The Application of Sonic Testing on Double-Leaf Historical Portuguese Masonry to Obtain Morphology and Mechanical Properties

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Abstract. In order to perform a conservation or repair intervention of a historic building, knowledge of the mechanical properties of the historical materials and building components is essential. Obtaining these properties should be performed inflicting as little damage to the historical fabric as possible. Methods to do so are defined as non-destructive test methods (NDT). The paper investigates the use of sonic testing (NDT) on historical masonry. Nine double-leaf wallets were constructed according to a traditional Portuguese building method, using light ochre schist and mortar made of local soil and water. Three wall variations were present concerning plaster finishing and grouting strengthening. A testing procedure was developed for sonic testing to determine the morphology and mechanical properties. The wallets were also classified according to the Masonry Quality Index method (MQI), which can be used to identify strength and stiffness parameters of masonry by visual inspection without testing procedures. The method was used in conjunction with the sonic testing. In addition, compression tests with loading and reloading cycles were performed. Young's moduli could be compared to those obtained by the MQI method and the sonic testing. The results revealed that the Young's moduli of the sonic testing had a good agreement with those of the compression testing, although the former presented an overestimation due to testing on the outer leaves. The Poisson's ratio presented inconsistent results due to a high scatter on experimental values. The sonic testing also showed a good indication of weak zones in the masonry. The MQI method produced less accurate results in terms of stiffness estimation but has potential and should be investigated further.

Keywords: Sonic testing · Historical masonry · Direct and indirect impact P and R waves · Double-leaf masonry

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1 Problem Statement

Before structural interventions in historical buildings can be designed, it is important to investigate the building on all its components. For masonry buildings, investigating the mechanical properties and the morphology of the walls is extremely important. Current techniques often involve partly or completely damaging masonry to obtain information, which is not to be preferred when investigating historical buildings. The question arises how to investigate masonry walls without damaging them, using a non-destructive technique. One technique that has been gaining traction in the civil engineering domain is the use of sonic testing [1]. By sending elastic waves through the walls (direct or indirect), information about the mechanical properties and morphology can be gathered in a non-destructive manner. The method does not require a wall to be built or transported to a lab and makes use of the accessible parts of the walls. The method is also cheap and easy to understand. This research paper looks into sonic testing on nine very irregular and inhomogeneous Portuguese historical double-leaf wallets to investigate their mechanical properties and morphology. The aim is to evaluate the efficiency and accuracy of sonic testing for an irregular historical wall layout. Additionally, the use of the Masonry Quality Index, or MQI method, will be investigated. The results of both methods are compared to compression testing.

2 Analysis Procedures

2.1 The Masonry Quality Index MQI

A first method of assessment of historical masonry is to classify the masonry and its present defects from visual observations. The Masonry Quality Index method, or MQI method, introduced by Borri and De Maria [1], integrated in the design codes of the Italian region of Umbria for interventions in historical structures, quantifies the strength properties of historical masonry from visual inspection. The Masonry Quality Index does so by giving a score to the masonry, with categories as follows:

- category A: good structural behaviour of masonry;
- category B: behaviour of average quality of the masonry;
- category C: inadequate behaviour of masonry.

A value MQI is estimated for a section. This value is obtained by evaluating 7 parameters concerning the masonry section. To each of these parameters, a weight is given and together they determine the MQI. Afterwards, considering the needed situation of the impact, Vertical actions (V), Out-of-plane actions (O) or In-plane actions (I), dependent on the MQI, the category A, B or C is given to the section. Important to note is that in this research, the determination of category A, B and C has been slightly adapted compared to the procedure proposed in Borri and De Maria [1]. Category A has been categorized as the highest quality, and thus highest MQI, where C represents the lowest quality.

2.2 Sonic Testing

Sonic and ultrasonic methods introduce sound energy into a material, which then propagates in the form of mechanical stress waves through the medium. The wave can be reflected at boundaries or diffracted by discontinuities such as voids. These waves are intercepted by a receiver, and the determination of wave velocities can give information about discontinuities such as flaws, dimensions and morphology, material properties and more.

