TEMA 3 – Caracterización de materiales

# Stone Masonry Characterization Through Sonic Tests

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**Palavras-chave:** NDT; masonry; stones; sonic tests; seismic waves.

## Abstract

This paper presents stone masonry characterization using sonic tests. These were performed on a stone masonry panel that was cut of a building wall and transported into LESE (Earthquake and Structural Engineering Laboratory) at FEUP (Faculty of Engineering of University of Porto).

Sonic tests were performed both on discrete stones and on the wall panel so that the local and global behaviour could be observed. These tests took place before, during and after a compression load test. The results show both a decrease of wave velocity on the stones during and after the load test and an increase of the wave velocity for the wall.

## Introduction

Sonic tests are a well known NDT technique used on masonry characterization [1]. Different applications of the technique can be used including the generation of the wave using an instrumented hammer and its reception using an accelerometer. In this way it is possible to obtain the time travel for the chosen path. Another application is that of sonic tomography, using several accelerometers measuring the waves propagating as a result of a series of single emissions in order to provide an “internal view” of a cross-section, [2].

Sonic tests are referred as being capable of providing non-quantitative results in the context of mechanical characterization of masonries [1]. The test is usually used with the following goals: qualification of the masonry through the morphology of the wall section; detection of internal defects (voids, cracks) or changes to physical characteristics of the wall; control repair using the injection technique; [1].

For several years, sonic tests were considered, along with Radar Tests, very promising techniques, [3]. A number of trials have already been made in order to obtain mechanical properties of walls using sonic tests, [4-5]. Nevertheless, the results still do not relate with the mechanical properties of masonries in a robust manner as opposed to concrete elements where sonic and ultrasonic Tests permit: the estimation of the depth of cracks, [6]; the evaluation of the effectiveness of the cracks repair, [7]; or the assessment of the thickness of a material, [8]. On discrete stones, it is possible to obtain some of its mechanical properties from the P-wave velocities, [9]. Concerning masonry walls, the sonic technology has been used to estimate the compacity

The processing of sonic data applied to masonry walls must take into account the characteristics of the wall, namely their constituents and internal structure. The setup used should also be chosen considering the specific parameters being studied. Finally, the data interpretation should account for the specific conditions on which the test is performed such as the load and stress distribution on the wall. In this work, the sonic technology is applied to a one-leaf stone masonry wall to determine its mechanical characteristics and the results are compared to those of a load test applied to the same wall; in particular, the Young´s modulus estimated through sonic tests applied to the wall before, during and after the load tests is analysed.

## Equipment and Bases to Calculation

The sonic equipment used consists of an instrumented hammer, a unidirectional accelerometer and a data acquisition system. The acquisition system is a NI-9233 Compact DAQ Module, with a resolution of 24bits and a maximum sampling rate of 50kHz. The central frequency of the hammer was bellow 5kHz. Fig. 1 present the sonic transmission procedure adopted in a direct test i.e., through the thickness of the wall. In an indirect test, the impact of the hammer and the accelerometer are positioned on the same side of the wall.

a) b)

Figure 1: A direct sonic Test: a) accelerometer (receiver) at face A of a wall and b) hammer (transmitter) at face B of the same wall.

Fig. 2 illustrates an example time history of a transmitted and received signal couple. A specific signal processing algorithm was developed to obtain the signals start and arrival, so as to obtain consistent measurements.

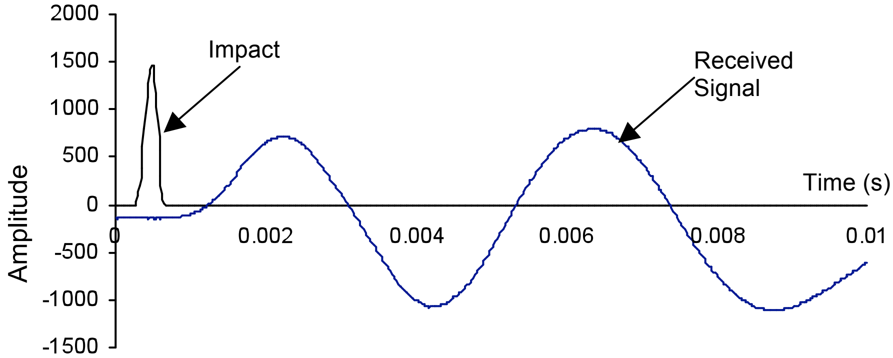


Figure 2: Typical signals obtained from sonic tests: impact and reception.

