Assessment of mechanical properties of full-scale masonry panels through sonic methods. Comparison with mechanical destructive tests

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1. INTRODUCTION

Sonic technique has been used to detect the quality of masonry, namely, to identify the physical characteristics of masonry sections, that is, the homogeneity and/or the compactness of masonry elements and therefore allowing to control, for instance, the effectiveness of masonry consolidation interventions through grout injection [1]. Sonic tests can be applied using a simple configuration that corresponds to a single measure with emitter and receiver placed on different positions of a structural element or using complex configurations with several receivers placed according to a prearranged disposition to provide more comprehensive analyses, or reliable results. Sonic tomography is an example of such type of configuration. Trials using the impact-echo technique [2] and other more complex sonic analyses [3] have also been made to obtain complementary information to characterize more in-depth masonry samples. In fact, non-destructive or slightly destructive *in situ* testing techniques (NDT and SDT techniques, respectively) are often employed to this purpose [4]; the use of these techniques assumes an even higher importance when built heritage of great cultural value is involved [5], because in this case, safeguarding is one of the main conditions involving any type of intervention or testing procedure. However, only a small number of existing NDT and SDT techniques

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enable accessing the masonry mechanical properties. Within this group, flat-jack tests (an SDT) are one of the few techniques available that allow quantifying the mechanical behaviour of masonry elements [6]; in most cases, these techniques give mostly qualitative information [7]. Nevertheless, it is nowadays accepted that the complementary use of different techniques is the best way to provide more reliable and comprehensive information [8,9].

In this research, the authors use a procedure called indirect sonic impact method (ISIM) [10] to estimate the elasticity modulus of stone masonry panels with different regularity layouts (six irregular and six regular wall panels). The specimens, made of granite stone and lime mortar, were constructed and tested at the Laboratory of Earthquake and Structural Engineering (LESE) of the Faculty of Engineering at the University of Porto. The paper also studies the influence of the characteristics of the stones (shape, mechanical properties and finishing) and of the joints on the sonic propagation velocities. At the end, the results were compared with those obtained through compression tests performed by Almeida [11] at two regular and two irregular stone masonry panels from the set of the 12 panels.

1.1. Specimens

The specimens used in this study consisted of 12 one-leaf stone masonry panels, $120 \times 179 \times 28\,\mathrm{cm}^3$, constructed at LESE at the University of Porto and presented in Figure 1. The panels present two different configurations:

- six perfectly regular wall panels, with regularly sawn stone units with lime mortar joints;
- six irregular wall panels, with irregular stones and irregular joints having small stones (shims), lime mortar and about 1% internal voids.

Notice that the irregular stone panels were built to represent real full-scale walls from constructions found at the Northern part of Portugal. In particular, the units and joints materials (granite and lime mortar) and dimensions and the construction procedures were fully respected [11].

1.2. Sonic apparatus

The sonic indirect tests were carried out using a 0.32 kg hammer with a range of frequencies of 0 to 1 kHz (flat response). In operational conditions, the hammer can send a pack of frequencies up to 6 kHz, a value that is much lower than the hammer resonance frequency that is higher than 22 kHz. A set of three unidirectional miniature accelerometers with a flat response up to 10 kHz was used as receivers. The accelerometers were coupled to the stone surfaces with grease to promote a better wave transmission [12].

The data acquisition system was an NI-9233 compact module with a resolution of 24 bits and a maximum sampling rate of 50 kHz. The signal processing consisted of measuring waves travel times. A LabView application developed at LESE enabled the visualization of the transmitted and received signals on time domain. The first arrival of the waves' package was obtained using an automatic algorithm that may be checked and corrected by the operator through visual access and manual operation. The distinction between P and R-waves was attained through a series of procedures settled within the ISIM method.

Figure 1. Wall specimens [11]: panels made with regular sawn stones with horizontal mortar joints (left); panels made by irregular stones with sub-horizontal joints (right).

Complementarily, ultrasonic equipment was also used: a basic commercial device, which includes its own signal generation, acquisition and processing units packed into a single module, calibrated to return only the first wave travel time without any interaction with the operator. Both the emitter and the receiver consist of metallic cylindrical transducers operating at 54 kHz (specially indicated for concrete structures) that were coupled to the stone surface using grease.

2. METHODOLOGY

First, the characteristics of the stones were accessed using standard sonic direct tests; six different stones per panel were tested to obtain the stones' velocity. A sample of mortar used on the construction of the walls was also tested; because of its small dimension, $12.0 \times 3.2 \times 3.2\,cm^3$, the ultrasonic equipment was used instead.

Notice that sonic tests applied to a masonry wall through its thickness (direct configuration) enable to assess the wall transversal characteristics, which, in the case of the one-leaf specimens considered in this work, correspond to assess the stones characteristics alone. To measure the influence of both stones and joints together, that is, to study the propagation of waves along the vertical direction, emitter and receiver should be placed on the top and bottom transversal sections of the wall. Because these surfaces are not usually accessible *in situ* and a signal may not have enough energy to travel along the whole height of a complete wall, the authors accessed the characteristics of the specimens along the vertical direction applying the ISIM technique, that is, performing tests with both the emitter and the receiver(s) placed on the same side of the wall (indirect tests).

The ISIM was applied using three accelerometers placed on different stones following a vertical alignment, with the emitter along the same surface (also called columns, ahead). As illustrated in Figure 2, sets of four points (i.e. columns) were marked on the surfaces of the walls, and the acquisition was carried out following two different setups under this order: (i) impact on the highest point of the column and reception at the three lower points (up-down) and (ii) impact on the lowest point of the column and reception at the three upper points (down-up). The reception at the three points was always carried out simultaneously using the three accelerometers placed on large stones.

