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Non-destructive characterization of ancient clay brick walls by indirect ultrasonic measurements

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Abstract

In this work, ultrasonic tests were carried out on the external walls of the Nossa Senhora do Rosário dos Pretos Church, an ancient masonry structure from the 18th century placed at Aracati, Brasil. The main aim of this research was to characterize the ultrasonic velocities of the external walls of the church, in view of further maintenance measures, as well to collect quantitative data on the state of conservation of the church. Fort that purpose, a methodology based on indirect ultrasonic measurements was developed and is presented in this paper. The results show that ultrasonic tests can be applied for characterizing wall homogeneity, offering useful information for control of maintenance or retrofitting measures.

Keywords: ultrasonic test, masonry structure, non-destructive characterization, heritage constructions, Nossa Senhora do Rosário dos Pretos Church;

1. Introduction

Currently, heritage construction characterization has been a subject of large interest worldwide, especially due to the necessity for further information on structural properties and its global behavior[1]–[3]. This way, some efforts had been done for make available the application of non-destructive testing (NDT) for supporting structural assessment of heritage constructions, as for instance, the employment of vibrational methods, advances on numerical models strategies, or by application of monitoring techniques [4]–[8].

While advances in the methodologies for assessment of heritage constructions have been most frequently reported in the literature in the last 20 years (see [9]–[15]), a very relevant concern is the employment of non-destructive methods for characterization of the static and dynamic structural parameters, as a form of identification of the linear and non-linear properties of the structural system [16]. Thus, the development of non-destructive techniques that allow the accuracy characterization of historic buildings elements, getting information on its physical or mechanical properties, are interesting topics for historic building assessment field.

Among NDT, sonic tests are the most applied worldwide for characterize the variability of the masonry walls. Actually, masonries characterization are always a difficult task due to its typologies variability and anisotropic properties [17]. In the work presented by [18], for instance, sonic tests were employed for characterize the variability of the materials of the walls of the Noto Cathedral (Italy). For that, a hammer and an accelerometer were placed directly on the wall, in opposite sides, distributed along of the walls perimeter, without any regularization layer. As results, was possible to identify and to characterize how the heterogeneity of the masonries walls can influences the sonic velocities collected. From a global perspective, the sonic test allowed the detection of the variations along of the walls analyzed and contributed for a successfully analysis of the walls quality.

Following, the work presented by [19] performed on the temple of S. Nicolò l’Arena (Italy), show an interesting case of sonic tests application for characterization of brick masonries elements. A careful visual inspection was done focusing the columns, and their main damages, essentially cracks, were identified, and then, flat-jack test were performed. The sonic test results were processed and sonic topographies were obtained, and the internal section of the columns were qualitatively characterized. The combination between visual inspection, sonic topographies and flat-jack tests allowed to the technical team state a global view of the columns behavior and homogeneity.

Regarding the employment of sonic tests to masonries characterization, a step forward was given by [8], where the authors developed a new technique for stone masonry characterization by sonic tests, precisely indirect sonic impact method (ISIM). The authors carried out an extensive experimental program on stone masonries walls, and ultrasonic velocities were collected and analyzed. Additionally, the *P* waves velocities were used for estimations of the Elasticity's Modulus and the results were compared with experimental tests carried out on stone masonries samples. Finally, in a global view, ISIM presented reliable data for non-destructive characterization of the stone masonries walls. It is also important to note that, in first step of this work ultrasonic tests were performed on the stone masonries walls, however the ultrasonic signal collected was insufficient, probably due to the high number of joint interfaces and the walls robustness, as pointed by the authors.

RILEM recommendations for ultrasonic velocity characterization on masonries clearly make reference to ultrasonic direct test, where the receiving accelerometer is placed on the opposite side of the signal emitter [20]. Then, the ultrasonic velocity can be calculated by Expression (1), where V is the ultrasonic velocity, l is the pulse path length, and t is the pulse path time, as shown below.

$$V = \frac{l}{t} \tag{1}$$

However, carry out direct ultrasonic measures on masonries walls not always is possible, making necessary the systematization of indirect ultrasonic velocities measurements. Thus, the present work intents to contribute for enlargement of the ultrasonic test application on masonries walls through ultrasonic velocities characterization of the external walls of the Nossa Senhora do Rosário dos Pretos Church. For that, a new method for clay brick masonries characterization based on ultrasonic waves, here assigned as indirect ultrasonic pulse method, IUPM, was developed and applied on a real structure.

Indirect ultrasonic measures are reported in the literature for stone masonries applications in the Europe Zone [21]. However, this is the first time that a case of Portuguese-Brazilian characterization by ultrasonic measures is reported in the literature. The methodology proposed in this paper considers the dimensions and composition of these Portuguese-Brazilian elements, and states a procedure for non-destructive characterization with distances between each measure very well stated.

2. Ultrasonic theory

Essentially, the materials are composed by particles, that in the most elementary level are Boson of Higgs[22], with a defined quantity of energy that is transported by waves causing vibrational movements. In the solids, these particles present a most organized arrangement form due to the fact that they are nearly from each other, but still presenting vibrational movements.