In this work, sonic tests' aim was to estimate the global Young´s modulus, E, of a one-leaf stone masonry walls by measuring the velocity of propagation of the elastic compression, P, and surface (Rayleight), R, waves through direct and indirect tests. The relationship between P-wave (Vp) and the R-wave (Vr) velocities with Young´s modulus (E) and Poisson´s ratio $(\upsilon)$ for a homogeneous material are given by Eq. 1 and 2.

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

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

In these analyses some redundancy was achieved, since only one of the wave types would be necessary if an estimated Poisson´s ratio was to be used. By using both the P-wave and R-wave results it was possible to obtain the Poisson´s ratio, using a combination of Eq. 1 and Eq. 2, as well as making it independent of the volumetric mass, $\rho$ – Eq. 3. Notice that a variation of $\rho$ from 2200 to 2800kg/m$^3$, a range of acceptable values for a masonry wall, causes a decrease of only about 12% in both velocities.

$$\frac{Vr}{Vp} = \frac{(0.87+1.12\upsilon)}{(1+\upsilon)} \sqrt{\frac{(1-2\upsilon)}{2(1-\upsilon)}} \tag{3}$$

Eq. 3 shows that a Poisson´s ratio in the range of [0.2-0.3] translates into a Vr/Vp in the interval [0.49-0.56]. When this relation was not available, in particular when a single stone was analysed and only P-wave velocities were measured, a Poisson´s ratio of 0.2 was adopted in the equations. Moreover, in the cases where the volumetric weight was not determined, the authors used a value of $\rho$ = 2600kg/m$^3$ for the wall, [10], and $\rho$ = 2800kg/m$^3$ for the stones, as given in [11].

**Object of study**

The results presented in this work are from a wall of António Carneiro building. It was constructed around 1910 in the city of Porto and is considered a typical building of the time. It has a basement, a ground floor and an upper floor. The walls are made of stone masonry walls which support a timber roof and timber floors. The implantation area, per level, is of about 30x10m$^2$. The masonry walls are composed of large stones with irregular surfaces and shapes, joints of bastard mortar and shims (frequently small stones). The larger stones have dimensions of more than 1.0m long per 0.6m tall, [10]. Figure 3 presents a view of the building and of the tested wall.

a) b)

Figure 3: António Carneiro building: a) general view and b) the tested wall.

Initially, Flat-Jacks were used to test the walls but with questionable results, [12]. In particular, most of the recommendations in the RILEM and ASTM standards couldn't be adopted in the tests. The use of sonic technology on these and similar walls has the potential of enabling, in some way, the mechanical characterization in a non-destructive way, overcoming some of the Flat-Jack test difficulties. The sonic characterization of stones is by definition relatively simple; similar tests are frequently performed on concrete. Being a composite material, when masonry is involved, the sonic characterization should involve all the constituents, i.e. a more complex testing is required.

**Test Conditions and Procedure**

The building presented on Figure 3 was being refurbished and the demolition of the internal wall presented on the same figure was planned. For that reason, the wall was cut into 6 panels and transported to the LESE at FEUP to be tested using sonic, compression, diagonal and shear tests, [10]. The wall represents a typical wall found on buildings constructed at Porto till the beginning of the 20th century. It's a one-leaf wall made of large stones and mortar joints. The results presented in this work correspond to tests made on one of the 6 masonry panels (named PP2): 2.44m tall, 1.22m wide and 0.40m thick.

Frequently, sonic tests on walls only consider the direct tests on which the wave travels through its thickness. In the present case, a wall made of just one-leaf, the direct test measures the velocity through a single stone at the time. Although the wave velocity on single individual elements gives an idea of the masonry quality, other aspects are also required to assess the masonry as the composite material that it is. Thus, the waves should travel along some or most of the wall in order to translate its complexity and heterogeneity. Only then can the characteristics of both stones and joints, and how they fit together, be obtained. For this purpose, in the present study, the authors chose to use indirect tests to characterize the “mixture” of joints and stones. In particular, the indirect sonic tests allowed determining both P-wave and R-wave velocities, increasing knowledge on the wall characteristics.

