 40 to 50 kHz frequency devices are used.

This method allows to detect the density variations and the modulus of elasticity of the masonry, as well as the presence of cracks and discontinuities. Higher velocities indicate a good and continuous material, while slower velocities may indicate voids or cracks. This method cannot be applied for poor quality masonry or with many defects and cracks, as the results are sensitive to the condition of the masonry surface.

2.3.3. Mechanical Pulse Velocity method consists in hitting the masonry wall with a special hammer and measuring the time needed for the wave to travel over a certain distance. This method is not standardized but can be used in place of the ultrasonic pulse velocity method when determining the properties of masonry on larger surfaces.

2.3.4. Impact – echo is an acoustic method is based on generating waves on the surface of the structural element (often done by using a special hammer). The waves are reflected by internal flaws and external surfaces.

The speed of the wave depends on the properties of the material but is also influenced by gaps, cracks or unfulfilled joints. So, by using this method, the presence of voids or embedded steel elements inside the structural wall can be identified.

2.3.5. Radiography tests are similar to those used in medicine. A beam of high energy radiation is passed through the structure and the signal is then detected on the remote face by transducers.

This method permits identifying the inhomogeneities and discontinuities in the masonry (e.g. reinforcements or other embedded elements). Due to special precautions regarding the safety for the people when using this technique and to possible interferences with equipment, special permits are nowadays required, and this technique is often replaced by radar scans.

2.3.6. Infrared thermography is a method of surface testing. A thermal energy flux is applied to the surface of the material or generated by the tensioning of the material. The flux is affected by the insulating properties of the material and by the degree to which its surface radiates energy. The surface temperature differences are recorded using infrared cameras or special thermal coatings.

For the masonry, data can be obtained regarding the damaged areas, or those with different moisture content in the brick and porous stone.

The method is capable of reporting only surface anomalies and their location. However, it cannot determine their depth and thickness. The results are influenced by external environmental factors (temperature and humidity).

2.3.7. Surface hardness using a Schmidt hammer. The testing method is described in [30, 31]. A certain correlation was observed between the rebound value and the uniaxial compressive strength. By performing this test, a rough estimate of the compressive strength can be obtained.

The method is sensitive enough so that differences in the strength on masonry elements can be identified. It is not, however, sensitive to the level of cracks in the wall. The roughness of the analysed surface can also influence the results.

2.3.8. Radar scan (microwaves). The penetration power of microwaves allows in-depth analysis of a material for locating defects, discontinuities or foreign bodies. In diagnosing the old buildings, especially the historical monuments, the method can be used for detecting the presence of several layers in the masonry, detecting the important voids, the presence of embedded steel elements, the cracked or damaged areas, or the moisture content of the masonry.
3. Discussion and conclusions

For assessing the structural safety level for old masonry buildings, it is fundamental to correctly determine the characteristics of the materials as well as the pre-existing damage. For buildings with high architectural or cultural value it is extremely important to minimise the interventions extent to a minimum. The same goes for the experimental campaigns, where extensive destructive investigations should be avoided.

In the same time, destructive methods are the most reliable in providing the necessary information for the structural assessment. The standardised testing methods for new buildings require numerous tests on large samples. As this approach is generally unacceptable for historically listed buildings, as a first step in the experimental campaign, non-destructive methods should be used. These have been proved to provide useful information regarding the geometry and damage levels of the building. But the interpretation of the results is more qualitative then quantitative and by themselves the non-destructive tests are not sufficient. They must always be accompanied by destructive or minor-destructive tests.

The minor-destructive evaluation methods are often preferred over the destructive techniques. The problems concerning the reliability of their results are related to the lack of sufficient experimental data on the effect of specimen size on the measured property so that tests performed on small-scale tests could be correlated with standardised tests on large specimens. Another problem arises from the difficulty of extracting and transporting the intact samples to be tested in the laboratory.

In the specific case of masonry structures, extracting brick and mortar samples and building similar specimens that reproduce the original characteristics of the masonry is highly unreliable. This is mostly related to the impossibility of correctly assessing the formulation of the mortar and the curing conditions, which impact on the mechanical properties. The characteristics of reconstructed samples must be compared to results performed on samples collected from the building. As the curing time is long in the case of lime-base mortars, this impacts on the total duration of the evaluation campaign.

Two directions should be pursued in order to increase the reliability of minor-destructive tests campaigns in the scope of correctly assessing the structural safety of old buildings. The first one consists in performing more investigations regarding the correlations between the measurements performed on small-scale specimens and the corresponding values obtained through large-scale tests. The second direction consists in creating extensive databases containing information regarding masonry types, material characteristics and constructive details, mechanical properties, construction period and region. A large database might serve for a reliable statistical analysis of experimental data with the possibility of identifying correlations between various measured properties and this way reducing the extent of mechanical tests required for each individual building. Such database could be developed in Romania by a consortium of Technical Universities, with financial support from the government. This type of database has, for example, been developed in Italy and its acronym is MADA (Masonry Database) [32]. In Italy, MADA was developed by ReLUIS (The Laboratories University Network of Seismic Engineering), over more than a decade (2005-2016), and has been funded through 3 research programs.

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