Thus, each impact corresponds to three indirect tests (one for each receiver/accelerometer), and each column collects information from two times three indirect tests. Furthermore, to compare the response considering different vertical alignments, four columns per panel (two per façade) were considered, that is, eight ISIM tests were performed per panel, which corresponds to a total of 24 indirect tests per panel. In conclusion, each wall typology (regular and irregular) provided 144 indirect tests.

3. THEORY AND CALCULATION

3.1. Sonic tests

Sonic tests can be performed using different layouts, according to the proposed objectives: direct, semi-direct and indirect or surface configurations [13], depending on the relative position between hammer (emitter) and accelerometer (receiver), as it is illustrated in Figure 3:

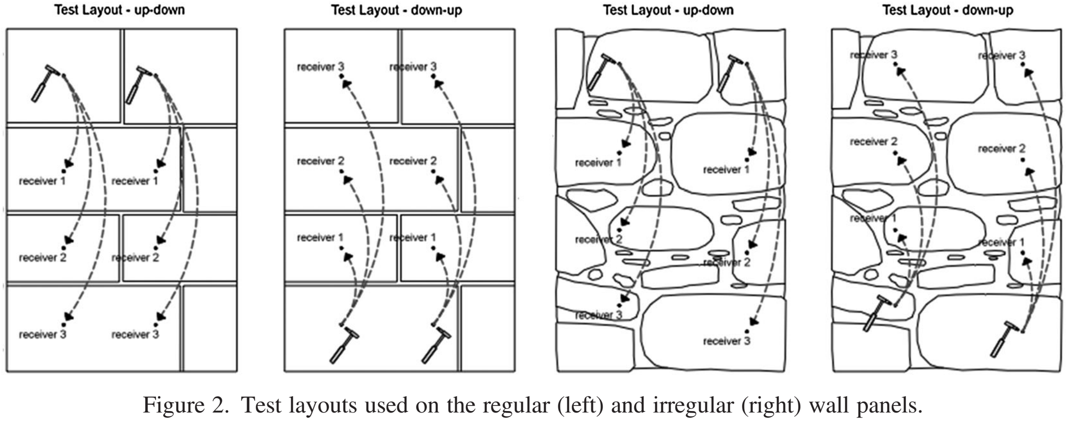

Figure 2. Test layouts used on the regular (left) and irregular (right) wall panels.

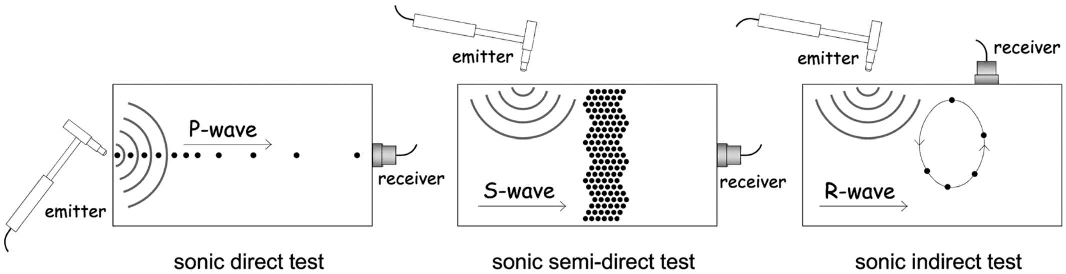

Figure 3. Sonic tests configurations.

- Direct test – hammer and accelerometer placed on opposite faces;
- Semi-direct test – hammer and accelerometer placed on adjacent faces;
- Indirect test – hammer and accelerometer placed on the same face.

The direct configuration is advisable to access P-wave velocities; P-waves propagate mainly along the direction of the impact, causing longitudinal displacements, and thus, the main particle accelerations are measured on the opposite side of the impact. The semi-direct configuration is used to access S-wave velocities; because S-waves cause displacements transversal to the impact surface, that is, to the propagation direction, the main particle accelerations are measured on the surface perpendicular to the impact surface. Finally, the indirect configuration is more used to access R-wave velocities, because this type of wave diffuses along the impact surface. Nevertheless, different waves can be detected in a same configuration, and the operator should be able to distinguish them. For instance, on an indirect test, the receiver will also detect P-waves that propagate along the impact surface [14]. However, in this case, and although being faster (P-waves are around two times as fast as R-waves) [12,14], that is, corresponding to the very first arrival in the time domain signal [14], P-waves contain less energy [14–16] than R-waves (7% against 67% of the total energy [17]), and the two may be distinguished by the operator, although it is not always easy to detect P-waves arrival through indirect type tests because of its low energy content [3]. Figure 4 illustrates P and R-wave distinction in a time domain signal.

Once only P and R-waves will be involved in the applications performed in this work, only these two types of waves will be referred to. As it was already mentioned, besides having different energy content, P and R-waves have different propagation velocities, V_P and V_R, respectively, which depend on the mechanical properties of the material they cross. Equations (1) and (2) present the velocities for both waves on homogeneous, elastic and semi-infinite media with a elasticity modulus E, a Poisson ratio ν and volumetric mass ρ:

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

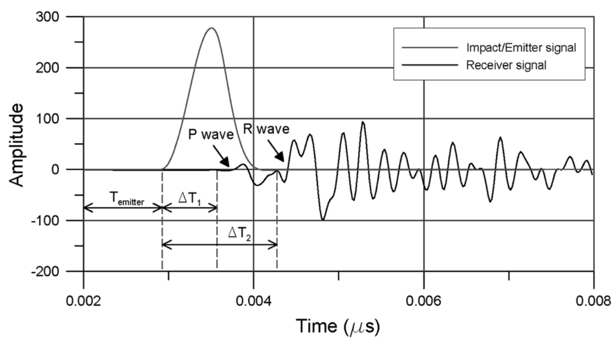

Figure 4. Example of P and R-wave distinction in a time domain signal.