Therefore, different series of direct and indirect sonic tests were done, namely direct and indirect and using 7 controlling points marked on each face (L and E), directly opposing each other, as illustrated in Fig. 4.

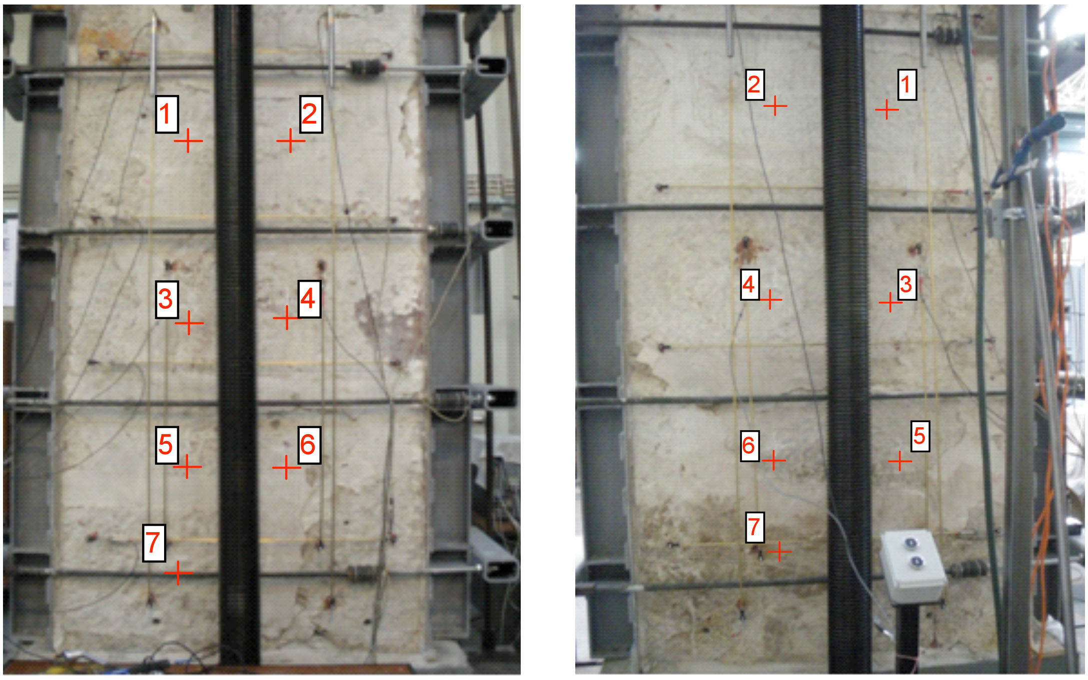


Figure 5: View of the panel before the compression test: a) face L; b) face E.

The direct tests involved pair of points on opposed faces (e.g. point 1 on face L and E, point 2 on face L and E…) and allowed determining the P-wave velocities along the thickness of the panel (i.e. crossing individual stones). The indirect tests consider sequences of points along vertical lines on the same face (e.g. point 1, 3, 5 and 7 on face L, point 2, 4 and 6 on face E…) and allowed determining the P and R-wave velocities along the height of the wall, i.e. when stones and joints are crossed. On each column the points are separated by, at least one joint.

Since the tested panel was meant to be submitted to a Compression Load Test (LT), the sonic testing campaign was performed in 3 different sequential conditions of the wall: before applying any compression load, with a compression load of 2.5MPa applied to the top and, finally, after unloading the panel. This campaign permitted comparing the P and R-waves velocities for the 3 different situations. In particular it made possible to measure how the stress on the wall affected the wave velocity and the Young´s modulus, estimated through Eq. 1 and 2.

## Results

### Direct tests on single stones

The direct tests, done with the impact on face L and the accelerometer on face E, enabled the determination of the average P-wave velocity on the stones and estimating the Young´s modulus (considering $\nu$ = 0.20 and $\rho$ = 2800kg/m$^3$). The results are presented in Table 1.