The waves can be divided in mechanic and electromagnetic waves, according to its propagation field, but for this work understanding only mechanic waves presents interest. Mechanical waves can be subdivided in body waves, that correspond to waves with propagation inside the materials, and in superficial waves. A complete description of waves characteristic can be found in [17]. In another way, according to the wave propagation behavior along of a body, the waves can be classified as *P*-waves, that have longitudinal propagation, while *S-waves* presents a perpendicular propagation and the *R-waves* have as main characteristic an elliptical propagation movement.

In this paper, the *R-waves* will be discussed because they are the bases for the clay brick masonries characterization presented in this report. Considering that due to dimensions of the historic building elements, as masonries, direct ultrasonic measurements are not possible. Thus, indirect ultrasonic measures are alternative way to characterize the ultrasonic properties of these elements. Also, the non-influence of the mortar layers in the ultrasonic velocities propagations, as discussed in [8], allow to collect information on the all masonry components (clay bricks and mortar), making the indirect characterization an accurate way for masonry data obtainment. However, while masonries can be treated as a surface, the statement of appropriated distances between each one ultrasonic measure is very important for an accurate characterization.

3. Nossa Senhora do Rosário dos Pretos Church

Nossa Senhora do Rosário dos Pretos Church (Figure 1) is a Brazilian masonry structure placed at Aracati downtown, 150 km away from Fortaleza, the capital of the Ceará State. The Aracati city was founded on 1747 and presents one of the most important historic center of the Ceará State, with buildings from XVIII and XIX centuries with high Portuguese influence on its architecture. In the beginning of 2000 years Aracati historical center was classified as national heritage by *Historical Heritage and National Artistic Institute (IPHAN, Brazil)*, a first step for be candidate to Word Heritage, by UNESCO.

The Nossa Senhora do Rosário dos Pretos Church was built in 1775 by black man come from Africa, motivated by social and religious exclusion, and retrofitted on 1930. After that, in 1974 the church was affected by a flooding and part of the lateral north of the church collapsed (Figure 2). Only in 1982 the church was retrofitted and opened to public visitation. Today, the church is considered as one of the most relevant examples of black resistance and a symbol of the black fights against the discrimination in Brazil.

Geometrically, the Rosário dos Pretos Church comprises a rectangular clay brick masonry structure, measuring 17.11 m along of the transversal direction and 35.79 m along the longitudinal direction, composed by the central nave with 8 columns distributed till the Altar-Mor, two lateral atriums and one tower in the left side of the main façade, with 22.87 m of height. The detailed view of the church is presented by Figure 3.

The main motivations for choosing Nossa Senhora do Rosário dos Pretos Church as case study, was the absence of structural records on the interventions performed on this building in the past, beyond it comprises an important heritage construction to Brazilian community. Moreover, in the final of 90s two reinforced concrete slabs were built in both lateral sides of the main nave, supported by the columns and the lateral walls of the church, as shown by Figure 3, and its long-time effect to structural safety of the church is not known, requesting regular assessment. Additionally, the clay brick masonries found in Brazil, especially in Northeast zone, are not extensively studied yet, and few cases on structural characteristic of this type of constructions can be found in the literature. The clay bricks of the Nossa Senhora do Rosário dos Pretos Church present an average dimension of 90x150x300mm and the detail of the clay brick masonry without mortar layer is presented through Figure 4.

4. IUPM - Indirect ultrasonic pulse method

In this experimental work, an ultrasonic equipment TICO *PROCEQ*® with transductors of 54 kHz were employed. The data processing was carried out based on [23] recommendations.

6 walls were selected for application of the ultrasonic testing, namely the walls were identified as P1L, P3L, P5L and P7L at the lateral north of the church, as P1MF at the main façade and as P3R at the lateral south of the church, as showed by Figure 5. For each wall, were performed ultrasonic tests considering horizontal (X) and vertical (Y)

directions, always with frames of acquisition of 0.50m x 0.50m. Each frame of data acquisition was composed by 5 measures (in the center of the frame) with the ultrasonic receptors spaced 50 mm at horizontal direction and the transductor in a fixed point, as showed by Figure 6. Sequentially, the walls P1L, P5L and P7L were divided in a panels of data acquisition composed by 3x3 frames, while the other walls were divided in panels of 2x3 frames. It is important to note that the lateral north of the church was selected as the principal wall of characterization due to the fact that this wall presents the original characteristic since it constructions.

The methodology followed in this work taken into account the dimensions of the clay bricks of the church, with 300 mm of length, and the walls arrangement. This way was stated that the minimum layer of data acquisition needed to have more than 400 mm (300 mm from clay brick and more 100 mm for include a join between two clay bricks), and that the transductor T should be stay always in a fixed point. Since these two statements, was stated as methodology for these ultrasonic tests characterization that the distance between the transductor T and the first receptor (R1) should be 200 mm and, sequentially, 50 mm should be added to each points of signal reception (R2, R3, R4 and R5), as showed in the Figure 7, making a total distance between the transductor T and the receptor R5 of 400 mm (see detail of the Figure 6). After five ultrasonic velocities be recorded, in each one frame, the data collected were submitted to statistical treatment and the maximum and minimum values of each one of the walls were identified, as well the ultrasonic velocities average and its respective standards deviation.