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

According to these expressions, the ratio between P and R-waves velocities in such a media (Equation (3)) depends only on the Poisson ratio [17]. It is known that for Poisson ratios of about 0.25, the relation between the velocity of P and R-waves is about $V_R/V_P = 0.5$ [17]. For concrete with a Poisson ratio of 0.2, Carino [12] verified that the same ratio on concrete samples was around 0.56.

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

The mechanical properties obtained using these equations are called dynamic because they are based on small deformations and fast load rates; their values are frequently higher than that of the static ones. On concrete specimens, it was shown that the strength depends on the loading rate [18]. According to the standard [19], the ratio between the static and the dynamic elasticity modulus varies from 0.5 to 0.9, increasing with the increase of the elasticity modulus. On granite samples, tests showed that although the value of the dynamic elasticity modulus tends to be higher than the static one, the difference is usually much smaller when compared with that of concrete [20]. However, there are results where the static elasticity modulus is higher than the dynamic one [21]. These differences reflect also the characteristics of granite, a natural material that presents a large variability of its mechanical properties.

Because no other analytical relations are available, Equations (1), (2) and (3) will be applied also to stone masonry (a heterogeneous composite material made of stones and mortar or dry joints), as if it could be considered a homogenized material represented by the masonry global mechanical properties.

3.2. Influence of stones and joints on masonry behaviour

The joints have a large influence on the mechanical behaviour of a masonry system. In theoretical terms, the elasticity modulus of a composite structure made of stones and joints placed in series corresponds to the global homogenized elasticity modulus of the structure. To exemplify, let us consider a masonry sample made of three stones with exactly the same characteristics, having polished surfaces and dry joints (Figure 5), that is, perfect contact between stones.

In these conditions, one could expect that the velocity of the P-waves that cross the stone units and the joints would be given by:

$$V_P = \frac{3x + 2y}{3t_x + 2t_y} \tag{4}$$

where t_x and t_y are the time intervals spent by the P-waves to cross each stone unit and joint, respectively. According to this simplified expression, if the sample is made of stones with smooth surfaces and dry joints, that is, y much smaller than x, it is expected that the velocity of the P-wave propagation along the sample would be (theoretically) quite close to the stones velocity, unless t_y assumes a significant value when compared with t_x. Acoustic waves propagation tests, herein referred to as sonic tests, show that even dry joints from regular stones in apparent perfect contact with one another, produce a wave velocity decrease that, according to Equations (1) and (2), would imply a decrease on the masonry global elasticity modulus [22].

In fact, joints cause dispersion phenomena on acoustic wave propagation [3], which makes the velocity decrease; the process of crossing the joints, in particular the first ones, makes the propagated signal to progressively lose its higher frequencies content, converging to a more narrow-banded spectrum. The remaining frequencies and the corresponding velocities are the parameters that better describe the global properties of masonry. Actually, this is in agreement with the results of mechanical tests, which show that the deformability of stone masonry samples is much higher than the deformability of stones alone.

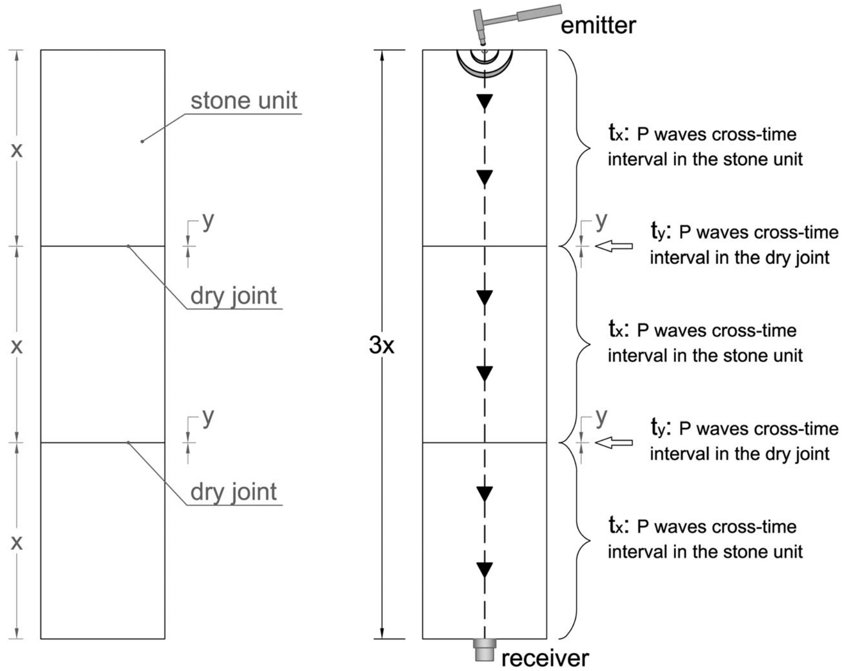

Figure 5. Sample with three stone units (each with a height of x) and two dry joints (each with a thickness of y).

3.3. Indirect sonic impact method

The ISIM allows measuring the surface wave velocities through indirect configurations, that is, hammer and accelerometer(s) placed on the same side of the wall. Moreover, the relative position of the hammer and of the accelerometer(s) should respect a specific layout, which depends on the analysis; if the operator wants to assess the deformability of a wall for a certain direction, hammer and accelerometer(s) should be placed along a straight line parallel to that direction. Therefore, and because this research is aimed at studying the vertical axial behaviour of the walls, the ISIM tests were performed along vertical trajectories.