Table 1 – P-wave velocities measured from the direct tests on stones and the correspondent Young´s modulus.

| | P-wave velocity (m/s) - tested points | | | | | | | Average velocity (m/s) | E (GPa) |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | |
| Before LT ($\sigma_c$=0) | 3333 | 2520 | 2500 | 2857 | 3333 | 3960 | 2880 | 3055 | 24 |
| During LT ($\sigma_c$=2.5) | - | 1530 | - | 2500 | - | 3401 | 2863 | 2574 | 17 |
| After LT ($\sigma_c$=0) | 2901 | 1971 | 1363 | 2500 | 2463 | 3353 | 2941 | 2499 | 16 |

The results show a tendency of P-wave velocity to decrease during the load test. Such a difference was expected and can be explained by the formation of cracks or internal micro-cracks in the stones (as it was verified by Vasconcelos, [9]). Despite the small load applied to the wall (2.5MPa) when compared to the compression strength of the stones (60MPa [10]), the boundary conditions for each stone can produce a concentration and redirection of stresses, generating enough traction so as to produce cracks. In the case of this wall, one such stone fractured during the load test, sustaining that in reality the stones were being loaded with considerably higher local stresses, particularly tensile stresses. Fig. 5 presents the results from Table 1 more clearly.

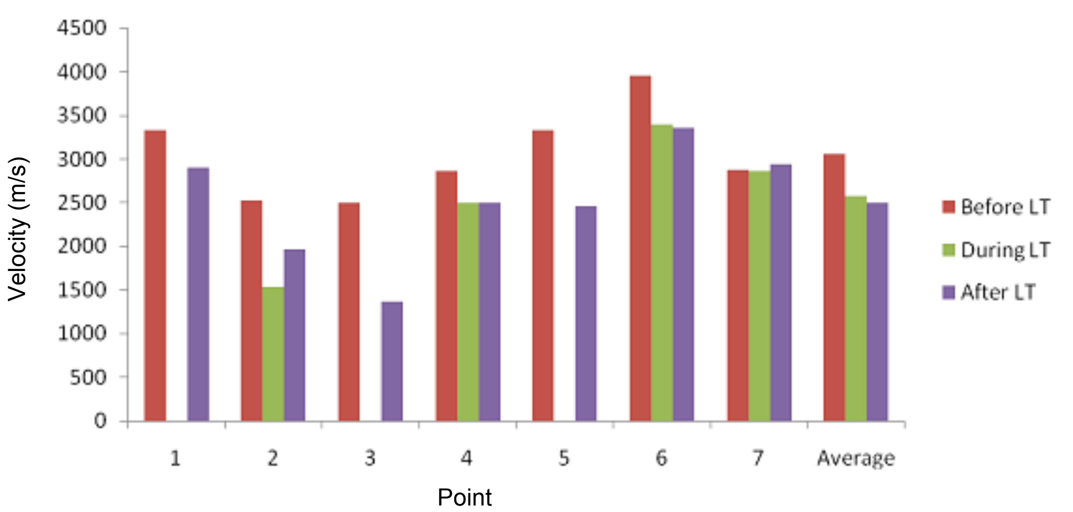


Figure 6: Evolution of the velocity on stones before, during and after the LT.

Considering the estimated Young modulus, compression tests on stone samples from another wall of the same building [11] produced an average Young´s modulus of 26GPa, but with a considerable scattering between 13GPa and 36GPa. The values in Table 1 show that, for the tested stones, the average Young´s modulus obtained using Eq. 1 is E = 24GPa.

### Indirect tests on single stones

The indirect tests were performed along the two columns defined by the set of points in Fig. 4. Impacts on Point 1 were received on the different points of the same column: points 3, 5 and 7; impacts on Point 2 were received on points 4 and 6 of the respective column. R and P-wave velocities were computed through the impact and the accelerometer time history curves and using a linear regression in a process similar to the one given in ultrasonic measurements on concrete British standard [13]. This process is referred to in previous works [11] and illustrated in Figure 7. Then, the velocities of R and P-waves were correlated in order to validate the results by computing the Poisson´s ratio in Eq. 3. Notice that R-waves are slower than P-waves, being the seconds around twice faster than the firsts. This and the fact that the content of acceleration perpendicular to the wall, i.e. caught by the accelerometer, is much higher for the R-waves than for the P-waves, allow distinguishing the arrival of the two waves at the receiver, [11] and [4].