5. Results

Regarding the ultrasonic velocities, P1L (Figure 8.a) presented highest values than the others clay brick panels (Figure 8.b, c and d). The range of ultrasonic velocities observed in P1L vary between 2379.33 m/s, at 1.00 m of height, to 675.67 m/s, at 2.00 m of height. It was also observed that if the same height was considered, the measures of ultrasonic velocities present variation along of the X direction, in which the ultrasonic velocities collected in 1.00 m of height presented more dispersion than other two measures at another two height analyzed, namely at 1.50 m and 2.00 m. The average of the ultrasonic velocities measures performed at 1.00 m of height was of 1546.40 m/s, while the averages in the heights of 1.50 m and 2.00 m were 1219.93 m/s and 144.93 m/s, respectively. Taking into account the ultrasonic velocity average in

1.00 m as referential, the values of ultrasonic velocities in 1.50 m and 2.00 m presented an average decrease of 26.76% and 51.82%. Similar behavior of the ultrasonic velocities found in this work also were found in [18].

Considering the ultrasonic velocities collected by P3L testing (Figure 8.b), it was observed that the ultrasonic velocities averages (considering variations in X direction) also vary from 317.46 m/s to 564.51 m/s, corresponding to 1.00 m and 1.50 m of height of the measures performed on the panel. The ultrasonic velocity average was of 663.93 m/s to the height of 1.00 m, while for 1.50 m and 2.00 m of height the averages were of 526.85 m/s and 366.40 m/s, respectively. These values represent a decreasing in the ultrasonic velocities of 20.46% and 44.81% to 1.50 m and 2.00 m of height, considering the height 1.00m as reference. Similar behavior also was observed in P7L clay brick panel (Figure 8.d), in which the maximum value of ultrasonic velocity recorded was of 1254.48 m/s and the minimum was of 694.44 m/s, and the ultrasonic velocities average to 1.00 m, 1.50 m and 2.00 m were of 1049.82 m/s, 898.87 m/s and 850.07 m/s, respectively, corresponding to an average variation of the ultrasonic velocities of less 14.37% and 19.02%, considering the ultrasonic velocities measures at 1.00 m of height of the panel as referential.

Now, in relation with P5L results (Figure 8.c), it was observed that while the records of ultrasonic velocities at X distance of 20.42 m decrease for height variations, the values of ultrasonic velocities at X distance of 19.28 m increase for height variations between 1.00 m and 2.00 m. In addition, the ultrasonic velocities collected at X distance of 18.14 m, presented an increase of 467.28 m/s to 798.72 m/s between 1.00 m and 1.50 m, and a decreasing of 798.72 m/s to 508.68 m/s, between the heights of 1.50 m and 2.00 m. The ultrasonic velocities averages at the heights of 1.00 m, 1.50 m and 2.00 m were of 736.34 m/s, 590.99 m/s and 732.82 m/s, respectively. Considering the ultrasonic velocity average at 1.00 m as reference, in terms of percentage, the ultrasonic velocities vary in the order of 19.73% and 0.47% for 1.50 m and 2.00 m. In this case, the ultrasonic velocity behavior of the P5L clay brick panel can be explained taking into account the P5L position (see Figure 5), where a column possibly influences the ultrasonic velocities measured due to rearrangement of the compression and tension forces (in comparison with the other panels), provoking an inversion of the ultrasonic velocities behavior as the X position moves away from the column. In other words, changes in the ultrasonic velocities can also be related with variation from a zone with less stiffness to a zone with greatest stiffness, in the case of the P5L panel from 20.42 m to 18.14 m along of the X direction.

Concerning the ultrasonic velocities results obtained by P1MF and P3R testing, shown by Figure 9.a and b, respectively, the ultrasonic velocities values vary from 576.69 m/s to 1853.22 m/s (to P1MF) and from 580.27 m/s to 1158.30 m/s (to P3R). The P1MF panel (Figure 9.a) presented an ultrasonic velocity average of 1688.40 m/s for height of 1.00 m, while for 1.50 m and 2.00 m the ultrasonic velocities averages obtained where of 647.98 m/s and 583. 04 m/s. Considering the ultrasonic velocity average at 1.00 m as referential, the average values found for height of the 1.50 m and 2.00 m represent a decreasing in the ultrasonic velocities by height variation of 61.62% and 65.46%. Now, in relation to P3R clay brick panel (see Figure 9.b), the ultrasonic velocities averages found at the heights of 1.00 m, 1.50 m and 2.00 m were of 1019.67 m/s, 708.90 m/s and 769.06 m/s. In terms of percentage, considering the ultrasonic velocity measured at 1.00 of height as reference, the ultrasonic velocities values decreased 30.47% (for 1.50 m of height) and 24.57 % (for 2.00 of height). Complementarily, it is possible to note a lower dispersion between the ultrasonic velocities found by P3R testing, really different than the others analyzed clay brick panels. This different behavior can be related with the fact that this wall was rebuilt around 1982 and, this way, presents different constructive methodology and clay bricks with different characteristic (perhaps with mechanical properties improved) than the clay bricks used in the original walls.