As it was already mentioned, in indirect configurations, P-waves are more difficult to distinguish because of their low energy content, especially when the receiver is placed far from the impact point. Because of this, the application of ISIM should include receivers positioned not far from the impact point to help recognizing the first waves' arrival (P-waves) and to make it easier to identify and distinguish P and R-waves, in particular, for points positioned at a fairer distance from the impact point. Notice that in spite of their higher energy content, R-waves are not always easily detectable either, because the acquired signal is the result of different contributions (P-waves, S-waves), which may disguise the R-waves' arrival. Nevertheless, the R-waves arrival is, in general, more evident [14], and the results based on its detection are usually more accurate than those based on the P-waves' arrival. The knowledge that P-waves are the first to arrive and that P and R-waves velocities are related by Equation (3) gives quite useful information to the analysis. In this research, and for the material involved, it was assumed ratios V_R/V_P in the range of [0.4, 0.6].

Therefore, a simple criterion was settled within ISIM to help identifying the arrival of R-waves; it corresponds to the time step on the received signal that crosses the zero line before the occurrence of a major increase of the signal amplitude. Following this procedure on the different receiver points for the same impact point, the operator can 'follow' the R-waves arrival time step and thus obtain the R-wave propagation velocity. This procedure is illustrated in Figure 6, where each dot represents the R-waves first arrival in correspondence to the same colour accelerometer.

In order to determine the tendency of the velocity, which is known to decrease with the number of crossed joints [23], linear regression time versus distance curves are settled according to the British Standard on the Determination of Sound Speed Propagation [19]. This mathematical operation allows computing the P and R-wave velocities, taking into account the quantity of material involved, that is,

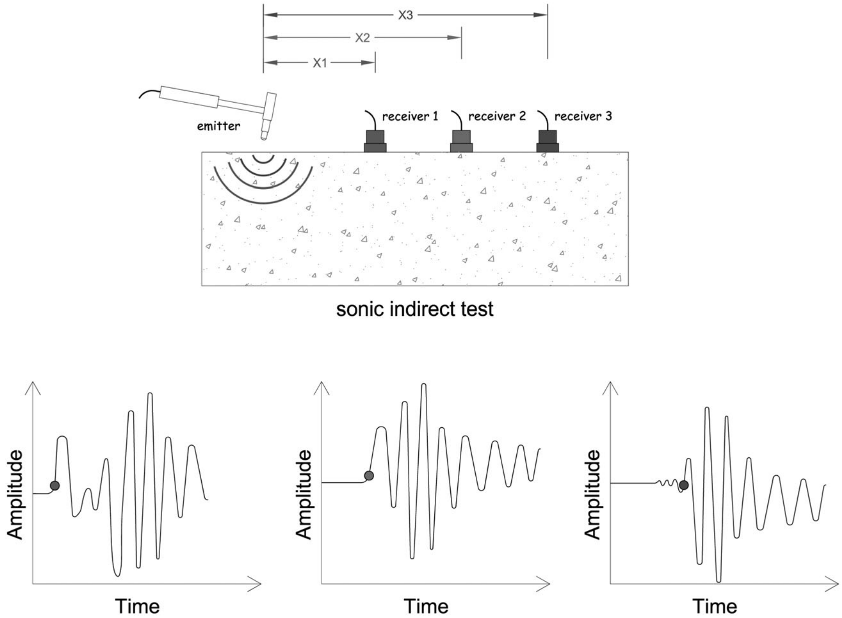

Figure 6. Indirect sonic impact method application (adapted from [27]) and corresponding received signals in time domain (adapted from [14]).

the distance between the emitter and the accelerometers and therefore the effect of the number of crossed joints. Figure 7 presents an example of the layout of the ISIM and the final data result.

The linear regression is also useful to reduce errors caused by incorrect interpretations of the acquired signals. Even if the initial time step of the signals, either from the hammer or the accelerometers, is not perfectly detected (the instant of the waves arrival is not always perfectly recognizable), the linear regression provides an estimation of the tendency for all travel times versus distance points, helping to interpret the signals. Figure 8 shows two indirect sonic results that express two paradigmatic situations: on the left, the slow development of the impact curve and some noise in the first part of the accelerometer curve produce ambiguity in the identification of the first wave travel time; and on the right, the starting time step for both signals is clearly identifiable.

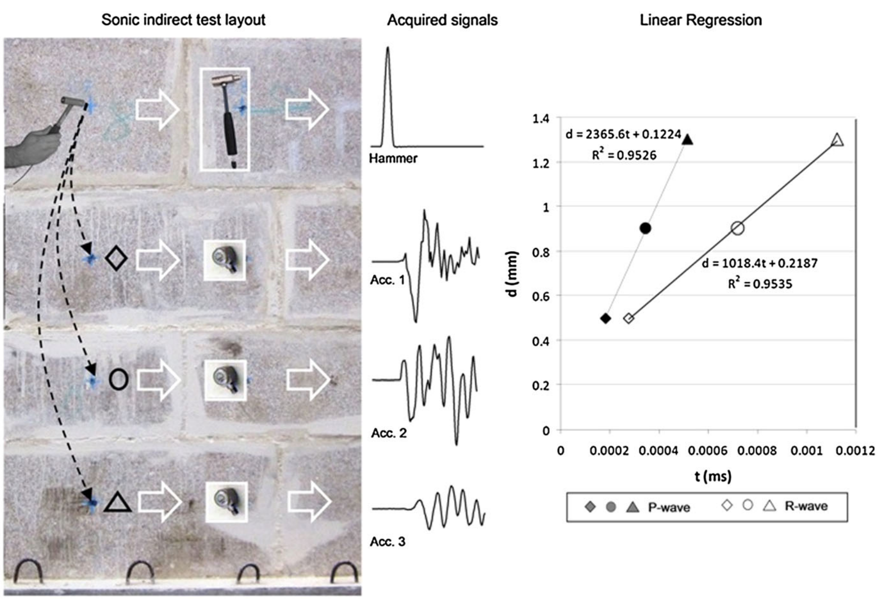

Figure 7. Indirect sonic impact method test layout; post-treatment of the results.