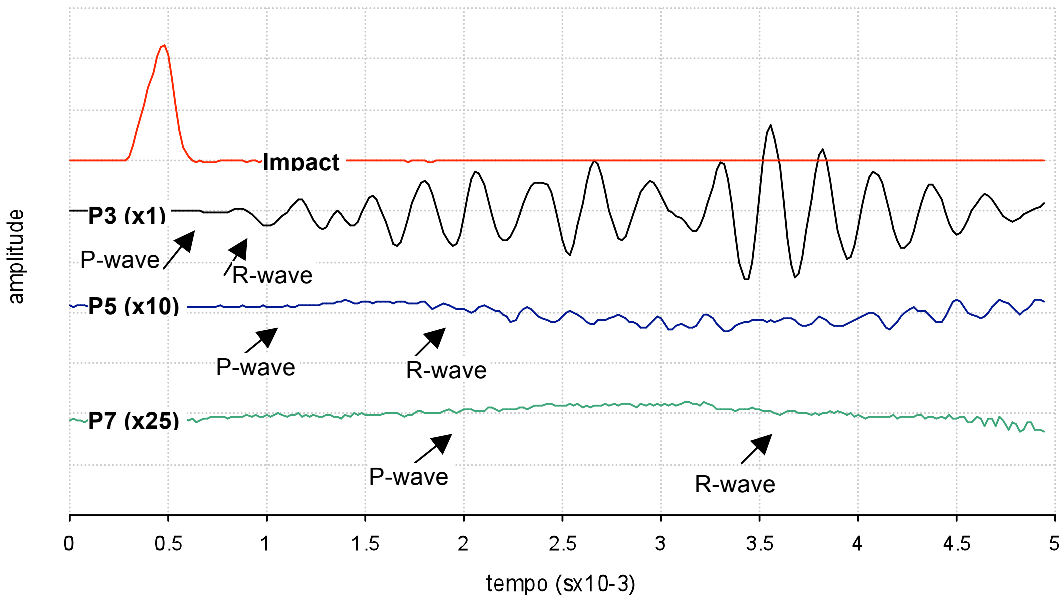


Figure 7: Illustration of the sonic tests results with the instant corresponding to the arrival of P and R-waves on Column 1 before the load test.

Table 2 presents the P and R-wave velocities results for indirect tests along each column. The linear correlation coefficient, $r^2$, and the values obtained from linear regression are also given. In the case of the impact on point 2, only 2 points were considered and, therefore, $r^2$ = 1. The last column shows the relation between R and P-waves velocities.

Table 2 – R and P-wave velocities obtained from the indirect tests.

| | **Wall face** | **Test direction** | **P-wave** | | **R-wave** | | **Vr/Vp** |
|---|---|---|---|---|---|---|---|
| | | | **Vp (m/s)** | **$r^2$** | **Vr (m/s)** | **$r^2$** | |
| Before LT ($\sigma_c$=0) | L | Column 1 (from 1 to 7) | 512 | 0.90 | 309 | 0.94 | 0.60 |
| | | Column 2 (from 2 to 6) | 613 | (1.00) | 316 | (1.00) | 0.52 |
| | E | Column 1 (from 1 to 7) | 680 | 0.94 | 354 | 0.96 | 0.52 |
| | | Column 2 (from 2 to 6) | 1036 | (1.00) | 396 | (1.00) | 0.38 |
| During LT ($\sigma_c$=2.5) | L | Column 1 (from 1 to 7) | 1289 | 1.00 | 882 | 1.00 | 0.68 |
| | | Column 2 (from 2 to 6) | 2150 | (1.00) | 877 | (1.00) | 0.41 |
| After LT ($\sigma_c$=0) | L | Column 1 (from 1 to 7) | 752 | 0.97 | 545 | 0.93 | 0.60 |
| | | Column 2 (from 2 to 6) | 961 | (1.00) | 320 | (1.00) | 0.52 |

Table 2 shows a tendency to increase the P and R-wave velocities with the compressive loading. The individual values of velocity were averaged and the Young´s modulus was computed with Eq. 1 and the Poisson´s ratio obtained through Eq. 3. The results are presented in Table 3.