Considering the joint of values of the ultrasonic velocities collected in each clay brick panel during the experimental tests, and in order of to state global values for each one of the panels, the maximum and minimum ultrasonic velocities were calculated and compared between then. In addition, the ultrasonic velocities averages and its respective standards deviations also were obtained. The comparison between all obtained values are presented in Table 1.

Additionally, the ultrasonic velocities mapping of the sections P1L, P3L, P5L, P7L, P1MF and P3R were carried out. Through Figure 10.a, it can be noted that high values of the ultrasonic velocities can be found in the bottom of the P1L layer, possible due to the fact that region is under higher compression forces than the top region of the layer. Following, the mapping of the P3L ultrasonic velocities (Figure 10.b) demonstrates a quite homogeneity in this panel, with values of ultrasonic velocities lower than 1660 m/s. Moreover, the top of the section P3L presents sensible low values of ultrasonic velocities that the bottom zone, and this can be related with the windows existences close the analyzed section.

From the analysis of the ultrasonic velocities distribution on the section P5L, shown by Figure 11.a, low ultrasonic velocities, aver around 600 m/s, were found between18.5 m and 19.5 m of the X axes, characterizing the heterogeneity of this section in comparison with the others, while the analysis of the section P7L (Figure 11.b) shows homogeneity in the ultrasonic velocities distribution. After removal of the recovering layer (Figure 4) of the PL5 section, it was observed that the (irregular) distribution of the massive bricks in the region between 18.5 m and 19.5 m of the X axes was different than the other analyzed sections, with regular distribution of the massive bricks.

The analysis of the P1MF section (Figure 12), in the main façade, demonstrates similar behavior than the found in the P1L analysis, the high values of ultrasonic velocities found in the bottom of this section can also be related with the compression loading. It can be also noted that, since the main façade wall presents 1.40 m of high, the ultrasonic velocities tend to stabilize around 1100 m/s. In the south façade, the wall section P3R mapping is presented by Figure 13, where the ultrasonic velocities present a homogeneity distribution, aver around 900 m/s, with low dispersion between the record values. The P3R panel is located in the wall built around 1982, after the partial collapse of the church. This way, a most homogenous ultrasonic velocity behavior in this wall section can be related with employment of modern clay-bricks and cement composites, as well with the employment of a different methodology for masonry construction than the employed in the other walls.

6. Conclusions

In this paper, an experimental study on characterization of the Nossa Senhora do Rosário dos Pretos Church by ultrasonic velocities was carried out. For that, six wall sections were selected and a new methodology for indirect ultrasonic pulse measurement was presented.

The results of the analysis of the sections located in the non-retrofitted walls of the Nossa Senhora do Rosário dos Pretos Church showed that the values of ultrasonic velocities can vary between 317.46 m/s and 2379.33 m/s. This large range can be related with constructive methodology employed in the begging of the 18th century at the Ceará, as well can be related with loading distribution and walls geometry. The analyses of the ultrasonic velocities of the retrofitted wall demonstrates lower dispersion between the collected values, with a standard deviation of 229.30 m/s.

Finally, the methodology employed for ultrasonic characterization of Portuguese-Brazilian masonries allowed to obtain data on the distribution/variation of the ultrasonic velocities on the analyzed sections. Additionally, the collected information contributes for understanding of the structural characteristics of the Brazilian heritage structures.

Acknowledgments

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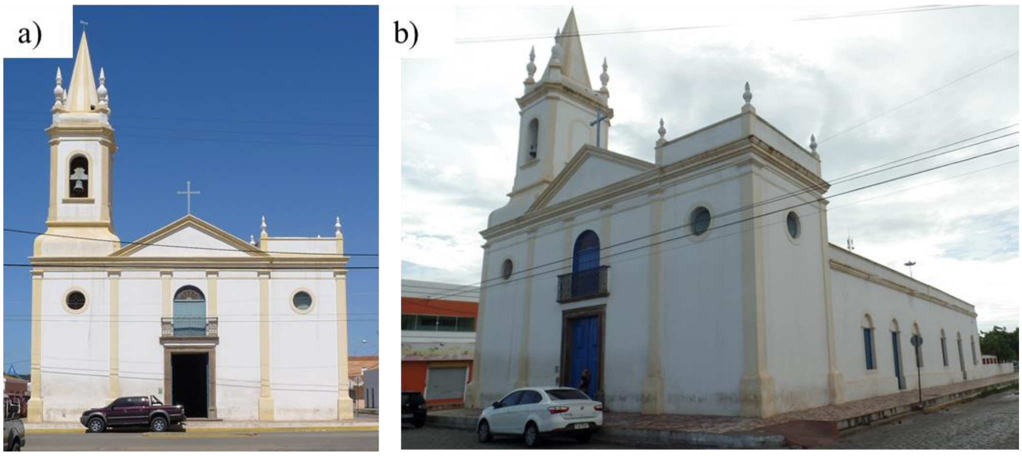

Figure 1. Nossa Senhora do Rosário dos Pretos Church: a) main façade and b) lateral view.

Figure 2. Partial collapse of the Nossa Senhora do Rosário dos Pretos Church, in 1974.