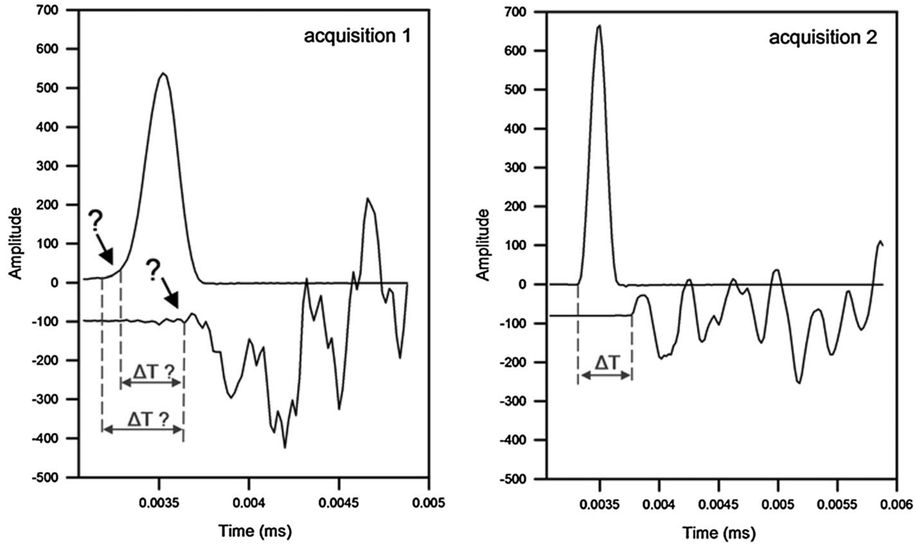

Figure 8. Two paradigmatic cases concerning the identification of the first waves travel time.

Thus, the ISIM is based on the determination of the linear regression between the P and R-waves travel time between the same impact point and points at increasing distances along a straight line. As a final result, it gives the tendency of the P and R-waves velocities crossing the composite material (stones and joints, in this case) and provides the global velocity of those waves propagating along materials surface.

To avoid local 'defects', such as localized voids or cracks, ISIM should be performed along different alignments positioned at different places of the same material in order to achieve representative and reliable values for the waves' propagation velocities. If these 'defects' are spread in the material, the waves' velocities will naturally decrease in all the alignments, reflecting the expected decrease of the material elasticity modulus due to the material damage and/or degradation. In reality, waves propagation methods estimate the material physical state, which has direct repercussion on its mechanical properties.

In the next section, the ISIM will be applied to the identification of the 12 one-leaf stone masonry panels presented before.

4. EXPERIMENTAL TESTS: RESULTS AND DISCUSSION

The velocity of propagation of P-waves on the stones of the two types of tested wall panels (regular and irregular) was measured using a direct configuration through the walls thickness. The following average values were obtained: 4200 m/s and 3000 m/s for the stones of the regular and irregular panels, respectively, with corresponding standard deviations of 668 m/s (16%) and 722 m/s (24%); a total of 72 direct sonic tests were considered per panel type. Thus, the stones of the irregular panels present an average propagation velocity that is 30% lower than that of the regular ones and a higher dispersion. This difference can be related to the provenience of the stones, which come from different quarries and represent two different classes or qualities. Table I presents the results for the six regular plus

Table I. Results of P-wave velocities measured on the stones and corresponding computed elasticity modulus using Equation (1) (coefficient of variation between parentheses).

		Regular panels stones	Irregular panels stones
Velocity (m/s)	Maximum	5036	4762
	Minimum	2820	1071
	Average	4181 (16%)	2981 (24%)
Young modulus (GPa)	Maximum	49.0	43.8
	Minimum	15.4	2.2
	Average	33.8 (30%)	17.2 (46%)

six irregular panels in terms of the maximum and minimum P-wave velocities measured by the direct tests applied to the stones and the corresponding elasticity modulus computed using Equation (1) and current values for the volumetric mass and Poisson ratio of this type of masonry, 2600 kg/m^3 and 0.3 (average plausible values), respectively.

Concerning these values, Equations (1) and (2) show that the elasticity modulus is proportional to the volumetric mass, that is, a variation from 2600 to 2400 kg/m^3 involves a variation of 7.7% on the elasticity modulus and that a variation of the Poisson ratio from 0.3 to 0.25 involves a variation of 12.2% and 2.2% on the elasticity modulus computed through Equations (1) and (2), respectively. This analysis shows that Equation (1) is more sensitive to the Poisson ratio than Equation (2) and that using plausible values for the density and Poisson ratio in the two equations does not introduce major differences on the elasticity modulus when compared with the results the 'hypothetic real values' would give.

A quite uniform average P-wave velocity was attained, as illustrated in Figure 9.

Under a PhD thesis [11], a series of mechanical tests were performed on samples retrieved from the walls stones to assess the modulus of deformability, giving average values of 19.98 GPa (15,33%) and 16.03 GPa (24.90%) for the regular and irregular panels, respectively.