Table 3 – Average results obtained before, during and after the LT.

| | **Vp (m/s)** | **Vr (m/s)** | **Vr/Vp** | **$\nu$** | **E (GPa)** |
|---|---|---|---|---|---|
| Before LT ($\sigma_c$=0) | 710 | 344 | 0.48 | 0.31 | 0.9 |
| During LT ($\sigma_c$=2.5GPa) | 1720 | 880 | 0.51 | 0.28 | 6.0 |
| After LT ($\sigma_c$=0) | 857 | 433 | 0.51 | 0.29 | 1.5 |

Because a compression test was performed at the same time of the sonic tests, the results from the two tests were crossed Figure 9 presents the Stress-Strain curve obtained from the load test on PP2 [10], with the Young modulus obtained under different conditions, including those of the sonic tests, namely:

- ✓ $E_{SBLT}$ – Young´s modulus obtained by sonic test before the LT;
- ✓ $E_{SDLT}$ – Young´s modulus obtained by sonic test during the LT;
- ✓ $E_{SALT}$ – Young´s modulus obtained by sonic test after the LT;
- ✓ $E_{EA}$ – Young´s modulus of the segment A-B of the LT curve;
- ✓ $E_{EE}$ – Young´s modulus of the segment D-E of the LT curve;
- ✓ $E_{EF}$ – Young´s modulus of the segment E-F of the LT curve;
- ✓ $E_{EH}$ – Young´s modulus of the segment G-H of the LT curve.

Notice that the LT on the panels were performed with a lateral confining structure, which imposed a maximum load of 70KN. After reaching the compressive strength, the panel was unloaded, the confining structure was retrieved and the panel was loaded again until the new load capacity was reached. These two steps are illustrated in Figure 9.

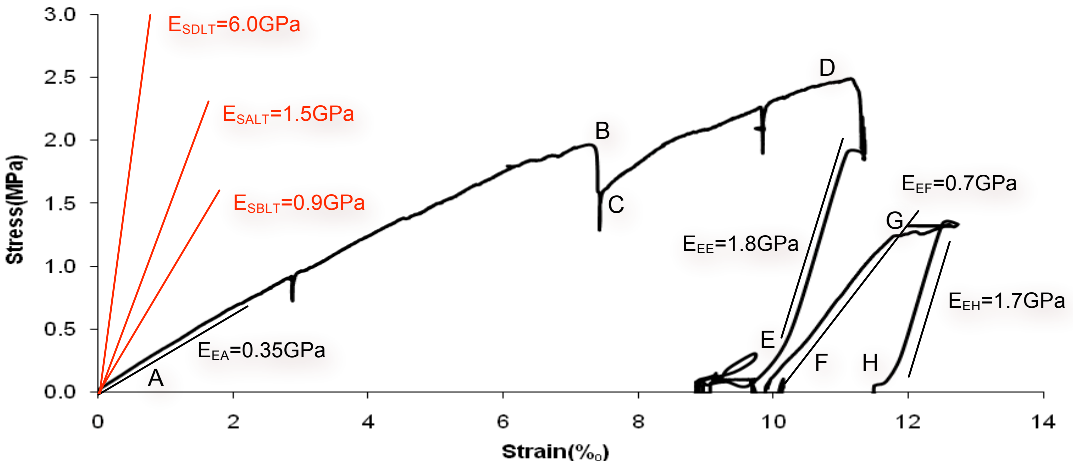


Figure 9: Stress-strain curve obtained from the load test and the Young modulus computed for different situations for PP2.

The results of the indirect sonic tests along the surface, i.e., reflecting the stones and the joints behaviour, showed an increase of the Young´s modulus when the compression force increased, the opposite of what happened to the individual stones. These results can be perceived as contradictory. Notice that the Young´s modulus refers to the unloading and reloading curves below the monotonic. As a matter of fact, this parameter defines the state of the masonry for a certain level of compression load, being estimated through the P or R-wave velocities.