The followed method is based on the measurements of the velocities of P- and R-Waves: V_P and V_R, by applying direct and indirect sonic tests, as seen on Fig. 1. After an impact on the material, such as by an instrumented hammer, the velocities are calculated by measuring the time passed between two different transducers at the surface of the material, separated by a known distance, $V = \frac{L}{t}$. By relating the velocities of the arriving waves V_P and V_R at the receiver, material parameters can be obtained afterwards.

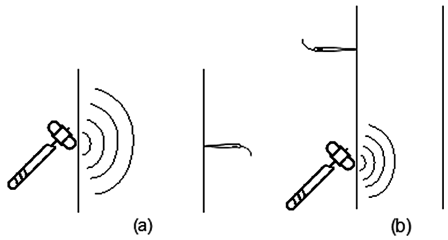

Fig. 1. Sonic transmission in a direct (a) and indirect (b) manner.

The results can be visualised in a graph with the data at the impact and the reception site, as shown in Fig. 2. As stated in [3], an easy way to distinguish the P- and R-waves is as follows:

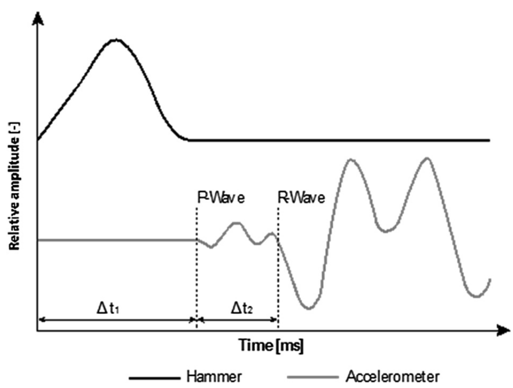

Fig. 2. Obtained data from an indirect sonic test on a granite block, showing the transmitted and received signals.

1. The P-wave V_P always corresponds to the very first arrival in the time domain signal, since its velocity is the largest.
2. The R-wave V_R, as seen in Fig. 2, has considerably more energy than the P-wave and because of that, its arrival is easily perceptible in a time domain signal.
3. The relationship between V_P and V_R can be approximated for materials by doing tests on a single item of that material. For masonry, the behaviour is more complex and a range is used for the ratio. Thus, having identified the very first arrival, it is relatively easy to search for the R-wave in a limited time range.

When, for all signals, the waves have been identified, mean velocities can be calculated, as seen in Eqs. (1) and (2).

$$V_P = \sqrt{\frac{E}{\rho}\frac{1-v}{(1+v)(1-2v)}} \tag{1}$$

$$V_R = \frac{0.87+1.12v}{1+v}\sqrt{\frac{E}{\rho}\frac{1}{2(1+v)}} \tag{2}$$

When both P- and R-wave velocities can be measured, the P- and R-waves can be related, and when this relation is known the Poisson coefficient can be obtained with Eq. (3) [4].

$$\frac{V_P}{V_R} = \sqrt{\frac{2(1-v)}{(1-2v)}\frac{(1+v)^2}{(0.87+1.12v)^2}} \tag{3}$$

Since a Poisson ratio of 0,2 to 0,3 is to be expected for historical masonry [3], a V_P/V_R -ratio between 0,49 and 0,56 should be used to define the arrival of V_P and V_R.

Knowing the mass density (by estimation or by measuring weight and size dimensions on small samples) and the Poisson coefficient, the Young's modulus can be estimated from both velocities. Also knowing the Young's modulus, it is possible to estimate the compressive and tensile strength.

3 Testing Scheme on Portuguese Historical Wallets

3.1 The Wallets

The traditional Portuguese wallets in question are often very difficult to test, since the stones, light ochre schist, are extremely irregular in shape, going from a few centimeters in diameter to blocks of 30 cm length and more. The stones also have foliation layers, which gives them different mechanical properties in different directions. On top of that comes the fact that the mortar is not homogenous. The mortar is a simple mix of local soil and water, mixed until it has the desired properties. This mixing procedure is done by hand by a stonemason, without measurements.

Three types of wallets were constructed (609 × 310 × 638 cm), with three wallets per type:

- Type A: Three wallets with no plaster on the main faces but plaster on the sides;
- Type B: Three wallets with plaster on the main faces and on the sides;
- Type C: Three wallets with plaster on the main faces and sides and strengthened by grouting.