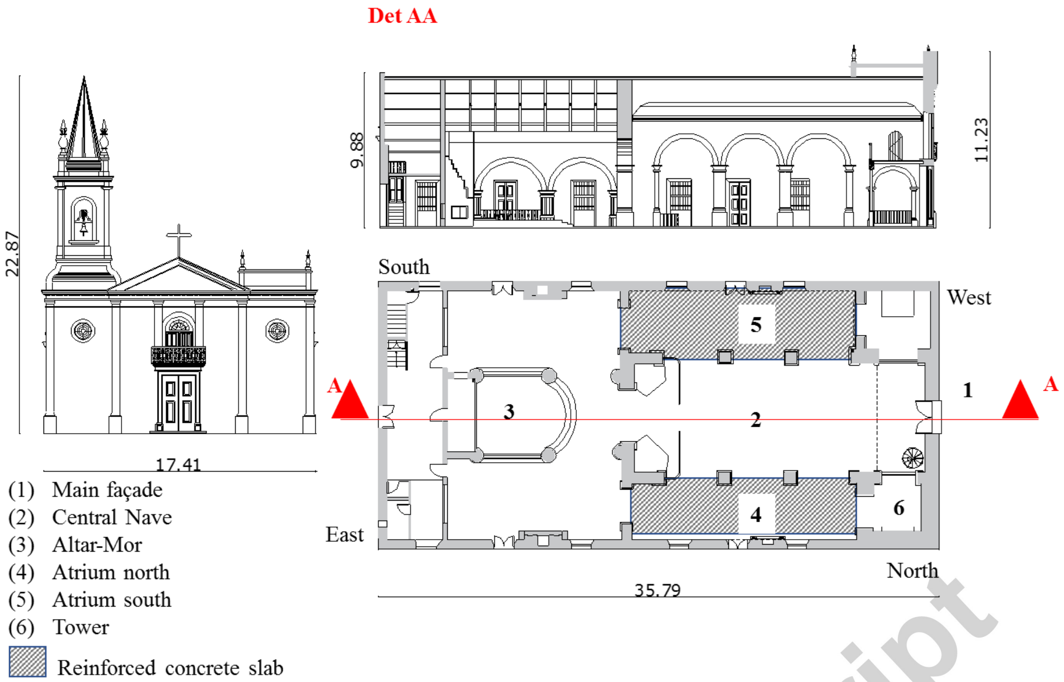

Figure 3. View in plant of the Nossa Senhora do Rosário dos Pretos Church.

Figure 4. Detail of a clay brick masonry without mortar layer.

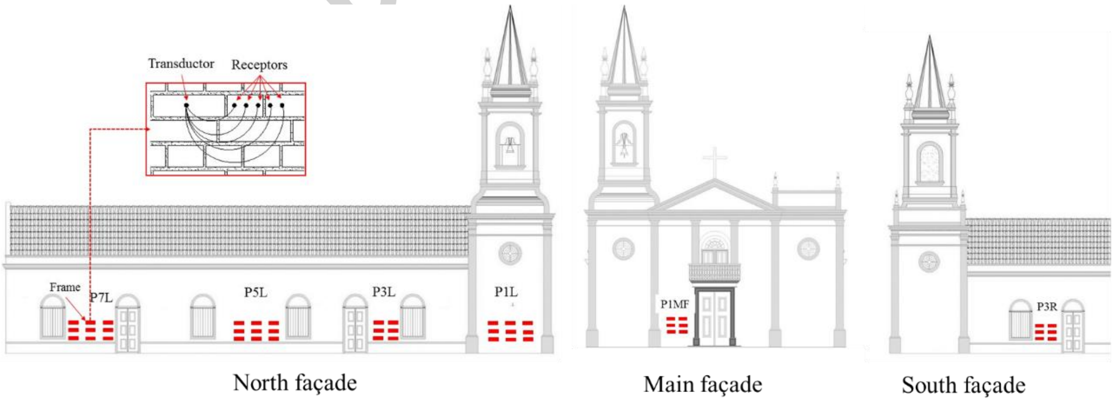

Figure 5. Detailed experimental setup of ultrasonic tests performed at Nossa Senhora do Rosário's Church.

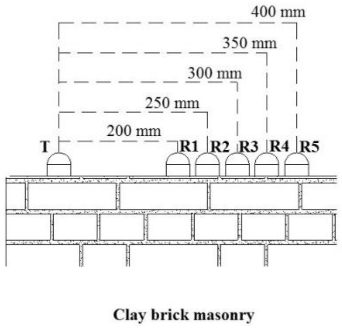

Figure 6. Schematic view of the distances between transductor and the receptors.