After characterizing the stones, the deformability of the wall panels was estimated applying ISIM tests along vertical columns. The results pointed out a decrease of the P and R-waves velocity with the number of crossed joints, as found in previous works [24]. However, this was mainly noticed on tests where impact was applied at the top, being not so evident otherwise. Figure 10 presents the results

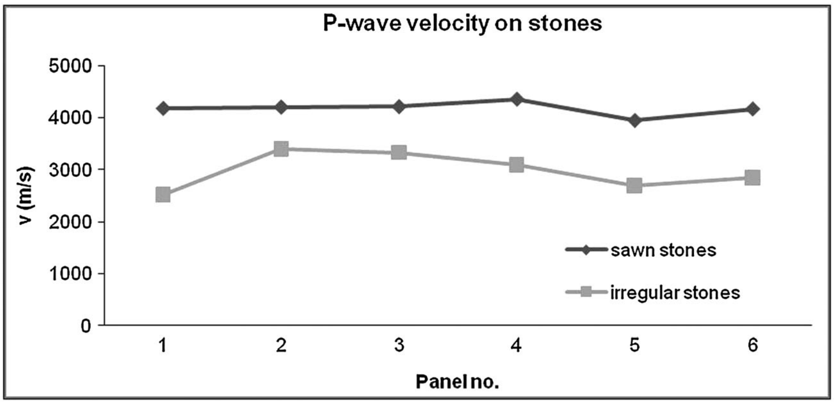

Figure 9. Average P-wave velocities measured on the stones of the regular and irregular panels.

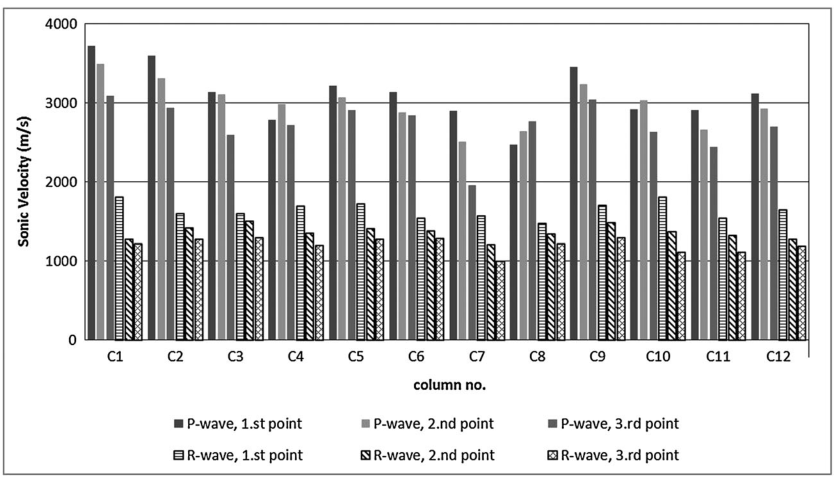

Figure 10. Results for P and R-waves velocities measured in one of the main facades of the six regular panels (two indirect sonic impact method tests per panel).

obtained by ISIM tests carried out on one of the facades of the six regular panels, considering up-down layouts (two columns per panel).

Figure 11 presents the linear correlation coefficients for the P and R-waves velocities assessed through the ISIM tests performed on the regular and irregular wall panels (48 ISIM tests per typology). With few exceptions, the coefficients were quite close to 1, denoting the presence of a trend.

Figure 12 shows the dispersion of the P and R-waves velocities computed for each ISIM test around the global average computed for each wave and wall panel type (horizontal lines). Nevertheless, P-waves velocities show much higher dispersion than R-waves.

Figure 13 represents for each column on both sides, M and H, of the regular panels the P and R-waves velocities computed by the two ISIM tests, up-down and down-up. The whole set of ISIM tests presented fairly different, but consistent results. For instance, column 7 (panel 4) presented, in all the four tests, the lowest P-wave velocity; on the contrary, column 9 (panel 5) showed the highest P-wave velocity. Moreover, it is also clear that the scattering of P-wave velocities is considerably higher than that of R-wave velocities, which, in general, presented more uniform values; thanks to their particular characteristics, R-waves were more clearly recognizable during the interpretation of the acquired signals. These conclusions were also true for the irregular wall panels, despite the higher heterogeneity observed in these panels, as confirmed by the graphic in Figure 14.

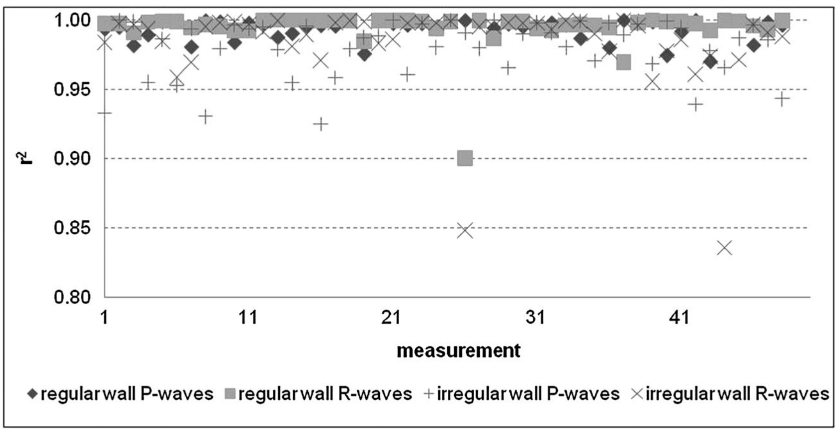

Figure 11. Linear correlation coefficients for the indirect sonic impact method test performed on both types of wall.