When the sonic tests were performed, the wallets were already completely set and hardened (more than four months of curing).

3.2 Application of MQI Method

The MQI method was applied to wallets of type A. Type C was grouted and cannot be quantified by the MQI method. Type B had plaster on the main faces and thus cannot be investigated with the MQI method, but was of the same build as type A and thus the analysis of type A can be used for type B. If plaster was to be removed, type B could be investigated as well. A brief, qualitative rather than quantitative illustration on the application of the MQI method is included below, aiming at giving an overall view and example of the use of the parameters. All results are shown in a data sheet, a representative example of which is shown in Fig. 3.

For the wallet of type A, Category C is obtained. The obtained result is thus of low quality. This is logical, since the wallets were made with limited attention to strength, arrangement or use of special mortar or stones. With this method, the Young's modulus and the compressive strength can be estimated, as seen in Fig. 3.

3.3 Application of Sonic Testing

Direct sonic testing is performed to obtain information about the morphology of the wallets and indirect sonic testing to obtain mechanical properties of the wallets. The investigation focusses on the accuracy of mechanical properties such as the Young's modulus and the Poisson coefficient obtained from an indirect sonic test.

3.3.1 Methodology

A grid was made on the wallets to indicate the impact and reception points. Each grid point can serve as an impact point or as a reception point. The points were taken 100 mm from the top and bottom and 200 mm from the sides to minimise interference from those sides, while having a large enough distance between the different points. All the wallets were weighed and measured and as such, the densities were calculated. 5 points were thus chosen on the main faces and three on the sides of the wallets, with minimum distance of 10 cm from the top and 20 cm from the sides. The direct testing was done by impacting on one side and receiving on the opposite side. The indirect tests were performed by impacting on the lower points and receiving on the higher points. It should be noted that for the wallets type A, the impact points were slightly altered while testing to impact on a stone itself. This was not possible for wallets with plaster on the main faces.

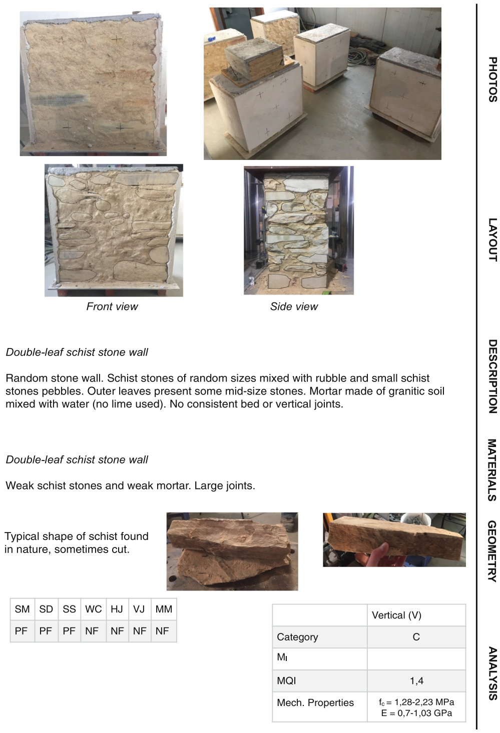

Fig. 3. Representative data sheet of the MQI method for a wallet of type A.

3.3.2 Sonic Apparatus

The used impact hammer was model 086D05 by PCB piezotronics. The hammer weighs 0,32 kg with flat response frequencies of 0 to 1 kHz. In operation, the hammer sends frequencies up to 6 kHz [2]. The accelerometer, also provided by PCB piezotronics, model 352B, had a frequency range from 2 to 10 kHz and a resonance frequency above 25 kHz. The accelerometer had a short nail attached to it, and could therefore easily be connected to the wallet at several locations. The software used to acquire and interpret the signals were LABVIEW programs called Sonic Acquire and Sonic Analyzer V5, designed at the University of Minho. The impact and reception point are selected according to the selection criteria mentioned under Sect. 2.2. The following criterion is chosen to define averages of high enough quality to be used in the further analysis:

- The average value must be taken out of a minimum of 6 well-identified signals, with a signal being an impact from the hammer on the same impact point and correctly registered by the accelerometer on the same reception point;
- The well-identified signals used for the calculation of the average must have a coefficient of variance lower than 10%.