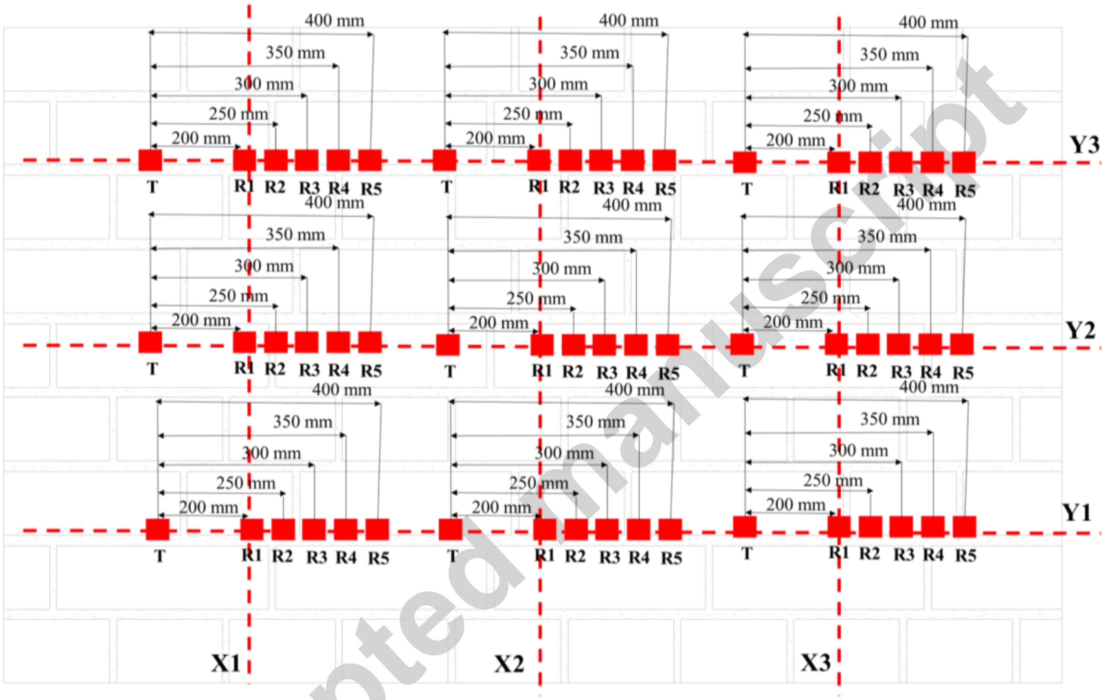

Figure 7. Schematic view of the IUPM setup, where T is transductor positioning while R refers to Receptors placement.

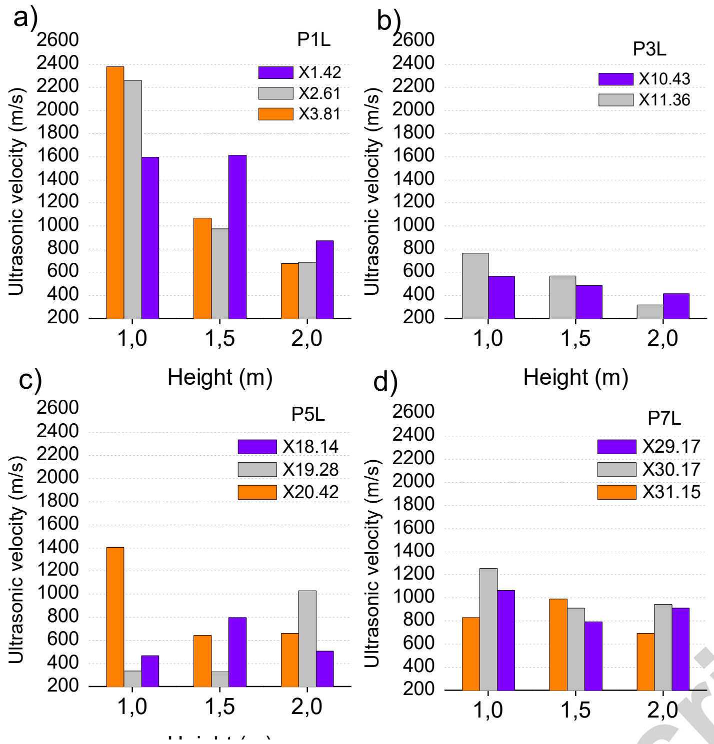

Figure 8. Height influence on ultrasonic velocities of the clay brick masonries P1L, P3L, P5L and P7L of the Nossa Senhora do Rosário dos Pretos Church.

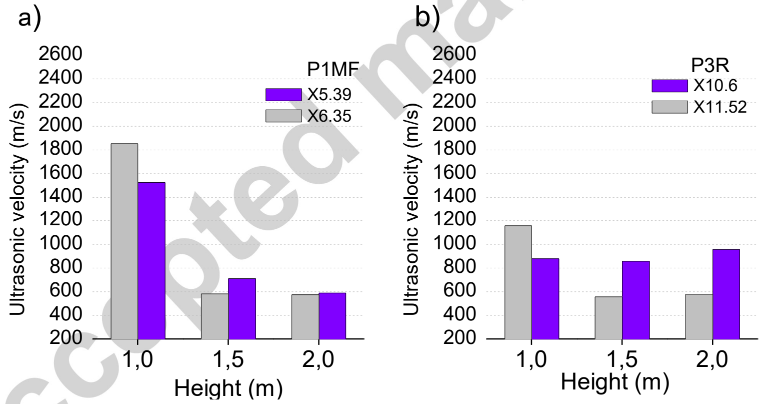

Figure 9. Influence of height on ultrasonic velocities of the clay brick masonries P1MF and P3R of the Nossa Senhora do Rosário dos Pretos Church.