To understand these results one should analyse the materials behaviour. In particular, two things can happen: the compression on the walls can make the void volume decrease and promote a better rearrangement at the joints, increasing the wave velocities; and it can create cracks and (or) micro-cracks that make the velocities decrease. These changes in velocity reflect the Young´s modulus variation of composite wall. In particular, for relatively high plasticity materials, or plastic structures like the tested panels, most of the imposed displacement comes from the rearrangement of the mortar joints and isn’t recovered; also, the compression load decreases the void size. As a result, a reduction of the joint thickness and void ratio occurs and consequently the wave velocity increases, i.e., the unloading and reloading stiffness of the masonry increases, as it is observed in Figure 11. A similar behaviour happens for soils: the compression can be due to rearrangement, fracture and (or) distortion of grains.

Notice that the variation of the Young´s modulus of just the mortar samples with the confining stress is being investigated by several authors. In particular, on the following three studies, different conclusions are reached: Khoo [14] concluded that for a mortar type 1:1:6 the Young´s modulus decrease with the confining stress; on the other hand, Atkinson and Noland [15], in 1985, obtained opposites results; in 1998, Mohamad [16] concluded that both increase (mortar types 1:0.25:3 and 1:0.5:4.5) and decrease (mortar type 1:1:6) of the Young´s modulus with the confining stress could take place, depending on the type of mortar.

If one were to look at the stone behaviour, similar results have been observed in sandstones, namely the increase of the Young´s modulus with the applied stress for a load below 60% of the ultimate load, [17]. Such increase is permanent, possibly due to the reconfiguration of particles and consequent filling of voids. Only for greater stresses, when formation of micro cracks occurs does the Young´s modulus starts decreasing. However, in the case of the granite stones that form the panels studied in this work, the reconfiguration of the particles does not occur. Instead, cracks or micro-cracks created by the compression load are formed, making the wave velocity decrease, as observed in the direct sonic tests. These results also show a high influence of the joints in the wall behaviour, in fact they dominate the plastic behaviour of the masonry.

Considering now the comparison of the results between the indirect sonic tests and the LT, the first estimated a Young´s modulus for the wall, before the LT, is almost 3 times higher than the Young´s modulus measured in the LT at the beginning of the test. However, the vertical cuts on the walls have shown that the joints exhibit mortar only close to the surface and that large voids exist between stones. Therefore, as in the indirect sonic test the waves propagate only along stone contact points or along joints with mortar continuity, the value for Young´s modulus obtained is not necessarily expected to be the same. This result was checked using another wall panel, PP3.

The panel PP3 was first tested in the same conditions as the ones already described for PP2. Then, its joints were injected with a mortar with poor mechanical characteristics, [10], and tested again. This test showed that with the injection of the mortar, the Young´s modulus increased from 0.3GPa to 0.9GPa as would be expected, see Figure 11.