This procedure is used to identify the average V_P for each impact-reception pair for each wallet of the direct testing and the average V_P and V_R for each impact-reception pair for each wallet of the indirect testing.

3.3.3 Results and Discussions

When analysing the results, the recorded signals often did not correspond to the criterion used to select the arrival of the waves. Two methods were defined to tackle this issue:

- Method 1: V_P and V_R are chosen based on the criterium that V_P is the first wave to arrive and that the reception point for V_R marks the arrival of an increase in energy in the time domain, located by a through-zero point. An often-occurring problem was that the ratio V_P/V_R was not in the range of [0,49 − 0,56], which in turn signifies a Poisson coefficient not expected for masonry walls.
- Method 2: V_P and V_R are chosen based on their preferred ratio of [0,49 − 0,56]. This ratio is tried to be satisfied by selecting V_P at a different location, namely by neglecting a very small increase in energy at arrival. That small increase can be caused due to various reasons and should only be neglected when the alternative impact point is reasonable to avoid a subjective interpretation of the measurements. It is still possible that the averaged value of this method does not satisfy the preferred ratio. When method 2 is not possible, only method 1 is applied.

The values obtained by the sonic testing and the MQI method are subsequently compared to compression tests in Table 1. The obtained values from the sonic testing are reasonable: the results differ from the compression testing, but the obtained Young's moduli and compressive strengths show a reasonable agreement, in the typical range for a low strength wall with low Young's moduli. When comparing the Young's moduli, we can see that it is always overestimated by the sonic testing, probably caused by the fact that the indirect testing only tests the outer leaves, which are much stiffer and stronger than the masonry as a monolithic whole. Since there is little rubble in the middle and some connections between the wallets, known prior from the construction process of the wallets, the overestimation seems not to be very large. Still, if the wallets were to have large infill and rubble with no connections or if only accessible from one side of the wallets and thus only to be tested on one outer leaf, the estimation could strongly overestimate the real value.

Table 1. Comparison of the obtained averaged mechanical properties from the sonic testing and the compression testing for each type of wallet. (SD indicates the standard deviation).

Compression testing	$E\ (GPa)$	$f_c\ (MPa)$	Sonic Testing	$E\ (GPa)$	SD of $E(GPa)$	$f_c\ (MPa)$	MQI method	$E\ (GPa)$	$f_c\ (MPa)$
Type A	0,21	0,72	Type A	0,34	0.095	0,62	Type A	0,7	1,28
Type B	0,22	0,62	Type B	0,78	0.153	1,43			
Type C	0,86	3,3	Type C	1,85	0.392	3,38			

Young's moduli from the MQI method show a lesser correspondence: the MQI method overestimates the modulus even stronger. The MQI method is by conclusion less accurate to determine the Young's modulus of the tested irregular walls. More walls should be included in the relation between the MQI value and the mechanical properties. If this were the case, the MQI method could prove to be a very handy tool.

The sonic testing on the other hand, shows reasonable fit to the compression testing. From the sonic testing, weak points can be found and information about the amount of leaves as well as mechanical properties can be determined. A possible solution to the stiffness overestimation is to perform impact-echo to obtain information about the thickness of the leaves. Using impact-echo could improve knowledge about the inner core, or the connection and strength of the leaves and thus improve the results.

When comparing the compressive strength, the results from compression tests indicate that the grouted wallets are 5 times stronger than the non-grouted ones. The sonic testing implies that it is 5,5 times stronger and can thus detect the improvement of grouting. The results of type B, comparing sonic to compression testing, are not as good as those of type A. This confirms the assumption that it is better to remove the plaster from the wallets. Similar for type C.

4 Conclusions

The aim of this paper was to evaluate the efficiency and accuracy of sonic testing for an irregular historical wall layout, by comparison with the Masonry Quality Index method and compression testing of wallets. The results revealed that the Young's moduli of the sonic testing had a good agreement with those of the compression testing, although the former presented an overestimation due to testing on the outer leaves. The Poisson's ratio presented inconsistent results due to a high scatter on experimental values. The MQI method produced less accurate results in terms of stiffness estimation but has potential and should be investigated further.

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