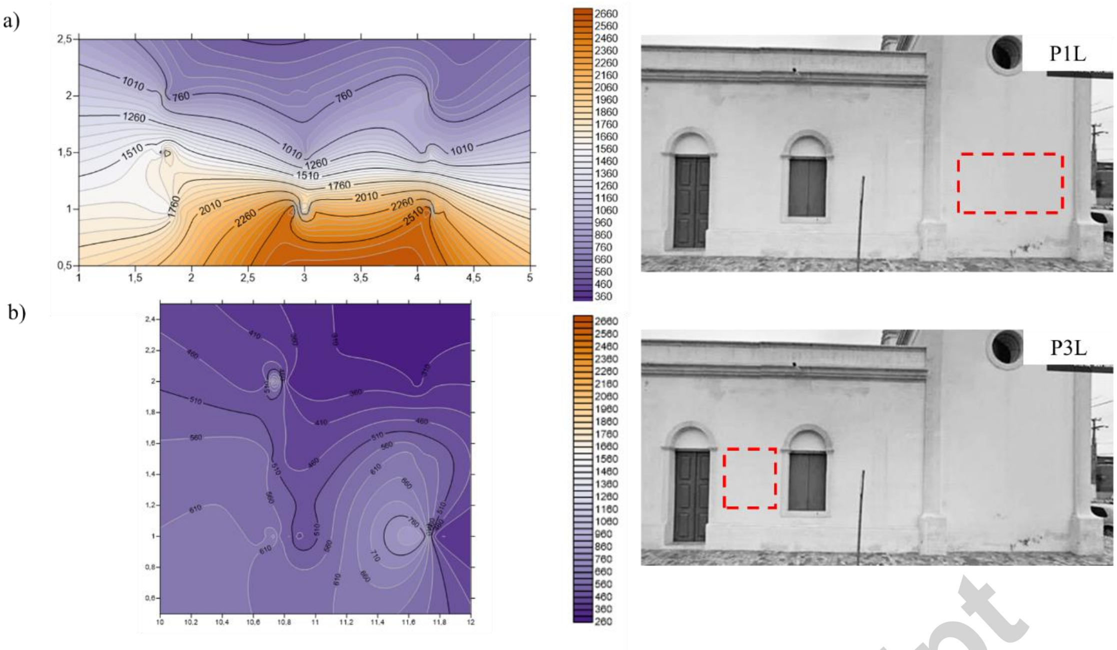

Figure 10. Ultrasonic velocities (m/s) distribution of the sections P1L and P3L.

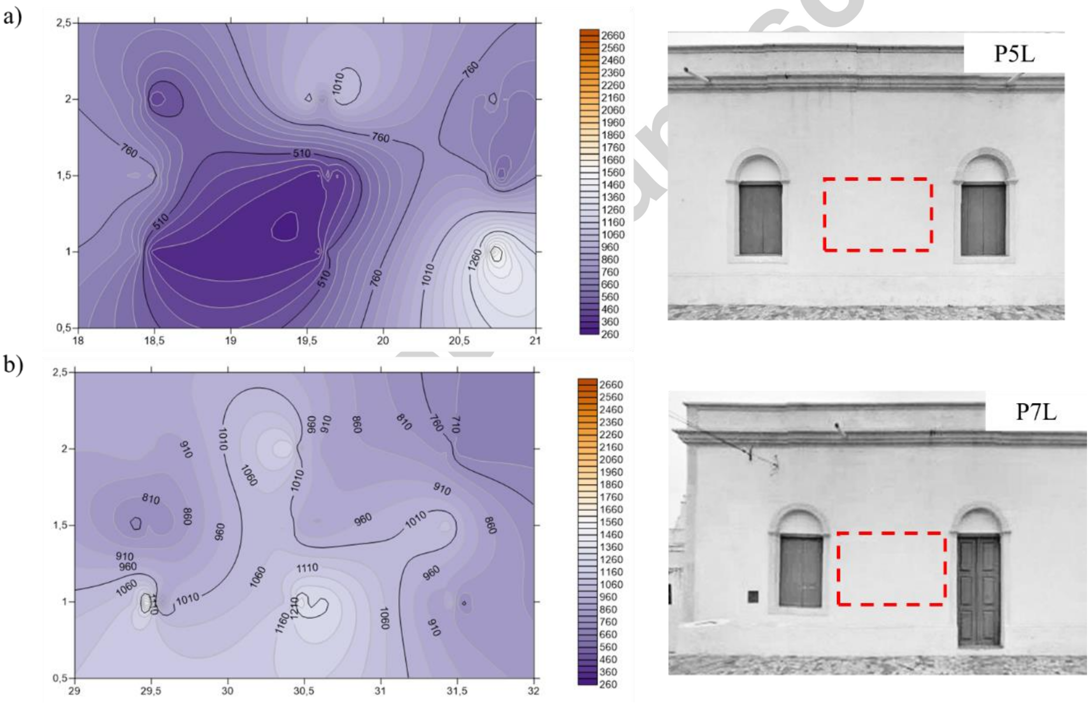

Figure 11. Ultrasonic velocities (m/s) distribution on the sections P3L and P7L.