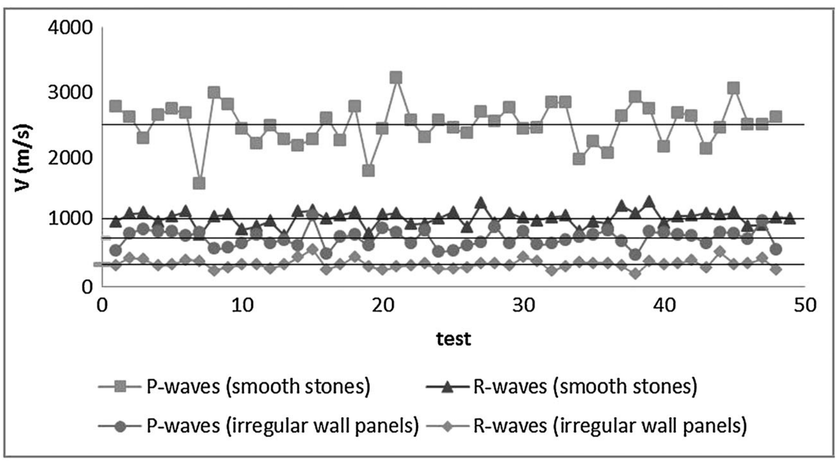

Figure 12. P and R-waves velocities per indirect sonic impact method test; horizontal lines represent global average velocities per wall panel type.

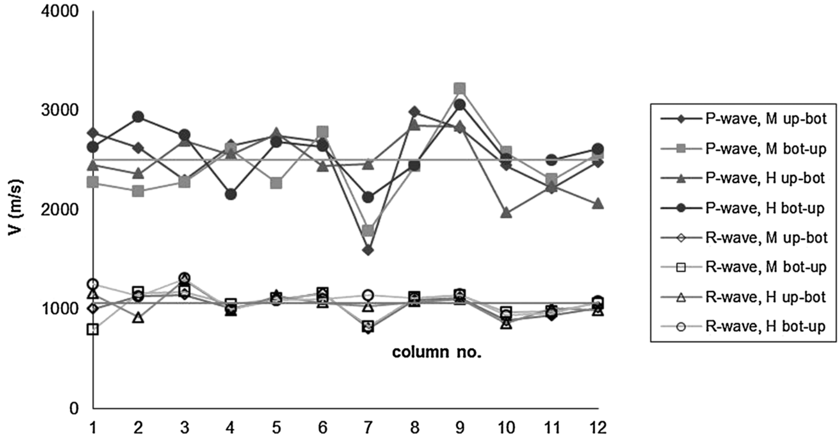

Figure 13. P and R-wave velocities on the two facades of the regular wall panels for both orientations (down-up and up-down); horizontal lines represent global average velocities per wave type.

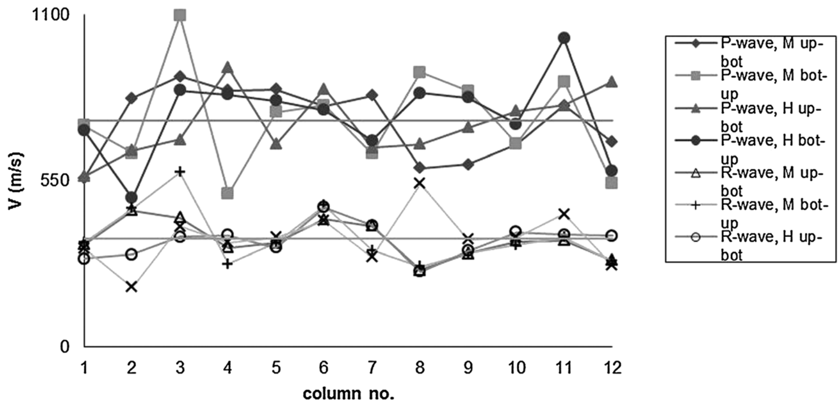

Figure 14. P and R-wave velocities on the two facades of the irregular wall panels for both orientations (down-up and up-down); horizontal lines represent global average velocities per wave type.

Figures 15 and 16 present the elasticity modulus obtained using the P and R-waves velocities on the regular panels, respectively. It was considered a volumetric mass of 2400 kg/m^3 and a Poisson ratio of 0.25 for the masonry (average plausible values).

Table II summarizes the extreme and average values of the P and R-wave velocities and the elasticity modulus obtained through Equations (1) and (2). It shows that a higher elasticity modulus is estimated when using P-waves velocities

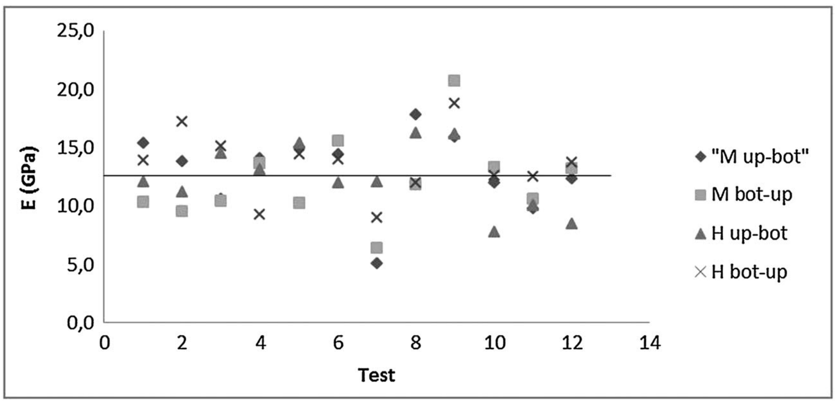

Figure 15. Modulus of elasticity obtained for the regular panels using P-waves and Equation (1).