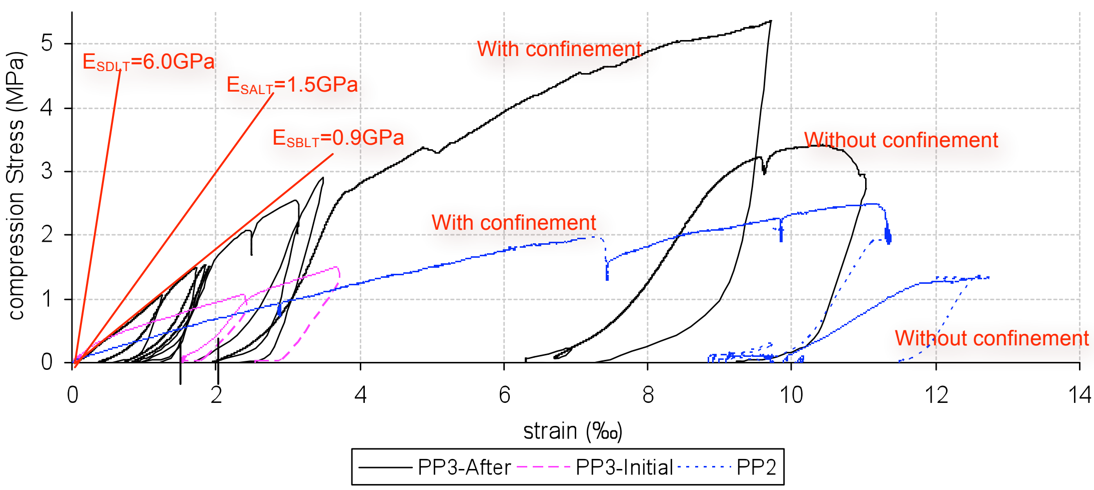


Figure 11: Stress-strain curve obtained from the LT and the Young modulus computed for different situations.

Interestingly, the sonic test results produce results more similar to the ones obtained for the injected panel than the ones obtained for the original "non-injected" panel, i.e., the value of E is higher. For this reason, the results of the sonic tests on PP2 are compared to those of the LT on PP3 after injection, knowing that the two panels are part of the same wall and had similar initial stiffness's, see Figure 11.

For example note how the maximum sonic Young´s modulus of 6.0GPa obtained during LT of PP2 at 2,5MPa is similar to the maximum Young´s modulus of PP3, E = 9.0GPa, during unloading, see Figure 11.

It is clear that the Young's modulus varies before, during and after loading of the wall. It is also clear that sonic and load tests produce different results for all three stages, despite varying in the same way, i.e, maximum during loading, minimum before loading and intermediate after loading. It is therefore relevant to note that despite their differences; both types of tests show a stiffer behaviour for a loaded wall and also seem to show that some rearrangement does take place with loading. As for how best to correlate mechanical and sonic tests, there is still room for more testing to be done until a robust correlation can be proposed which further reflects the complex nature of a composite, non-continuum masonry wall.

## Conclusion

Sonic tests were performed on a stone masonry panel which was compressed vertically and confined laterally. The results concerning the sonic wave velocities and, therefore, the Young´s modulus of the panel before, during and after the LT were analysed and compared to the results of the Young modulus obtained in the LT during loading and unloading.

The sonic test campaign included tests on discrete stones (direct tests) and tests along the panel facade (indirect tests) in order to account for the composed effect of joints and stones, simultaneously. In particular, the Young´s modulus estimated for the stones through the direct sonic tests before the LT was, on average, of 24GPa. Compression tests performed on stones of the same building reached an average Young´s modulus of 26GPa, quite close to the previous ones.

The velocity measured during the direct sonic tests on stones showed a decrease of about 17%, during the load test (for the maximum load), probably, as a result of micro-cracks generation on the stones. Because of the irreversibility of this damage, that reduction maintained after the LT.

The indirect sonic tests reflected the particular characteristics of the masonry and showed a good agreement with the stress strain curve of the LT on PP3 after injection:

- ✓ Before the load test it was obtained a Young´s modulus of 0.9GPa, equal to the one obtained at the beginning of the LT;
- ✓ During the load test the Young´s modulus (understood as the unloading and reloading modulus) increased, as the result of the compression of the joints mortar, which corresponds to a decrease of the voids and a better rearrangement of the particles. The Young´s modulus estimated by the sonic test and measured

in the LT for the maximum applied load is 6.0 and 9.0GPa, respectively;

- ✓ After the LT, the Young´s modulus reduced. However, it is higher than the Young´s modulus measured before the LT. This happens because the compression, especially in the mortar, is mostly irreversible. Comparing the Young´s modulus estimated by the sonic tests and the one measured in the LT, they are 1.5 and 3.4GPa, respectively.

Sonic tests do not allow, just by themselves, to explain the behaviour of a wall, they contribute for a global understanding of local and global phenomena involved. However, if properly applied to a masonry wall, sonic tests give useful information concerning Young´s modulus. Through sonic tests it is possible, in a non-destructive way, to characterize masonries. However, to be able to extrapolate the results obtained and the method used in this work in analyses of this or other types of walls, the procedure should be applied and validated for a higher number of samples.

As final conclusion, the indirect sonic tests allowed estimating, with a quite good approximation, the Young´s modulus of a masonry wall. The values obtained with the sonic procedures are in the range of the measured values in the LT.

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