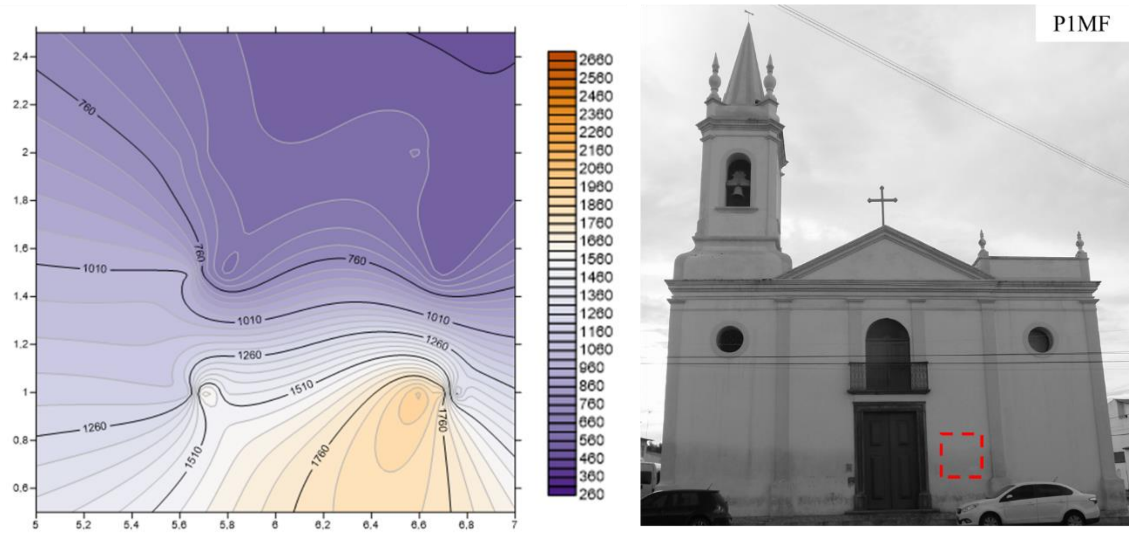

Figure 12. Ultrasonic velocities (m/s) distribution on the sections P1MF.

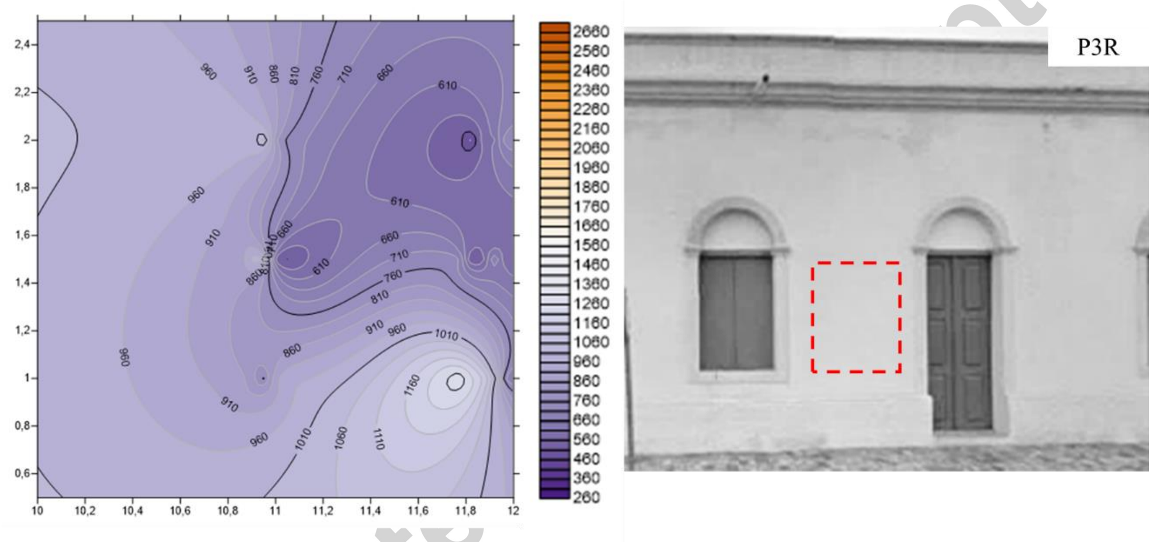

Figure 13. Ultrasonic velocities (m/s) distribution on the sections P3R.

Table 1. General results of the ultrasonic velocities and respective Elasticity's Modulus of the brick stones panels of the Nossa Senhora do Rosário dos Pretos' Church.

		Clay brick masonries panels					
		P1L	**P3L**	**P5L**	**P7L**	**P1MF**	**P3R**
Velocity (m/s)	Maximum	2379.33	763.36	1029.41	1254.48	1853.22	1158.30
	Minimum	675.68	317.46	330.28	694.44	576.69	580.27
	Average	1070.34	525.66	643.98	912.89	651.30	869.71
	Standard deviation	647.65	152.63	349.84	163.09	566.03	229.38

Highlights

[1] A Portuguese-Brazilian heritage construction is characterized by ultrasonic method.

[2] A new method for non-destructive masonries characterization is presented.

[3] The new ultrasonic characterization method was employed in full scale structure.

[4] Influence of loads and openings on ultrasonic velocities were identified.