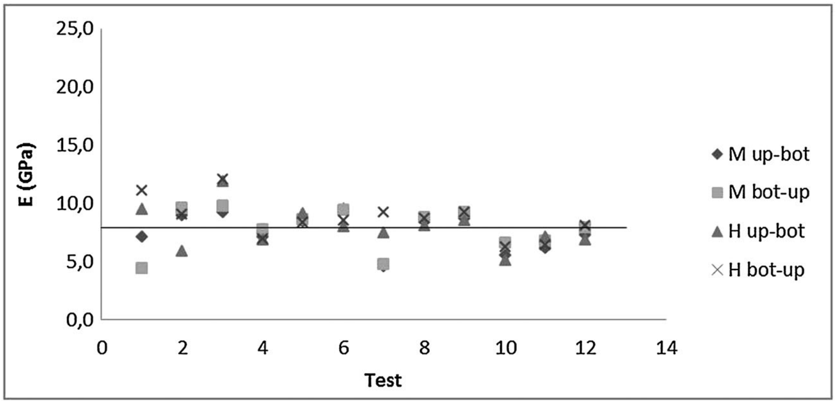

Figure 16. Modulus of elasticity obtained for the regular panels using R-wave and Equation (2).

Table II. P and R-wave velocities and corresponding estimated elasticity modulus (the coefficient of variation is presented between parentheses).

		Regular walls		Irregular walls	
	Value	P-wave	R-wave	P-wave	R-wave
Velocity (m/s)	Maximum	3216	1305	1097	579
	Minimum	1591	787	493	197
	Average	2508 (13%)	1056 (11%)	751 (17%)	357 (21%)
Elasticity modulus (GPa)	Maximum	20.7	12.1	2.4	2.4
	Minimum	5.1	4.4	0.5	0.3
	Average	12.6 (23%)	7.9 (21%)	1.1 (35%)	0.9 (45%)

Before going further in the analysis, it should be noticed that because of the previous considerations, the elasticity modulus estimated through the R-waves velocities should represent a more reliable estimation of the deformability properties of the tested walls. Therefore, and using R-waves as reference, the results show that a much higher elasticity modulus is expected for the regular walls when compared with the irregular walls, in this case around eight times higher. These results are in agreement with other studies performed on stone masonry panels in different physical conditions [21].

After this analysis, the same regular and irregular panels were submitted to a large experimental campaign that included vertical compression tests on three out of the six panels within each typology of specimens [11,25]: one for monotonic and two for cyclic loading. Table III presents the elasticity modulus that corresponds to the unloading/reloading paths under the monotonic/virgin curve, obtained through the cyclic compression tests on two regular and two irregular specimens. Notice that a sonic test does not impose stress levels higher than those already felt before by the walls. It introduces very small amplitude vibrations and therefore 'detects' only the unloading and reloading characteristics of the masonry below the monotonic curve. Masonry has a quite plastic behaviour and unloads and reloads under the monotonic with an elasticity modulus much higher than the one that corresponds to the inclination of the virgin curve.

Table III. Results obtained by Almeida [11] on the vertical compression cyclic tests applied to the wall panels for low level of axial stress.

		Test		
	Wall type	1	2	Average
Reloading elasticity modulus (GPa)	Regular walls	8,10	7,63	7,87
	Irregular walls	1,26	1,26	1,26

Table IV. Average results obtained by Almeida compression tests [21,26] applied to granite masonry walls and evaluation by indirect sonic impact method.

		Mechanical tests		Indirect sonic impact method	
		Walls		Walls	
Type of stone faces	Type of joint	E_w (GPa)	E_w/E_s (%)	E_w (GPa)	E_w/E_s (%)
Sawn	Lime mortar	7,87	39	7,9	23
Irregular	Lime mortar	1,26	8	0,9	5

The comparison of the elasticity modulus obtained through the mechanical and ISIM tests (using R-wave velocities) is quite similar. Moreover, it is also interesting to notice that although the velocity of P-waves on the stones of the regular wall panels was only 30% higher (on average) than the velocity on the stones of the irregular panels, the regular walls presented an average P-wave velocity about 70% higher than that of the irregular walls, meaning that other parameters, other than the stone quality, have more influence on the final results. The irregular shape of the stones and the mortar joints are among the most important causes for this reduction. This tendency is in agreement with Almeida [26] and Vasconcelos [21] experiments; the final ratios between the average elasticity modulus of the wall panels (E_w) and the stones (E_s) obtained through sonic tests are similar to those found by mechanical tests reported by other authors for regular and irregular wall panels, as presented in Table IV.

These results show that ISIM is sensitive to the walls quality and presents results close to those obtained through mechanical tests. Finally, and in spite of the promising results, this technique, as any other NDT or SDT procedure, should be used together with other testing techniques, or cross-checked with results from other tests and specialized bibliography.

5. CONCLUSIONS

This research presents a series of direct sonic tests and a recent procedure called ISIM applied to 12 one-leaf stone masonry wall panels: six with regular joints and sawn stones and six with irregular joints and stones; the same mortar was used in both cases.

The results showed that although the single stones of the regular wall panels presented a P-wave velocity 1.4 times higher than that of the stones of the irregular wall panels, the P-wave velocity on the regular wall panels was, on average, 3.3 times the P-wave velocity measured on the irregular ones. Moreover, the ratio between the estimated (using R-waves velocities) elasticity modulus of the walls and of the stones for the regular wall panels was 23%, four times higher than the same ratio calculated for the irregular wall panels that was about 5%. These results underline the importance of the geometry of the joints and stones on the walls mechanical characteristics, as it was concluded by experimental studies using mechanical tests [11,21].

Furthermore, the comparison of the average elasticity modulus of the walls obtained through sonic and mechanical tests (performed on the same samples) showed quite similar results: $E = 7.9$ GPa for both tests on the regular walls and $E = 1.3$ GPa and $E = 0.9$ GPa for the mechanical and ISIM tests on the irregular walls, respectively. These results took into consideration the velocities of R-waves, because its high energy content reduces errors when identifying the waves arrival.

Finally, it is important to say that ISIM, like other *in situ* NDT and SDT tests, should be applied together with other techniques and that both results should be confronted. To attain some consistency, a large number of tests in different zones of a stone masonry wall should be performed to obtain more accurate values and avoid the influence of local defects.

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